TOMSK POLYTECHNIC UNIVERSITY | ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ

The Ministry of Science and Higher Education of the Russian Federation
Federal state autonomous educational institution of higher education
"National Research Tomsk Polytechnic University"

School School of Energy and Power Engineering
Major 14.05.02 Design, Operation and Engineering of Nuclear Power Plants
Department The Butakov Research Center

GRADUATION THESIS

UDC __________

Topic
NPP POWER UNIT PROJECT WITH VVER ELECTRIC REACTOR CAPACITY 1300 MW

Student

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Tomsk – 2020

Planned learning outcomes

Code	Learning Outcome	Requirements of FSES of HE and (or) interested employers
General by specialty		
	Universal competencies	
O1	To use the methodological foundations of the modern picture of the world for scientific cognition and creativity, to reveal the natural-science essence of problems arising in professional activity	Requirements of FSES OF HE, SSES of TPU (GC-1, PC-10), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS
O2	Analyze socially significant processes and phenomena, economic problems and social processes, responsibly participate in public and political life, apply methods of social interaction based on accepted moral and legal norms	Requirements of FSES OF HE, SSES OF TPU (GC-2, 5, 9), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS
O3	To carry out communications in the professional environment and in society as a whole, including in a foreign language, develop documentation, present and publicly defend results, master the methods of propaganda of scientific achievements	Requirements of FSES OF HE, SSES OF TPU (GC-3, 5), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS
O4	Use a systematic approach in professional activity, set goals and choose ways to achieve them, generalize, analyze, critically comprehend, systematize	Requirements of FSES OF HE, SSES OF TPU (GC-6, PC-1), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS
O5	To realize the need and demonstrate the ability to independently learn throughout life, continuous self-improvement, the development of social and professional competencies, to use the knowledge gained for training and educating new cadres	Requirements of FSES OF HE, SSES OF TPU (GC-7), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS
O6	To achieve the proper level of physical preparedness for ensuring full-fledged social and professional activity and a proper level of life safety, including protection of personnel and the	Requirements of FSES OF HE, SSES OF TPU (GC-8; GPC-1, PC-7, 19), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS

	population from the consequences of accidents, disasters, natural disasters	
O7	It is effective to work individually and in a team, including multinational, to take responsibility for their decisions, including non-standard decisions, to manage the team, to find organizational and managerial solutions in unusual situations	Requirements of FSES OF HE, SSES OF TPU (GC-5, 13, 14, PC-3), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS
	Professional competences	
O8	Use information technology to work with information, manage it and create new information; work with information in global computer networks, understand and comply with basic information security requirements	Requirements of FSES OF HE, SSES OF TPU (GPC-1, PC-2, 6, 13, 26), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS
O9	Understand the importance of their specialty, strive for a responsible attitude to their work activities, demonstrate special competencies related to the uniqueness of tasks, facilities in the design and operation of NP	Requirements of FSES OF HE, SSES OF TPU (PC-4), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS
O10	To use deep mathematical, natural scientific knowledge in professional activity with application of mathematical modeling of objects and processes in the field of design and operation of nuclear reactors	Requirements of FSES OF HE, SSES OF TPU (GC-1, PC-9–11), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS
O11	Conduct innovative scientific research on the systems and equipment of nuclear power plants and nuclear power plants, participate in the implementation of research results	Requirements of FSES OF HE, SSES OF TPU (GPC-2, PC-5- 16), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS
O12	Analyze and use scientific and technical information, formulate project goals, set and solve innovative problems of integrated engineering analysis in the design and operation of NPPs	Requirements of FSES OF HE, SSES OF TPU (PC-12; 17, 20), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS
O13	To select, create and use equipment of nuclear power plants and nuclear	Requirements of FSES OF HE, SSES OF TPU (GPC-3, PC-18), requirements of

	power plants, means of measuring thermophysical parameters and automated control, protection and control of technological processes	international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS
O14	Conduct a preliminary feasibility study of design developments of AS systems and nuclear power plants, prepare initial data for the selection and justification of scientific, technical and organizational solutions, carry out innovative engineering projects using basic and specialized knowledge, modern design methods to achieve optimal results with taking into account the principles and means of ensuring nuclear and radiation safety	Requirements of FSES OF HE, SSES OF TPU (PC-20 – 25, PSC-1.5, 1.6, 1.8, 1.10), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS
O15	To develop design and working technical documentation, to complete completed design and engineering work in the field of designing the AS	Requirements of FSES OF HE, SSES OF TPU (PC-22), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS
O16	Analyze neutron-physical, technological processes and algorithms for monitoring, diagnostics, control and protection, perform neutron-physical, thermal-hydraulic and strength calculations of AS equipment and its elements in stationary and non-stationary operating modes	Requirements of FSES OF HE, SSES OF TPU (PC-6, PSC-1.4), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS
O17	To make an assessment of nuclear and radiation safety in the operation of nuclear power plants, as well as in handling nuclear fuel and other wastes	Requirements of FSES OF HE, SSES OF TPU (PC-29), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS
O18	Analyze the technologies of installation, repair and dismantling of AS equipment in relation to the conditions for the construction, operation and decommissioning of power units of NPPs	Requirements of FSES OF HE, SSES OF TPU (PC-13, 14), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS
Specialization No. 1 Design and operation of nuclear power plants		
O19	o apply the basics of ensuring optimal operating conditions for a nuclear reactor, thermal mechanical equipment and the power unit of the whole system when starting up, stopping, operating at	Requirements of FSES OF HE, SSES OF TPU (PSC-1.14, PSC- 1.15), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS

	power and switching from one power level to another in compliance with safety requirements, to perform typical operations for controlling the reactor and the power unit in a functional analytical simulator	
O20	To carry out and analyze technological activity as an object of management, organize workplaces, provide their technical equipment, place technological equipment, monitor compliance with technological discipline and maintain technological equipment, investigate the causes of its malfunctions, take measures to eliminate them	Requirements of FSES OF HE, SSES OF TPU (PSC-1.9), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS
O21	To compile technical documentation and organize examination of technical documentation, compile established reports on approved forms, manage small teams of performers, plan personnel work and pay funds	Requirements of FSES OF HE, SSES OF TPU (PSC-1.9), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS
O22	To carry out work on standardization and preparation for certification of technical means, systems, processes, equipment and materials of nuclear power plants, to conduct an analysis of production costs for ensuring the required quality of products	Requirements of FSES OF HE, SSES OF TPU (PSC-1.11), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS
O23	To compose and use thermal schemes and mathematical models of processes and apparatuses of nuclear power and thermal mechanical installations of various types of AS, to prepare initial data for the calculation of thermal schemes	Requirements of FSES OF HE, SSES OF TPU (PSC-1.1, 1.3, 1.7), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS
O24	To conduct physical experiments at the stages of physical and power start-up of the power unit in order to determine the neutron-physical parameters of the reactor installation and the AS as a whole	Requirements of FSES OF HE, SSES OF TPU (PSC-1.2), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS
O25	To apply in practice the principles of organizing the operation of modern equipment and AS devices, to understand the fundamental features of stationary and transient regimes of reactor plants and power units and the reasons for imposing restrictions in normal operation, in case of violations, repair and overloads	Requirements of FSES OF HE, SSES OF TPU (PC-8, PSC-1.12, 1.13), requirements of international standards EUR-ACE and FEANI, 24.014 PS, 24.032 PS, 24.036 PS, 24.039 PS

Abstract

sources, 4 adj.

Key words: reactor, coolant, flow rate, fuel element, thermal power, heat exchange tubes, steam generator.

The object of the study is the power unit of a nuclear power plant with a VVER reactor with an electrical power of 1300 MW.

The purpose of the work is to design a power unit for a nuclear power plant with a VVER-1300 reactor.

In the course of work, thermal, design, calibration, hydrodynamic calculations of the STU, steam generator and reactor plant were performed.

As a result of the research, a reactor was designed, steam generator and thermal diagram of the power unit.

List of abbreviations

SG – steam Generator

ECT – Eddy Current testing

VVER – Analyzer – Based Imaging

PWR – Pressurized water reactor

NPP – Nuclear Power Plant

MSLB – Main steam line break

RCP – Reactor coolant pump

DG – Diesel generator

TG – Turbine generator

RCC – Reactor collention chamber

MSIV – Main steam isolation Valve

PRZ – Pressurizer

RP – Reactor Plant

PSD – Pulse Safety Device

EFWP – Emergency feed water pump

NPP – Nuclear power plant

HPIS – High pressure injection system

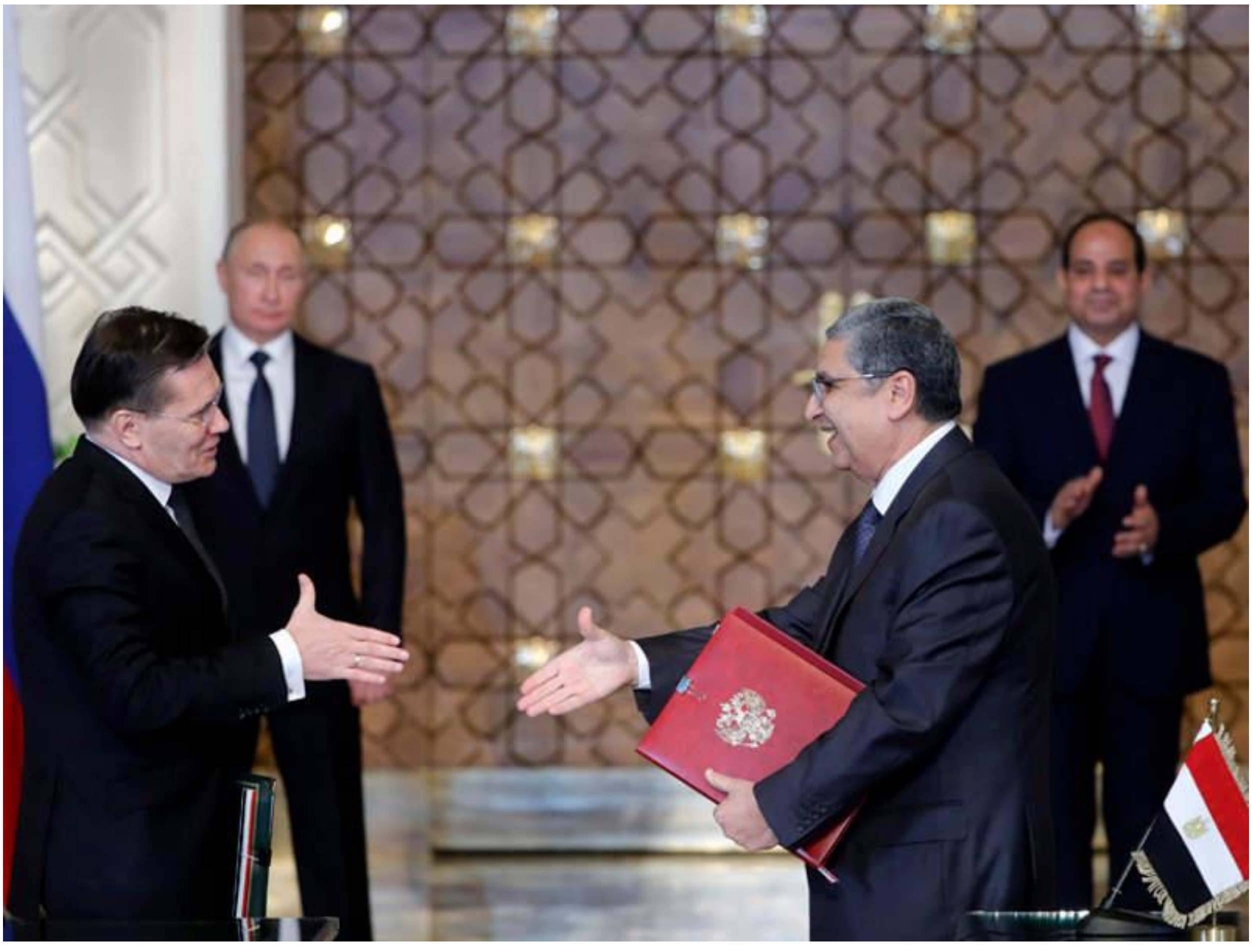
TS – Technical Specification

Contents

1. Nuclear Power in Egypt

El Dabaa nuclear power plant (NPP), which will be Egypt's first nuclear power plant, is planned to be built in Matrouh Governorate on the Mediterranean coast, 250km west of Alexandria. Construction on the plant is expected to start in 2020, with commissioning expected to begin in 2026.

Plant Type	Location	Capacity	Start of Construction
Nuclear power plant	El Dabaa, Matrouh Governorate, Egypt	4.8GW	2020
Commissioning	**Developer**		
2026	ROSATOM		



El Dabaa nuclear power plant (NPP), which will be Egypt's first nuclear power plant, is planned to be built in Matrouh Governorate on the Mediterranean coast, 250km west of Alexandria. Construction on the plant is expected to start in 2020, with commissioning expected to begin in 2026.

Russian State Atomic Energy Corporation (ROSATOM) will develop the proposed El Dabaa nuclear power plant, which will be owned and operated by the Nuclear Power Plant Authority (NPPA) of the Arab Republic of Egypt.

1.1 El Dabaa nuclear power plant location and details

The El Dabaa nuclear power plant site is in close proximity to rail, road and transmission interconnections. It has low regional seismic activity and sufficient cooling water supply.

The plant will consist of four VVER-1200 nuclear reactors, which are capable of producing 1.2GW each. The first unit is expected to begin commercial operations in 2026, while commissioning of the remaining three reactors is scheduled for 2028.

The VVER-1200 reactor is a third-generation pressurised water reactor that is fully compliant with all international safety and post-Fukushima IAEA requirements. It is designed to withstand the crash of a 400t airplane or earthquakes up to an intensity of 9 on the Richter scale.

Site	Type	MWe gross	Construction start
El Dabaa 1	VVER-1200/V-529	1200	TBC
El Dabaa 2	VVER-1200/V-529	1200	TBC
El Dabaa 3	VVER-1200/V-529	1200	TBC
El Dabaa 4	VVER-1200/V-529	1200	TBC
Total (4)		4800	

Financing of El Dabaa nuclear power plant

Russia will fund approximately 85% of the construction cost of the El Dabaa nuclear power project. It will provide a $25bn loan,

under a financing agreement signed

between the Ministry of Finance of Egypt and the Ministry of Finance of the Russian Federation.

The loan is repayable over a period of 22 years at an interest rate of 3% a year.

The remaining 15% will be raised by Egypt from private investors

1.2 why Aldabaa in Egypt ?

Egyptian President Abdel-Fattah El-Sisi and his Russian counterpart Vladimir Putin met in Cairo on December 11, 2017, to attend the signing of an agreement officially launching work on Egypt's nuclear power plant at El -Dabaa. Egypt's Minister of Electricity Mohamed Shaker and Alexi Likhatchev, the Director General of Russian state atomic energy corporation Rosatom, have signed the document to officially commence the project.1 President Putin said that "upon the completion of the El - Dabaa project, Egypt will not only benefit from having a nuclear plant but also from gaining the latest and safest technology of nuclear energy."2 Rosatom has announced that work on the El-Dabaa plant, situated west of Alexandria, will start in December 2017and that the company will service the plant’s four reactors for 60 years.3 The first reactor, with a capacity of 1,200 MW, is expected to begin commercial operations in 2026.The remaining three reactors should be online by 2028

The nuclear plant will be established in El - Dabaa, located in the Marsa Matrouh governorate on the Mediterranean coast.5 The plan will be implemented by Russian state-owned company Rosatom. The reactor will be composed of four nuclear power units each capable of producing 1,200 megawatts of energy (4,800 megawatts). 6 El - Dabaa reactor will have new technology with strong safety measures that take into account lessons learned during the March 2011 Fukushima disaster in Japan. It will be able to withstand earthquakes up to 9 degree on a Richter scale, and the crash of a 400-tonne airplane.7 According to the agreement, Russia will loan Egypt the $25 billion needed to finance the building and operation.8 Hussein El-Shafie, manager of the Egyptian Russian Foundation for Culture and Science, said that the loan provided by Russia will cover 85 percent of the project and Egypt will raise the remaining 15 per cent from private investors. The El - Dabaa project will be paid over 22 years at an interest rate of 3 percent. "Egypt 2 will begin repaying the loan in 2029, though by that time the El - Dabaa nuclear reactors will have generated $17 billion in sovereign revenues for the government of Egypt," said El-Shafie

The main benefits of the nuclear reactor are:

Electricity - according to Nuclear Affairs and Energy Adviser at the Ministry of Electricity Ibrahim Al-Osery, the project has the potential to provide up to 50% of Egypt's electric energy capacity.

Clean source of energy - the nuclear power reactor in El-Dabaa will not emit any gas pollutants or cause any greenhouse effect.

Water supply - the scarcity of water has become a rising concern. The state's statistics agency reported in May 2014 that Egyptians have on average access to 663 cubic meters of clean water annually, well below the international water poverty threshold. Nuclear technology - it will help Egypt to obtain the nuclear technology necessary for the country become a pioneer in this field in the long-run.

" The nuclear waste" - generated by the plant will be handled by an international company that is an expert in this field.

Job opportunities - the plant will create over 50,000 job opportunities.

Egypt as a center for energy generation - the Egyptian government planning to turn Egypt into a center for energy generation, the goal being not just self-sufficiency but to generate power for export

1.3 Population and environment protection

The radiation safety is arranged and implemented to prevent inadmissible impacts caused by ionizing radiation sources on the materials, population and environment in the area that surrounds a Nuclear power plant.

The concept of providing radiation and nuclear safety in VVER-1300 project is based on the following:

- requirements provided by domestic safety rules and regulations in force in the field of nuclear-power engineering, which are applicable for the designed
- power unit considering their further development;
- modern philosophy and safety principles developed by the world nuclear community and reflected in the IAEA Safety Standards;
- materials published by International Nuclear Safety Advisory Group (INSAG) on nuclear safety issues, EUR requirements;
- complex of the technical solutions worked-out and checked through operation considering the efforts targeted at their upgrading, and elimination of the “weak links” revealed during operation;
- verified and certified calculation methods, codes and programs; worked-out safety analysis methodology, reliable database;
- organizational and technical measures to prevent and restrict severe accidents repercussions, which are developed according to the results of investigations in the field of severe accidents;
- experience in development of new generation and increased safety plants;
- to provide low sensibility to the errors and personnel mistaken solutions;
- to ensure low risks of considerable radionuclide emission in case of accident;
- to provide possibility of exercising safety functions without external power supply, as well as making control through “human–machine” interface;
- to ensure conditions required to avoid evacuation of the population living near

Anuclear power plant in case of severe accidents.

The first VVER-TOI construction began in April 2018 at the Kursk Nuclear Power Plant, with a predicted completion date of April 2022.

In addition, there are an additional 11 VVER-TOI units planned

2. Introduction about VVER-1300

The VVER-1300 is developed from the VVER-1200. It is aimed at development of typical optimized informative-advanced project of a new generation III+ Power Unit based on VVER technology, which meets a number of target-oriented parameters using modern information and management technologies.

The main improvements from the VVER-1200 are:

- power increased to 1300 MWe gross
- upgraded pressure vessel
- improved core design to improve cooling
- further developments of passive safety systems
- lower construction and operating costs with a 40-month construction time
- use of low-speed turbines

The construction of the first two VVER-1300 units was started in 2018 and 2019 at the Kursk II Nuclear Power Plant.

In June 2019 the VVER-TOI was certified as compliant with European requirements for nuclear power plant safety.

An upgraded verison of AES-2006 with TOI standards, the VVER-1200/513, is being built in Akkuyu Nuclear Power Plant in Turkey

Generally in my project iam working for 3 loops of steam generators not 4 loop these three loops also have an important safety role
because they constitute one of the primary barriers between the radioactive and non-radioactive sides of the plant as the primary coolant becomes radioactive from its exposure to the core.

2.1 Types of Reactors
The advantages and disadvantages between 3 ,4 and 2 loops

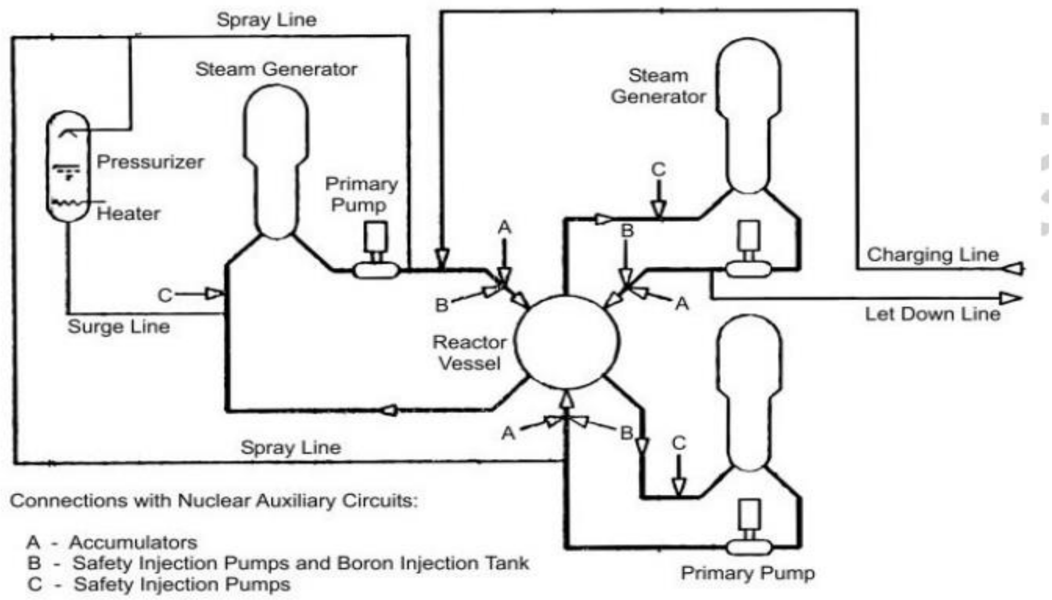
There are two major flow systems, the primary system and the secondary system, utilized to transport and convert the heat generated in the fuel into electrical power for industrial and residential use. The primary system transfers the heat from the fuel to the steam generator, where the secondary system begins. The steam formed in the steam generator is transferred by the secondary system to the main turbine generator, where its energy is converted into electricity. After passing through the turbine, the steam is routed to the main condenser. Cool water, passing through the tubes in the condenser from an external source, removes excess heat from the steam, allowing the steam to condense on the outside of the tubes. The condensate is then pumped back to the steam generator

The primary system, also called the reactor coolant system, consists of 2, 3, or 4 cooling loops connected to the reactor, each containing a reactor coolant pump and steam generator. The systems built by the three main vendors consist of the same major components, but they are arranged in slightly different ways

NPP WITH 3-LOOP REACTORS

Consist of 3 loops in VVER-1800 reactor applying design decisions for VVER-1500 and VVER-1200A;

Three-loop arrangements are used at NPPs with sodium-cooled fast neutron reactors of BN type. To exclude contact of radioactive sodium with water, the second loop holding non-radioactive sodium is built. This makes the arrangement three-loop one.



The Advantage

Pressurized water reactors have advantages over the other light water reactors and earlier generation nuclear sites. One major advantage of this reactor is that it is easy to operate because less power is being produced as the heat increases. In addition, the core of the reactor contains less fissile material, decreasing the chances of additional fission events to occur, making the reactor safer and more controllable. In other words, it contains "less fissile material than is required for them to go prompt critical". Lastly, the most advantageous element of the PWR is the turbine cycle. Since the primary and secondary loops are separate, water can never be contaminated by radioactive material in the main system loop. Conclusively, the water from the primary and secondary loops will never touch or mix, so there is no chance for contamination

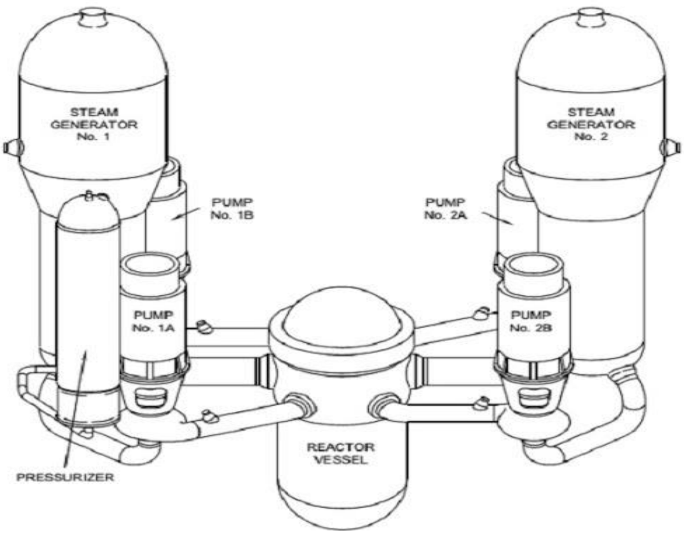
The Disadvantage

Although the PWR makes up the majority of Western Nuclear plants and is the reactor choice for most Navy Nuclear Propulsion Systems, there are some notable disadvantages to using such a reactor. For one thing, the reactor requires very strong piping and a heavy pressure vessel in order to ensure that the highly pressurized water remains at a liquid state when sustaining high temperatures, making the construction of the PWR costly. Meanwhile, most reactors need to be refueled after about 18 months, and cannot be refueled while the reactor is running. Since the refueling process takes a few weeks, the reactors must go offline for this time. Lastly, although no water contamination in the main cycle exists, boric acid, which is corrosive to carbon steel, can get melted into the coolant causing radioactive products to circulate throughout the loop. These radioactive yields are destructive to the reactor (i.e. potential for radiation exposure) ultimately limiting the reactor's operating life

NPP WITH 2-LOOP REACTORS

Consist of 2 loops iv VVER-1200A reactor applying design decisions for SG PGV-1500

Two-loop arrangements are used at the plants with water-water reactors of WWER type. Water under pressure is supplied to the reactor core and heated up. The coolant energy is used in the steam generator to produce saturated steam. The second loop is non-radioactive. The reactor unit consists of one condensing turbine of 1000 MW or two turbines of 500 MW each with corresponding generators.



VVER-600 (650, 700) design concept:

- ✓ 2-loop reactor;
- ✓ Developed on the basis of VVER-1200 (Leningrad-2):
  - direct borrowing of components;
  - referentiality;
- ✓ Providing for safety of the same level as requirements for 3 generation NPP;
- ✓ Designed life time - 60 years;
- ✓ Retaining core melt inside the reactor vessel during BDB severe;
- ✓ Maximum application of R&D results for VVER-1000 an VVER-1200 reactor design;
- ✓ Arrangement of components manufacturing does not need much costs.

Advantages of 2-loop design over the 4-loop one:

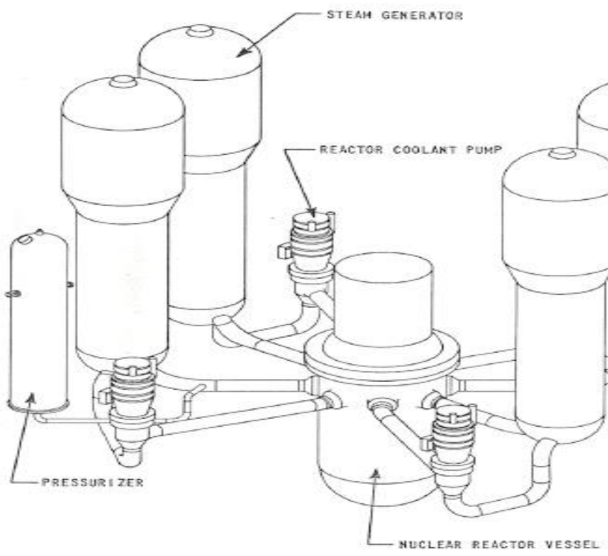
- ✓ Reduction of reactor specific metal consumption;
- ✓ Reduction of component installation terms;
- ✓ Reduction of containment inner diameter;
- ✓ Reduction of operational costs by 20-25%.

Maximum borrowing of main components from VVER-1200 design allows for reduction of reactor design development and simplification of components delivery to the site.

NPP WITH 4-LOOP REACTORS

Consist of 4 loops

Every loop has one steam generator with one pressurizers with a Mutual Reactor in the middle



	Advantages	*Disadvantages*
Bobbin probe	1) High sensitivity to axial cracks. 2) High inspection speed. 3) Determination of defect location in axial direction. 4) Determining defect depth and length. 5) High reliability and durability. 6) Comparatively low price.	1) Low sensitivity to circumferential cracks. 2) Unrecognizing and false interpretation when several defects are situated with the same axial location.
Rotating probe	1) High sensitivity to cracks of different orientation. 2) Crack orientation determination. 3) Length and depth of crack determination. 4) Determination of defect location in axial direction. 5) Good inspection results visualization.	1) Low inspection speed. 2) Comparatively low reliability and durability. 3) Comparatively low passing ability. 4) High price.
Array probe	1) High sensitivity to cracks of different orientation. 2) High inspection speed. 3) Crack orientation determination. 4) Determination of flaw location in axial direction. 5) Determination of defect parameter.	1) Very high price. 2) Comparatively low reliability and durability. 3) Comparatively low passing ability.

