TOMSK POLYTECHNIC UNIVERSITY | ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ

Министерство науки и высшего образования Российской Федерации
федеральное государственное автономное
образовательное учреждение высшего образования
«Национальный исследовательский Томский политехнический университет» (ТПУ)

Школа Инженерная школа ядерных технологий
Направление подготовки 14.04.02 Ядерные физика и технологии
Отделение школы (НОЦ) Ядерно топливного цикла

МАГИСТЕРСКАЯ ДИССЕРТАЦИЯ

Тема работы
ИССЛЕДОВАНИЯ ПРОЦЕССА СЕПАРАЦИИ В ГОРИЗОНТАЛЬНОМ ПАРОГЕНЕРАТОРЕ НАСЫЩЕННОГО ПАРА ПРОИЗВОДИТЕЛЬНОСТЬЮ 150 КГ/С

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Томск – 2019 г.

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School Nuclear Science and Engineering
Field of training (Specialty)14.04.02 Nuclear Physics and Technology
Division Nuclear Fuel Cycle

MASTER'S GRADUATION THESIS

Topic of research work
SEPARATION PROCESS IN HORIZONTAL STEAM GENERATOR OPERATING ON SATURATED STEAM WITH CAPACITY OF 150KG/S

UDC 621.181:621.177.001.5

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Tomsk – 2019

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School Nuclear Science and Engineering
Field of training (Specialty)14.04.02 Nuclear Physics and Technology
Division Nuclear Fuel Cycle
APPROVED BY:
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«____» ____________ 2019

ASSIGNMENT
for the Graduation Thesis completion

In the form:

Master's Thesis

For a student:

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Topic of research work:

SEPARATION PROCESS IN HORIZONTAL STEAM GENERATOR OPERATING ON SATURATED STEAM WITH CAPACITY OF 150KG/S	
Approved by the order of the Director of School of Nuclear Science & Engineering (date, number):	No1711/c at 05.03.2019

Deadline for completion of Master's Graduation Thesis:	04.06.2019

TERMS OF REFERENCE:

Initial date for research work: *(the name of the object of research or design; performance or load; mode of operation (continuous, periodic, cyclic, etc.); type of raw material or material of the product; requirements for the product, product or process; special requirements to the features of the operation of the object or product in terms of operational safety, environmental impact, energy costs; economic analysis, etc.)*	– Steam generator characteristics – list of recommended literature

List of the issues to be investigated, designed and developed *(analytical review of literary sources with the purpose to study global scientific and technological achievements in the target field, formulation of the research purpose, design, construction, determination of the procedure for research, design, and construction, discussion of the research work results, formulation of additional sections to be developed; conclusions).*	– To under the hydrodynamic process for heat transfer in VVER SG – Analytical and numerical calculations of steam quality – Determine the Structural and characteristics of the steam volume (with and without louver separator) are currently being carried out.
List of graphic material *(with an exact indication of mandatory drawings)*	N/A

Advisors to the sections of the Master's Graduation Thesis
(with indication of sections)

Section	**Advisor**
Introduction	Gvozdyakov D.V
Literature review	Gvozdyakov D.V
Theoretical aspect of the reconstruction	Gvozdyakov D.V
Practical aspect of the reconstruction	Gvozdyakov D.V
Social responsibility	Verigin D.A
Financial management	Menshikova E.V

Date of issuance of the assignment for Master's Graduation Thesis completion according to the schedule	

Assignment issued by a scientific supervisor / advisor (if any):

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Associate Professor	Gvozdyakov.D.C	Ph.D		

Assignment accepted for execution by a student:

Group	**Full name**	**Signature**	**Date**
0АМ7И	Nnodi Akelachi Chinweikpe		

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School Nuclear Science and Engineering
Field of training (specialty) 14.04.02 Nuclear Physics and Technology
Level of education Master's Degree
Division Nuclear Fuel Cycle
Period of completion (fall/spring semester 2018 /2019)

Form of presenting the work:

SEPARATION PROCESS IN HORIZONTAL STEAM GENERATOR OPERATING ON SATURATED STEAM WITH CAPACITY OF 150KG/S

SCHEDULED ASSESSMENT CALENDAR
for the Master's Graduation Thesis completion

Deadline for completion of Master's Graduation Thesis:	04.06.2019

Assessment date	**Title of section (module) /type of work (research)**	**Maximum score for the section (module)**
19.12.18	Literature Review and Methodology	...
05.03.19	Theoretical reconstruction analysis	...
12.03.19	Practical training and the development of the algorithm	
24.05.19	Financial management and Social Responsibility	
11.06.19	Compilation of the dissertation (full report)	