Increasing the parameters of the primary and secondary circuit media made it possible to increase the reactor thermal power, SG rated capacity and generator electric power

The cost of the unit is significantly reduced. The safety level is significantly increased due to an optimal compromise between active and passive systems. Each safety function is backed up by at least two different systems in each channel.

Increased safety, deeper subcriticality after the core. The re-criticality temperature is less than 100 °C.

Increased thermal power. The pump bearings are cooled with water. The oil system is located next to the electric motor.

Increased SG lifetime. A new scheme is used without SG blowdown flash tanks

Fire protection, decreased dimensions

Increasing the number of BRU-Ks and decreasing their response time from 15 to 3 s made it possible to significantly the unit maneuverability in off-design modes.

3.Thermal calculation of the heating surface of SG

Installed rated power of the power unit, MW(e)	1200
Nominal thermal Power of the reactor , MW	3200
Steam pressure in steam generators, MPa	7,0
Fuel	UO_2
Moderator	H_2O
Coolant	H_2O
Coolant parameters:	
Primary Coolant Pressure , MPa	17.64
The temperature of the coolant at the inlet of reactor, ^0C	298.2
The temperature of the coolant at the outlet of reactor, ^0C	328.9
Features of the grid, cassette, fuel element , ^0C	Prototype

3.1 Initial data

Table 1

Parameter	Denomination, units	Value
Coolant		water
Thermal power of reactor	Q_r, MW	3200
Thermal power of SG	Q_{sg}, MW	1067
Mass flow of steam	D_{st} *or* D_2, kg/s	545.1
Coolant flow	G_1, kg/s	6.132
Coolant pressure at the inlet to the SG	p_1, MPa	17,64
Coolant temperature at the inlet to the SG	t_1', °C	328,9
Coolant temperature at the outlet of the SG	t_1'', °C	298,2
Steam pressure at the SG	p_{st} *or* p_2, MPa	7,0
Steam temperature at the outlet of the SG	t_{st} *or* t_s, °C	$t_s = f(p_2)$ $= 285.80$
Feed water temperature	t_{fw}, °C	200
Blowdown flow rate, % (as a percentage of mass flow of steam)	α_{bd}, %	0.3

Notes:

- purpose is for the production of saturated steam with natural circulation;
- thermal circuit is evaporator;
- basic type is SG WWER, horizontal, U-shaped tubes.

Calculation and construction of tQ diagram

1.1 Determination of coolant flow

To do this, use the heat balance equation of the steam generator (from the coolant side)

$$\text{hin} = f(p_1, t_1') = 1500 \ \text{kJ/kg}$$

$$\text{hin} = f(p_1, t_1'') = 1326 \ \frac{\text{kJ}}{\text{kg}}$$

$$t_{1avr} = \frac{328.9 + 298.2}{2} = 313.55 \text{ c}$$

$$\text{Cp} = f(p_1, t_{1avr}) = 5.754 \ \frac{\text{kj}}{(\text{kg} * \text{c})}$$

$$Q_{sg} = G_1 * (\text{hin} - \text{hout})$$

$$Q_{sg} = \frac{Q_r}{3} = \frac{3200}{3} = 1067 \text{ MW}$$

$$G_1 = \frac{1067 * 10^3}{\text{Cp} \ * (328.9 - 298.2)} = \frac{1067}{\text{hin} - \text{hout}}$$

$$G_1 = \frac{1067}{1500 - 1326} = 6132.18 \text{ kg/s}$$

$$\text{Ne} = 1200 \text{ mW}$$

$$\text{Qr} = 3200 \text{ Mw}$$

$$\frac{1200}{3200} = \frac{\text{Ne}}{\text{Qr}} = 0.375 = \eta$$

Where

G_1 is coolant flow rate, kg/s;

Q_{sg} is thermal power of the steam generator, kW. It is determined by the thermal power of the reactor, taking into account the number of loops;

$h_{1inl} = f\left(p_1, t_1'\right)$ is coolant enthalpy at the steam generator inlet, kJ/kg;

$h_{1out} = f\left(p_1, t_1''\right)$ is coolant enthalpy at the outlet of the steam generator, kJ/kg.

1.2 Determination of steam flow rate

To do this, use the heat balance equation of the steam generator (from the side of the working fluid)

$$Q_{sg} = k_{hl} \cdot D_2 \cdot \left[(h' - h_{fw}) + (h'' - h') \right] + D_{bd} \cdot (h' - h_{fw})$$

$$1067 * 10^3 = 1.02 * \mathrm{D}_2 * \left((1267 - 855) + (2773 - 1267)\right) + \left(\frac{0.3}{100}\right) * \mathrm{D}_2 * (1267 - 855)$$

$$1067 = 1956.36\ \mathrm{D}_2 + 1.236\ \mathrm{D}_2$$

$$\mathrm{D}_2 = 545.1\ \mathrm{kg/s}$$

Where

D_2 is steam flow rate from the steam generat, kg/s;

$k_{hl} = 1.02$ is coefficient that takes into account heat losses in the steam generator;

$h'' = f(p_{st})$ is steam enthalpy at saturation temperature, kJ/kg;

$$\mathrm{h}'' = \mathrm{f}(\mathrm{p_{st}}) = \mathrm{f}(7\ \mathrm{MW}) = 2773\ \ \mathrm{kJ/kg}$$

$h' = f(p_{st})$ is steam enthalpy at saturation temperature, kJ/kg;

$$\mathrm{h}' = \mathrm{f}(\mathrm{p_{st}}) = \mathrm{f}(7\ \mathrm{MW}) = 1267\ \ \mathrm{kJ/kg}$$

$h_{fw} = f\left(p_2, t_{fw}\right)$ is enthalpy of feed water, kJ/kg;

$$\mathrm{h_{fw}} = \mathrm{f}(\mathrm{p_2}, \mathrm{t_{fw}}) = \mathrm{f}(7\ \mathrm{MW}, 200\ \mathrm{c}) = 855\ \ \mathrm{kJ/kg}$$

$D_{bd} = (\alpha_{bd}/100) \cdot D_2$ is flow rate of blowdown water, kg/s.

$$\mathrm{D_{bd}} = (\frac{0.3}{100}) * \mathrm{D}_2$$

1.2 Determination of feed water flow rate

$$D_{fw} = D_2 + D_{bd}\text{, kg/s.}$$

$$\mathrm{D_{fw}} = \mathrm{D}_2 + (\frac{0.3}{100}) * \mathrm{D}_2$$

1.4 Building a tQ diagram

Figure 1: tQ-diagrams of the steam generator

2 Choice of tube material, heat carrier collector and vessel

We will focus on the prototype. We accept the following steel grades:

- for heat transfer surface tubes – corrosion-resistant heat-resistant steel 08X18H10T;
- for the heat carrier collector-heat-resistant high-alloy steel 10ГН2МФА, clad on the side washed by the heat carrier, steel 08X18H10T;
- for vessel elements - 10ГН2МФА.

3 Calculation of the wall thickness of the tubes of the heat transfer surface of the steam generator

The thickness of the tube wall is determined by the conditions of sufficient strength at the maximum operating temperature , taking into account corrosion and technological factors.

To calculate the nominal wall thickness of tubes use the formula

$$/\delta_{tube} = \frac{p_{calc} \cdot d_{out}}{2 \cdot \varphi \cdot [\sigma] - p_{calc}} + C. \quad (1)$$

$$\delta_{tube} - c = \frac{p_{calc} * d_{out}}{2 * \varphi * (\sigma) - p_{calc}}$$

$$\delta_{tube} - c = \frac{19.8 * 16}{2 * 1 * (91.33) - 19.8} = 0.088 \text{ mm}$$

Here: δ_{tube} is in mm;

$\varphi = 1$ is coefficient of strength (load factor);

$p_{calc} = 0,9 \cdot 1,25 \cdot p_1$ is the rated (design) pressure, MPa;

$$p_{calc} = 19.8 \text{ MPa}$$

$t_{tube.\max} = 0.5 \cdot (t_1' + t_s)$

is maximum operating temperature of the tube wall, ºC;

d_{out} is the outer diameter of the tubes, mm. The value of the diameter of the tubes is recommended to take equal:

- 16 mm for horizontal WWER steam generators;

Calculate nominal stress design

This stress design is defined as the minimum of two values.

$$[\sigma] = \min\left\{\frac{\sigma_{sl}}{n_{sl}}; \frac{\sigma_{0,2}}{n_{0,2}}\right\}, \qquad (3)$$

Form initial date

$$t_{1.\max} = t' = 328.9 \quad t_{2.\max} = t_s = 285.8 \quad t_{tube.\max} = (328.9 + 285.8)/2 = 307.35$$

From table 2 at a temperature of 307.35 degrees, selec

$$\sigma_{sl} = 363 \quad \sigma_{0.2} = 137$$

We calculate stresses taking into account safety factors

$$\frac{\sigma_{sl}}{n_{sl}} = \frac{363}{2.6} = 139.6 \text{ MPa} \qquad \frac{\sigma_{0,2}}{n_{0,2}} = \frac{137}{1.5} = 91.33 \text{ ..MPa}$$

Compare the obtained values. Nominal voltage tolerance is equal to a lower value

$$[\sigma] = 91.33 \text{ MPa}$$

Here n_{sl} =2,6 and $\sigma_{0,2}$ =1,5 are relevant safety factors

σ_{sl} is shakedown limit of the tubes material at the design temperature $t_{calk} = t_{tube.\max}$, MPa;

$\sigma_{0,2}$ is yield point of the tubes material at the design temperature $t_{calk} = t_{tube.\max}$, MPa;

08H18N10T type steel is used for manufacturing steam generator tubes in Russia (Table 2).

Table 2 . Mechanical properties of steel 08X18H10T

t_{calc}, °C	100	150	200	250	300	350
σ_{sl}, MPa	412	392	392	373	363	353
$\sigma_{0,2}$, MPa	177	167	157	147	137	132

C is an addition to the calculated wall thickness associated with a negative technological tolerance, thinning of tubes during bends and as a result of corrosion, mm

$$C = C_1 + C_2 + C_3 + C_4 .$$

$$c = 0.1 + 0 + 0 + 0.831$$

$$c = 0.931 \text{ mm}$$

Where: C_1 is minus technological tolerance, mm. Accepted according to the data from Table 3 for the precision manufacturing "high accuracy".

Table 3. Permissible deviations of tube sizes along wall thickness [3]

Wall thickness, mm	The deviation value with precision manufacturing		
	conventional accuracy	high accuracy	very high accuracy
0.5…0.6	± 0.1 mm	± 0.07 mm	
0.7… 1.0	± 0.15 mm	± 0.1 mm	
1.0… 3.0	± 15 %	± 12.5 %	± 12.5 %
> 3.0			- 10 %

C_2 is increasing the calculated wall thickness to compensate for the impact of corrosion processes, taking into account the service life of the steam generator. For austenitic steels this correction is 0;

C_3 is the necessary increase in wall thickness for technological, installation and other considerations of design and production enterprises, mm. for tubes, heating surfaces, this correction is 0;

c_4 is a decrease in the wall thickness of tubes in places of tube bends, mm. It is taken equal to the largest of the two values obtained by the formulas:

$$[\delta_{tube} - C] > 0.75 \cdot 10^{-2} \cdot a$$

$$C_4 = (\delta_{tube} - C) \cdot \left[1 - 2 \cdot \left(1 - \frac{b}{100}\right) \cdot \frac{2 \cdot \left(\frac{R_b}{d_{out}}\right) + 1}{4 \cdot \left(\frac{R_b}{d_{out}}\right) + 1} \right].$$

$$c_4 = 0.088 * \left(1 - 2 * \frac{5}{100} * \frac{2 * \left(\frac{1.9 * 16}{16}\right) + 1}{4 * \left(\frac{1.9 * 16}{16}\right) + 1} \right) = 0.831 \text{ mm}$$

Here: $R_b = (1.9...3.5) \cdot d_{out}$ is the bending radius of the tube along the neutral line, mm;

a is ovality of the tube in the bent section,%;

b is relative decrease in wall thickness in the stretched part of the bent section,%. Usually accepted $a = 5...15$ %; $b = 10...30$ %.

The tube wall thickness determined by formula (1) is rounded to the nearest higher value available in the tube assortment (Table 4). Rounding to the lower side by an amount of not more than 3% is allowed

$$\delta_{tube} = \frac{p_{calc} * d_{out}}{2 * \varphi * (\sigma) - p_{calc}} + c$$

$$\delta_{tube} = \frac{19.8 * 16}{2 * 1 * (91.33) - 19.8} + 0.931 = 2.9 \text{ mm}$$

Table 4. Parameters of corrosion-resistant steel tubes

Outer diameter, mm	12, 13, 14, 15, 16, 17
tube wall thickness, mm	0.8, 1.0, 1.2, 1.4, 1.5, 1.8

Then the internal diameter of the heat exchange tube will be equal:

$$d_{in} = d_{out} + 2 \cdot \delta_{tube}.$$

$$\mathrm{d_{in}} = 16 + (2 * 2) = 20 \text{ mm}$$

4 Determining the number of tubes

$$N_{tube} = \frac{G_1}{\rho_{avr} \cdot w \cdot f_{1tube}}, \text{ pc.}$$

$$\mathrm{N_{tube}} = \frac{6132.18}{701.5 * 4 * 3.14 * 10^{-4}} \approx 7000$$

Where

G_1 is coolant flow, kg/s;

$\rho_{avr} = f\left(p_1, t_{1avr}\right)$ is the average density of the coolant;

$$\rho_{avr} = \mathrm{f}(17.64\,, 313.55) = 701.5\ \frac{\mathrm{kg}}{\mathrm{m}^3}$$

w is the speed of the coolant in the tubes, m/s. Accept in the range from 4 to 6 m/s;\

$f_{1tube} = \pi \cdot d_{in}^2/4$ is is cross-section area of one tube, m².

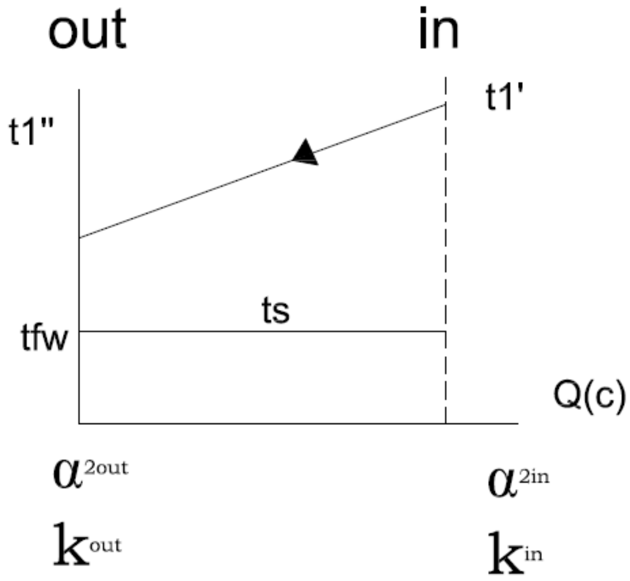
$$\mathrm{f_{1\ tube}} = \frac{\pi * (0.02^2)}{4} = 3.14 * 10^{-4}\ \mathrm{m}^2$$

5 Calculation of heat transfer in a steam generator

5.1 Determination of average temperature head in a steam generator

ºC.

$$\Delta t_{ave} = \frac{\Delta t_{max} - \Delta t_{min}}{\ln \frac{\Delta t_{max} - ts}{ts - \Delta t_{min}}}$$



$$ts' = f(ps) = f(7\ \text{Mpa}) = 285.80\ c$$

$$\Delta t_{ave} = \frac{328,9 - 298,2}{\ln \frac{328.9 - 285.80}{298.2 - 285.80}} = 24.64\ c$$

5.2 Determination of the heat transfer coefficient from the coolant to the tube walls

This coefficient can be calculated from the average parameters of the coolant p_1 and t_{1avr} using the following equation

$$\alpha_{1avr} = 0,021 \cdot \left(\frac{\lambda_{1avr}}{d_{in}}\right) \cdot (\text{Re}_{avr})^{0,8} \cdot (\text{Pr}_{avr})^{0,43}.$$

$$\alpha_{1avr} = 30831.4$$

Where

$v_{1avr} = f(p_1, t_{1avr})$ is average kinematic viscosity of the coolant, m²/s;

$$v_{1avr} = f(17.64\ ,313.55) = 1.198 * 10^{-7}\ m^2/s$$

$\lambda_{1avr} = f\left(p_1, t_{1avr}\right)$ is the average coefficient of thermal conductivity of the coolant, W/(m·ºC);

$$\lambda_{1avr} = f(17.64\ ,313.55) = 0.5381\ \ W/(m \cdot ºC);$$

$\mathrm{Pr}_{avr} = f\left(p_1, t_{1avr}\right)$ is Prandtl criterion with medium coolant parameters;

$$\mathrm{Pr}_{1avr} = f(17.64\ ,313.55) = 0.90$$

$\mathrm{Re}_{avr} = w \cdot d_{in} / \nu_{1avr}$ is Reynolds criterion with medium coolant parameters.

$$\mathrm{Re}_{avr} = \frac{4 * 0.02}{1.198 * 10^{-7}} = 667779.63$$

5.3 Determination of the heat transfer coefficient from the walls of the tubes to the working fluid

The calculation of the heat transfer coefficient from the tubes to the working fluid is carried out for two sections of the heating surface: inlet and outlet. The procedure for calculating the heat transfer coefficient α_{2in} for the input section is shown below. The calculation of the coefficient α_{1out} for the output section is carried out similarly.

Heat transfer from the wall to the working fluid in a horizontal steam generator occurs under boiling conditions in a large volume. Therefore the calculation method is interactive and consists of the following steps:

- we accept the initial value of the heat flux $q_{in} = 3 \cdot 10^5$ W/m² (for the output section it is recommended to take $q_{out} = 6 \cdot 10^4$ W / m²);

- calculate the coefficient of heat transfer from the tubes to the working fluid

$$\alpha_{2in} = \frac{10.45}{3.3 - 0.0113 \cdot (t_s - 100)} \cdot q_{in}^{0,7}\text{, W/(m}^2\cdot\text{ºC);}$$

$$\alpha_{2in} = \frac{10.45}{3.3 - 0.0113(285.80 - 100)} * 3 * 10^5 = 59395.49$$

- determine the average temperature of the pipe wall in the inlet section, ºC

$$t_{tube.in} = t_s + 0.3 \cdot (t_1' - t_s)\text{, ºC;}$$

$$t_{tube\ in} = 285.80 + 0.3(328{,}9 - 285.80) = 298.73$$

- we calculate the average coefficient of thermal conductivity of the pipe wall in the inlet section using the approximation formula for steel 08X18H10T

$$\lambda_{wal.in} = 14.48 + 0.0156 \cdot t_{tube.in}, \text{ W/(m·°C)};$$

$$\lambda_{wal.in} = 14.48 + 0.0156 * 298.73 = 169.140 \ {}^{W}/_{(m*c)}$$

- calculate the heat transfer coefficient

$$k_{in} = \left[\frac{1}{\alpha_{1avr}} + \frac{\delta_{tube}}{\lambda_{tube.in}} + 2 \cdot R_{ox} + \frac{1}{\alpha_2} \right]^{-1}, \text{ W/(m}^2\text{·°C)};$$

$$K_{in} = (\frac{1}{30831.4} + \frac{0.029}{169.140} + 2 * 10^{-5} + \frac{1}{59395.49})^{-1} = 11571.88$$

here

δ_{tube} is the wall thickness of the tubes, m;

$R_{ox} = 10^{-5}$ m·°C/Вт is the thermal resistance of the oxide film on stainless steel tubes;

- calculate the heat flow

$$q'_{in} = k_{in} \cdot (t'_1 - t_s), \text{ W/m}^2;$$

$$q'_{in} = 11571.88 * (43.1) = 498748.028$$

$$\frac{q'_{in}}{q_{in}} = 1.66 \quad \text{not accept}$$

The second traiel

$$\alpha_{2in} = \frac{10.45}{3.3 - 0.0113 \cdot (t_s - 100)} \cdot q_{in}^{0,7}, \text{ W/(m}^2\text{·°C)};$$

$$\alpha_{2in} = \frac{10.45}{3.3 - 0.0113(285.80 - 100)} * 498748.028 = 84778.44$$

$$k_{in} = \left[\frac{1}{\alpha_{1avr}} + \frac{\delta_{tube}}{\lambda_{tube.in}} + 2 \cdot R_{ox} + \frac{1}{\alpha_2} \right]^{-1}, \text{ W/(m}^2\text{·°C)};$$

$$K_{in} = (\frac{1}{30831.4} + \frac{0.029}{169.140} + 2 * 10^{-5} + \frac{1}{84778.44})^{-1} = 12288.71$$

$$q'_{in} = 12288.71 * (43.1) = 529643.58$$

$$\frac{q'_{in}}{q_{in}} = 1.06 \quad \text{not accept}$$

The third trail

$$\alpha_{2in} = \frac{10.45}{3.3 - 0.0113 \cdot (t_s - 100)} \cdot q_{in}^{0,7}$$, W/(m²·ºC);

$$\alpha_{2in} = \frac{10.45}{3.3 - 0.0113(285.80 - 100)} * 529643.58 = 87760.48$$

$$k_{in} = \left[\frac{1}{\alpha_{1avr}} + \frac{\delta_{tube}}{\lambda_{tube.in}} + 2 \cdot R_{ox} + \frac{1}{\alpha_2}\right]^{-1},$$ W/(m²·ºC);

$$K_{in} = \left(\frac{1}{30831.4} + \frac{0.029}{169.140} + 2 * 10^{-5} + \frac{1}{87760.48}\right)^{-1} = 12349.54$$

$$q'_{in} = 12349.54 * (43.1) = 532265.17$$

$$\frac{q'_{in}}{q_{in}} = 1.004 \quad \text{accept}$$

- let's compare the found heat flow q'_{in} with the one set earlier q_{in}.

If the condition $0.95 \le \frac{q'_{in}}{q_{in}} \le 1.05$ is met, the calculation ends. If the condition is not met, the calculation continues and the value is taken q'_{in} as the new value q_{in}.

Repeat the calculation of heat transfer (α_{out} q_{out}, k_{out}) for the output section of the steam generator.

The first trail

$$\alpha_{2in} = \frac{10.45}{3.3 - 0.0113 \cdot (t_s - 100)} \cdot q_{in}^{0,7}$$, W/(m²·ºC);

$$\alpha_{2out} = \frac{10.45}{3.3 - 0.0113(285.80 - 100)} * (6 * 10^4)^{0.7} = 19251.93$$

$$k_{in} = \left[\frac{1}{\alpha_{1avr}} + \frac{\delta_{tube}}{\lambda_{tube.in}} + 2 \cdot R_{ox} + \frac{1}{\alpha_2} \right]^{-1}, \quad W/(m^2 \cdot {}^oC);$$

$$K_{out} = \left(\frac{1}{30831.4} + \frac{0.029}{169.140} + 2 * 10^{-5} + \frac{1}{19251.93}\right)^{-1} = 3625.38$$

$$q'_{out} = 3625.38 * (43.1) = 156254.01$$

$$\frac{q'_{out}}{q_{out}} = 2.60 \qquad \text{not accept}$$

The second trail

$$\alpha_{2in} = \frac{10.45}{3.3 - 0.0113 \cdot (t_s - 100)} \cdot q_{in}^{0,7}, \quad W/(m^2 \cdot {}^oC);$$

$$\alpha_{2out} = \frac{10.45}{3.3 - 0.0113(285.80 - 100)} * (156254.01)^{0.7} = 37622.73$$

$$k_{in} = \left[\frac{1}{\alpha_{1avr}} + \frac{\delta_{tube}}{\lambda_{tube.in}} + 2 \cdot R_{ox} + \frac{1}{\alpha_2} \right]^{-1}, \quad W/(m^2 \cdot {}^oC);$$

$$K_{out} = \left(\frac{1}{30831.4} + \frac{0.029}{169.140} + 2 * 10^{-5} + \frac{1}{37622.73}\right)^{-1} = 3992.49$$

$$q'_{out} = 3992.49 * (43.1) = 172076.67$$

$$\frac{q'_{out}}{q_{out}} = 1.101 \qquad \text{not accept}$$

The third trail

$$\alpha_{2in} = \frac{10.45}{3.3 - 0.0113 \cdot (t_s - 100)} \cdot q_{in}^{0,7}, \quad W/(m^2 \cdot {}^oC);$$

$$\alpha_{2out} = \frac{10.45}{3.3 - 0.0113(285.80 - 100)} * (172076.67)^{0.7} = 40250.75$$

$$k_{in} = \left[\frac{1}{\alpha_{1avr}} + \frac{\delta_{tube}}{\lambda_{tube.in}} + 2 \cdot R_{ox} + \frac{1}{\alpha_2} \right]^{-1}, \quad \text{W/(m}^2\cdot{}^{o}\text{C);}$$

$$K_{out} = (\frac{1}{30831.4} + \frac{0.029}{169.140} + 2 * 10^{-5} + \frac{1}{40250.75})^{-1} = 4020.35$$

$$q'_{out} = 4020.35 * (43.1) = 173277.25$$

$$\frac{q'_{out}}{q_{out}} = 1.006 \quad \text{accept}$$

6 Calculation of the average overall heat transfer coefficient

After completing the heat transfer calculations for the input and output sections, you can calculate the average heat transfer coefficient k_{avr}

For this, the values of k_{in} and k_{out} are compared.

$$\frac{k_{in} - k_{out}}{k_{out}} = \frac{12349.54 - 4020.35}{4020.35} = 2.07 > 0.25$$

If $\left| \frac{k_{in} - k_{out}}{k_{out}} \right| \le 0.25$, then $k_{avr} = 0.5 \cdot (k_{in} + k_{out})$.

If $\left| \frac{k_{in} - k_{out}}{k_{out}} \right| > 0.25$, then it is necessary to calculate the heat transfer coefficient in the middle section k_{1-2}, i.e. when $t_{1avr} = 0.5 \cdot (t'_1 + t''_1)$. And only then can the average heat transfer coefficient be calculated $k_{avr} = 0.333 \cdot (k_{in} + k_{out} + k_{1-2})$.

The first trail

$$t_{1avr} = 0.5 * (328.9 - 298.2) = 15.35$$

$$\alpha_{2in} = \frac{10.45}{3.3 - 0.0113 \cdot (t_s - 100)} \cdot q_{in}^{0,7}, \text{ W/(m}^2\cdot{}^{o}\text{C);}$$

$$\alpha_{1-2} = \frac{10.45}{3.3 - 0.0113(285.80 - 100)} * (5 * 10^4)^{0.7} = 16945.23$$

$$k_{in} = \left[\frac{1}{\alpha_{1avr}} + \frac{\delta_{tube}}{\lambda_{tube.in}} + 2 \cdot R_{ox} + \frac{1}{\alpha_2}\right]^{-1}, \text{ W/(m}^2\cdot{}^{o}\text{C);}$$

$$K_{1-2} = \left(\frac{1}{30831.4} + \frac{0.029}{169.140} + 2 * 10^{-5} + \frac{1}{16945.23}\right)^{-1} = 3534.77$$

$$q'_{1-2} = 3534.77 * (15.35) = 54258.71$$

$$\frac{q'_{1-2}}{q_{1-2}} = 1.008 \qquad \text{not accept}$$

The second trail

$$\alpha_{2in} = \frac{10.45}{3.3 - 0.0113 \cdot (t_s - 100)} \cdot q_{in}^{0,7}, \text{ W/(m}^2\cdot{}^{o}\text{C);}$$

$$\alpha_{1-2} = \frac{10.45}{3.3 - 0.0113(285.80 - 100)} * (54258.71)^{0.7} = 17943.08$$

$$k_{in} = \left[\frac{1}{\alpha_{1avr}} + \frac{\delta_{tube}}{\lambda_{tube.in}} + 2 \cdot R_{ox} + \frac{1}{\alpha_2}\right]^{-1}, \text{ W/(m}^2\cdot{}^{o}\text{C);}$$

$$K_{1-2} = \left(\frac{1}{30831.4} + \frac{0.029}{169.140} + 2 * 10^{-5} + \frac{1}{17943.08}\right)^{-1} = 3576.25$$

$$q'_{1-2} = 3576.25 * (15.35) = 54895.56$$

$$\frac{q'_{1-2}}{q_{1-2}} = 1.01 \qquad \text{accept}$$

$$k_{avr} = 0.333 \cdot (k_{in} + k_{out} + k_{1-2})$$

$$k_{avr} = 0.333 * (12349.54 + 4020.35 + 3576.25) = 6642.06$$

Determine the area of the heat exchange surface

$$F = \frac{k_{sf} \cdot Q_{sg}}{k_{avr} \cdot \Delta t_{avr}}, \text{ m}^2$$

$$F = \frac{1.05 * 1067}{6642.06 * 24.64} = 6.845 * 10^{-3}$$

Here k_{sf} = 1.05 ... 1.10 is the safety factor for taking into account deposits and plugged tubes;

k_{avr} is the average heat transfer coefficient, kW/(m²·ºC);

Q_{sg} is thermal power of the steam generator, kW;

Δt_{avr} is average temperature head in the steam generator, °C;

8 Calculate the average length of one tube of the steam generator

$$l_{avr} = \frac{F}{\pi \cdot d_{avr} \cdot N_{tube}}, \text{ m,}$$

$$l_{avr} = \frac{6.845 * 10^{-3}}{\pi * 18 * 10^{-3} * 7000} = 13.37 \text{ m}$$

where $d_{avr} = 0.5 \cdot (d_{out} + d_{in}) = d_{in} + \delta_{tube}$ is the average diameter of the heat transfer

tubes, m;

$$davr = 18 * 10^{-3}$$

N_{tube} is number of tubes in the steam generator.

Attention. The maximum length of pipes for a horizontal steam generator should not exceed 17 m, for a vertical one - 20 m.

3.2 Design calculation of horizontal SG of saturated vapor with U-shaped tubes

Table 5.inial data

Parameter	Denomination, units	Value
Coolant		water
Thermal power of reactor	Q_r, MW	3200
Thermal power of SG	Q_{sg}, MW	1067
Mass flow of steam	D_{st} or D_2, kg/s	0.5451
Coolant flow	G_1, kg/s	6132.18
Coolant pressure at the inlet to the SG	p_1, MPa	17,64
Coolant temperature at the inlet to the SG	t_1', °C	328,9
Coolant temperature at the outlet of the SG	t_1'', °C	298,2
Steam pressure at the SG	p_{st} or p_2, MPa	7,0
Steam temperature at the outlet of the SG	t_{st} or t_s, °C	$t_s = f(p_2) = 285.80$
Feed water temperature	t_{fw}, °C	200
Blowdown flow rate, % (as a percentage of mass flow of steam)	α_{bd}, %	0.3

2.1. Basic data for the calculation

- G_1 и D_2 is mass flow of coolant and working fluid, kg/s;
- p_{1avr}, t_{1avr} - average pressure (MPa) and coolant temperature (ºC);
- p_2 is working medium pressure, MPa;
- D_{col}^{in} =0.75 m is internal diameter of the collector, m;
- S_1= 0,022 m is step between the holes along the height (vertical);

- S_2 = 0.030 m is step between holes along the circle (horizontal);
- d_{tube}^{out} - outer diameter of tubes, m;
- l_{tube} is average length of tubes, m;
- arrangement of tubes is corridor;
- collector material is steel 10ГН2МФА.

2.2. Calculation of the wall thickness of the collector, m

$$\delta_{coll} = \frac{p_{1calk} \cdot D_{col}^{in}}{2 \cdot \varphi_{\min} \cdot [\sigma] - p_{1calk}},$$

$$\delta_{col1} = \frac{19.8 * 0.75}{2 * 0.27 * (215) - 19.845} = 0.1542 \text{ m}$$

where $p_{1calk} = 0,9 \cdot 1,25 \cdot p_{1avr} \approx 0,9 \cdot 1,25 \cdot p_1$ is the rated pressure, MPa;

$$p_{1calk} = 0.9 * 1.25 * 17.64 = 19.845 \text{ MPa}$$

$[\sigma] = 215$ MPa is nominal stress design for steel 10ГН2МФА;

$\varphi_{\min}$ is minimum coefficient of strength. Let's accept the smallest value of

$$\varphi_1 = \frac{s_1 - d_{tube}^{out}}{s_1} = \frac{0,022 - 0.016}{0.022} = 0.27$$

$$\varphi_1 = \frac{2 \cdot \left(s_2 - d_{tube}^{out}\right)}{s_2} = \frac{2(0.030 - 0.016)}{0.030} = 0.93$$

If $\varphi_1 \geq \varphi_2$, then $\varphi_{\min} = \varphi_2$, but if $\varphi_1 < \varphi_2$, then $\varphi_{\min} = \varphi_1$.

2.3. Outer diameter of the collector, m

$$D_{col}^{out} = D_{col}^{in} + 2 \cdot \delta_{coll}.$$

$$D_{col}^{out} = 0.75 + 2 * 0.1542 = 1.06 \text{ m}$$

2.4. Recalculation of step s2 on to the outer diameter (Fig. 2.1), m

$$s_{2out} = s_2 \cdot \frac{D_{col}^{out}}{D_{col}^{in}}$$

$$s_{2out} = 0.030 * \frac{1.06}{0.75} = 0.0424 \text{ m}$$

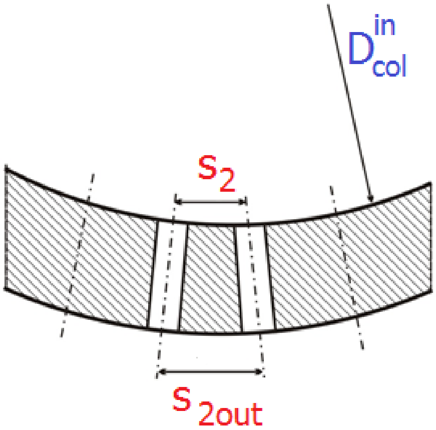


Figure 2.1. Fragment of the wall of the collector.

2.5. The length of the arc along the circumference of the collector occupied by tubes of the upper row, m

$$L_{c1} = \pi \cdot D_{col}^{out}.$$

$$L_{c1} = \pi * 1.06 = 3.33 \text{ m}$$

2.6. Number of tubes in the upper row, pcs.

$$N_{tube1} = \frac{L_{c1}}{s_{2out}}.$$

$$N_{tube1} = \frac{3.33}{0.0584} = 57$$

2.7. The maximum width of the tube bundle at the level of the upper row of tubes (taking into account 3 vertical corridors), m

$$B_{bund}^{max} = N_{tube1} \cdot s_{2out} + 3 \cdot B_{cor},$$

$$B_{band}^{max} = 57 * 0.0584 + (3 * 0.15) = 3.779 \text{ m}$$

where $B_{cor} = 0,15...0,2$ m is width of vertical corridors.

2.8. Width of the heat exchange tube bundle package, m

$$B_{pack} = \frac{B_{bund}^{max} - 3 \cdot B_{cor}}{2}.$$

$$B_{pack} = \frac{3.779 - (3 * 0.15)}{2} = 1.6645 \text{ m}$$

2.9. The distance between the axes of the collectors, m

$$B_{dac} = 2 \cdot B_{pack} + 2 \cdot B_{cor}.$$

$$B_{dac} = 2 * 1.6645 + 2 * 0.15 = 3.629 \text{ m}$$

2.10. Width of submerged perforated plate (PP) , m

$$B_{pp} = (1,05...1,1) \cdot B_{bund}^{max}.$$

$$B_{pp} = (1.05 * 3.779) = 3.967 \text{ m}$$

2.11. SG vessel width at level perforated plate, m

$$B_{ves.pp} = B_{pp} + 2 \cdot B_{gap},$$

$$B_{ves.app} = 3.967 + (2 * 0.15) = 4.267 \text{ m}$$

where $B_{gap} = 0,15...0,25$ m is the width of the passages (the distance between the PP and the walls of the SG housing) for the flow of water, m.

2.12. Height of the location of the submerged perforated plate relative to the horizontal axis of the PG vessel, m

$$h_{pp} = h_0 + h_1 - h_{wl},$$

$$h_{pp} = 0.2 + 0.2 - 0.1 = 0.3 \text{ m}$$

where $h_0 = 0,2...0,35$ m is height of the arrangement of the upper row of tubes relative to the horizontal axis of the SG;

$h_1 = 0,2...0,35$ m is the height of the location of the weight level of water above the upper row of tubes;

$h_{wl} = 0,1$ m is height of the weight level above the submerged perforated plate.

2.13. The distance of the lower row of pipes of the heat exchange surface from the lower generatrix of the steam generator vessel. Take equal $h_{dlr} = 0,08...0,120$ м.

2.14. Internal diameter of the steam generator vessel, m

$$D_{ves.in} = \sqrt{4 \cdot h_{pp}^2 + B_{ves.pp}^2}.$$

$$D_{ves.in} = \sqrt{4 * 0.3^2 + 4.267^2} = 4.3089$$

2.15. Area of the evaporation surface, m²

$$F_{es} = B_{ves.pp} \cdot l_{tube}.$$

$$F_{es} = 4.2677 * 13.37 = 57.059$$

2.16. Superficial steam velocity, m/s

$$w_o'' = \frac{D_2}{F_{es} \cdot \rho_2''},$$

$$w_0'' = \frac{545.1}{57.059 * 36.52} = 0.2616\ \frac{m}{s}$$

where ρ_2'' is density of saturated vapor at the pressure p_2 of the working fluid , kg/m³.

2.17. The true volumetric vapor content in the water layer above the submerged perforated plate, m

$$\varphi_{bub} = \frac{w_0''}{w_0'' + (0,65 - 0,039 \cdot p_2)}.$$

$$\varphi_{\text{bub}} = \frac{0.2616}{0.2616 + (0.65 - 0.039 * 7)} = 0.4096$$

2.18. Actual (real) water level above above the submerged perforated plate, m

$$h_{real} = \frac{h_{wl}}{(1 - \varphi_{bub})}$$

$$\text{h}_{\text{real}} = \frac{0.1}{1 - 0.4096} = 0.17$$

2.19. Height of steam volume, m

$$h_{sv} = \frac{D_{ves.in}}{2} - (h_{pp} + h_{real}).$$

$$\text{h}_{\text{sv}} = \frac{4.3089}{2} - (0.3 + 0.17) = 2.62 \text{ m}$$

Attention! The value h_{sv} found should be checked in terms of the effectiveness of precipitation separation.

The minimum permissible height of the vapor volume must correspond to the following condition

$$h_{sv} \geq 0,4 \text{ m}.$$

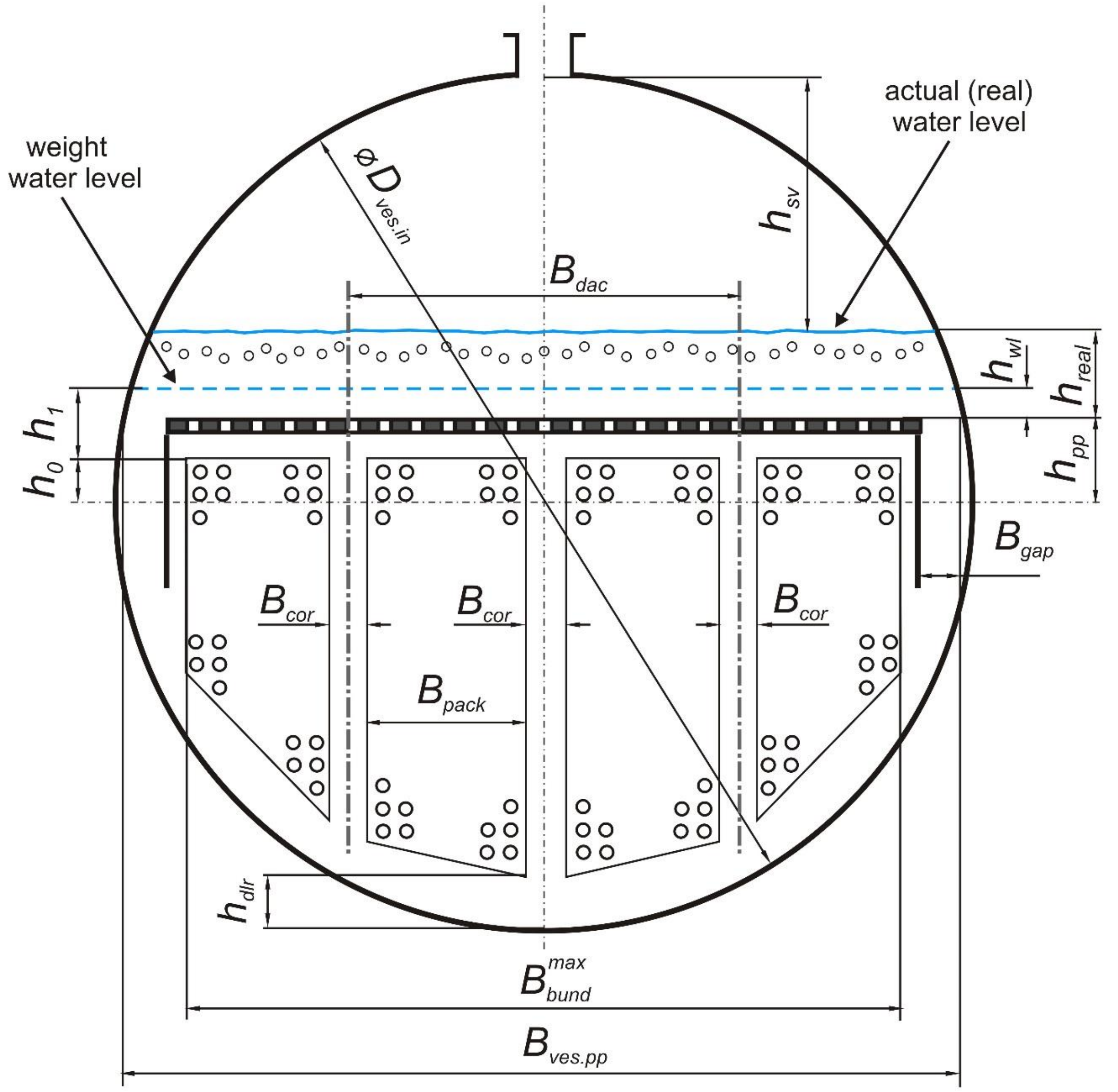


Figure 2.2. To determine the main layout dimensions horizontal SG

2.20. Characteristics of steam outlet nozzles

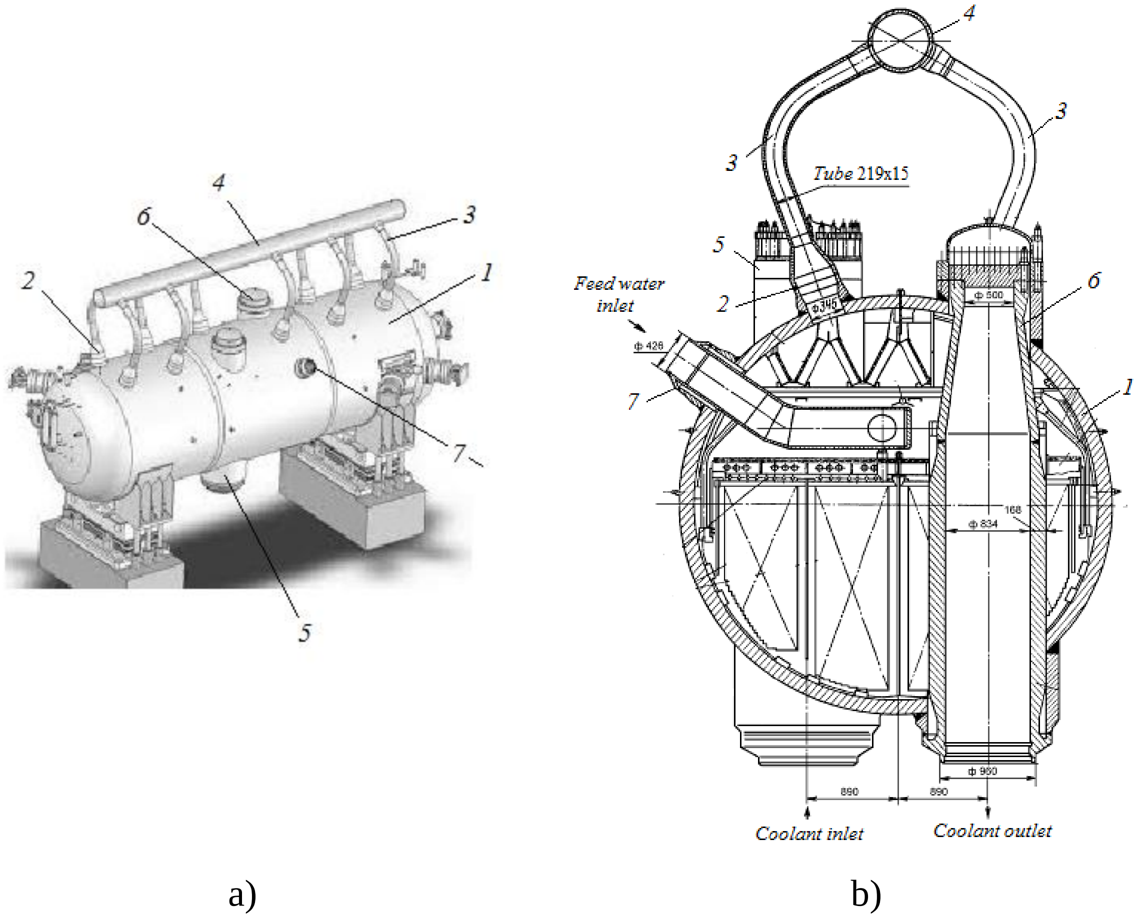


Figure 2.3. Exterior (a) and cross section (b) of a horizontal steam generator:

1 - vessel; 2 - steam outlet nozzles; 3 - steam pipes; 4 - steam collector; 5 - input collector of the coolant; 6 - output collector of the coolant; 7 - pipe feed water

Steam outlet nozzles 2 are used to divert the generated steam from the steam generator. They are located in pairs in the upper part of the housing 1. Two nozzles are located in the same sections as the coolant collectors (5 and 6). Steam exhaust nozzles are connected to steam pipes, which are combined by a common steam collector 4.

The inner diameter of the steam outlet nozzles $d_{noz.in}$ can be determined from the following continuity equation

$$N_{noz} \cdot \frac{\pi \cdot d_{noz.in}^2}{4} \cdot w_{noz} = \frac{D_2}{\rho''},$$

$$d_{noc} = \sqrt{\frac{\frac{D_2}{\rho''}}{N_{noc} * w_{noc} * \pi} * 4}$$

$$d_{noc} = \sqrt{\frac{\frac{0.5451}{36.52}}{8 * 30 * \pi} * 4} = 0.089$$

where $N_{noz} = 8...10$ pc. is number of steam outlet nozzles;

$w_{noz} = 30...40$ m/s is steam speed in steam outlet nozzles;

D_2 is mass flow of steam, kg/s;

ρ_2'' is density of saturated steam at the pressure p_2, kg/m³.

2.21. Characteristics of the feed pipe

The inner diameter of the feed pipe $d_{fw.in}$ can be determined from the following continuity equation

$$\frac{\pi \cdot d_{fw.in}^2}{4} \cdot w_{fw} = \frac{D_{fw}}{\rho_{fw}},$$

$$d_{fw} = \sqrt{\frac{4 * \frac{D_{fw}}{\rho_{fw}}}{w_{fw} * \pi}} = \sqrt{\frac{4 * \frac{546.74}{868.75}}{4 * \pi}} = 0.4475$$

where $w_{fw} = 4...5$ m/s is feed water speed in feed pipe;

$D_{fw} = D_2 + D_{bd}$ is mass flow of feed water, kg/s;

D_{bd} is flow rate of blowdown water, kg/s;

$\rho_{fw} = f\left(p_2, t_{fw}\right)$ is density of feed water, kg/m³. =868.75

3.3 Mechanical calculation of horizontal SG of saturated vapor with U-shaped tubes

The purpose of the mechanical calculation is to calculate the static strength of the main elements of the steam generator and determine the wall thickness of these elements.

A full mechanical calculation includes the calculation of the following elements:

- calculation of heat transfer tubes;
- calculation of coolant collectors;
- calculation of the steam generator housing

The mechanical calculation of heat transfer tubes was carried out in section 1 "Thermohydraulic calculation". The mechanical calculation of the collectors was carried out in section 2 "Design calculation".

The mechanical calculation procedure for the steam generator housing is given below.

Calculation of the SG vessel

The vessel of a horizontal steam generator (Fig. 3.1) is a thick-walled vessel of large diameter. It consists of a central shell 1, two side shells 2 and two bottoms 3. All elements are connected to each other by welding.

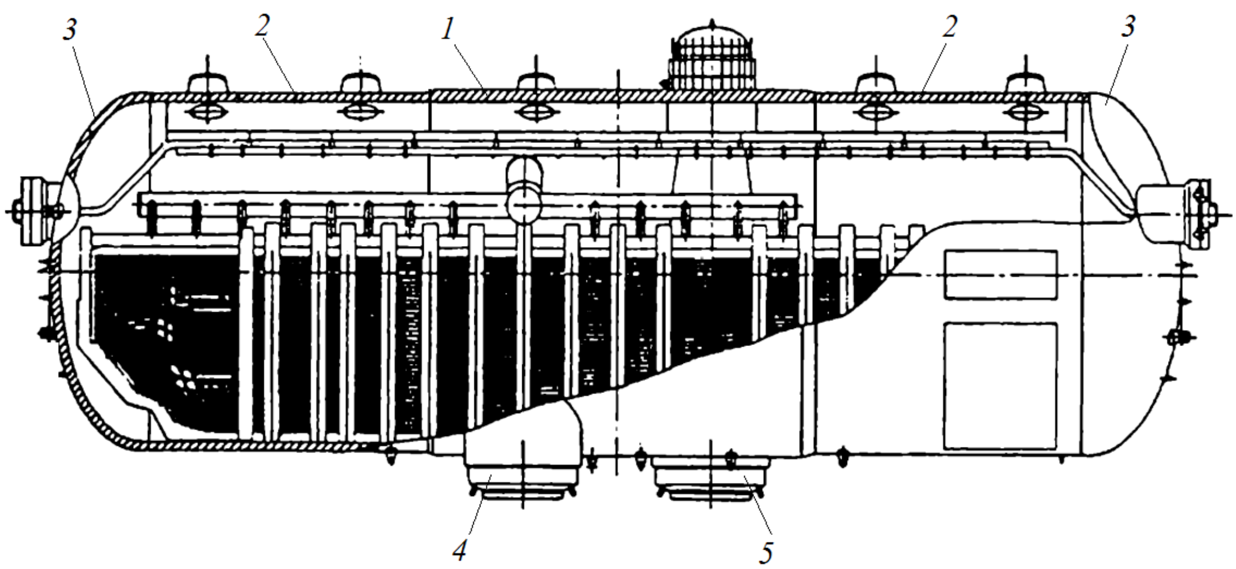


Figure 3.1. Longitudinal section of a horizontal steam generator:

1 is central shell; 2 are side shells; 3 are bottoms; 4 - input collector of the coolant; 5 - output collector of the coolant

3.1. Calculation of the wall thickness of the side shell

The following formula should be used to calculate the nominal wall thickness of the side shell (vss)

$$\delta_{vss} = \frac{p_{calc} \cdot D_{ves.in}}{2 \cdot \varphi \cdot [\sigma] - p_{calc}} + C.$$

$$\delta_{ves} + c = \frac{19.8*4.3089}{2*1*181.153-19.8} = 0.248 \text{ m} \qquad (3.1)$$

where: δ_{vss} is in m;

$D_{ves.in}$ is internal diameter of the steam generator vessel, m. It is calculated in the section "Design calculation of the steam generator";

φ is coefficient of strength (load factor). Side shells do not have large diameter holes and therefore this coefficient can be taken $\varphi = 1$;

$p_{calc} = 0,9 \cdot 1,25 \cdot p_2$ is the rated (design) pressure, MPa;

$t_{vss.\max} = t_s$ is maximum operating temperature of the side shell, ºC;

C is increase to the nominal thickness of the shell and bottom of the vessel. This increase is assumed to be equal to:

C=1 mm with a wall thickness less than 20 mm;

C=0 with a wall thickness of more than 20 mm.

$[\sigma]$ is nominal stress design, MPa;

Calculate nominal stress design

This stress design is defined as the minimum of two values.

$$[\sigma] = \min\left\{\frac{\sigma_{sl}}{n_{sl}}; \frac{\sigma_{0,2}}{n_{0,2}}\right\}, \qquad (3.2)$$

$$\sigma = 181.15$$

Here n_{sl} =2,6 and $\sigma_{0,2}$ =1,5 are relevant safety factors

σ_{sl} is shakedown limit of the tubes material at the design temperature $t_{calk} = t_s$, MPa;

$\sigma_{0,2}$ is yield point of the tubes material at the design temperature $t_{calk} = t_s$, MPa;

10ГН2МФА type steel is used for manufacturing steam generator vessels in Russia (Table 3.1).

Table 3.1. Mechanical properties of steel 10ГН2МФА

t_{calc}, °C	100	150	200	250	300	350
σ_{sl}, MPa	510	510	510	491	471	491
$\sigma_{0,2}$, MPa	323	314	304	304	304	294

3.4. Calculation of the wall thickness of the central shell

The following formula should be used to calculate the nominal wall thickness of the central shell (vcs)

$$\delta_{vcs} = \frac{p_{calc} \cdot D_{ves.in}}{2 \cdot \varphi \cdot [\sigma] - p_{calc}} + C . \qquad (3.3)$$

The values of all variables in this formula can be taken as for the side shell with the exception of the coefficient of strength φ.

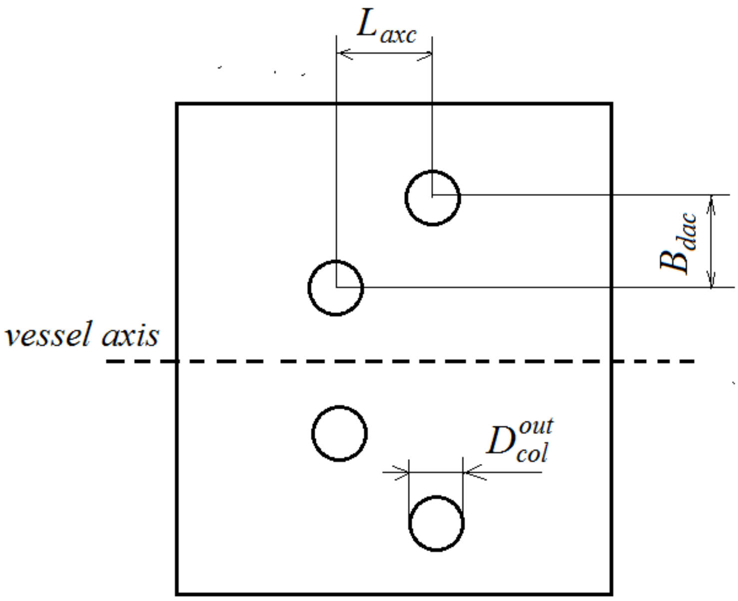


Fig. 3.2. To the calculation of the strength coefficient

In the central shell there are 4 large-diameter holes for the passage of coolant collectors. Therefore, the coefficient $\varphi = \min\{\varphi_1, \varphi_2, \varphi_3\}$ *is defined as the smallest* $\varphi = \min\{\varphi_1, \varphi_2, \varphi_3\}$ *of the three values* φ_1, φ_2 *and* φ_3*. The formulas for calculating these coefficients are given here.*

$$\varphi_1 = \frac{2 \cdot L_{axc} - D_{col}^{out}}{2 \cdot L_{axc}};$$

$$\varphi_1 = \frac{2 * 2.12 - 1.06}{2 * 2.12} = 0.75$$

$$\varphi_2 = \frac{2 \cdot \left(2 \cdot B_{dac} - D_{col}^{out}\right)}{2 \cdot B_{dac}};$$

$$\varphi_2 = \frac{2 * (2 * 3.629 - 1.06)}{2 * 3.629} = 1.708$$

$$\varphi_3 = \frac{1 - \frac{D_{col}^{out}}{L_{axc}} \cdot \frac{1}{\sqrt{1+m^2}}}{\sqrt{1 - 0.75 \cdot \left(\frac{m^2}{1+m^2}\right)^2}},$$

$$\varphi_3 = \frac{1 - \frac{1.06}{2.12} * \frac{1}{\sqrt{1 + 1.712}}}{\sqrt{1 - 0.75 * (\frac{1.712^2}{1 + 1.712^2}}} = 1.05$$

where: δ_{vcs} *is in m;*

$m = B_{dac} / L_{axc}$;

$$m = \frac{3.629}{2.12} = 1.712$$

B_{dac} *is the radial distance between the axes of the collectors, m. It is calculated in the section "Design calculation of the steam generator".*

$L_{axc} \approx 2 \cdot D_{col}^{out}$ *is axial distance between collector axes, m;*

$$L_{axc} = 2 * 1.06 = 2.12$$

D_{col}^{out} *is outer diameter of the collector, m. It is calculated in the section "Design calculation of the steam generator".*

3.5 Calculation of the thickness of bottom

$$\delta_{bot} = \frac{p_{calk} \cdot D_{ves.in}}{4 \cdot \varphi \cdot [\sigma]} \cdot \frac{D_{ves.in}}{2 \cdot h}, \qquad (3.4)$$

$$\delta_{bot} = \frac{19.8 * 4.3089}{4 * 1 * 181.15} * \frac{4.3089}{2 * 0.86178} = 0.2943$$

where: δ_{bot} *is in m;*

h *is height of the bottom, m. It can be calculated from relation* $h/D_{ves.in} \geq 0,2$.

$$h = 0.2 * 4.3089 = 0.86178$$

$\varphi = 1$ *is coefficient of strength.*

The remaining variables in this formula are the same as when calculating the thickness of the central shell.