COMPILED BY:
Scientific supervisor:

Position	**Full name**	**Academic degree,academic status**	**Signature**	**Date**
Associate Professor	Gvozdyakov D.V	Ph.D		

AGREED BY:

Director of the programme	**Full name**	**Academic degree, academic status**	**Signature**	**Date**
Programme Director	Verhoturova V.V	**Ph.D**		

TASK FOR SECTION
«FINANCIAL MANAGEMENT, RESOURCE EFFICIENCY AND RESOURCE SAVING»

To the student:

Group	Full name
0AM7И	Nnodi Chinweikpe Akelachi

School	Nuclear Science & Engineering	**Division**	Nuclear-Fuel Cycle
Degree	Master	**Educational Program**	14.04.02 Nuclear physics and technologies

Input data to the section «Financial management, resource efficiency and resource saving»:	
1. *Resource cost of scientific and technical research (STR): material and technical, energetic, financial and human*	Salary costs – ;85000 STR budget – ;95700
2. *Expenditure rates and expenditure standards for resources*	Electricity costs – 5,8 rub per 1 kW
3. *Current tax system, tax rates, charges rates, discounting rates and interest rates*	Labor tax – 27,1 %; Overhead costs – 30%;
The list of subjects to study, design and develop:	
1. *Assessment of commercial and innovative potential of STR*	comparative analysis with other researches in this field;
2. *Development of charter for scientific-research project*	SWOT-analysis;
3. *Scheduling of STR management process: structure and timeline, budget, risk management*	calculation of working hours for project; creation of the time schedule of the project; calculation of scientific and technical research budget;
4. *Resource efficiency*	integral indicator of resource efficiency for the developed project.
A list of graphic material *(with list of mandatory blueprints):*	
1. *Competitiveness analysis* 2. *SWOT- analysis* 3. *Gantt chart and budget of scientific research* 4. *Assessment of resource, financial and economic efficiency of STR* 5. *Potential risks*	

Date of issue of the task for the section according to the schedule	05.03.2019

Task issued by adviser:

Position	Full name	Scientific degree, rank	Signature	Date
Associate professor	E.V. Menshikova	PhD		

The task was accepted by the student:

Group	Full name	Signature	Date
0AM7И	Nnodi Chinweikpe Akelachi		

TASK FOR SECTION
"SOCIAL RESPONSIBILITY"

To the student:

Group	**Full name**
0AM7И	Nnodi Chinweikpe Akelachi

School	National Research Tomsk Polytechnic University (TPU)	**Department**	Nuclear Fuel Cycle
Degree	Masters	**Specialization**	Nuclear Physics and Technology

Input data to the "social responsibility":	
1. Describe workplace (work area) for occurrence of:	Harmful factors of the environment (microclimate, illumination, noise, vibration, electro magnetic fields, ionizing radiation); dangerous factors of environment factors (electrical, fire and explosive nature).
2. Acquaintance and selection of legislative and normative documents on the topic	electrical safety; fire and explosion safety; labor protection requirements when working on a PC. radiation safety
The list of subjects to study, design and develop:	
1. Analysis of the identified harmful factors of the environment in the following sequence:	The effect of the factor on the human body; Reduction of permissible standards with the required dimensionality (with reference to the relevant normative and technical document); Proposed remedies (collective and individual).
2. Analysis of identified hazards of the environment:	Electrical safety (including static electricity, protective equipment); fire and explosion safety (causes, preventive measures, primary fire extinguishing agents).

Date of issue of the task for the section according to the schedule	

Task issued by consultant:

Position	Full name	Scientific degree, rank	Signature	date
Senior Lecturer	D.A Verigin	Ph.D		

The task was accepted by the student:

Group	Full name	Signature	date
0АМ7И	Nnodi Chinweikpe Akelachi		

Expected learning outcomes

Result code	The result of the training (the graduate should be ready) professional competencies	Requirements of the FSES HE, criteria and / or stakeholders
LO1	To apply deep mathematical, natural scientific, socio-economic and professional knowledge for theoretical and experimental research in the field of the use of nuclear science and technology	FSES HE Requirements (PC-1,2, 3, 6, UC-1,3), Criterion 5 RAEE (p 1.1)
LO2	Ability to define, formulate and solve interdisciplinary engineering tasks in the nuclear field using professional knowledge and modern research methods	FSES HE Requirements (PC-2,6,9,10,14 UC-2,3,4, BPC1,2), Criterion 5 RAEE (p 1.2)
LO3	Be able to plan and conduct analytical, simulation and experimental studies in complex and uncertain conditions using modern technologies, and also critically evaluate the results	FSES HE Requirements (PC-4,5,6,9,22 UC-1,2,5,6), Criterion 5 RAEE (p 1.3)
LO4	To use the basic and special approaches, skills and methods for identification, analysis and solution of technical problems in nuclear science and technology	FSES HE Requirements (PC-7,10,11,12,13 UC-1-3,BPC1,3), Criterion 5 RAEE (p 1.4)
LO5	Readiness for the operation of modern physical equipment and instruments, to the mastery of technological processes during the preparation of the production of new materials, instruments, installations and systems	FSES HE Requirements (PC-8,11,14,15, BPC-1), Criterion 5 RAEE (p 1.3)
LO6	The ability to develop multivariate schemes for achieving the set production goals, with the effective use of available technical means cultural competencies	FSES HE Requirements (PC-12,13,14,16, BPC-2), Criterion 5 RAEE (p 1.3)
LO7	The ability to use the creative approach to develop new ideas and methods for designing nuclear facilities, as well as modernize and improve the applied technologies of nuclear production	FSES HE Requirements (PC-2,6,9,10,14, UC-1,2,3), Criterion 5 RAEE (p 1.2,2.4,2.5)

	basic professional competencies	
LO8	Independently to study and continuously to raise qualification during all period of professional work.	FSES HE Requirements (PC-16,17,21, UC-5,6, BPC-1), Criterion 5 RAEE (p 2.6) coordinated with the requirements of the international standard EURACE & FEANI
LO9	Actively own a foreign language at a level that allows you to work in a foreign language environment, develop documentation, present results of professional activity.	FSES HE Requirements (BPC-3, UC-2,4), Criterion 5 RAEE (p 2.2)
LO10	To demonstrate independent thinking, to function effectively in command-oriented tasks and to have a high level of productivity in the professional (sectoral), ethical and social environments, and also to lead the team, form assignments, assign responsibilities and bear responsibility for the results of work	FSES HE Requirements (PC-18,20,21,22,23 UC-1,4, BPC-2), Criterion 5 RAEE (p 1.6,2.3) coordinated with the requirements of the international-al standard EUR-ACE & FEANI

Abstract

The master's dissertation consists of (136) pages; 47 figures; 34 tables; 23 references; 30 and 1 appendix.

Keywords: Horizontal SG, heat exchanger tubes, NPP water chemistry, Nuclear steam generator design/ specification, separator and hydrodynamics of heat transfer.

The goal and objective of the research is to study the mechanics and working fluid process in VVER 1000 horizontal steam generator with saturated steam.

From the result of the research, the goal was achieved with the mathematical, numerical, geometrical and algorithmic deep understanding relating to hydrodynamics of heat transfer process in tubes of VVER steam generator with saturated steam of 150Kg/s. Practical section was also carried out on the detection of defect using capillary testing at the ROSTOV NPP manufacturing industry in Russia

The degree implementation on theoretical studies and analytical effect in assessment of pressure of the working fluid (steam) on its basic parameters, as well as the moisture content of the steam entering the louvered separator or steam receiving ceiling was calculated. The obtained values allowed to estimate the preliminary capital costs for the design and creation of a steam generator.

Contents

List of abbreviations

SG –Steam Generator

ECT – Eddy current testing

VVER – Analyzer – Based Imaging

PWR – Pressurized water reactor

NPP-Nuclear power plant

MSLB – Main stream line break

RCP -Reactor coolant pump

DG- Diesel generator

TG- Turbine generator

RCC- Reactor collection 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

Introduction

The horizontal steam generator (SG) is a Russian pressurized water reactor which belongs to the principal NPP equipment of WWER-1200, PGV-1200 SG designed for generation of saturated steam of 6.4 MPa pressure and 0.2% moisture content. PGV-1200 steam generator is a horizontal, single-vessel heat exchanger which is critical component of VVER with a submerged tube heat transfer surface and incorporated separation devices.[1]

Steam generators (SGs) are large shell and tube heat exchangers, containing several thousand tubes. They transfer heat from the primary reactor coolant to the secondary side to produce steam, which then powers turbine generators to produce electricity. Most nuclear power plants (NPPs) have anywhere from 2 to 6 SGs per reactor; however, some designs have up to 12, with a total of more than 1300 SGs being in service in 357 of the total 450 reactors in the world.

The performance of SGs is critical to the overall efficiency and safety of an NPP, particularly as plant ages. Operating experience has shown that overtime SGs become more susceptible to material degradations, which can affect plant life expectancy and overall safety. Generally, SG tubes must withstand more than 15 MPa of pressure from within the tube, while maintaining a safe and structurally important barrier between the primary and secondary side.