3.6 Hydraulic calculation of the steam generator

The purpose of hydraulic calculation of the steam generator is to determine the pressure loss when the coolant moves in it

The steam generator is connected to the reactor by main circulation pipelines. The coolant enters the inlet collector from the hot circulation pipeline. Then the coolant is distributed through the heat exchange tubes, passes through them and is collected in the output collector. From the output collector, the coolant goes to the cold circulation pipeline (Figure 4.1.).

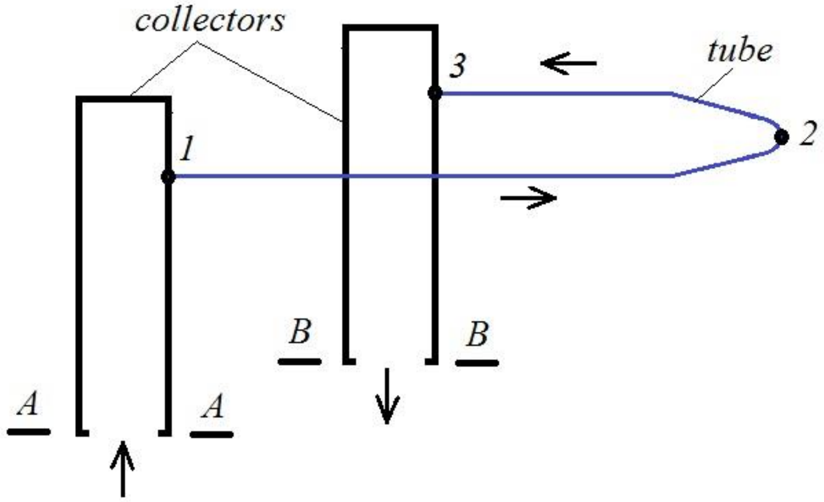


Figure 4.1. Flow diagram of the coolant circulation in a horizontal steam generator

The hydraulic resistance of the horizontal steam generator along the coolant path can be represented as follows

$$\Delta p_{\Sigma} = \Delta p_{col.in} + \Delta p_{col.out} + \Delta p_{tube},$$

$$\Delta p_{\Sigma} = 4662.50 + 145316.7334 + 4662.50 = 154641.7334\, pa$$

where $\Delta p_{col.in}$ and $\Delta p_{col.out}$ are hydraulic resistances of the input and output collectors;

Each term in the previous equation includes friction pressure losses Δp_{fr}, local pressure losses Δp_{loc}, static pressure differences Δp_{cpd} and pressure losses due to flow acceleration Δp_{acc}

$$\Delta p_i = \Delta p_{fr.i} + \Delta p_{loc.i} + \Delta p_{cpd.i} + \Delta p_{acc.i},$$

$$p_{total} = 4662.50 + 145316.7334 + 4662.50 + 4384.375 + 8768.75 = 167794.8584 \text{ Pa};$$

where i is plot number.

Static pressure differences and losses from flow acceleration can be ignored, taking into account a small change in the temperature and density of the coolant in a steam generator with a water coolant.

For the calculate the friction pressure losses it is necessary to use the Altshul formula

$$\Delta p_{fr} = \xi_{fr} \cdot \frac{L}{d_h} \cdot \frac{\rho_{avr} \cdot w^2}{2}, \qquad (4.1)$$

where L is plot length, m;

$d_h = D_{col}^{in} = 1$m is characteristic size (hydraulic diameter), m;

$\rho_{avr} = f(p_1, t_{1avr})$ = f (17.64 , 313.55) = 701.5 kg/m³ is the average density of the coolant in the SG, kg/m³;

w is the characteristic velocity of the coolant, m/s;

$$w_{col} = \frac{4 \cdot G_{col}}{\rho_{avr} \cdot \pi \cdot (D_{col}^{in})^2} = \frac{4 \cdot 6132.18}{701.5 \cdot \pi \cdot (0.75)^2} = 19.78 \text{ m/s}$$

$\xi_{fr} = 0{,}11 \cdot \left[(\Delta/d_h) + (68/\mathrm{Re})\right]^{0{,}25}$ is coefficient of friction;

Δ is absolute surface roughness, m. For collectors made of perlite steel $\Delta_{col} \le 0.1 \cdot 10^{-3}$ m; for tubes made of austenitic steel $\Delta_{tube} \le 0.05 \cdot 10^{-3}$ m;

$\mathrm{Re} = w \cdot d_h / \nu_{avr}$ is Reynolds number;

$\nu_{avr} = f(p_1, t_{1avr}) = 1.1975 * 10^{-7}$ m^2/s is the average kinematic viscosity of the coolant in the SG;

4.1.1 For the plot lifting movement of the coolant in the inlet collector (from section A-A to point 1):

$$\Delta p_{fr} = \xi_{fr} \cdot \frac{L}{d_h} \cdot \frac{\rho_{avr} \cdot w^2}{2} \ ;$$

$$D_{col}^{in} = 1\text{m} \ ;$$

$\rho_{avr} = f(p_1, t_{1avr})$ = f (17.64 , 313.6) = 701.4 kg/m³

$$w_{col} = \frac{4 \cdot G_{col}}{\rho_{avr} \cdot \pi \cdot (D_{col}^{in})^2} = \frac{4 \cdot 6132.18}{701.5 \cdot \pi \cdot (0.75)^2} = 19.78\ m/s$$

$$d_h = D_{col}^{in} = 0.75m\ ;$$

$$L \approx \frac{D_{ves.in}}{2} = \frac{4.3083}{2} = 2.154\ m\ ;$$

$$Re = \frac{w_{col} \cdot d_h}{\nu} = \frac{19.78 \cdot 0.75}{1.1975\ *\ 10^{-7}} = 123.88 \cdot 10^6\ ;$$

$$\xi_{fr.col} = 0,11\left[\left(\Delta/d_h\right) + \left(68/Re\right)\right]^{0,25}\ ;$$

$$\xi_{fr.col} = 0,11\left[\left(\frac{0,1 \cdot 10^{-3}}{0.75}\right) + \left(\frac{68}{123.88 \cdot 10^6}\right)\right]^{0,25} = 0,01183\ ;$$

$$\Delta p_{fr} = 0,01183 \cdot \frac{2.154}{0.75} \cdot \frac{701.5 \cdot (19.78)^2}{2} = 4662.50\ Pa\ ;$$

4.2.1 For the plot movement of the coolant in heat exchange tubes (from point 1 to point 3)

$$\Delta p_{fr} = \xi_{fr} \cdot \frac{L}{d_h} \cdot \frac{\rho_{avr} \cdot w^2}{2}\ ;$$

$$D_{col}^{in} = 0.75m\ ;$$

$\rho_{avr} = f(p_1, t_{1avr})$ = f (17.64 , 313.6) = 701.5 kg/m³

$$w_{tube} = 5\ m/s\ ;$$

$$d_h = d_{in} = 20\ mm\ ;$$

$$L = l_{avr} = 13.37\ m\ ;$$

$\nu_{avr} = f(p_1, t_{1avr}) = 1,1975 * 10^{-7}\ \frac{m^2}{s}$

$$Re = \frac{w_{tube} \cdot d_h}{\nu} = \frac{5 \cdot 20 * 10^{-3}}{1,1975\ *\ 10^{-7}} = 835.37 \cdot 10^3\ ;$$

$$\xi_{fr.col} = 0,11\left[\left(\Delta/d_h\right) + \left(68/Re\right)\right]^{0,25}\ ;$$

$$\xi_{fr.col} = 0,11\left[\left(\frac{0,05 \cdot 10^{-3}}{20 * 10^{-3}}\right) + \left(\frac{68}{835.37 \cdot 10^3}\right)\right]^{0,25} = 0,02479\ ;$$

$$\Delta p_{fr} = 0{,}02479 \cdot \frac{13.37}{20 * 10^{-3}} \cdot \frac{701.5 \cdot (5)^2}{2} = 145316.7334 \ \text{Pa}$$

4.3.1 Downward movement of the coolant in the output collector

$$\Delta p_{fr} = \xi_{fr} \cdot \frac{L}{d_h} \cdot \frac{\rho_{avr} \cdot w^2}{2} \ ;$$

$$D_{col}^{in} = 1\text{m} \ ;$$

$\rho_{avr} = f\left(p_1, t_{1avr}\right)$ = f (17.64 , 313.6) = 701.4 kg/m³

$$w_{col} = \frac{4 \cdot G_{col}}{\rho_{avr} \cdot \pi \cdot \left(D_{col}^{in}\right)^2} = \frac{4 \cdot 6132.18}{701.5 \cdot \pi \cdot (0.75)^2} = 19.78 \ \text{m/s}$$

$$d_h = D_{col}^{in} = 0.75\text{m} \ ;$$

$$L \approx \frac{D_{ves.in}}{2} = \frac{4.3083}{2} = 2.154 \text{ m} \ ;$$

$$Re = \frac{w_{col} \cdot d_h}{\nu} = \frac{19.78 \cdot 0.75}{1.1975 \ * \ 10^{-7}} = 123.88 \cdot 10^6 \ ;$$

$$\xi_{fr.col} = 0{,}11 \left[\left(\Delta / d_h\right) + \left(68 / Re\right)\right]^{0,25} \ ;$$

$$\xi_{fr.col} = 0{,}11 \left[\left(\frac{0{,}1 \cdot 10^{-3}}{0.75}\right) + \left(\frac{68}{123.88 \cdot 10^6}\right)\right]^{0,25} = 0{,}01183 \ ;$$

$$\Delta p_{fr} = 0{,}01183 \cdot \frac{2.154}{0.75} \cdot \frac{701.5 \cdot (19.78)^2}{2} = 4662.50 \text{ Pa} \ ;$$

(from point 3 to section B-B)For the calculate of local pressure losses it is necessary to use the following formula

$$\Delta p_{loc} = \xi_{loc} \cdot \frac{\rho_{avr} \cdot w^2}{2} , \qquad (4.2)$$

where ξ_{loc} is local resistance coefficient. The values of this coefficient for some types of local resistances are given in the table

Table 6. The values of the coefficient of local resistance

Type of local resistance	Coefficient value ξloc

Inlet of the coolant to the tubes from the collector	0.5
Output of the coolant from the tubes to the collector	1.0
Rotation of the coolant in U-shaped tubes	0.5

4.2) For the calculate of local pressure losses:

4.2.1) For the plot inlet of the coolant to the tubes from the collector (point 1):

$$\Delta p_{loc} = \xi_{loc.in} \cdot \frac{\rho_{avr} \cdot w_{tube}^2}{2} = 0{,}5 \cdot \frac{701.5 \cdot (5)^2}{2} = 4384.375 \text{ Pa} \ ;$$

4.2.2) For the plot Output of the coolant from the tubes to the collector (point 3) :

$$\Delta p_{loc} = \xi_{loc.in} \cdot \frac{\rho_{out} \cdot w_{out}^2}{2} = 1 \cdot \frac{701.5 \cdot (5)^2}{2} = 8768.75 \text{Pa} \ ;$$

Then :

$$\Delta p_{total} = 4662.50 + 145316.7334 + 4662.50 + 4384.375 + 8768.75 = 167794.8584 \text{ Pa} \ ;$$

The General scheme, characteristic parameters and results of hydraulic calculation of the horizontal steam generator are presented in the Table

№	Plot name	Type of hydraulic resistance	Characteristic coolant velocity, m/s	Characteristic dimensions, m	Pressure losses, Па
1	**Lifting movement of the coolant in the inlet collector (from section A-A to point 1)**	**Pressure drops due to friction. Friction factor** $\xi_{fr.col}$ **(Altshul formula)**	$W_{col} =$ **19.78 m/s** **(the continuity equation for the collector)**	$d_h = D_{col}^{in} =$ **0.75 m** $L \approx D_{ves.in}/2 =$ **2.154m** **(section 2 " Design calculation")**	**4662.50**
2	**Inlet of the coolant to the tubes from the collector (point 1)**	**Local pressure drops Local resistance coefficient** $\xi_{loc.in}$	$W_{tube} =$ **5 m/s** **(section 1.4. «Thermal calculation»)**	$d_h = d_{in} =$ **mm** **(section 1.3. «Thermal calculation»)**	**4384.375**
3	**Movement of the coolant in heat exchange tubes (from point 1 to point 3)**	**Pressure drops due to friction. Friction factor** $\xi_{fr.tube}$ **(Altshul formula)**	$W_{tube} =$ **5 m/s** **(section 1.4. «Thermal calculation»)**	$d_h = d_{in} =$ **20 mm** $L = l_{avr} =$ **13.37 m** **(section 1.3. «Thermal calculation»)**	**145316.7334**
4	**Output of the coolant from the tubes to the collector (point 3)**	**Local pressure drops Local resistance coefficient** $\xi_{loc.out}$	$W_{tube} =$ **5 m/s** **(from section 1.4. «Thermal calculation»)**	$d_h = d_{in} =$ **12,4 mm** **(from section 1.3. «Thermal calculation»)**	**8768.75**
5	**Downward movement of the coolant in the output collector (from point 3 to section B-B)**	**Pressure drops due to friction. Friction factor** $\xi_{fr.col}$ **(Altshul formula)**	$W_{col} =$ **19.78 m/s** **(from the continuity equation for the collector)**	$d_h = D_{col}^{in} =$ **0.75 m** $L \approx D_{ves.in}/2 =$ **2.154m** **m** **(section 2 " Design calculation")**	**4384.375**

Table 4.2. To the hydraulic calculation of the horizontal steam generator

Calculation of separation in a horizontal saturated steam generator

Modern horizontal saturated steam generators do not have louver separators and the main method of steam dehumidification is gravity separation in the steam volume. Therefore, the purpose of calculating separation in a horizontal steam generator is to estimate the humidity of steam in front of the steam receiving ceiling, which is located at the top of the steam volume

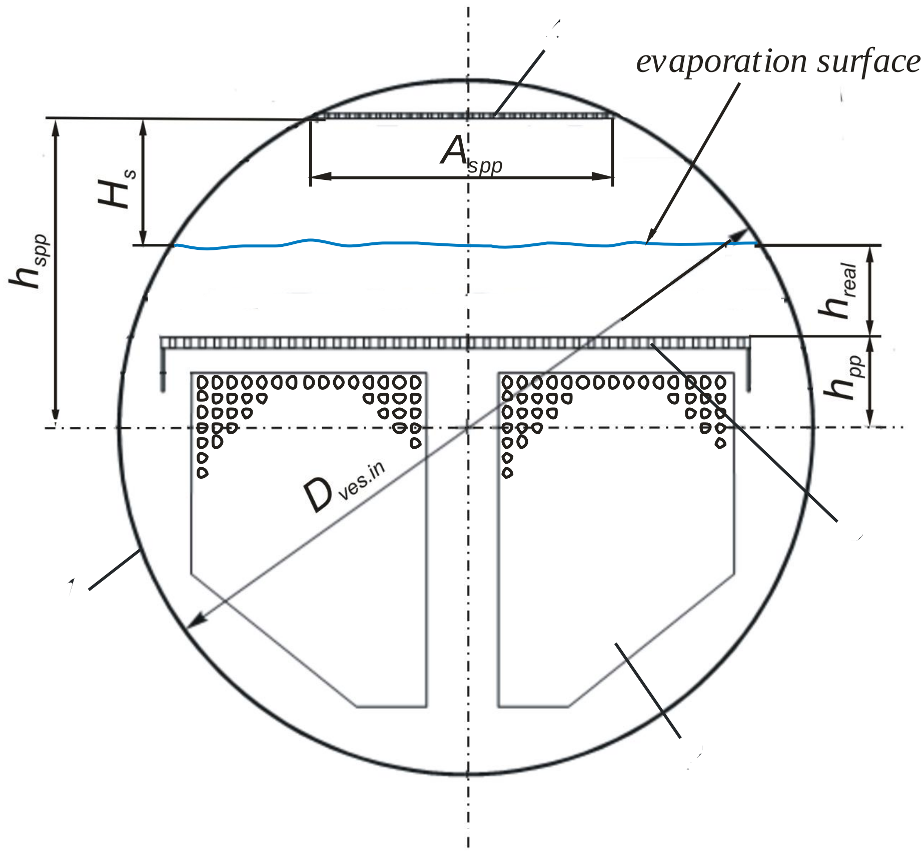


Figure 5.1. To the calculation of separation

1 is vessel; 2 are tubes; 3 is submerged perforated plate; 4 is steam-receiving perforated plate

The procedure for calculating separation in a horizontal steam generator is given below.

3.7 Basic data for the calculation:

- D_2 = 545.1 kg/s is mass flow of working fluid (steam);
- p_2 = 7.0 is working medium pressure;
- $D_{ves.in}$ = 4.3089 m is internal diameter of the steam generator vessel, m. It is calculated in the section "Design calculation of the steam generator";
- F_{es} = 57.059 m² is area of the evaporation surface, m². It is calculated in the section "Design calculation of the steam generator";
- l_{avr} = 14.4 m is average length of tubes. It is calculated in the section "Thermal calculation of the SG of saturated vapor".
- w_0'' = 2.6*10^-4
m/s is superficial steam velocity. It is calculated in the section "Design calculation of the steam generator".

Determination of the area steam-receiving perforated plate

$$F_{spp} = A_{spp} \cdot l_{avr} = \quad \text{m}^2,$$

$$\boldsymbol{F_{spp}} = 2.595 * 14.4 = 37.37\ m^2$$

where

$$A_{spp} = 2 \cdot \sqrt{\left(\frac{D_{ves.in}}{2}\right)^2 - \left(h_{spp}\right)^2} =$$

$A_{spp} = 2 * \sqrt{\left(\frac{4.3089}{2}\right)^2 - (1.72)^2} = 2.595$ m² is width of the steam-receiving perforated plate;

$$h_{spp} = (0{,}8...0{,}85) \cdot \frac{D_{ves.in}}{2} =$$

$0.8 * \frac{4.3089}{2} = 1.72$ m is height of the steam-receiving perforated plate relative to the axis of the SG vessel, m.

Distance (height) from the evaporation surface to steam-receiving perforated plate

$$H_s = h_{spp} - h_{pp} - h_{real} = \quad \text{m},$$

$$= 1.72 - 0.3 - 0.17 = 1.25m$$

where

h_{pp} = 0.3 m is height of the location of the submerged perforated plate relative to the horizontal axis of the PG vessel. It is calculated in the section "Design calculation of the steam generator";

h_{real} = 0.17 m is actual (real) water level above above the submerged perforated plate. It is calculated in the section "Design calculation of the steam generator".

5.4. Steam velocity before steam-receiving perforated plate

$$w''_{spp} = \frac{D_2}{\rho'' \cdot F_{spp}} = \quad \text{m/s},$$

$$= \frac{545.1}{36.52 * 37.37} = 3.994\ m/s$$

where

ρ'' = 36.52 kg/m³ is vapor density at saturation at pressure.

Determining the critical height of the steam volume

$$H_{sv}^{cr} = 0{,}087 \cdot \left[w''_0 \cdot F(p) \right]^{1{,}3},$$

$$H_{sv}^{cr} = 0.087 * (\mathbf{0.2616 * 12.37})^{1.3} = 0.4004$$

where

$$F(p) = 3{,}45 \cdot 10^3 \cdot \left[\frac{\rho'' \cdot (\rho')^2}{(\rho' - \rho'')^6} \right]^{0{,}25},$$

$$F(p) = 3.45 * 10^3 * \left(\frac{36.52 * (739.72)^2}{(739.72 - 36.52)^6}\right)^{0.25} = 12.37$$

where

ρ'' = 36.52 kg/m³ is vapor density at saturation at pressure;

ρ' = 739.72 kg/m³ is water density at saturation at pressure.

Steam moisture at the top of the steam volume

- If $H_s > H_{sv}^{cr}$, then

$$Y = M \cdot 10^{-4} \cdot \frac{\left(w_0''\right)^{2,76}}{H_s^{2,3}},$$

$$Y = 27.82 * 10^{-4} * \frac{(0.2616)^{2.76}}{1.25^{2.3}} = 4.113 * 10^{-5}$$

where

M is a pressure dependent coefficient. Determined by the following formula

$$M = 2,05 - 3,049 \cdot p_2 + 0,9614 \cdot p_2^2;$$

p_2 in MPa.$M = 2.05 - 3.049 * 7 + 0.9614 * 7^2 = 27.82$

where

N coefficient that depends on the area ratio F_{es}/F_{spp}. Is determined table 5.1.

Table 7. The values of the coefficient of N

F_{es}/F_{spp}	1	1,6	2…2,5
N	6	9	12…16

Attention! The found value Y should be compared with the maximum allowable moisture $Y_{cr} = 0,2\,\%$ at the exit of the steam generator.

The following condition must be met $Y \le Y_{cr}$.

3.7 Calculation of thermal insulation of the steam generator

Thermal insulation of the steam generator is used to reduce heat loss to the environment during operation of the power unit. Thermal insulation is also necessary to protect personnel from burns in contact with a hot surface.

As a thermal insulation material for the NPP steam generator, you can use mats of the MTP-as brand made of super-thin glass fiber.

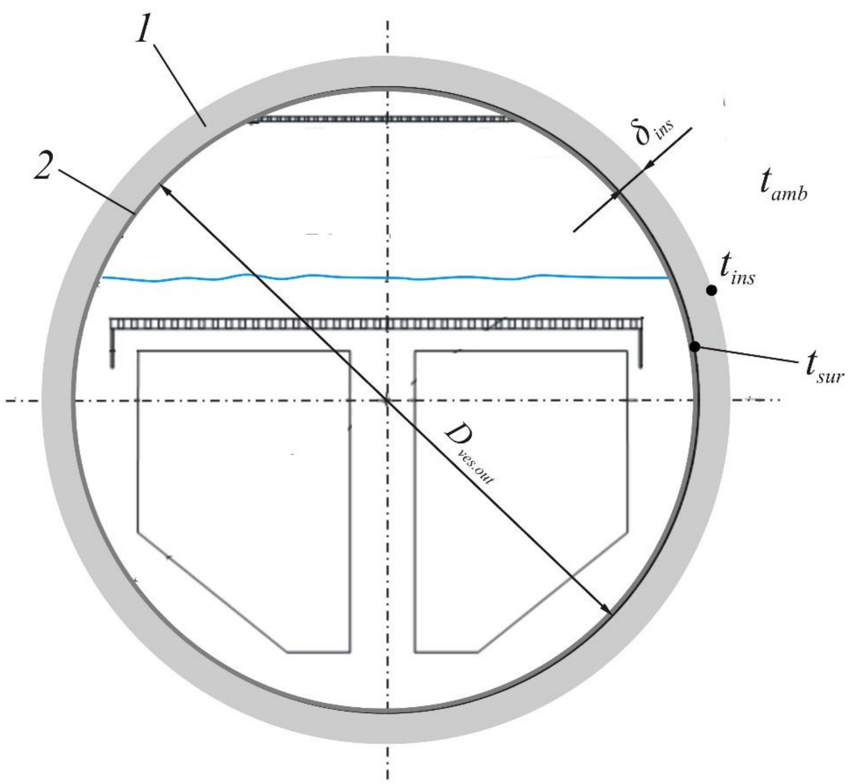


Fig. 1. Design scheme of single-layer thermal insulation with a coating layer:

1 is thermal insulation; 2 is vessel of SG

Several methods for calculating the thickness of the thermal insulation layer exist depending on the purpose of thermal insulation, namely:

- by the set temperature on the surface of an isolated object;

- for a given heat flux density;

- according to the set speed of cooling or heating of substances in containers, etc.

We will use the first method for calculating the thickness of the insulating layer of a steam generator.

The temperature on the insulation surface t_{ins} is assumed to be equal:

- for insulated surfaces located in closed rooms 45 °C;
- in the open air 60 °C with a plaster protective coating and 50…55 °C with a metal coating.

The thickness of the heat-insulating layer, providing a given temperature on the surface of a single-layer insulation, is determined by the formulas:

- for flat and cylindrical surfaces with a diameter of 2 m and more

$$\delta_{ins} = \frac{\lambda_{ins} \cdot (t_{sur} - t_{ins})}{\alpha_{out} \cdot (t_{ins} - t_{amb})}; \qquad (1)$$

$$\delta_{ins} = \frac{0.06908 * (285.80 - 45)}{6 * (45 - 20)} = 0.1108$$

$$, \qquad (2)$$

In this equation:

δ_{ins} is the thickness of the insulation layer, m;

d_{ins} is outer diameter of insulation, m;

$d_{out} = D_{ves.out} = D_{ves.in} + \delta_{vss}$ is diameter of the external insulated object, m;

$D_{ves.in}$ is internal diameter of the steam generator vessel, m. It is calculated in the section "Design calculation of the steam generator";

δ_{vss} is the central shell's wall thickness of the steam generator vessel, m. It is calculated in the section " Mechanical calculation of the steam generator";

$t_{sur} = t_s$ is surface temperature of the insulated object, °C; in practical calculations, an equal temperature of the medium (coolant);

$t_{amb} = 20...25$ °C is the temperature of the ambient air (environment);

$\alpha_{out} = 6...10$ W/(m²·K) - coefficient of heat transfer from the insulation surface to the surrounding air;

λ_{ins} is coefficient of thermal conductivity of the insulation layer, W/(m·K). It determined by the formula $\lambda_{ins} = 0.0002 \cdot t_{ins}^{avr} + 0.036$ for super-thin fiberglass mats;

$t_{ins}^{avr} = 0,5 \cdot (t_{sur} + t_{ins})$ is average temperature of the insulation layer, °C.

$$t_{ins}^{avr} = 0.5 * (285.80 + 45) = 165.4$$

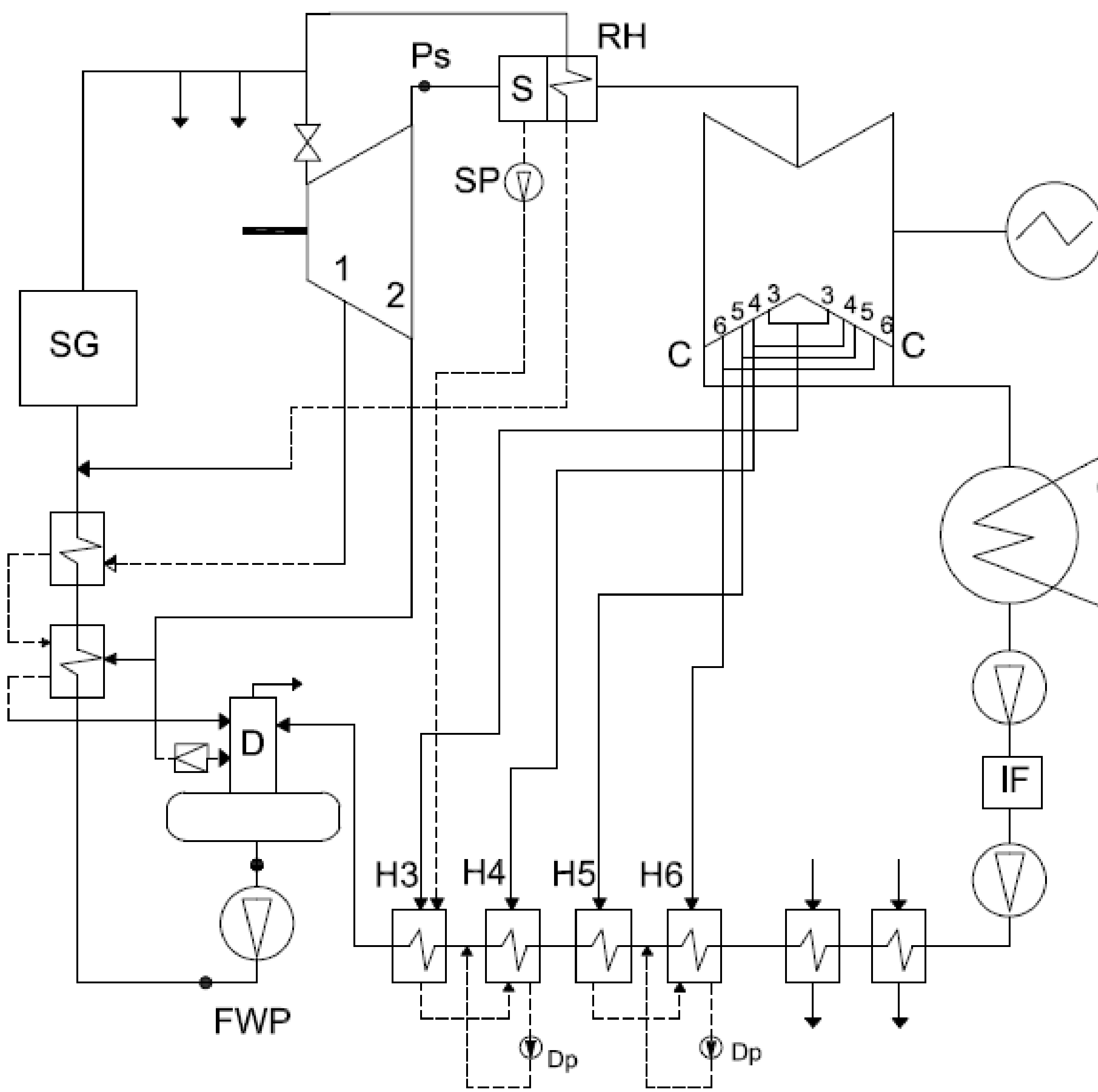
$$\lambda_{ins} = 0.0002 * 165.4 + 0.036 = 0.06908$$

4. Initial data of term Project on "Nuclear Power Plants " For thermal calculations

$Power\ MW\,(N_e)$	$1200\ MW$
P_0	$7.0\ Mpa$
t_0	t_s
$Resuper\ heating$	$One - stage$
$Exsuat\ Pressure\ (P_c)$	$0.004\ MPa$
$Separation\ Pressure(P_s)$	$0.28\ MPa$
$Deaerator\ Pressure(P_d)$	$0.60\ MPa$

$Number\ of\ HPH$	3
$Number\ of\ LPH$	4

$$for\ one - stage$$



$$t_{sD} = f(P_D) = f(0.7\ MP) = 158.8\ C$$

$$\Delta t_D = 12 \ldots .15\ c$$

$$\Delta t_D = 12\ c$$

$$t_{mc3} = t_{sD} - \Delta t_D = 146.8\ c$$

$$t_{sc} = f(P_c) = f(4\ MP) = 28.9\ c$$

$$\Delta t_{cse+cej} = 3 \ldots .5\ c$$

$$t_{cse} = t_{sc} + \Delta t_{cse+cej}$$

$$t_{cse} = 28.9 + 3.1 = 32\ c$$

$$h_{cse} = f(t_{cse}) = f(32\ ℃) = 134$$

Number of LPH

$$\Delta t_{mcj} = \frac{t_{mc3} - t_{cse}}{Z} = \frac{146.8 - 32}{4} = 28.7\ ℃$$

$$t_{mc4} = 146.8 - 28.7 = 118.1\ c$$

$$t_{mc5} = 118.1 - 28.7 = 89.4\ c$$

$$t_{mc6} = 89.4 - 28.7 = 60.70\ c$$

$$t_{cse} = 60.70 - 28.7 = 32$$

After Dearator

$$\vartheta' = f(0.6\ MP) = 1.1 * 10^{-3}\ \frac{M^3}{Kg}$$

$$P_{fw} \approx 1.3\ P_0$$

$$P_{fw} = 1.3 * 7 = 9.1\ MPa$$

for Pressurizing water

$$\Delta h_{fwp} = \vartheta'(P_{fw} - P_D)$$

$$\Delta h_{fwp} = 1.1 * 10^{-3}(9.1 - 0.6) * 10^3 = 9.4 \approx 9\ \frac{kj}{kg}$$

$$h' = f(0.6\ MP) = 671\frac{kj}{kg}$$

$$h_{fwp} = h' + \Delta h_{fwp}$$

$$h_{fwp} = 671 + 9 = 680\frac{kj}{kg}$$

$$t_{fwp} = f(P_{fwp}, h_{fwp})$$

$$t_{fwp} = f\left(7.8\ MPa, 679\ \frac{kj}{kg}\right) = 159.81\ ℃$$

The difference in tempreture between from Inlet and outlet in the feed water pump have to be little

$$t_{fw} = 200\ c$$

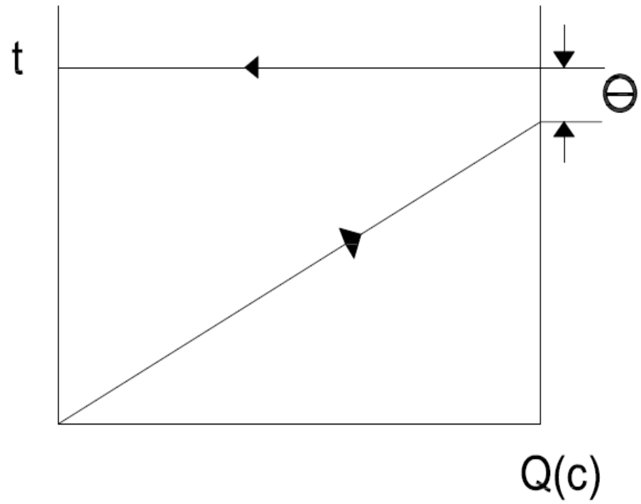
$$\Delta t_{HPH} = \frac{t_{fw} - \Delta t_{fwp}}{3} = \frac{198 - 146.8}{2} = 25.6\ ℃$$

$$PH_j = f(t_{sj})$$

$$t_{sj} = t_{fwj} + \theta$$

$$tfw1 = tfw - \Delta t = 200 - 2 = 198\ ℃$$

$$tfw2 = tfw1 - \Delta t_{lph} = 198 - 25 = 173\ ℃$$



$$\theta = 2\ ℃$$

$$\theta_{lpH} = 1.2\ ℃$$

$$t_{s1} = 198 + 3.2 = 201.2\ ℃$$

$$PH_1 = f(201.2\ c) = 1.59\ MP$$

$$P_1 = 1.59 * 1.03 = 1.6377\ Mpa$$

$$t_{s2} = 173 + 3.2 = 176.2\ ℃$$

$$PH_2 = f(176.2\ ℃) = 0.918\ MP$$

$$P_2 = 0.918 * 1.03 = 0.96\ MPa$$

$$t_{s3} = t_{mc3} + \theta_{LpH}$$

$$t_{s3} = 146.8 + 1.2 = 148\ ℃$$

$$P_{H3} = f(148\ ℃) = 0.45\ MPa$$

$$P_3 = 0.45 * 1.03 = 0.4635\ MPa$$

$$t_{s4} = 118.1 + 1.2 = 119.3\ ℃$$

$$P_{H4} = f(119.3\ c) = 0.19\ MPa$$

$$P_4 = 0.19 * 1.03 = 0.1957\ MPa$$

$$t_{s5} = 89.4 + 1.2 = 90.6℃$$

$$P_{H5} = f(90.6\ ℃) = 0.0718\ \ MPa$$

$$P_5 = 0.0718 * 1.03 = 0.0739\ MPa$$

$$t_{s6} = 60.70 + 1.2 = 61.9\ ℃$$

$$PH_6 = f(61.9\ ℃) = 0.0218\ MP$$

$$P_6 = 0.0218 * 1.03 = 0.0225\ MPa$$

$$P_0 = 7 * 0.95 = 6.65\ MPa$$

$$t_0 = f(P_0) = f(7\ MPa) = 285.83\ ℃$$

$$h_0 = f(P_0, t_0) = 2772\ \frac{kj}{kg}$$

$$P_0' = P_0 * 0.98 = 7 * 0.98 = 6.86\ MPa$$

$$s_0 = f(P_0', h_0) = f(6.86\ ,2772) = 5.822\ \frac{kj}{kg * ℃}$$

$$\therefore\ s_0 = s_1 = s_2$$

$$h_{1t} = f(P_1\ , s_0) = f(1.6377\ ,5.822) = 2513\ \frac{kj}{kg}$$

$$h_{2t} = f(P_2\ , s_0) = f(0.96\ ,5.822) = 2425\ \frac{kj}{kg}$$

$$h_1 = h_0 - (h_0 - h_{1t}) * 0.83$$

$$h_1 = 2772 - (2772 - 2513) * 0.83 = 2557 \ \frac{kj}{kg}$$

$$h_2 = h_0 - (h_0 - h_{2t}) * 0.83$$

$$h_2 = 2772 - (2772 - 2425) * 0.83 = 2484 \ \frac{kj}{kg}$$

$$x = f(P_2, h_2) = f(0.96 \, , 2484) = 85.571 \ \%$$

$$P_s = P_2$$

$$P_s' = P_2 * 0.98 = 0.96 * 0.98 = 0.9408 \ MPa$$

$$h_s' = f(P_s') = 751 \ \frac{kj}{kg}$$

$$h_s'' = f(P_s' \, , x = 0.995) = 2765 \ \frac{kj}{kg}$$

$$P_{sh} = P_s' * 0.97 = 0.9408 * 0.97 = 0.9125 \ MPa$$

$$t_0 = f(P_0) = 282.38 \ ℃$$

$$t_{sh} = t_0 - 15 = 282.38 - 15 = 267.38 \ ℃$$

$$h_{sh} = f(P_{sh} \, , t_{sh}) = 2984 \ \frac{kj}{kg}$$

$$s_{sh} = f(P_{sh} \, , h_{sh}) = 7.0442 \ \frac{kj}{kg * ℃}$$

$$s_{sh} = s_3 = s_4 = s_5 = s_6$$

$$P_3 = 0.4635 \ MPa$$

$$h_{3\,th} = f(P_3 \, , s_{sh}) = 2832 \ \frac{kj}{kg}$$

$$h_3 = h_{sh} - (h_{sh} - h_{3t}) * 0.82$$

$$h_3 = 2984 - (2984 - 2832) * 0.82 = 2859 \ \frac{kj}{kg}$$

$$P_4 = 0.1957\ MPa$$

$$h_{4\,th} = f(P_4\,, s_{sh}) = 2670\ \frac{kj}{kg}$$

$$h_4 = h_{sh} - (h_{sh} - h_{4t}) * 0.82$$

$$h_4 = 2984 - (2984 - 2670) * 0.82 = 2727\ \frac{kj}{kg}$$

$$P_5 = 0.0739\ MPa$$

$$h_{5\,th} = f(P_5\,, s_{sh}) = 2510\ \frac{kj}{kg}$$

$$h_5 = h_{sh} - (h_{sh} - h_{5t}) * 0.82$$

$$h_5 = 2984 - (2984 - 2510) * 0.82 = 2595\ \frac{kj}{kg}$$

$$P_6 = 0.0225\ MPa$$

$$h_{6\,th} = f(P_6\,, s_{sh}) = 2337\ \frac{kj}{kg}$$

$$h_6 = h_{sh} - (h_{sh} - h_{6t}) * 0.82\ \frac{kj}{kg}$$

$$h_6 = 2984 - (2984 - 2337) * 0.82 = 2453\ \frac{kj}{kg}$$

$$h_{ct} = f(p_c, s_{sh}) = f(0.004\,, 7.0442) = 2122\ \frac{kj}{kg}$$

$$h_c = h_{sh} - (h_{sh} - h_{ct}) * 0.82 = 2277\ \frac{kj}{kg}$$

$$H_1 = h_0 - h_1 = 2772 - 2557 = 215\ \frac{kj}{kg}$$

$$H_2 = h_0 - h_2 = 2772 - 2484 = 288\ \frac{kj}{kg}$$

$$H_3 = h_0 - h_2 + (h_{sh} - h_3) = 2772 - 2484 + (2984 - 2859) = 413\frac{kj}{kg}$$

$$H_4 = h_0 - h_2 + (h_{sh} - h_4) = 2772 - 2484 + (2984 - 2727) = 545\frac{kj}{kg}$$

$$H_5 = h_0 - h_2 + (h_{sh} - h_5) = 2772 - 2484 + (2984 - 2595) = 677\frac{kj}{kg}$$

$$H_6 = h_0 - h_2 + (h_{sh} - h_6) = 2772 - 2484 + (2984 - 2453) = 819\frac{kj}{kg}$$

$$H_i = h_0 - h_2 + h_{sh} - h_c = (2772 - 2484) + (2984 - 2277) = 995\frac{kj}{kg}$$

$$y_1 = \frac{H_i - H_1}{H_i} = \frac{995 - 215}{995} = 0.783$$

$$y_2 = \frac{H_i - H_2}{H_i} = \frac{995 - 288}{995} = 0.7105$$

$$y_3 = \frac{H_i - H_3}{H_i} = \frac{995 - 413}{995} = 0.585$$

$$y_4 = \frac{H_i - H_4}{H_i} = \frac{995 - 545}{995} = 0.4523$$

$$y_5 = \frac{H_i - H_5}{H_i} = \frac{995 - 677}{995} = 0.3196$$

$$y_6 = \frac{H_i - H_6}{H_i} = \frac{995 - 819}{995} = 0.17688$$

$$P_{mc} = 1.4 * P_0 = 1.4 * 7 = 9.8\ MPa$$

No	P_j MPa	t_j $°C$	$h_{real\,j}$ kJ/kg	P_{Hj} MPa	t_{sHj} $°c$	h' kJ/kg	t_{wj} $°c$	P_{wj} MPa	h_{wj} kJ/kg	H_j kJ/kg	y_j
0	7.0	285.83	2772								
1	1.6377	202.5	2557	1.59	201	857	198	9.1	847	$h_0 - h_1$ **215**	0.783
2	0.96	178.12	2484	0.918	176.2	746	173	9.1	737	$h_0 - h_2$ **288**	0.7105
D	1.38			0.60	158.8	670	158.8	0.60	671		
SH	0.9125	175.94	2984								
3	0.4635	149	2859	0.45	148	623	146.8	0.84	619	**413**	0.585
4	0.1957	119.53	2727	0.19	118.6	498	118.1	0.84	496	**545**	0.4523
5	0.0739	91.365	2595	0.0718	90.601	380	89.4	0.84	375	677	0.3196
6	0.0225	62.627	2453	0.0218	61.933	259	60.70	0.84	255	819	0.17688
C	0.004	28.962	2277	0.0039	28.5	120	28.5	0.0039	120	995	-------------

4.1 Material and thermal balance equations :

$$\alpha_{SG} = \alpha_0 + \alpha_{SE} + \alpha_{leak} + \alpha_{RH1}$$

$$\alpha_{bd} = 0$$

$$\alpha_{fw} = \alpha_{SG} + \alpha_{bd}$$

<u>For Heater (1):</u>

$$\alpha_{fw} = \alpha_{se} + \alpha_{leak} + \alpha_0 = 1 + 0.002 + 0.005 = 1.007$$

$$\alpha_{dr1}(h_1 - h_1') = \alpha_{fw}\left(h_{fw1} - h_{fw2}\right) * \frac{1}{\eta_H}$$

$$\alpha_{H1} = 0.067$$

$$\alpha_{dr1} = \alpha_{H1} = \alpha_1 = 0.067$$

<u>For Heater (2):</u>

$$\alpha_{dr1}(h_1' - h_2') + \alpha_{H2}(h_2 - h_2') = \alpha_{fw}\left(h_{fw2} - h_{fw3}\right) * \frac{1}{\eta_H}$$

$$\alpha_{H2} = 0.0297$$

$$\alpha_{dr2} = \alpha_{H2} + \alpha_{dr1} = 0.0297 + 0.067 = 0.0967$$

<u>For Heater (3):</u>

$$\alpha_s(h_2' - h_3') + \alpha_{H3}(h_3 - h_3') = \alpha_{mc}\left(h_{fw3} - h_{mix1}\right) * \frac{1}{\eta_H}$$

$$\alpha_{dr3} = \alpha_{H3} + \alpha_s = 0.0451 + 0.0967 = 0.1418$$

$$\alpha_3 = \alpha_{H3} + \alpha_D = 0.0283 + 0.0162 = 0.0445$$

<u>For Dearator :</u>

$$\alpha_{mc} + \alpha_{dr2} + \alpha_D = \alpha_{fw} + \alpha_{ej}$$

$$\alpha_{mc} * h_{fw3} + \alpha_{dr2} * h_2' + \alpha_D * h_2 = \alpha_{fw} * h_D' + \alpha_{ej} * h_D''$$

For Separator :

$$\alpha_S^{in} = 1 - \alpha_1 - \alpha_2$$

$$\alpha_S^{in} = \alpha_{RH} + \alpha_s$$

$$\alpha_S^{in} * h_4 = \alpha_{RH}^{in} * h_s'' + \alpha_s * h_s'$$

For Reheater :

$$\alpha_{RH1}(h_0 - h_0') = \alpha_{RH}^{in}(h_{RH} - h_s)\frac{1}{\eta_H}$$

$$\alpha_{RH}^{in} = 1 - \alpha_1 - \alpha_2 - \alpha_S$$

For Heater (4):

$$\alpha_{dr4} = \alpha_{H4} + \alpha_{dr3}$$

$$\alpha_{H4}(h_4 - h_4') + \alpha_{dr3}(h_3' - h_4') = \alpha_{mc4}\left(h_{mc4} - h_{fw5}\right) * \frac{1}{\eta_H}$$

Mixing point (1):

$$\alpha_{mc} = \alpha_{mc5} + \alpha_{dr5}$$

$$\alpha_{mc} * h_{mc5} + \alpha_{dr5} * h_S' = \alpha_{mc} * h_{mix1} * \frac{1}{\eta_H}$$

$$\alpha_{dr5} = 0.093$$

$$h_{mix1} = 491$$

For Heater (5):

$$\alpha_{dr5} = \alpha_5$$

$$\alpha_{H5}(h_5 - h_5') = \alpha_{mc4}(h_{mc5} - h_{mix2}) * \frac{1}{\eta_H}$$

For Heater (6):

$$\alpha_{H6}(h_6 - h_6') + \alpha_{dr5}(h_5' - h_6') = \alpha_{mc6}\left(h_{fw6} - h_{cse}\right) * \frac{1}{\eta_H}$$

$$\alpha_{dr6} = \alpha_6 + \alpha_{dr5}$$

Mixing point (2):

$$\alpha_{mc4} = \alpha_{dr6} + \alpha_{mc6}$$

$$\alpha_{mc6} * h_{fw6} + \alpha_{dr6} * h_6' = \alpha_{mc4} * h_{mix2} * \frac{1}{\eta_H}$$

Condenser :

$$\alpha_{mc}^* = \alpha_{mc6} - \alpha_{mfw} - \alpha_{se} - \alpha_{ej}$$

$$\alpha_{mc}^* = 0.627 - 0.01 - 0.005 - 0.002 = 0.61$$

$$\alpha_c = \alpha_0 - \alpha_1 - \alpha_2 - \alpha_3 - \alpha_4 - \alpha_5 - \alpha_6 - \alpha_s$$

$$\alpha_c = 1 - 0.067 - 0.0537 - 0.0451 - 0.0293 - 0.039 - 0.033 - 0.1227 = 0.61$$

$$\alpha_{Rh}(h_0 - h_0') = \alpha_{Rh.in}(h_{sh} - h_s'') * 1/0.98$$

$$\alpha_{Rh}(2772 - 1267) = 0.7566(2984 - 2722) * 1/0.98$$

$$\alpha_{Rh} = 0.134402$$

$$\alpha_{fw1} = \alpha_{fw} + \alpha_{Rh}$$

$$\alpha_{fw1} = 1.007 + 0.134402 = 1.14140$$

$$\alpha_{fw1}h_{fw} = \alpha_{fw}h_{fw1} + \alpha_{Rh}h_0'$$

$$h_{fw} = \frac{\alpha_{fw} h_{fw1} + \alpha_{Rh} h'_0}{\alpha_{fw1}} = \frac{1.007 * 847 + 0.134402 * 1267}{1.14140} = 896\ \frac{kj}{kg}$$

Table(8)

α_{h1}	0.067
α_{dr1}	0.067
α_{rh1}	0.0995
α_{h2}	0.0297
α_{dr2}	0.0967
α_{mc}	0.8963
α_{d}	0.024
$\alpha_{s.in}$	0.8793
$\alpha_{rh1.in}$	0.7566
α_{s}	0.1227
α_{h3}	0.0451
h_{mix1}	491
α_{dr3}	0.01678
α_{mc4}	0.6992
$\alpha_{h4} = \alpha_4$	0.0293
α_{dr4}	0.1971
α_1	0.067
α_2	0.0537
α_3	0.0451
$\alpha_5 = \alpha_{h5}$	0.039
h_{mix2}	253
$\alpha_6 = \alpha_{h6}$	0.033
α_{dr5}	0.039
α_{mc6}	0.627
α_{dr6}	0.072

4.2 Determining steam flow to a turbine:

$$G_0 = \frac{N_e \cdot 10^3}{H_i \cdot \eta_м \cdot \eta_г \cdot (1 - \sum \alpha_i \cdot y_i - \alpha_s \cdot y_s)}$$

$$\frac{1300 \cdot 10^3}{951 \cdot 0.98 \cdot 0.99 \cdot (1 - 0.067 * 0.783 - 0.0537 \cdot 0.7105 - 0.0451 \cdot 0.585 - 0.0293 \cdot 0.4523 - 0.039 \cdot 0.3196 - 0.03 \cdot 0.17688 - 0.1227 * 0.7105)} =$$

$$G_0 = 1842.27\ kg/s$$

$$N_e = G_0 \cdot [\alpha_1 \cdot H_1 + \alpha_2 \cdot H_2 + \alpha_3 \cdot H_3 + \alpha_4 \cdot H_4 + \alpha_5 \cdot H_5 + \alpha_6 \cdot H_6 + \alpha_s \cdot H_3 + \alpha_c \cdot H_i] \cdot \eta_м \cdot \eta_г$$

$$1842.27 \cdot [0.067 \cdot 215 + 0.0537 \cdot 288 + 0.0451 \cdot 413 + 0.0293 \cdot 545 + 0.039 \cdot 677 + 0.033 \cdot 819 + 0.1227 \cdot 288 + 0.61 \cdot 995] \cdot 0.98 \cdot 0.99 = 1358.728\ MW$$

4.3 Steam and water consumption at characteristic points:
Table(9)

$G_1 = \alpha_1 \cdot G_0 = 0.067 \cdot 1359 = 91.053\ kg/s$	$G_{H1} = \alpha_{H1} \cdot G_0 = 0.067 \cdot 1359 = 91.053\ kg/s$
$G_2 = \alpha_2 \cdot G_0 = 0.0537 \cdot 1359 = 72.97\ kg/s$	$G_{H2} = \alpha_{H2} \cdot G_0 = 0.0297 \cdot 1359 = 40.36\ kg/s$
$G_3 = \alpha_3 \cdot G_0 = 0.0451 \cdot 1359 = 61.29\ kg/s$	$G_{H3} = \alpha_{H3} \cdot G_0 = 0.0451 \cdot 1359 = 61.29\ kg/s$
$G_4 = \alpha_4 \cdot G_0 = 0.0293 \cdot 1359 = 39.81\ kg/s$	$G_{H4} = \alpha_{H4} \cdot G_0 = 0.0293 \cdot 1359 = 39.81\ kg/s$

$G_5 = \alpha_5 \cdot G_0 = 0.039 \cdot 1359$ $= 53.001\ kg/s$	$G_{H5} = \alpha_{H5} \cdot G_0 = 0.039 \cdot 1359$ $= 53.001\ kg/s$
$G_6 = \alpha_6 \cdot G_0 = 0.033 \cdot 1359$ $= 44.847\ kg/s$	$G_{H6} = \alpha_{H6} \cdot G_0 = 0.033 \cdot 1359$ $= 44.847\ kg/s$
$G_{RH1} = \alpha_{RH1} \cdot G_0 = 0.0086 \cdot 1359$ $= 11.27\ kg/s$	
$G_{FW} = \alpha_{FW} \cdot G_0 = 1.015 \cdot 1359$ $= 1652.1\ kg/s$	$G_{SG} = G_{fw1} = \alpha_{fw1} \cdot G_0 = 1.007 \cdot 1359$ $= 1368.513\ kg/s$
$G_s = \alpha_s \cdot G_0 = 0.1191 \cdot 1331.9$ $= 193.86\ kg/s$	$G_D = \alpha_D \cdot G_0 = 0.024 \cdot 1331.9$ $= 31.96\ kg/s$

4.4 Calculation of indicators of thermal efficiency:

Define the thermal load of the steam generator:

$$Q_{SG} = G_0 \cdot (h_0 - h_{fw}) * (\alpha_0 + \alpha_{RH1} + \alpha_{leak} + \alpha_{sea})$$
$$= 1842.27 \cdot (2772 - 896) * (1 + 0.134402 + 0.01 + 0.005)$$
$$= 3972.446\ \ MW$$

Define the total thermal load of the turbine:

$$Q_{tb} = G_0[(\alpha_0 + \alpha_{RH1} + \alpha_{sea}) \cdot (h_0 - h_{fw}) + \alpha_{leak} \cdot (h'_c - h_{fw})]$$
$$Q_{tb} = 1842.27[(1 + 0.134402 + 0.005)(2772 - 896) + 0.01(121 - 896)$$
$$= 3924\ MW$$

Efficiency of an electric power turbine:

$$\eta_e = \frac{N_e'}{Q_t^e} = \frac{1300}{3924} = 0.331 = 33.1\ \%$$

Efficiency of pipelines connecting a steam generating unit with a turbine:

$$\eta_{pipe}^{II} = \frac{Q_{tb}}{Q_{SG}} = \frac{3924}{3972.446} = 0.988 = 98.8\ \%$$

Steam turbine plant heat rate, for generating electricity:

$$\mathrm{q_{tb}} = \frac{3600}{\eta_e} = \frac{3600}{33.1} = 108.76\ \frac{\mathrm{kJ}}{\mathrm{kW\ h}}$$

NPP Efficiency.

$$\eta_{npp} = \eta_R \cdot \eta_{pip}^{I} \cdot \eta_{pip}^{II} \cdot \eta_{sg} \cdot \eta_{tb}$$

$$\eta_{npp} = 0.99 \cdot 0.99 \cdot 0.988 \cdot 0.985 \cdot 0.331 = 0.317 = 31.7\ \%$$

$$= 1313.13\ \mathrm{MW}$$

Rector power

$$Q_R = 3200$$

Specific consumption of burned-out nuclear fuel for electricity supply:

$$\mathrm{T_{eff}} = 6000 \frac{\mathrm{hr}}{\mathrm{year}} \quad , \quad \overline{\mathrm{B}} = 35 \cdot 10^3\ \frac{\mathrm{MW\ day}}{\mathrm{ton}}$$

$$\mathrm{b_{nf}} = \frac{\mathrm{Q_{total}} \cdot \mathrm{T_{eff}}}{24 \cdot \overline{\mathrm{B}} \cdot 10^3} = \frac{3200 \cdot 6000}{24 \cdot \overline{35} \cdot 10^3} = 22.85\ \frac{\mathrm{ton}}{\mathrm{year}}$$

Where:

$\eta_R = 0.99$- the efficiency of the reactor installation;

$\eta_{pipe}^{I} = 0.99$- Efficiency of pipelines of the 1st circuit;

$\eta_{SG} = 0.985$ -Steam generator efficiency;

$k_{ec} = 0.05$ -specific energy consumption for own needs.

4.5 Choice of equipment for the water-steam circuit The regenerative heaters

We will choose heaters according to the area of the heat exchange surface and the water consumption. In this case, the steam and water pressure in the heater must be taken into account.

The characteristics of existing heaters are available in the handbook [1].

Evaluate heat transfer area F m^2

$$F = \frac{Q}{k \cdot \overline{\Delta t}}.$$

Where

$Q = G \cdot \Delta h$ is heat load of the heater, kW;

Δh is deference enthalpy between outlet and inlet, kJ/kg;

G mass flow rate of water, kg/s;

$k = 3500 \div 4000$ (4000) W/(m²·K) is heat transfer coefficient;

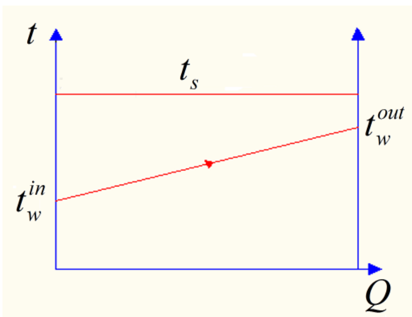


Figure 6. To the calculation of the logarithmic temperature difference

$\overline{\Delta t}$ is logarithmic temperature difference, °C

$$\overline{\Delta t} = \frac{\Delta t_{big} - \Delta t_{small}}{\ln\left(\frac{\Delta t_{big}}{\Delta t_{small}}\right)}.$$

Where

$\Delta t_{big} = t_s - t_w^{in}$;

$\Delta t_{small} = t_s - t_w^{out}$.