Tube damage may decrease the integrity and lead to leakage and possible release of contaminants into the secondary side. The significance of these issues exemplifies the importance of maintenance, inspections, and testing of SG components, especially because of the safety significance of SG tubing (Revankar and Riznic, 2009). As of Jan. 2017, there were 450 operational nuclear reactors in the International Atomic Energy Agency's (IAEA) Power Reactor Information System (PRIS), representing 392 GW of electrical power.

Aging is a relevant factor due to the fact that the majority of NPPs within the PRIS database are over 30 years of age. NPPs over the age of 30 are responsible for the highest total net electricity capacity of operational reactors, possessing 251,069 MW of the 392,012 MW of total operational net electricity capacity. However, many older NPPs use a variety of more corrosion-prone materials than used in modern plants, such as mill-annealed Inconel 600 (I600). For economic and safety reasons, a proper understanding of operating experience and plausible degradation mechanisms is of great importance.

To understand the future of nuclear SGs, it makes sense to explore past development in steam technology and SGs, and their contribution to the advancement of society by providing carbon-free electricity. A summary of the history of nuclear SGs was obtained from a variety of sources, with the purpose of detailing the origins of steam-powered technology through its development into NPP SG models (Cormier et al., 2016).

The summary presented in this introductory chapter is not comprehensive of all advancements that were made through the development of the steam generation processes, systems, and engineered equipment for power applications; however, many of the milestones such as the first device to produce useful work, the first NPP connected to the grid, or the first patent on nuclear SGs are included.

When discussing international experience with SGs, statistics and information are provided on various but most frequently used design types. Nuclear SG types discussed include the most common vertical U-tube design for pressurized water reactors (PWRs), combustion engineering and Korean AP1400 reactors, the straight-tube design of once-through steam generators (OTSGs), SGs for pressurized heavy-water reactors (PHWRs), as well as the horizontal SG design for Vodo-Vodyanoj Energeticheskij Reaktor (VVER) plants. Statistics on SGs were obtained using the IAEA’s PRIS database.

A search of patents was conducted on The World Intellectual Property Organization’s (WIPO) Patents cope database, the purpose being to compare trends in the evolution of SGs.

Furthermore, the growth of academic interest in SG related topics was tracked by conducting a literature survey of SG-related publications found in the IAEA’s International Nuclear Information System (INIS) database, the Electric Power

Research Institute's (EPRI) database, and Elsevier's SCOPUS database of scientific publications.

Goals of the research is to study and understand comprehensively the mechanics and working fluid process in VVER 1000 horizontal steam generator with saturated steam. Various choice of the constructive scheme of the steam generator was carried out. Also, calculation and construction of the heat diagram (t-Q), thermal calculation of the heating surface, calculation of separation and the water regime and calculation of thermal insulation was capture in the process of my research.

The task of the research work was to understand the choice authentication using a constructive scheme of the VVER 1000 steam generator with saturated steam. And also learn how calculate and construct the heat diagram (t-Q), thermal calculation of the heating surface, design calculation, strength calculation of individual components, hydraulic calculation, calculation relating to the separation of water regime and thermal insulation

Practical on SG capillary testing, eddy current testing among others was carried out at the ROSTOV NPP manufacturing company to understand the real and physical dynamics on the functions and manufacturing process of SG.