We will show the selection of one heater in detail. The results of the selection of all heaters are placed in the table

<u>For RGFW 6 (LPH):</u>

$$\Delta h = hw_6 - h_{cse} = 255 - 134 = 121 \text{ kJ/kg}$$

$$Q = G_{mc6} * \Delta h = 1155 * 121 = 139.75 * 10^3 \text{ kW}$$

$$\Delta t_{big} = t_{S6} - t_{cse} = 61.933 - 32 = 29.9\ °C$$

$$\Delta t_{small} = t_{S6} - t_{W6} = 61.933 - 60.70 = 1.233\ °C$$

$$\overline{\Delta t} = \frac{\Delta t_{big} - \Delta t_{small}}{\ln\left(\frac{\Delta t_{big}}{\Delta t_{small}}\right)} = \frac{29.9 - 1.233}{\ln\left(\frac{29.9}{1.233}\right)} = 8.99\ °C$$

$$F = \frac{Q}{k \cdot \overline{\Delta t}} = \frac{139.75 * 10^3 \cdot 10^3}{4000 \cdot 8.99} = 3886.26 \text{ m}^2$$

For RGFW 5 (LPH):

$$\Delta \mathrm{h} = hw_5 - hw_6 = 375 - 255 = 120\ \ \mathrm{kJ/kg}$$

$$Q = G_{mc4} * \Delta \mathrm{h} = 1288 * 120 = 154.56 \cdot 10^3\ \ \mathrm{kW}$$

$$\Delta \mathrm{t_{big}} = \mathrm{t_{S5}} - \mathrm{t_{W6}} = 90.60 - 60.70 = 29.9\ ^\circ\mathrm{C}$$

$$\Delta \mathrm{t_{small}} = \mathrm{t_{S5}} - \mathrm{t_{W5}} = 90.60 - 89.4 = 1.2\ ^\circ\mathrm{C}$$

$$\overline{\Delta \mathrm{t}} = \frac{\Delta \mathrm{t_{big}} - \Delta \mathrm{t_{small}}}{\ln\left(\frac{\Delta \mathrm{t_{big}}}{\Delta \mathrm{t_{small}}}\right)} = \frac{29.9 - 1.2}{\ln\left(\frac{29.9}{1.2}\right)} = 8.9\ ^\circ\mathrm{C}$$

$$\mathrm{F} = \frac{\mathrm{Q}}{\mathrm{k} \cdot \overline{\Delta \mathrm{t}}} = \frac{154.56 \cdot 10^3 \cdot 10^3}{4000 \cdot 8.9} = 4341.57\ \mathrm{m}^2$$

For RGFW 4 (LPH):

$$\Delta \mathrm{h} = hw_4 - h_{w5} = 496 - 375 = 121\ \ \mathrm{kJ/kg}$$

$$Q = G_{mc4} * \Delta \mathrm{h} = 1288 * 121 = 155.85 \cdot 10^3\ \ \mathrm{kW}$$

$$\Delta \mathrm{t_{big}} = \mathrm{t_{S4}} - \mathrm{t_{W5}} = 118.6 - 89.4 = 29.9\ ^\circ\mathrm{C}$$

$$\Delta \mathrm{t_{small}} = \mathrm{t_{S4}} - \mathrm{t_{W4}} = 118.6 - 118.4 = 1.2\ ^\circ\mathrm{C}$$

$$\overline{\Delta \mathrm{t}} = \frac{\Delta \mathrm{t_{big}} - \Delta \mathrm{t_{small}}}{\ln\left(\frac{\Delta \mathrm{t_{big}}}{\Delta \mathrm{t_{small}}}\right)} = \frac{29.9 - 1.2}{\ln\left(\frac{29.9}{1.2}\right)} = 8.6\ ^\circ\mathrm{C}$$

$$\mathrm{F} = \frac{\mathrm{Q}}{\mathrm{k} \cdot \overline{\Delta \mathrm{t}}} = \frac{155.85 \cdot 10^3 \cdot 10^3}{4000 \cdot 8.6} = 4530.52\ \mathrm{m}^2$$

For RGFW 3 (HPH):

$$\Delta h = hw_3 - h_{fwp} = 680 - 619 = 61 \ \text{kJ/kg}$$

$$Q = G_{mc} * \Delta h = 1651 * 61 = 100.7 \cdot 10^3 \ \text{kW}$$

$$\Delta t_{big} = t_{S3} - t_{fwp} = 148 - 159.8 = 11.8\ °C$$

$$\Delta t_{small} = t_{S3} - t_{W3} = 148 - 146.8 = 1.2\ °C$$

$$\overline{\Delta t} = \frac{\Delta t_{big} - \Delta t_{small}}{\ln\left(\frac{\Delta t_{big}}{\Delta t_{small}}\right)} = \frac{11.8 - 1.2}{\ln\left(\frac{11.8}{1.2}\right)} = 4.63\ °C$$

$$F = \frac{Q}{k \cdot \overline{\Delta t}} = \frac{100.7 \cdot 10^3 \cdot 10^3}{4000 \cdot 4.63} = 5437.36\ m^2$$

For RGFW 2(HPH):

$$\Delta h = hw_2 - hw_3 = 737 - 619 = 118 \ \text{kJ/kg}$$

$$Q = G_{fw} * \Delta h = 1855.16 * 118 = 218.91 \cdot 10^3 \ \text{kW}$$

$$\Delta t_{big} = t_{S2} - t_{w3} = 176.2 - 146.8 = 29.4\ °C$$

$$\Delta t_{small} = t_{S2} - t_{W2} = 176.2 - 173 = 3.2\ °C$$

$$\overline{\Delta t} = \frac{\Delta t_{big} - \Delta t_{small}}{\ln\left(\frac{\Delta t_{big}}{\Delta t_{small}}\right)} = \frac{29.4 - 3.2}{\ln\left(\frac{29.4}{3.2}\right)} = 11.81\ °C$$

$$F = \frac{Q}{k \cdot \overline{\Delta t}} = \frac{218.91 \cdot 10^3 \cdot 10^3}{4000 \cdot 11.81} = 4633.99\ m^2$$

<u>For RGFW 1(HPH):</u>

$$\Delta \mathrm{h} = hw_1 - hw_2 = 847 - 737 = 110\ \ \mathrm{kJ/kg}$$

$$Q = G_{fw} * \Delta \mathrm{h} = 1855.16 * 110 = 204 \cdot 10^3\ \ \mathrm{kW}$$

$$\Delta \mathrm{t_{big}} = \mathrm{t_{S1}} - \mathrm{t_{w2}} = 201 - 173 = 28\ {}^\circ\mathrm{C}$$

$$\Delta \mathrm{t_{small}} = \mathrm{t_{S1}} - \mathrm{t_{W1}} = 201 - 198 = 3\ {}^\circ\mathrm{C}$$

$$\overline{\Delta \mathrm{t}} = \frac{\Delta \mathrm{t_{big}} - \Delta \mathrm{t_{small}}}{\ln\left(\frac{\Delta \mathrm{t_{big}}}{\Delta \mathrm{t_{small}}}\right)} = \frac{28 - 3}{\ln\left(\frac{28}{3}\right)} = 11.19\ {}^\circ\mathrm{C}$$

$$\mathrm{F} = \frac{\mathrm{Q}}{\mathrm{k} \cdot \overline{\Delta \mathrm{t}}} = \frac{204 \cdot 10^3 \cdot 10^3}{4000 \cdot 11.19} = 4557.6\ \mathrm{m}^2$$

Table. 5 . Characteristic of RFWH in NPP

RFWH No	G, kg/s	Δh, kj/kg	Q, mW	$\overline{\Delta}$t, ℃	F, m^2	Selected heaters	Type	G, kg/s	F, m^2	Number of heaters
1	1855.16	110	$204 \cdot 10^3$	11.19	4557.6		ПВД-К-2470-23-2.8	745-860	2470	1
2	1855.16	118	$218 \cdot 10^3$	11.81	4633.9		ПВД-К-2470-23-2.8	745-860	2470	1
3	1651.22	61	$100.7 \cdot 10^3$	4.63	5324		ПВД-К-2470-23-2.8	745-860	2470	1
4	1288.11	121	$155.85 \cdot 10^3$	8.6	4530.52		ПН-1900 42-4-IA	733.9	1900	1
5	1288.11	120	$154.5 \cdot 10^3$	8.9	4341.57		ПН-1800-428-IA	700	1800	1
6	1155.11	121	$139.7 \cdot 10^3$	8.9	3886.26		ПН-1800-428-IA	700	1800	1

5. Design calculation of the turbine condenser

The purpose of calculating a condenser is to determine its geometric dimensions and operational characteristics.

Modern powerful steam turbines of nuclear power plants have usually several double-flow low-pressure cylinders (Fig. 1). Steam from each cylinder is sent to a separate condenser. So first you need to determine the number of exhaust steam outputs of the turbine.

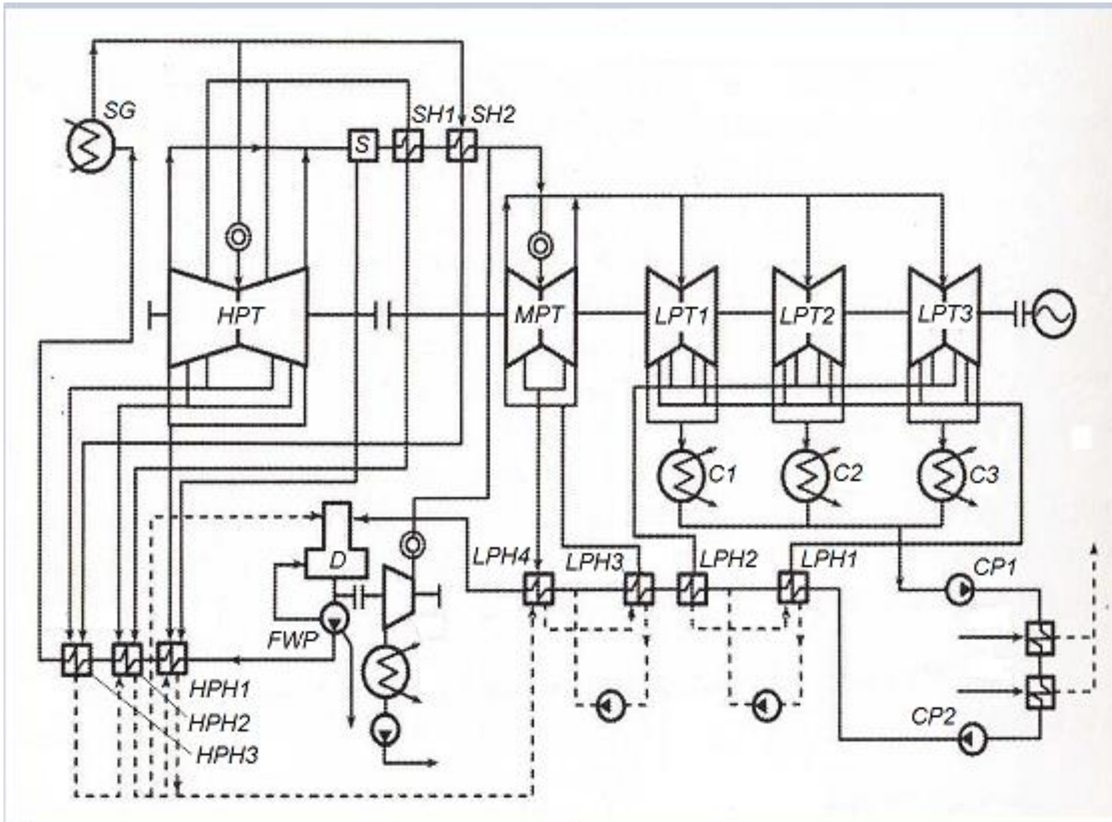


Figure 1. Schematic diagram of the VVER power unit

1. Calculation of the number of flows in the low-pressure cylinder of turbine

1.1. Number of flows of spent steam going to the condenser

$$i = \frac{N_e}{\eta_m \cdot \eta_g \cdot N_i^{max}} = \frac{1300}{0.98 * 0.99 * 327.108} = 3.699 .$$

Where N_i^{max} is the maximum power of a single-flow turbine, MW;
N_e is total electric power of the turbine unit, MW;
η_m is mechanical efficiency of the turbine unit;
η_g is the efficiency of the generator.

1.2. Maximum power of a single-flow turbine, MW

$$N_i^{max} = \frac{m1}{2 \cdot 10^{-3} \cdot \pi} \cdot k_{unl} \cdot H_i \cdot \frac{[\sigma] \cdot c_2}{\rho_{mat} \cdot n^2 \cdot v_2} = 362.289 .$$

Where $m1 = 1.1 \div 1.3$ is coefficient that takes into account power generation by steam streams of regenerative bleed-offs;
$k_{unl} = 2.3 \div 2.4$ is unloading coefficient, which depends on the geometric characteristics of the blades of the last stage of the turbine;
H_i is extracted steam work in turbine, kJ/kg;

$[\sigma]$ is allowable tensile stress for the material of the blades. For stainless steel $[\sigma] = 450$ MPa; for titanium alloy BT6 $[\sigma] = 950 \div 1000$ MPa;
$\rho_{mat} = 7800$ kg/m³ is density of the blade material (stainless steel); for titanium alloy BT6 $\rho_{mat} = 4300$ kg/m³;
n is rotor's rotation frequency, rev/s;
v_2 is specific volume of steam at the outlet of the last stage of the turbine, m³/kg. It is determined by the known parameters of the steam p_c and h_c at the outlet of the turbine.
c_2 is output steam speed, m/s. Depends on the allowable power loss at the output speed $\Delta h_{os} = 20 \div 35$ kJ/kg.

The output speed of steam is determined from the following equation

$$\Delta h_{os} = \frac{c_2^2}{2000}.$$

The resulting number of flows i must be rounded up to the nearest even integer.

1.3. Exhaust steam flow per condenser

$$G_c = 0.61 * 1842.17 = 1039$$

$$G_{c1} = \frac{2 \cdot G_c}{i}.$$

$$G_{c1} = \frac{2 * 1124}{4} = 546.296$$

Where $G_c = \alpha_c \cdot G_0$ is total total exhaust steam flow, kg/s;
i is Number of flows of spent steam going to the condenser.

2. Initial data for the calculation of the condenser

Table 1. Initial data

Parameter	Denomination, units	Value
Exhaust steam flow per condenser	G_{c1}, kg/s	561.89
Condenser pressure	p_c, MPa	0.004
Number of tube-side passes for cooling water	z	1
Coolant temperature at the inlet to the condenser	t_{w1}, °C	20
Speed of the cooling water in the tubes of the condenser	w_w, m/s	2
Condenser tube sizes	$d_{out} \times \delta_{wall}$, mm	28×1 28×0.7

Tube material		stainless steel; titanium

Notes:
- take the cooling water density equal to $\rho_w = 1000$ kg / m³;
- take the average heat capacity of cooling water equal to c_w =4.19 kJ/kg;
- the coefficient that takes into account the contamination of pipes is equal to $a_0 =$ 0.65...0.85.

5.1 Determining the characteristics of a condenser

3.1. Flow rate of cooling water per condenser

$$W_1 = m \cdot G_{c1},$$

$$W1 = 115 * 561.89 = 6.282 * 10^4$$

here $m = 40...50$ is the cooling ratio for two-way condensers ($z = 2$), kg/kg.

3.2. The number of heat transfer tubes, pieces

$$n_{tube} = \frac{4 \cdot W_1 \cdot z}{\pi \cdot d_{inn}^2 \cdot \rho_w \cdot w_w},$$

$$n_{tube} = 5916$$

here z is number of tube-side passes for cooling water;
$d_{inn} = d_{out} - 2 \cdot \delta_{wall}$ is the inner diameter of the tubes, m;
w_w is speed of water in tubes, m / s.

3.3. Cooling water heating in the condenser, ºC

$$\Delta t_w = \frac{r}{c_w \cdot m},$$

$$\Delta t = 5.029$$

here $r = h'' - h'$ is latent heat of vaporization under pressure p_c, kJ/kg;
c_w is heat capacity of cooling water, kJ/(kg °C).

3.4. Temperature of the cooling water at the condenser outlet, ºC

$$t_{w2} = t_{w1} + \Delta t_w.$$

$$t_{w2} = 25.029\ c$$

3.5. The Heat power that is transferred to the cooling water in the condenser, kW

$$Q_{w1} = W_1 \cdot c_w \cdot \Delta t_w.$$

$$Q_{w1} = 1.324 * 10^6$$

3.6. The average temperature difference, ºC

$$\Delta t_{avr} = \frac{\Delta t_w}{\ln\left(\frac{t_s - t_{w1}}{t_s - t_{w2}}\right)} = 6.106 \text{ c}$$

here t_s is saturation temperature at condenser pressure p_c.

3.7. Specific vapor load of the condenser d_c. Initially set in the range of 40 ... 60 kg / (m² · h), and then must be checked.

3.8 . The overall heat transfer coefficient (ВТИ formula) is calculated using one of two expressions.
If $t_{w1} \leq 35$ °C

$$k = 4070 \cdot a \cdot \left(\frac{1{,}1 \cdot w_w}{d_{inn}^{0,25}}\right)^x \cdot \left[1 - \frac{0{,}52 - 0{,}002 \cdot d_c \cdot \sqrt{a}}{1000} \cdot \left(35 - t_{w1}\right)^2\right] \cdot$$

$$\cdot \left[1 - \frac{z-2}{10} \cdot \left(1 - \frac{t_{w1}}{35}\right)\right] \cdot \Phi_d;$$

$$k = 3.195 * 10^3$$

here k - in W/(m²·°C);
$x = 0{,}12 \cdot a \cdot \left(1 + 0{,}15 \cdot t_{w1}\right);$
$a = a_0 \cdot a_m$ is coefficient taking into account pollution of tubes and tube material;
a_0=0,65…0,85 is coefficient that takes into account tube contamination;
a_m is correction factor that takes into account the tube material: 1 – for brass; 0,92 – for cupronickel; 0,85 – for stainless steel; 0,9 – for titanium.
d_{inn} is the inner diameter of the tubes, m;
w_w is speed of water in tubes, m / s.
t_{w1} is the temperature of the cooling water at the inlet to the condenser; °C;
z is number of tube-side passes for cooling water;
Φ_d - coefficient taking into account the effect of the vapor load of the condenser.
Under load from d_c^{nom} to $d_c^{bn} = \left(0{,}9 - 0{,}012 \cdot t_{w1}\right) \cdot d_c^{nom}$ value Φ_d =1, under load $d_c < d_c^{bn}$ value $\Phi_d = \delta \cdot \left(2 - \delta\right)$, here $\delta = d_c / d_c^{bn}$.
When designing condensers, this coefficient is taken equal to 1.

3.9. Heat transfer surface area, m²

$$F = \frac{Q_w}{k \cdot \Delta t_{avr}}.$$

$$F = 6.785 * 10^4\ m^2$$

3.10. The length of the heat transfer tubes, m

$$L = \frac{F}{n \cdot \pi \cdot d_{out}},$$

$$L = 13.037\ m$$

here d_{out} is outer diameter of the tubes, m.
The length of the tubes must be less than 16 m.

3.11. The calculated value of the specific steam load of the condenser, kg / (m²·h)

$$d_c^{calk} = \frac{3600 * G_{c1}}{F} = 28.987 \quad \text{kg / (m}^2\text{·h)}$$

3.12. The obtained value d_c^{calk} must be compared with the specified in paragraph (3.7). If there is a significant (more than 2%) discrepancy, it is necessary to assign $d_c = d_c^{calk}$ and repeat the calculation, starting with paragraph 3.7.

3.13. Mass of condenser tubes

$$M_{tube} = n_{tube} \cdot L \cdot \frac{\pi \cdot \left(d_{out}^2 - d_{inn}^2\right)}{4} \cdot \rho_{mat}, \text{ kg.}$$

Where L, d_{out} and d_{inn} are in m;
ρ_{mat} is density of the pipe material, kg/m³. For brass tubes ρ_{mat}= 8750 kg/m³; for cupronickel tubes ρ_{mat}= 8900 kg/m³; for stainless steel tubes ρ_{mat}= 7800 kg/m³; for titanium tubes ρ_{mat}= 4500 kg/m³.

$$M_{tube} = 2.813 * 10^5$$

3.14. Cost of condenser tubes

$$C_{tube} = \frac{M_{tube} \cdot c_{mat}}{10^6}, \text{ million rubles.}$$

Where c_{mat} is price 1 kg of tubes, rub./kg. For brass tubes c_{mat} = 675…700 rub./kg; for cupronickel tubes c_{mat} = 2400…2500 rub./kg; for stainless steel tubes c_{mat} = 350…400 rub./kg; for titanium tubes c_{mat} = 1900…2100 rub./kg.

$$c_{tube} = 583.097$$

3.15. Cost of the condenser

$$C_{cond} = K_c \cdot C_{tube}, \text{ million rubles.}$$

Where K_c=1.75…2 is empirical coefficient.

$$c_{cond} = 1.75 * 583.097 = 1020.41$$

5.2 Hydraulic calculation of the condenser

4.1. Pressure losses in the condenser along the cooling water path

The purpose of the hydraulic calculation of a condenser is to determine the pressure loss during the movement of cooling water in it.

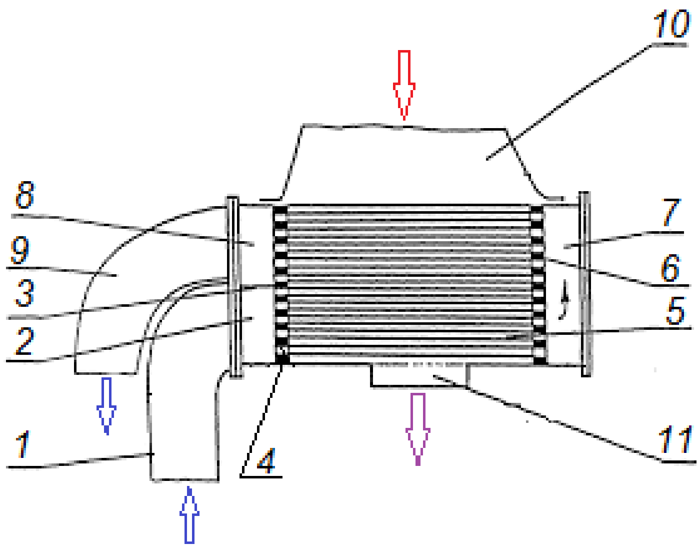


Figure 2. To the hydraulic calculation of the condenser

The hydraulic resistance of a two-way condenser with straight tubes can be represented as follows

$$\Delta p_{\Sigma} = \Delta p_{loc} + \Delta p_{fr};$$

$$\Delta p_{loc} = 2 \cdot \Delta p_{wch.in} + 2 \cdot \Delta p_{wch.out} + \Delta p_{turn},$$

$$\Delta p_{loc} = 7000$$

where Δp_{loc} is local pressure losses;

Δp_{fr} is friction losses in the condenser tubes;

$\Delta p_{wch.in}$ is local hydraulic resistance at the water inlet to the tubes from the water chamber;

$\Delta p_{wch.out}$ is local hydraulic resistance at the water outlet from the pipes to the water chamber;

Δp_{turn} is local hydraulic resistance from turning the water in the water chamber;

For the calculate of local pressure losses it is necessary to use the following formula

$$\Delta p_{loc} = \xi_{loc} \cdot \frac{\rho_w \cdot w_w^2}{2}, \text{ Pa}$$

$$\Delta P_{loc1} = 1000\ Pa.$$
$$\Delta P_{loc2} = 2000\ Pa.$$
$$\Delta P_{loc3} = 1000\ Pa.$$

Where $\rho_w \approx 1000$ kg/m³ is the average density of the cooling water;
w_w is speed of the cooling water in the tubes of the condenser, m/s;
ξ_{loc} is local resistance coefficient. The values of this coefficient for some types of local resistances are given in the table 4.1.

Table 4.1. The values of the coefficient of local resistance

Type of local resistance	Coefficient value ξ_{loc}
Inlet to the tubes from the water chamber	0.5
Outlet from the pipes to the water chamber	1.0
Turning the water in the water chamber	0.5

For the calculate the friction pressure losses it is necessary to use the Altshul formula

$$\Delta p_{fr} = \xi_{fr} \cdot \frac{2 \cdot L}{d_h} \cdot \frac{\rho_w \cdot w_w^2}{2}, \text{ Pa.}$$
$$\Delta Pfr = 7020\ Pa$$

Where L is length of the heat transfer tubes, m;
$d_h = d_{inn}$ is characteristic size (hydraulic diameter), m;
ξ_{fr} =0.035 is coefficient of friction.

4.2. Power of the pump for pumping water through the condenser

$$N_p = \Delta p_\Sigma \cdot \frac{W}{\rho_w \cdot \eta_p \cdot 1000}, \text{ kW.}$$
$$\Delta p\varepsilon = 1000$$
$$N_p = 5639$$

Where Δp_Σ is total hydraulic resistance of a two-way condenser, Pa;
$\eta_p = 0.86$ is the efficiency of the pump.

4.3. Electric power consumption for the circulation pump drive

$$E_p = N_p \cdot \tau_{rp}, \text{ kW·h.}$$
$$E_p = 3.581 * 10^7\ Kw.h$$

Where $\tau_{rp} = 6500$ h is number of hours of use of rated power.

4.4. The cost of electricity for pumping water through the condenser

$$C_{el} = \cdot \frac{E_p \cdot T_{el}}{10^6}, \text{ million rubles.}$$

$$c_{el} = 512.183 \quad \text{million rubles}$$

Where $T_{el} = 14$ rub./kW·h is electricity tariff for nuclear power plants.

	Design options	
	1	2
	d_{out} = 28 mm; δ_{wall}=1 mm	d_{out} = 28 mm; δ_{wall} =2 mm
C_{cond}, million rubles	172.312	169.385
C_{el}, million rubles	513.183	503.05

Condenser

There is usually one condenser for each low pressure turbine. The condenser has thousands of small tubes, that are made out of admiralty metal, copper, stainless steel, or titanium. The condenser is simply a large heat exchanger with tubes usually horizontally mounted. The tubes may be supported

d_{out} mm	25
f, m^2	$6.785 * 10^4$
L, m	13.037

3.16. Mass of condenser tubes

$$M_{tube} = n_{tube} \cdot L \cdot \frac{\pi \cdot \left(d_{out}^2 - d_{inn}^2\right)}{4} \cdot \rho_{mat}, \text{ kg.}$$

Where L, d_{out} and d_{inn} are in m;

ρ_{mat} is density of the pipe material, kg/m³. For brass tubes ρ_{mat} = 8750 kg/m³; for cupronickel tubes ρ_{mat} = 8900 kg/m³; for stainless steel tubes ρ_{mat} = 7800 kg/m³; for titanium tubes ρ_{mat} = 4500 kg/m³.

$$M_{tube} = 2.765 * 10^5$$

3.17. Cost of condenser tubes

$$C_{tube} = \frac{M_{tube} \cdot c_{mat}}{10^6}, \text{ million rubles.}$$

Where c_{mat} is price 1 kg of tubes, rub./kg. For brass tubes c_{mat} = 675…700 rub./kg; for cupronickel tubes c_{mat} = 2400…2500 rub./kg; for stainless steel tubes c_{mat} = 350…400 rub./kg; for titanium tubes c_{mat} = 1900…2100 rub./kg.

$$c_{tube} = 96.791$$

3.18. Cost of the condenser

$$C_{cond} = K_c \cdot C_{tube}, \text{ million rubles.}$$

Where K_c=1.75…2 is empirical coefficient.

$$c_{cond} = 1.75 * 1204 = 169.385$$

4. Hydraulic calculation of the condenser

4.1. Pressure losses in the condenser along the cooling water path

The purpose of the hydraulic calculation of a condenser is to determine the pressure loss during the movement of cooling water in it.

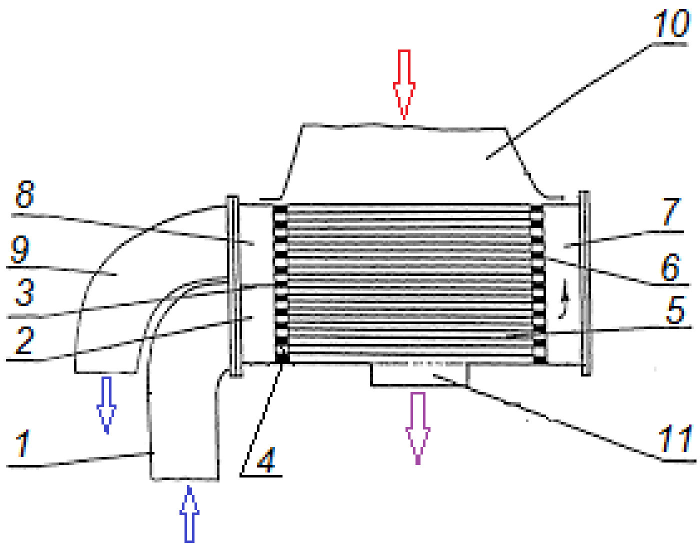


Figure 2. To the hydraulic calculation of the condenser

The hydraulic resistance of a two-way condenser with straight tubes can be represented as follows

$$\Delta p_{\Sigma} = \Delta p_{loc} + \Delta p_{fr};$$

$$\Delta p_{loc} = 2 \cdot \Delta p_{wch.in} + 2 \cdot \Delta p_{wch.out} + \Delta p_{turn},$$

=7000

where Δp_{loc} is local pressure losses;

Δp_{fr} is friction losses in the condenser tubes;

$\Delta p_{wch.in}$ is local hydraulic resistance at the water inlet to the tubes from the water chamber;

$\Delta p_{wch.out}$ is local hydraulic resistance at the water outlet from the pipes to the water chamber;

Δp_{turn} is local hydraulic resistance from turning the water in the water chamber;

For the calculate of local pressure losses it is necessary to use the following formula

$$\Delta p_{loc} = \xi_{loc} \cdot \frac{\rho_w \cdot w_w^2}{2}, \text{ Pa}$$

$$\Delta P_{loc1} = 1000\ Pa.$$

$$\Delta P_{loc2} = 2000\ Pa.$$

$$\Delta P_{loc3} = 1000\ Pa$$

Where $\rho_w \approx 1000$ kg/m³ is the average density of the cooling water;

w_w is speed of the cooling water in the tubes of the condenser, m/s;

ξ_{loc} is local resistance coefficient. The values of this coefficient for some types of local resistances are given in the table 4.1.

Table 4.1. The values of the coefficient of local resistance

Type of local resistance	Coefficient value ξ_{loc}
Inlet to the tubes from the water chamber	0.5
Outlet from the pipes to the water chamber	1.0
Turning the water in the water chamber	0.5

For the calculate the friction pressure losses it is necessary to use the Altshul formula

$$\Delta p_{fr} = \xi_{fr} \cdot \frac{2 \cdot L}{d_h} \cdot \frac{\rho_w \cdot w_w^2}{2}, \text{ Pa.}$$

$$\Delta Pfr = 6867\ Pa$$

Where L is length of the heat transfer tubes, m;

$d_h = d_{inn}$ is characteristic size (hydraulic diameter), m;

ξ_{fr} =0.035 is coefficient of friction.

4.2. Power of the pump for pumping water through the condenser

$$N_p = \Delta p_\Sigma \cdot \frac{W}{\rho_w \cdot \eta_p \cdot 1000}, \text{ kW.}$$

$$\Delta p\varepsilon = 1000$$

$$N_p = 5528$$

Where Δp_Σ is total hydraulic resistance of a two-way condenser, Pa;
$\eta_p = 0.86$ is the efficiency of the pump.

4.3. Electric power consumption for the circulation pump drive

$$E_p = N_p \cdot \tau_{rp}, \text{ kW·h.}$$

$$E_p = 3.593 * 10^7 \ Kw.h$$

Where $\tau_{rp} = 6500$ h is number of hours of use of rated power.
4.4. The cost of electricity for pumping water through the condenser

$$C_{el} = \cdot \frac{E_p \cdot T_{el}}{10^6}, \text{ million rubles.}$$

$$c_{el} = 503.05 \ \text{ million rubles}$$

Where $T_{el} = 14$ rub./kW·h is electricity tariff for nuclear power plants.

5.3 Financial management, resource efficiency and resource conservation

Analysis of competitive technical solutions

With the help of this analysis, adjustments are made to the scientific project that help to successfully withstand competitive capacitor designs. During the analysis, it is necessary to assess the strengths and weaknesses of the compared structures. For this purpose, all available information on competitive developments is used (Table 5.1).

calculated my calculations for 2 parts of condencers the first one at dout=28 mm with δ=1 mm and the second one at dout=28 with δ=2 and I see that the second condencer is better because of law cost

Table 5.1 – The results of calculations of the competitive structures of the condenser

	Design options	
	1	2
	d_{out} = 28 mm; δ_{wall}=1 mm	d_{out} = 28 mm; δ_{wall} =2 mm
C_{cond}, million rubles	172.312	169.385
C_{el}, million rubles	513.183	503.05

Notes:

- C_{cond} is cost of the condenser;
- C_{el} is the cost of electricity for pumping water through the condenser.

The analysis is carried out using a scorecard. The scorecard is shown in table 5.2.

The object of research is a steam turbine condenser, which uses two types of heat exchange tubes. Therefore, the comparison will be made on the basis of data on two options for the design of the condenser with different sizes of heat exchange tubes.

This analysis allows you to choose the option that will be the most competitive, and also to determine in which direction it is necessary to act to further improve it.

Table 5.2 - Scorecard for comparing competitive technical solutions

Items to assess	Value of criteria C_i	Points		Competitiveness	
		B_1	B_2	$К_1$	$К_2$
Technical criteria for evaluating resource efficiency					
1. Energy efficiency	0,2	4	3	0,8	0,6
2. Dimensions and weight	0,15	2	4	0,3	0,6
3. Environmental safety	0,05	3	4	0,15	0,2
4. Lifetime	0,2	4	3	0,8	0,6
5. Reliability	0,2	4	2	0,8	0,4
Economic performance indicators					
1. Price	0,15	2	4	0,3	0,6
2. Maintenance	0,02	3	3	0,06	0,06
3. The competitiveness of the product	0,03	3	3	0,09	0,09
Total	1			3,3	3,15

The analysis of competitive technical solutions is defined as follows:

$$К = \sum C_i \cdot B_i,$$

where: К - competitiveness of scientific research;

C_i - indicator weight (in unit fractions);

B_i - score of the i-th indicator.

Indices for indicators "1" - the first type of heat exchange tubes; "2" - the second type of heat exchange tubes.

Calculation example:

$$К_1 = \sum C_i \cdot B_{1i} = 0{,}2 \cdot 3 + 0{,}15 \cdot 4 + \ldots + 0{,}03 \cdot 3 = 3{,}15.$$

The results show that the competitiveness of option 1 was 3.15, while that of option 2 was 3.3.

Thus, the investigated scientific development (condenser design), which uses tubes with d_{out} = 28 mm; δ_{wall} = 2 mm, is competitive and has a number of advantages in terms of technical and economic indicators of resource efficiency.

5.4 Project initiation

Initiation processes define initial goals and content and fix initial financial resources. The internal and external stakeholders of the project are determined, which will interact and influence the overall result of the scientific project.

5.5 Project goals and results

Information about the stakeholders of the project, the hierarchy of project goals and criteria for achieving goals is presented in table below.

Table 5.3 – Stakeholders of the project

Stakeholders of the project	**Stakeholders of the project expectations**
Power engineering, nuclear power plants	High efficiency equipment (condenser)

Information about the hierarchy of project goals and criteria for achieving goals is given in the table below.

Table 5.4 – Project goals and results

Project goals	Provide reliable condensers for the turbine installation of a nuclear power plant, reduce energy costs for driving circulation pumps, and increase the efficiency of using the condenser

Expected results of the project	Based on the conducted research, analyze the sensitivity, find shortcomings, suggest the necessary measures to improve these indicators.
Acceptance criteria of the project result	Improving efficiency in relation to the proposed measures to improve the reliability of the equipment.
Requirements to the project results	Project completion on time
	Stability of technological equipment
	The efficiency of the equipment used
	Convenience in usage

5.5.1 Organizational structure of the project

The organizational structure of the project is presented in the table 5.5.

Table 5.5 – Project Working Group

№	**Name**	**Position**	**Functions**	**Hours spent**
1	Abdallah Mohamed Ali Abdelaziz	Project Executor	Work on project implementation	54.6
2	Vorobyov A.V.	Project Manager	Coordination of work activities and assistance in project implementation	9.2
Total:				63.8

5.5.2 Assumptions and constraints

Limitations and assumptions are summarized in table 5.6.

Table 5.6 – Limitations and assumptions

Factor	Limitations/assumptions
1. Project budget - for design	250 000 RUB
1.1 Source of budgeting	Own funds / bank loan
2. Project timeline:	13 April 2020 – 6 September 2020
2.1 Date of approval of the project management plan	13 April 2020
2.2 Project completion date	6 September 2020
3. Other	-

As a result of the initialization of the project, the goals and expected results were formulated, the stakeholders of the project and the financial framework were identified, which is very important for the successful completion of the project and its implementation.

5.5.3 Project planning

The main way to develop a design implementation schedule is called a Gantt chart. A Gantt chart is a horizontal graph that depicts work on a topic in long time periods, described by completion dates and start dates for the assigned work (tables 5.7 and 5.8).

Table 5.7 – Design and research timing

№	Task	The laboriousness of the task						Duration of the task in working days T_{pi}		Duration of the task in calendar days $T_{кi}$	
		t_{min}, person-days		t_{max}, person-days		$t_{ожi}$, person-days					
		Supervisor	Engineer	Supervisor	Engineer	Supervisor	Engineer	Supervisor	Engineer	Supervisor	Engineer
1	Drawing up the technical assignment	2		4		2.8		2.8		5	
2	Literature review		4		9		6		6		10
3	Selection of the research field		2		4		2.8		2.8		5
4	Calendar planning	2		5		3.2		3.2		5	
5	Description of the design object		4		9		6		6		10
6	Statement of the design problem		4		9		6		6		10
7	Development of the calculation model		7		12		9		9		15

8	Variational calculations of the object		6		14		9.2		9.2		15
9	Evaluation of calculation results	2		5		3.2		3.2		5	
10	Comparative calculations of economic efficiency object		5		8		6.2		6.2		10
11	Choosing the optimal design		2		5		3.2		3.2		5
12	Drawing up a final report		5		8		6.2		6.2		10

Note:

$t_{ож} = (3 \cdot t_{\min} + 2 \cdot t_{\max}) \cdot 0.2$ is expected labor intensity of performing one job, person-days;

$T_p = t_{ож} / Ч$ is the duration of the execution of one job , working days,

where $Ч = 1$ is number of performers performing the same job, person.

$T_k = T_p \cdot k_k$ - duration of one job, calendar days,

where $k_k = 1.65$ is calendar factor.

Table 5.8 – Schedule of the project design

№	Task	Executors		Duration of the task

			$T_{кi}$ days	April		May				June				July				August					Septe mber	
				3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	5	1	2
1	Drawing up the technical assignment	Supervisor	5																					
2	Literature review	Student	10																					
3	Selection of the research field	Supervisor	5																					
4	Calendar planning	Supervisor	5																					
5	Description of the design object	Student	10																					
6	Statement of the design problem	Student	10																					
7	Development of the calculation model	Student	15																					
8	Variational calculations of the object	Student	15																					
9	Evaluation of calculation results	Supervisor	5																					

10	Comparative calculations of economic efficiency object	Student	10																					
11	Choosing the optimal design	Supervisor	5																					
12	Drawing up a final report	Student	10																					

Thus, the duration of the task performed by the engineer and the supervisor. In general, the duration of work in calendar days for an engineer is 82 days, and for a supervisor is 8 days.

5.5.4 Project budgeting

The project budget must display reliable values for all types of costs associated with its implementation. The costs of this project include:

- costs of purchasing equipment;
- costs for materials and other products;
- expenses for the main and additional salaries of the theme performers;
- costs for special equipment;
- costs of social security contributions;
- overhead costs.

5.5.4.1 Costs for materials and other products

These costs include office supplies, printing costs, and various equipment required for paperwork.

Table 5.9 – Costs for materials for the project

Name	Unit of measurement	Number	Price per unit, RUB	Expenses (E_{M}), RUB
Paper	Pack	1	250	250
Pens	Unit	2	50	100
Pencils	Unit	1	50	50
Ruler	Unit	1	40	40
Printing	Page	200	2	400

Folder	Unit	2	5	10
Stapler	Unit	1	150	150
Staples	Pack	1	40	40
Hole puncher	Unit	1	250	250
Total				**1 290**

5.5.4.2 Costs for specialized equipment

This item includes all costs that are associated with the purchase of special equipment (for example, instruments, instrumentation, stands, devices and mechanisms) necessary for the project.

Table 5.10 – Costs for specialized equipment

№	Name	Number	Price per unit, RUB	Total price of equipment, RUB
1	Laptop	1	30 000	30 000
2	Microsoft Windows 10 Professional RU x64	1	4 000	4 000
3	Kaspersky Anti-Virus	1	1 320	1 320
4	Microsoft Office 2019 Home and Student	1	2 500	2 500
Total, RUB				**37 820**

The cost of specialized equipment is recorded in the form of depreciation charges.

Depreciation is the gradual transfer of costs incurred to purchase or build property, plant and equipment to the cost of the finished product. With its help, money spent on the construction or purchase of property is compensated. Depreciation deductions are paid during the entire period of property exploitation.

Let's calculate the amount of monthly depreciation deductions in a linear way. Equipment costs are 37 820 RUB. The operating life of the computer is 7 years, the Microsoft Windows 10 license is 4 years, the rest of the software is a year. Then the annual depreciation rate for them, respectively:

$$N_{DL} = \frac{1}{7} \cdot 100\% = 14{,}29\%;$$

$$N_{DWin} = \frac{1}{4} \cdot 100\% = 25\%;$$

$$N_{DSS} = \frac{1}{1} \cdot 100\% = 100\%.$$

Academic year depreciation (9 months) for Laptop, Microsoft Windows 10 License, and Supporting Software:

$$D_L = 30000 \cdot \frac{N_{DL}}{100\%} \cdot \frac{T}{365} = 30000 \cdot \frac{14{,}29\%}{100\%} \cdot \frac{90}{365} = 1\ 057 \text{ RUB},$$

$$D_{Win10} = 4000 \cdot \frac{N_{DWin}}{100\%} \cdot \frac{T}{365} = 4000 \cdot \frac{25\%}{100\%} \cdot \frac{90}{365} = 2\ 46{,}6 \text{ RUB},$$

$$D_{SS} = 3820 \cdot \frac{N_{DSS}}{100\%} \cdot \frac{T}{365} = 3820 \cdot \frac{100\%}{100\%} \cdot \frac{90}{365} = 941{,}9 \text{ RUB},$$

where T – number of working days

Total depreciation for a year:

$$D = D_L + D_{Win10} + D_{SS} = 2\ 245{,}5\ RUB$$

5.5.4.3 Basic salary

The amount of expenses for wages of employees is determined based on the labor intensity of the work performed and the current system of salaries and tariff rates.

The calculation of the basic salary of the head of a scientific project is based on the sectoral wage system. The branch system of remuneration at TPU assumes the following composition of wages:

1) Salary - determined by the enterprise. In TPU, salaries are distributed in accordance with the positions held, for example, assistant, art. lecturer, associate professor, professor (see "Regulations on remuneration" given on the website of the Planning and Finance Department of TPU).

2) Incentive payments - set by the head of departments for effective work, performance of additional duties, etc.

3) Other payments; district coefficient.

Since incentive bonuses, other payments and incentives depend on the activities of the manager in particular, we will take the coefficient of incentive bonuses equal to 30%, and the coefficient of incentives for the manager for conscientious work activity is 25%.

The basic salary of a manager is determined by the formula:

$$S_{\mathrm{b}} = S_r \cdot T_w, \qquad (11)$$

where S_r is worker’s regular salary;

T_{p} is duration of work, work days.

Additional salary:

$$S_{\mathrm{add}} = 0{,}15 \cdot \ S_{\mathrm{b}} \qquad (12)$$

Average daily salary for a 5-day working week:

$$S_{\mathrm{d}} = \frac{S_m \cdot M}{F_d}, \qquad (13)$$

where S_m is worker's monthly salary, RUB;

F_d is number of working days in a month, days,

M =11.2 is number of months of work without vacation during the year

Full salary can be defined as:

$$S_F = S_b + S_{add}, \qquad (14)$$

Taking into account the document "Regulations on wages", associate professor, candidate of technical sciences, working at TPU has a salary equal to S_r =36 000 rubles (senior teacher – 30000 rubles, professor, doctor of technical sciences – 45000 rubles). A design engineer with no experience in Tomsk has an average salary of 18,000 rubles. With this in mind, we calculate the size of the total salary of the project manager and design engineer during the study.

Monthly salaries:

- For project supervisor:

$$S_{b.sup} = S_r \cdot \left(1 + k_{\text{pr}} + k_d\right) \cdot k_r = 36000 \cdot (1 + 0{,}3 + 0{,}25) \cdot 1{,}3 = 72540 \text{ RUB};$$

$$S_{F.sup} = S_{b.sup} + S_{add} = 72\,540 + 0{,}15 \cdot 72\,540 = 83420 \text{ RUB}.$$

- For engineer developer:

$S_{b.eng} = S_r \cdot \left(1 + k_{\text{pr}} + k_d\right) \cdot k_r = 18000 \cdot (1 + 0{,}3 + 0{,}25) \cdot 1{,}3 =$ 36 270 RUB;

$$S_{F.eng} = S_{b.eng} + S_{add} = 36270 + 0{,}15 \cdot 36270 = 41711 \text{ RUB}.$$

Average daily salary:

$$S_{\text{D.sup.}} = \frac{S_{\text{b.sup.}}}{F_d} = \frac{72540}{20{,}58} = 3524{,}1 \text{ RUB};$$

$$S_{\text{D.eng.}} = \frac{S_{\text{b.eng.}}}{F_d} = \frac{36270}{20{,}58} = 1762{,}4 \text{ RUB},$$

where the average number of working days in a month was determined as:

$$F_d = \frac{\text{T}_w}{12} = \frac{247}{12} = 20{,}58.$$

Let's assume that the project manager spent 25 working days on it, then the design engineer was engaged in the rest of the time (80 days). Salaries of project participants for the period of work:

$$S_{sup} = S_{\text{D.sup.}} \cdot t_{\text{sup}} = 3524{,}1 \cdot 25 = 88110{,}9 \text{ RUB};$$

$$S_{eng} = S_{\text{D.eng.}} \cdot t_{\text{eng}} = 1762{,}4 \cdot 80 = 14\,2754{,}4 \text{ RUB}.$$

Additional salaries of project participants:

$$S_{add.sup.} = 0{,}15 \cdot 72540 = 10880{,}3 \text{ RUB};$$

$$S_{add.eng.} = 0{,}15 \cdot 36270 = 5440{,}5 \text{ RUB}.$$

Daily additional salaries:

$$S_{D.add.sup.} = \frac{10880{,}3}{20{,}58} = 528{,}63 \text{ RUB};$$

$$S_{D.add.eng.} = \frac{5440{,}5}{20{,}58} = 264{,}4 \text{ RUB}.$$

Additional salary for the entire project period:

$$S_{\text{Padd.sup}} = S_{D.add.sup} \cdot t_{sup} = 528{,}63 \cdot 25 = 13220{,}7 \text{ RUB};$$

$$S_{\text{Padd.eng}} = S_{D.add.eng.} \cdot t_{\text{eng}} = 264{,}4 \cdot 80 = 21150{,}4 \text{ RUB}.$$

Full salary for the period of the project:

$$S_{F.sup} = S_{b.sup} + S_{Padd.sup} = 72540\ + 13\ 220{,}7 = 85760{,}6 \text{ RUB};$$

$$S_{F.eng} = S_{b.eng} + S_{\text{Padd.eng}} = 36270\ + 21416{,}4 = 57420{,}8. \text{ RUB}.$$

5.5.4.4 Contributions to social funds

Here I will consider the obligatory contributions according to the norms established by the legislation of the Russian Federation to the state social insurance bodies (FSS), the pension fund (PF) and medical insurance (FFOMS) from the costs of wages of employees. The amount of contributions to extra-budgetary funds is determined by the formula:

$$S_{\text{exb}} = k_{\text{exb}}(S_{F.sup} + S_{F.eng}), \quad (15)$$

where k_{exb}– contribution rate to extrabudgetary funds.

To date, the following contributions must be made from the amount provided as payment for labor:

• 22% towards the accrual of future pension;

• 5,1% to the Mandatory Health Insurance Fund;

• 2,9% to the Social Insurance Fund;

• from 0,2 to 8,5% for insurance against accidents that may occur at work (the exact amount depends on the risk class, which includes the profession and position of the employee).

The work of a manager and a design engineer belongs to the 1 risk class. Thus, the total deductions amount to 30,2%.

$$S_{\text{exb}} = 0{,}302 \cdot (85760{,}6 + 57420{,}8) = 43240\ \text{ RUB}.$$

5.5.4.5 Organization of research costs budget

In the previous subchapters, the values of the main costs of the research were calculated. Let us take them all in one table 5.11.

Table 5.11 – Research cost budgeting

Name	Cost, RUB.	Cost, %
Costs for materials and other products	1290	0.57
Costs for specialized equipment	2245,5	0.99
Supervisor salary costs	85760	37.6
Design engineer salary costs	57420	25.2
Contributions to social funds	43240	18.97
Overheads	37990	16.67
Research budget	227900	100

Conclusion:

I calculated my calculations for 2 parts of condencers the first one at dout=28 mm with δ=1 mm and the second one at dout=28 with δ=2 and I see that the second condencer is better because of law cost for economical salaries

6. Part of Environmental

In this work, we developed a software package for the rehabilitation and assessment of motor disorders of the central nervous system in augmented reality. The work was carried out in the laboratory of the Department of Biomedical Cybernetics of the Biomedical Faculty of Siberian State Medical University. This laboratory is equipped with tools that allow you to study finger movements for assessing motor impairment "Leep Motion" and glasses "Epson Moveiro BT-

300” as well as personal computers for managing, processing information and rehabilitating patients. To ensure the safety of workers and the environment, it is necessary to develop a set of technical and organizational measures that minimize the negative consequences of system design actions.

The purpose of this section is to analyze and evaluate harmful and hazardous labor factors that may affect project development personnel. Development of protective measures against these factors, assessment of working conditions. This section also discusses issues related to safety, fire protection and environmental protection, recommendations for creating optimal working conditions.

The potential risk is the use of equipment based on energy consumption GOST 12.1.030-81

When working with equipment should be guided by the following document: GOST R 12.1.019-2009

Collective protective equipment includes the use of a special research room. Personal protective equipment includes: when working with the equipment, hands should be clean and dry, the room temperature must correspond to the data specified in table №3, in order to avoid high or too low humidity of the room. At the end of the work, it is necessary to turn off all equipment and check the room in order to avoid dangerous situations.

1 Legal and organizational safety issues

1.1 Special legal norms of labor legislation

Most of the work that is carried out in production is directly related to the presence of dangerous and harmful production factors.

When hiring, the applicant is informed about this, and also indicated in the employment contract. And, accordingly, the employer is also obliged to familiarize not only with such working conditions, but also to teach safety measures, safe work practices, conduct internships at the workplace, provide training on labor protection, and periodically check the employee's knowledge of labor protection requirements.

In accordance with Art. 221 - 225 of the Labor Code of the Russian Federation in the conditions of dangerous and (or) harmful production factors, it should be provided by the employer of workers with personal protective equipment, special clothing, disinfecting or rinsing agents, all necessary share of first aid, etc. Also, at his own expense, the employer must ensure the issuance of special shoes and clothes, as well as other personal protective equipment. In addition, according to part 3 of article 221 of the Labor Code of the Russian Federation, the employer must provide care for special clothing (i.e. storage, repair, replacement, washing, drying).

It is also envisaged to undergo a medical examination for workers who perform work in conditions with dangerous and (or) harmful production factors, which is indicated in Article 213 of the Labor Code of the Russian Federation. Moreover, both during employment and in the process of work. In the order of the Ministry of Health and Social Development of the Russian Federation dated 12.04.2011 № 302n. The procedure for conducting a medical examination is indicated. The requirements of this document stipulate that a medical examination should be carried out once a year, or twice a year. It depends on the type of activity of the employee in the workplace, as well as on the presence of specific harmful factors.

According to part 6 of article 213 of the Labor Code of the Russian

Federation, for workers whose work is associated with sources of increased danger (for example, the influence of adverse production factors and harmful substances), as well as for those working under conditions of increased danger, a mandatory psychiatric examination should be performed at least once every 5 years. According to the Decree of the Ministry of Labor of the Russian Federation and the Ministry of

Education of the Russian Federation of 13.01.2003 No. 1/29 “On approving the procedure for training on labor protection and testing knowledge of labor protection requirements for employees of organizations”, a production worker must, in addition to a medical examination at least once every 3 years, pass his knowledge test occupational safety, as well as first aid training for injured people [8].

6.1 Organizational arrangements for the layout of the working area

6.1.1 Microclimate of the working room

During work in the laboratory, it is necessary to create favorable conditions for the microclimate of the workplace. Prolonged exposure of a person to adverse weather conditions can dramatically worsen his well-being, reduce labor productivity and lead to diseases. The microclimate is determined by combinations of temperature, humidity, air velocity and thermal radiation acting on the human body.

High air temperature contributes to rapid fatigue of the worker, and can lead to overheating of the body, cause a violation of thermoregulation, poor health, decreased attention, heat stroke, increased stress on the heart. Low air temperature can cause local or general hypothermia, cause colds, and lead to diseases of the peripheral nervous system (radiculitis, bronchitis, rheumatism). Low humidity can cause the mucous membranes of the respiratory tract to dry out. Air mobility effectively contributes to the heat transfer of the human body and is positively manifested at high temperatures and negatively at low.

According to SanPin 2.2.4.548–96, work in the laboratory belongs to category 1b in terms of energy consumption - this is light physical work, which does not require lifting and carrying heavy loads, is performed while sitting or is connected with walking.

We give the optimal and permissible microclimate indicators of industrial premises in accordance with SanPin 2.2.4.548–96.

Table 1 - Optimum microclimate indicators

Period of the year	Temperature, degrees, □ C	Relative humidity, %	Air speed, m / s
Cold	21–23	40–60	0.1
Warm	22–24	40–60	0.1

Table 2 - Permissible indicators microclimate

Period of the year	Temperature, degrees, □ C		Surface temperature, □ C	Relative humidity, %	Air speed, m / s	
	Range below r.h.	Range above r.h.			for air temperature range below (relative humidity), no more	for air temperature range above (relative humidity), no more
Cold	19.0 – 20.9	23.1 – 24.0	18.0 – 25.0	15 - 75	0.1	0.2

Warm	20.0 – 21.9	24.1 – 28.0	19.0 – 29.0	15 - 75	0.1	0.3

Laboratory and housing water heating using radiators.

The measured microclimate indicators of the laboratory correspond to acceptable indicators: air temperature and surface temperature are 20℃ and 21℃ with a relative humidity of 50% in the cold season; 23℃ and 24℃ with a relative humidity of 55% in the warm season, which complies with SanPin N 2.2.4.548-96.

[1,6].

6.1.2 Work area illumination

Not only eye health and human performance, but also his physical and psychoemotional state directly depends on the degree of illumination. Moreover, in premises for various purposes, the lighting requirements should vary. Also, when calculating the illumination, it is reasonable to take into account the characteristics of the working process carried out by a person in such a room, its frequency and duration.

In practice, two types of lighting are used: natural and artificial. Natural lateral and artificial working, as well as combined, which consists of local lighting of workplaces and general lighting of the room. These types of lighting are standardized by Set of rules 52.13330.2011.

In this laboratory, work is carried out on personal computers. According to

SanPin 2.2.2 / 2.4.1340–03 “Hygienic requirements for personal electronic computers and organization of work”, artificial lighting in premises for the operation of a personal computer should be carried out by a general uniform lighting system. Illumination on the table surface in the area of the working document should be 300 - 500 lux. Lighting should not create glare on the surface of the screen. Illumination of the screen surface should not be more than 300 lux.

In the laboratory, medium-precision work is carried out with the smallest size of the object of discrimination 0.5 - 1.0 mm, the contrast of the object of discrimination with the background is medium. The category of visual work is IV, subdischarge b, thus the illumination of the working surface from general lighting systems is 200 lux (Set of rules 52.13330.2011 “Natural and artificial lighting”).

Table 3 - Lighting requirements for residential and public buildings.

Artificial lighting		Natural lighting, DLR,%, at	
Illumination on the working surface from the general lighting system, lux	Coefficient of pulsation of illumination CP,%, no more	Top lighting or combined	Side
300	20	2.5	0.7

Thus, there are no violations of the lighting standards in the laboratory [5].

6.1.3 Noise level at the workplace

Noise pollution of the environment at the workplace adversely affects workers: attention is reduced, energy consumption increases with the same physical activity, the speed of mental reactions slows down, etc. As a result, labor productivity and the quality of the work performed are reduced.

The main sources of noise in rooms equipped with computer technology are printers, plotters, copying equipment and equipment for air conditioning, fans of cooling systems.

n accordance with SanPin 2.2.2 / 2.4.1340–03 “Hygienic requirements for personal electronic computers and organization of work”, the noise level at workplaces should not exceed 50 dBA [6].

6.1.4 Elevated electromagnetic radiation

PCs are sources of broadband electromagnetic radiation:

• soft x-ray;

• ultraviolet 200-400 nm;

• visible 400–750 nm;

• near infrared 750–2000 nm;

• 3 kHz radio frequency range;

• electrostatic fields;

Table 4 - Temporary permissible levels of EMF created by PC in the workplace.

Name of parameters	Temporary Permissible Levels	
Electric field strength	In the frequency range 5 Hz - 2 kHz	25 V/m

	In the frequency range 2 kHz - 400 kHz	2.5 V/m
Magnetic flux density	In the frequency range 5 Hz - 2 kHz	250 nT
	In the frequency range 2 kHz - 400 kHz	25 nT
Electrostatic field strength		15 kV/m

If at the surveyed workplace equipped with a PC, the intensity of the electric and / or magnetic field in the range of 5 - 2000 Hz exceeds the values given above, it is necessary to measure the background EMF levels of industrial frequency (with the equipment turned off). The background level of the electric field with a frequency of 50 Hz should not exceed 500 V / m.

The background levels of the magnetic field induction should not exceed the values causing violations of the requirements for the visual parameters of the VDT. As a precaution, you should limit the duration of work with the PC, do not place them concentrated in the work area and turn them off if they are not working. Along with this, it is necessary to install air ionizers in the room, ventilate the room more often and, at least once during the work shift, clean the screen of dust (SanPin 2.2.2 / 2.4.1340–03) [2,3].

7. Industrial safety

Industrial safety is understood as a system of organizational measures and technical means that prevent or reduce the likelihood of exposure to working personnel of dangerous traumatic production factors that arise in the work area during the course of labor activity. In our work, it is necessary to find out dangerous and harmful factors that may arise when working with an information system. Subsequent selection is made using GOST 12.0.003–2015 "Dangerous and harmful production factors. Classification". The selection results are shown in the table below.

Table 6 - Harmful and dangerous factors when working with a computer.

Source of factor, name of the type of work	List of factors (according to GOST12.0.003–2015)		Relevant regulatory documents
	Harmful	Dangerous	
1) Computer work	1) The microclimate of the working room; 2) increased or decreased humidity of the air of the working area 3) Illumination of the working area; 4) Increased noise in the workplace; 5) Increased level of electromagnetic radiation	1) Exposure to electrical current	1) SanPin 2.2.4.548–96; 2)GOST R 12.1.019–2009; 3)GOST 12.1.030–81; 4)SP 52.13330.2011; 5)SanPin 2.2.2/2.4.1340–03; 6) GOST 12.1.003–83; 7) SanPin 2.2.2/2.4.1340–03

7.1 Analysis of harmful and dangerous factors that can be created by object of study and laboratory during research

7.1.1 Analysis of identified hazardous factors

The laboratory room where the work was carried out belongs to category B

The causes of the fire may be:

1. Short circuit currents.
2. Malfunction of electric networks.

3. Ignorance of fire safety rules or negligence of staff.
4. Smoking in the wrong places.

In this regard, the following fire safety standards must be observed in the laboratory:

1. To protect the network from overloads, it is forbidden to include additional non-intended consumers.
2. Carry out work in the laboratory only when the equipment and electrical wiring are in good condition.
3. For extinguish a fire (fire extinguisher).
4. Have a plan of evacuation of people, which should hang in a conspicuous place.
5. Place the equipment so that there is sufficient passageway to the exit.

The building of the Siberian State Medical University, in which the laboratory is located, meets the fire safety requirements.

7.1.2 Electrical safety

Electrical safety is a system of organizational and technical measures aimed at protecting people from the harmful and dangerous effects of electric current.

There is a danger of electric shock in all cases where electrical installations and equipment are used. Electrical installations are classified by voltage - with a rated voltage of up to 1000 V (rooms without increased danger), up to 1000 V with the presence of an aggressive environment (rooms with increased danger) and over 1000 V (rooms especially dangerous) (according to the Rules for the Installation of Electrical Installations).

To ensure safe operation, it is necessary to exclude possible sources of electric shock:

1. Accidental contact with live parts under voltage.
2. The appearance of voltage on the mechanical parts of electrical equipment (cases, covers, etc.) due to insulation damage or other reasons.
3. The occurrence of stress on the ground or supporting surface.

According to the degree of danger of electric shock, this laboratory belongs to rooms without increased danger, it is a dry room without increased dusting, the air temperature is normal, the floor is covered with insulating material. All electrical equipment and devices are in place and have protective grounding with a resistance of not more than 4 ohms (GOST 12.1.030-81.) All employees undergo initial electrical safety training.

Before starting work, it is necessary to check the serviceability of conductive wires. It is forbidden to use wires with damaged insulation or without insulation, as well as wires that are not equipped with plugs or soldered terminals, to connect electrical appliances.

Instruments must be kept clean. At the end of the work, disconnect the equipment from the network.

Electric shock during GQW can occur during careless handling of the connecting wires or in the event of an emergency - shorting of live parts to the equipment case in the absence of grounding and grounding. This can happen when working with electrical laboratory equipment [2].

Table 5 - Permissible levels of touch voltages and currents.

Mode	Type Of Current					
	Variable, 50 Hz			Constant		
	U, B	I, мA	Duration, min	U, B	I, мA	Duration, min
Normal	2	0.3	<10	8	1	<10

First aid to the victim should consist in immediately disconnecting the current that caused the injury, disconnecting (in rubber gloves) the victim from the leads and calling the doctor. If the victim is conscious, but before that he was swooning or has been under current for a long time, he needs to ensure peace before the doctor arrives. If the victim lost consciousness, but breathing persists, it is necessary to put him in comfortably, evenly, unfasten his tight clothes, create an influx of fresh air, remove unnecessary people from the room, breathe ammonia, spray with water, rub and warm the body. With convulsive and rare breathing, artificial respiration is necessary. In the absence of signs of life (lack of pulse and breathing), the victim cannot be considered dead. It is necessary immediately, without wasting time, before the arrival of the doctor to do artificial respiration.

7.2 Air exchange in laboratory

Air exchange in public buildings is necessary to clean the air of harmful substances: to remove harmful substances (emitted harmful gases, vapors and dust), to remove water vapor and excess heat.

In residential and public buildings, carbon dioxide (CO_2) exhaled by people is a constant harmful emission. The required air exchange is determined by the amount of carbon dioxide exhaled by a person and by its permissible concentration. The amount of carbon dioxide, depending on the age of the person and the work performed, as well as the permissible concentration of carbon dioxide for different rooms. The carbon dioxide content in the air can be determined by the chemical composition of the air. However, given the increased carbon dioxide content in the atmosphere of settlements, the CO_2 content should be taken into account when calculating:

- for large cities (over 300 thousand inhabitants)– 0.5 l/m^3.

Determine the required rate of air exchange in a laboratory for two people, if the volume of the room is V=68 m3. The laboratory is located in 603 office of the laboratory building SibSMU. The amount of carbon dioxide exhaled by an adult with light work in an institution is 18 l/h [12]. The maximum permissible concentration of carbon dioxide for institutions is 1.25 l/m3 [12]. The required air exchange in the laboratory is determined by the formula 1:

$$L = \frac{G * P}{x_v - x_n} \qquad (13)$$

where L – air exchange required, m^3/h;

G – the amount of harmful substances released into the room air, g/h;

P – number of people working in the laboratory; x_v – maximum permissible concentration of harmfulness in the air of the working area of the room [9], mg/m^3; x_n – the maximum possible concentration of the same harmfulness in the air

of populated areas [10], mg/m^3.

The rate of air exchange (n), which shows how many times in one hour the air is completely replaced in the room, which is determined by the formula 2.

$$n = \frac{L}{V_n}, h^{-1} \quad (2)$$

where V_n is the internal volume of the room, m^3

According to [11], the permissible air exchange rate should be in the range from 3 to 10 h^{-1}.

Required air exchange in the laboratory, according to 1:

$$L = \frac{18 * 2}{1.25 - 0.5} = 48 \frac{m^3}{h}$$

The required air exchange rate is:

$$n = \frac{48}{68} = 0.7\ h^{-1}$$

Thus, the calculated consumed air exchange in the laboratory should be 48 m^3/h.

Safety in emergency situations

In case of emergency, you must immediately call the fire department at number “01” from your business phone or “101” from your mobile phone.

The notification of civil defense alerts in the event of an emergency to the personnel of the objects is carried out using voice information through broadcasting channels, radio broadcast networks and communication networks. On the territory of the Siberian State Medical University they do not use, do not produce, do not process, do not store radioactive, fire hazardous, and also explosive substances that create a real threat of an emergency source. As the most probable technological emergencies, the project considers

Fire at the territory object.

Fire hazards for humans include toxic combustion products, low oxygen concentration, open flames, smoke, and high air temperatures.

The following measures must be observed to prevent fire:

Reducing the determining size of the combustible medium.

Prevention of the formation of a combustible medium.

In case of overheating, short circuits, etc. possible ignition of electrical installations, wiring. To extinguish the fire, it is necessary to use special means, it is impossible to use water and other conductive substances. Therefore, the premises should be equipped with means for extinguishing electrical installations and electrical wiring under voltage.

8. Ecological safety

Environmental impact of nuclear power

The environmental impact of nuclear power results from the nuclear fuel cycle, operation, and the effects of nuclear accidents.

The greenhouse gas emissions from nuclear fission power are much smaller than those associated with coal, oil and gas, and the routine health risks are much smaller than those associated with coal. However, there is a "catastrophic risk" potential if containment fails, which in nuclear reactors can be brought about by overheated fuels melting and releasing large quantities of fission products into the environment.

The most long-lived radioactive wastes, including spent nuclear fuel, must be contained and isolated from the environment for a long period of time. On the other side, spent nuclear fuel could be reused, yielding even more energy, and reducing the amount of waste to be contained.

Other waste

Moderate amounts of low-level waste are through chemical and volume control system (CVCS). This includes gas, liquid, and solid waste produced through the process of purifying the water through evaporation. Liquid waste is reprocessed continuously, and gas waste is filtered, compressed, stored to allow decay, diluted, and then discharged. The rate at which this is allowed is regulated and studies must prove that such discharge does not violate dose limits to a member of the public (see radioactive effluent emissions).

Solid waste can be disposed of simply by placing it where it will not be disturbed for a few years.

Power plant emission

Radioactive gases and effluents

Most commercial nuclear power plants release gaseous and liquid radiological effluents into the environment as a byproduct of the Chemical Volume Control System.

Civilians living within 50 miles (80 km) of a nuclear power plant typically receive about 0.1 μSv per year.[2] For comparison, the average person living at or above sea level receives at least 260 μSv from cosmic radiation.

All reactors are to have a containment building. The walls of containment buildings are several feet thick and made of concrete and therefore can stop the release of any radiation emitted by the reactor into the environment. If a person is to worry about an energy source that releases large amounts of radiation into the environment, they should worry about coal-fired plants. "The waste produced by coal plants is actually more radioactive than that generated by their nuclear counterparts. In fact, the fly ash emitted by a [coal] power plant—a by-product from burning coal for electricity—carries into the surrounding environment 100 times more radiation than a nuclear power plant producing the same amount of energy." Coal-fired plants are much more hazardous to people's health than nuclear power plants as they release much more radioactive elements into the environment and subsequently expose people to greater levels of radiation than nuclear plants do. "Estimated radiation doses ingested by people living near the coal plants were equal to or higher than doses for people living around the nuclear facilities. At one extreme, the scientists estimated fly ash radiation in individuals' bones at around 18 millirems (thousandths of a rem, a unit for measuring doses of ionizing radiation) a year. Doses for the two nuclear plants, by contrast, ranged from between three and six millirems for the same period. And when all food was grown in the area, radiation doses were 50 to 200 percent higher around the coal plants."

The total amount of radioactivity released through this method depends on the power plant, the regulatory requirements, and the plant's performance. Atmospheric dispersion models combined with pathway models are employed to accurately approximate the dose to a member of the public from the effluents emitted. Effluent monitoring is conducted continuously at the plant.

8.1 Comparison to coal-fired generation

In terms of net radioactive release, the National Council on Radiation Protection and Measurements (NCRP) estimated the average radioactivity per short ton of coal is 17,100 millicuries/4,000,000 tons.

In terms of dose to a human living nearby, it is sometimes cited that coal plants release 100 times the radioactivity of nuclear plants. This comes from NCRP Reports No. 92 and No. 95 which estimated the dose to the population from 1000 MWe coal and nuclear plants at 4.9 man-Sv/year and 0.048 man-Sv/year respectively (a typical Chest x-ray gives a dose of about 0.06 mSv for comparison). The Environmental Protection Agency estimates an added dose of 0.3 μSv per year for living within 50 miles (80 km) of a coal plant and 0.009 milli-rem for a nuclear plant for yearly radiation dose estimation. Nuclear power plants in normal operation emit less radioactivity than coal power plants.

Unlike coal-fired or oil-fired generation, nuclear power generation does not directly produce any sulfur dioxide, nitrogen oxides, or mercury (pollution from fossil fuels is blamed for 24,000 early deaths each year in the U.S. alone). However, as with all energy sources, there is some pollution associated with support activities such as mining, manufacturing and transportation.

A major European Union-funded research study known as ExternE, or Externalities of Energy, undertaken over the period of 1995 to 2005 found that the environmental and health costs of nuclear power, per unit of energy delivered, was €0.0019/kWh. This is lower than that of many renewable sources including the environmental impact caused by biomass use and the manufacture of photovoltaic solar panels, and was over thirty times lower than coals impact of €0.06/kWh, or 6 cents/kWh. However, the energy source of the lowest external costs associated with it was found to be wind power at €0.0009/kWh, which is an environmental and health impact just under half the price of Nuclear power.[7]

Waste heat

As with all thermoelectric plants, nuclear power plants need cooling systems. The most common systems for thermal power plants, including nuclear, are:

- Once-through cooling, in which water is drawn from a large body, passes through the cooling system, and then flows back into the water body.
- Cooling pond, in which water is drawn from a pond dedicated to the purpose, passes through the cooling system, then returns to the pond.
- Cooling towers, in which water recirculates through the cooling system until it evaporates from the tower.

Nuclear plants exchange 60 to 70% of their thermal energy by cycling with a body of water or by evaporating water through a cooling tower. This thermal efficiency is somewhat lower than that of coal-fired power plants, thus creating more waste heat.

It is possible to use waste heat in cogeneration applications such as district heating. The principles of cogeneration and district heating with nuclear power are the same as any other form of thermal power production. One use of nuclear heat generation was with the Ågesta Nuclear Power Plant in Sweden. In Switzerland, the Beznau Nuclear Power Plant provides heat to about 20,000 people. However, district heating with nuclear power plants is less common than with other modes of waste heat generation.

A number of thermal stations use indirect seawater cooling or cooling towers that in comparison use little to no freshwater.

8.2 Water consumption and risks

During the process of nuclear power generation, large volumes of water are used. The uranium fuel inside reactors undergoes induced nuclear fission which releases great amounts of energy that is used to heat water. The water turns into steam and rotates a turbine, creating electricity.[10]

When intaking water for cooling, nuclear plants, like all thermal power plants including coal, geothermal and biomass power plants, use special structures. Water is often drawn through screens to minimise to entry of debris. The problem is that many aquatic organisms are trapped and killed against the screens, through a process known as impingement. Aquatic organisms small enough to pass through the screens are subject to toxic stress in a process known as entrainment. Billions of marine organisms are sucked into the cooling systems and destroyed.

8.3 Greenhouse gas emissions

Many stages of the nuclear fuel chain — mining, milling, transport, fuel fabrication, enrichment, reactor construction, decommissioning and waste management — use fossil fuels, or involve changes to land use, and hence emit carbon dioxide and conventional pollutants.

Nuclear energy contributes a very small amount of emissions into the atmosphere which can cause many environmental problems such as global warming. Uranium is not burned in a nuclear power plant as coal is so there are no emissions from it. All of the waste that comes from the fission of uranium stays in the plant and is therefore able to be disposed of in a safe way in which the uranium is kept out of the environment. "

Nuclear energy produces far less carbon dioxide than coal, 9 grams per kilowatt hour compared with 790–1017 grams per kilowatt hour for coal. Also, nuclear energy produces the same amount if not less greenhouse gasses than renewable resources. Like all energy sources, various life cycle analysis (LCA) studies have led to a range of estimates on the median value for nuclear power, with most comparisons of carbon dioxide emissions show nuclear power as comparable to renewable energy sources.

Nuclear power, primarily from ~1970 to 2013, is estimated to have prevented the atmospheric emission of 64 gigatonnes of CO2-equivalent.

9. Calculation of the maximum permissible discharge

It is required to calculate *maximum permissible discharge (MPD)* of radionuclides for a NPP designed specifically for given region. Calculation has to be carried out for normal operation mode and repair period, if electrical capacity, N_e, of the NPP is known.

Emission goes through the chimney consisting of the main chimney and internal one. The internal one has diameter d, and it is used during normal operation mode, when the gas mixture is being vented with the volumetric flow rate V_1. The main chimney is needed to emit the gas mixture during repair period, when the volumetric flow rate is V_2. The diameter of the main tube is D.

NPP's normal operation mode time assumed equal to t_{no}. Temperature difference of the gas mixture and the air, where the mixture is emitted, is ΔT.

Capacity expansion limit and *buffer area sizes* are needed to be determined either.

Notes:

1. Critical groups of population are exposed to external and internal irradiations; internal one includes irradiation due to breathing and with dietary intake (all of the possible ways).

Maximum Permissible Discharge

If the value of C_{ni} is unknown, the evaluation of MPD_i can be done via the formula below:

$$MPD_i = \frac{1}{\gamma} K_d TC_i = \frac{1}{10} * K_d * TC_i \ \ \frac{Bq}{s},$$

where is γ is a factor; $\gamma = 30$ for operating NPP and, if the following capacity expansion is planned; $\gamma = 10$ at the stage of NPP design.

Tolerable concentrations are calculated according to the algorithm represented in the formula

$$TC_i = \frac{\eta_i}{\sum_k \frac{\eta_k}{TC_k}}$$

$$TC_i = 621.746 \ \ Bq/m^3$$

$$TC_i\left({}^{41}\mathrm{Ar}\right) = \frac{TC_i\left({}^{134}\mathrm{Cs}\right) * \eta_k\left({}^{41}\mathrm{Ar}\right)}{\eta_k\left({}^{134}\mathrm{Cs}\right)} = \frac{621.746 \ *7{,}4*10^7}{4.8*10^7} = 958.52\ Bq/m^3$$

Permissible concentration and maximum permissible emission of radionuclides from the designed NPP during its normal operation and in the repair mode

Radionuclide	Blowout η_k, rel. units	TC_i $Bq/m3$	TC_i Bq/m^3	MPL op ($\frac{Bq}{s}$)	MP re ($\frac{Bq}{s}$)	$\sum MPD_i$ op ($\frac{Bq}{day}$)	$\sum MPD_i$ re ($\frac{Bq}{day}$)
^{41}Ar	$7,4\cdot10^7$	18 13	958.525	2058911700	3237897450	$1.779*10^{14}$	$2.797*10^{14}$
^{85m}Kr	$1,2\cdot10^7$	14 800	155.4365	333877602	525064497	$2.884*10^{13}$	$4.536*10^{13}$
^{85}Kr	$1,2\cdot10^6$	96 200	15.54	33379920	52494120	$2.88*10^{12}$	$4.535*10^{12}$
^{87}Kr	$2,5\cdot10^7$	29 97	323.826	695578248	1093884228	$6*10^{13}$	$9.4511*10^{13}$
^{88}Kr	$3,4\cdot10^7$	11 47	440.40	945979200	1487671200	$8.17*10^{13}$	$1.285*10^{14}$
^{133}Xe	$6,7\cdot10^7$	51 800	867.853	1864148244	2931607434	$1.610*10^{14}$	$2.532*10^{14}$
^{135}Xe	$4,8\cdot10^7$	62 900	621.746	1335510408	2100257988	$1.153*10^{14}$	$1.8146*10^{14}$
^{89}Sr	$4,0\cdot10^{-1}$	35	$5.18*10^{-6}$	11.12664	17.49804	961341.696	1511830.656
^{90}Sr	1,0	1,5	$1.29*10^{-5}$	27.7092	43.5762	2394074.88	3764983.68
^{131}I	$1,2\cdot10^3$	5	0.01554	33379.92	52494.12	2884025088	4535491968
^{134}Cs	$1,0\cdot10^{-1}$	0,023	$1.29*10^{-6}$	2.77092	4.35762	239407.488	376498.368
^{137}Cs	$3,0\cdot10^{-1}$	18	$3.89*10^{-6}$	8.35572	13.14042	721934.208	1135332.288
^{140}Ba + ^{140}La	$4,0\cdot10^{-1}$	56	$5.18*10^{-6}$	11.12664	17.49804	961341.696	1511830.656

If the value of C_{ni} is unknown, the evaluation of MPD_i can be done via the formula below:

$$MPD_i = \frac{1}{\gamma} K_d TC_i = \frac{1}{10} * K_d * TC_i \quad \frac{Bq}{s},$$

where is γ is a factor; $\gamma = 30$ for operating NPP and, if the following capacity expansion is planned;

$\gamma = 10$ at the stage of NPP design.

Tolerable concentrations are calculated according to the algorithm represented in the task 1.

Coefficient of meteorological dilution of component in the atmosphere is calculated with the formula

$$K_{d1} = \frac{H^2\sqrt{V\Delta T}}{A \cdot F \cdot m \cdot n \cdot \alpha \cdot c \cdot \left(\frac{v}{v_0}\right)} = \frac{155^2 * \sqrt{65 * 17}}{0.16 * 1 * 0.59 * 1.28 * \frac{1}{13} * 2 * 2} = 21.48 * 10^6 \ \frac{m^3}{s},$$

$$K_{d2} = \frac{H^2\sqrt{V\Delta T}}{A \cdot F \cdot m \cdot n \cdot \alpha \cdot c \cdot \left(\frac{v}{v_0}\right)} = \frac{155^2 * \sqrt{165 * 17}}{0.16 * 1 * 0.76 * 1.07 * \frac{1}{13} * 2 * 2} = 33.78 * 10^6 \ \frac{m^3}{s}$$

where H is height of the tube, m;

V is volumetric flow rate of the gas mixture, $\frac{m^3}{s}$;

A is a factor depending on temperature stratification of the atmosphere and defining the conditions of vertical or horizontal dissipation at an intensive turbulent exchange in the atmosphere, $s^{\frac{2}{3}} \cdot {}^{\circ}C^{\frac{1}{3}}$;

F is a factor taking account of component settling capability;

m and n are dimensionless correcting factors;

α is factor of temporal settling, it is taken equal to $\frac{1}{13}$;

$\left(\frac{v}{v_0}\right)$ is wind rose factor;

c is wind rose correction factor.

Table 3. F factor values

$F = 1$	Gases and aerosol

$$m1 = \frac{1}{0,67 + 0,1\sqrt{f} + 0,34\sqrt[3]{f}} = \frac{1}{0.67 + 0.1\sqrt{10.896} + 0.34\sqrt[3]{10.896}} = 0.5701$$

$$m2 = \frac{1}{0,67 + 0,1\sqrt{f} + 0,34\sqrt[3]{f}} = \frac{1}{0.67 + 0.1\sqrt{4.4812} + 0.34\sqrt[3]{4.4812}} = 0.693$$

$$f1 = \frac{10^3 w_{01}^2 D}{H^2 \Delta T} = \frac{10^3 * 39.611^2 * 1.5}{120^2 * 15} = 10.896$$

$$f2 = \frac{10^3 w_{02}^2 D}{H^2 \Delta T} = \frac{10^3 * 16.6300^2 * 3.5}{120^2 * 15} = 4.4812$$

where w_0 is outlet velocity of gases, $\frac{m}{s}$;

$$w_0 1 = \frac{v_1}{s} = \frac{4 \cdot v_1}{\pi \cdot d^2} = \frac{4 * 70}{\pi \cdot 1.5^2} = 39.611 \frac{m}{s}$$

$$w_0 2 = \frac{v_2}{s} = \frac{4 \cdot v_2}{\pi \cdot D^2} = \frac{4 \cdot 160}{\pi \cdot 3.5^2} = 16.6300\ m/s$$

D is chimney diameter ($D \equiv d$ in case repair period).

The factor n depends on parameter V_m:

$$V_{m1} = 0,65\sqrt[3]{\frac{V\Delta T}{H}} = 0,65\sqrt[3]{\frac{70*15}{120}} = 1.34$$

$$V_{m2} = 0,65\sqrt[3]{\frac{V\Delta T}{H}} = 0,65\sqrt[3]{\frac{160*15}{120}} = 1.764$$

$$n1 = 3 - \sqrt{(V_m - 0,3)(4,36 - V_m)} = 3 - \sqrt{(1.34 - 0,3)(4,36 - 1.34)} = 1.23$$

$$n2 = 3 - \sqrt{(V_m - 0,3)(4,36 - V_m)} = 3 - \sqrt{(1.764 - 0,3)(4,36 - 1.764)} = 1.05$$

Table 4. n factor values

$n = 3 - \sqrt{(V_m - 0,3)(4,36 - V_m)}$	$V_m \in (0,3; 2]$

Buffer area size

Size of the buffer area is calculated by the formula

$$X = 2\beta H \text{ m}$$

where β is a factor depending on V_m:

- $\beta = 4,95V_m\left(1 + 0,28f^{\frac{1}{3}}\right) = 4,95 * 1.34\left(1 + 0,28 * 10.896^{\frac{1}{3}}\right) = 10.75$ if $V_m \leq 2$;
- $\beta = 4,95V_m\left(1 + 0,28f^{\frac{1}{3}}\right) = 4,95 * 1.764\left(1 + 0,28 * 4.4812^{\frac{1}{3}}\right) = 12.76$ if $V_m \leq 2$;
  - $X1 = 2\beta H = 2 * 10.75 * 120 = 2580$ m
  - $X2 = 2\beta H = 2 * 12.76 * 120 = 3062.4$ m

Taking more meaning, size of the buffer area $X = 3062.4$ m.

- In this work, it was calculated the average values maximum allowable emissions of radioactive materials into the atmosphere from the designed nuclear power station with the possibility of further expansion.
- $\sum_i MPD_i^{RNG}$values obtained in the normal operation mode and repair mode can be concluded that in the repair mode emission limit values higher than during normal operation of the planned power plant.
- This is due to the dilution factor meteorological, namely repair mode uses primary vent stack, where in the diameter of the mouth 2 times the inner tube, and also increases an average volumetric flow of air-gas mixture, to a larger volume of air necessary to lower the concentration of radioactive substances.

10.Conclusion

The solutions adopted in the Generation III+ designs of VVER can reduce the probability of a SA due to an internal IE to a level of 10−7/year. Under these conditions, the risk of exceeding the release criterion may be related mainly to the consequences of beyond-design external events, which is important for NPP sites with high external impact hazard. This places special demands both for the selection of calculated scenarios of SAs, which shall be representative for accident classes with typical properties and bounding consequences, and the methods for modeling accident progression with radiation effect prediction in terms of dose loads.

A suggested approach to solving these problems is based on the application of an advanced integrated computer code system that implements the best-estimate physical models. On the example of two bounding scenarios of SAs with fuel melting in the core and spent fuel pool, the accident timing is presented, and the doses are assessed in reference settlements at different distances from the conventional NPP. The assessment of doses is based on the use of a Lagrangian stochastic model of atmospheric dispersion that allows calculations for long-term releases accounting for the nonhomogeneous spatial and temporal structure of atmospheric currents, features of site location, and climatic and geographical features of the terrain. The use of a non-Gaussian approach accounting for three-dimensional meteorological fields removes the significant limitation on the distance from the source of release, thus meeting the requirements of foreign regulators.

As a result of the analysis of these bounding scenarios, it can be concluded that in the VVER-1200 and VVER-1300 NPP designs (which are equipped with passive

SSs and alternative safety features), an early LR is practically eliminated, and conditions for the application of serious population protection measures can only be formed in the worst case with extremely low probability well after a 24-h time interval due to containment overpressurization or fuel melting in the spent fuel pool. During the first day of the accident, the tightness of the containment is ensured, and the possibility of connecting alternative safety equipment to reduce containment pressure and to cool the spent fuel pool without any significant consequences outside the NPP site is justified.

For thermal Power the Efficiency of an electric power turbine is 33.1%

And the Efficiency of pipelines connecting a steam generating unit

with a turbine 98.8 %

for Steam turbine plant heat rate, for generating electricity 108.76 KJ/KWh

that's why the NPP Efficiency.

$$\eta_{npp} = \eta_R \cdot \eta_{pip}^{I} \cdot \eta_{pip}^{II} \cdot \eta_{sg} \cdot \eta_{tb}$$

$$\eta_{npp} = 0.99 \cdot 0.99 \cdot 0.988 \cdot 0.985 \cdot 0.331 = 0.317 = 31.7\ \%$$

$$= 1313.13\ \text{MW}$$

Then for Rector power

$$Q_R = 3200$$

Specific consumption of burned-out nuclear fuel for electricity supply:

$$T_{eff} = 6000 \frac{\text{hr}}{\text{year}} \ , \ \overline{B} = 35 \cdot 10^3 \ \frac{\text{MW day}}{\text{ton}}$$

For Condenser

calculated my calculations for 2 parts of condencers the first one at dout=28 mm with δ=1 mm and the second one at dout=28 with δ=2 and I see that the second condencer is better because of law cost

	Design options	
	1	2
	d_{out} = 28 mm; δ_{wall}=1 mm	d_{out} = 28 mm; δ_{wall} =2 mm
C_{cond}, million rubles	172.312	169.385
C_{el}, million rubles	513.183	503.05

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