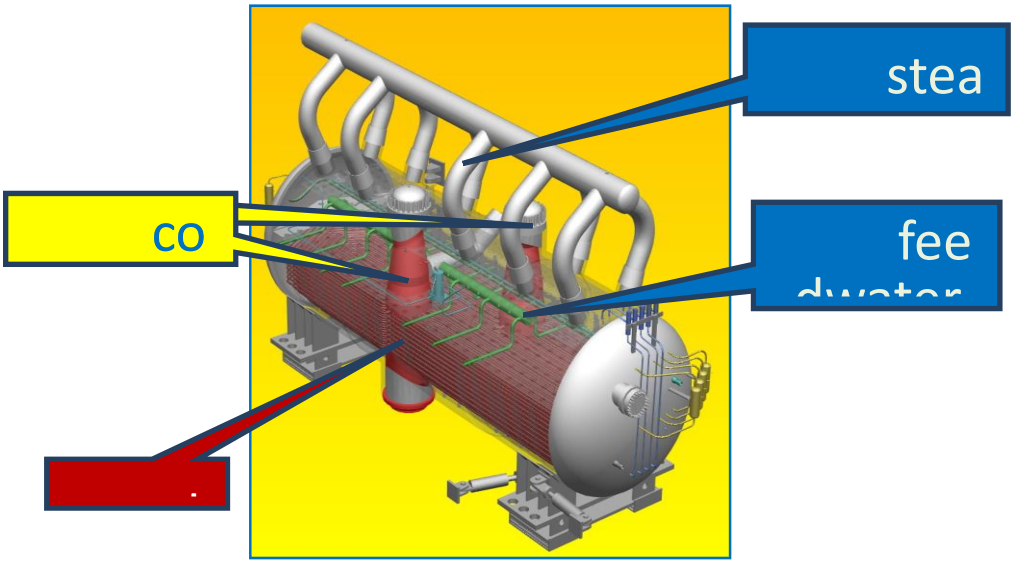


Figure 1.1 – Image of Russia Saturated horizontal steam generator with natural circulation.

Figure 1. 2 –Image of Horizontal Steam generator in Atomenergomash

Chapter 1 Literature review

1.1 History of steam generators

Water is source of life and energy. Since ancient times, people have used power derived from falling or fast-running water to support and improve their quality of life. Power extracted from various kinds of watermills and waterfalls has been the driving force for irrigation of agricultural lands and the operation of engineered devices such as grist and sawmills ore mills pumps, or lifting and load moving inventions of particular time. A Greek mathematician and scientist named Heron of Alexandria is readily credited with inventing the first SG back in 62 AD.

It was named the Aeolipile, a word derived from Aeolos (the Greek god of the winds) and pilos (sphere) (Fig. 1.1). The device consisted of a sphere that received steam through tubing along its diameters. This tubing doubled as an axis of rotation for the sphere. The steam was generated in the cauldron and base of the device and released through the L-shaped tubes creating a reaction torque around the axis of rotation of the device.

Although the Aeolipile did not produce useful work, it was a pivotal step toward the invention of the contemporary SG (Papadopoulos, 2007). Even today, the fundamental concept for industrial steam generation has remained the same: generate heat; use the heat to boil the water, and collect and use the steam.

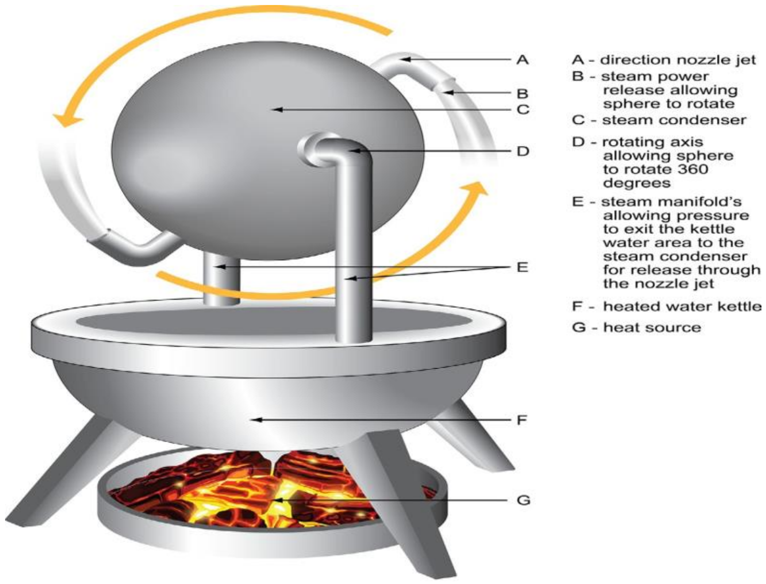


Figure 1.3 - Schematics of Heron's aeolipile.

Steam generator efficiency

$$\eta_{sg} = Qsg / Q_{rs}^{1} \tag{1.1}$$

1.2 The steam Engine

Sixteen centuries after Heron of Alexandria, was a man named Jero´nimo de Ayanzy Beaumont, who built the first modern steam engine in 1606. His invention was a steam-powered water pump used for draining flooded mines. Although it was probably the first example of steam-powered technology completing useful and practical tasks, Beaumont's innovation is often overshadowed by his more celebrated successors, Savery and Watt.

The next notable progression for steam generation technologies was created by Giovanni Brance in 1629, when he experimented with a jet of steam, turning a modified water wheel. The wheel was successfully turned by the power of steam; however, not enough power was generated to do useful work. From there onward, many inventors experimented with steam-powered machines that were not necessarily what we would consider turbines. Not long after, in 1698, the first steam-powered machine to produce useful work was invented by Thomas Savery.

Savery constructed a steam engine whose function was to pump water using the vacuum created by condensing steam. Much like Beaumont's invention, Savery's steam engine was purposed to remove water from mines in Southern England. Later in 1705, Thomas Newcomen designed and constructed an atmospheric engine, which consisted of a piston connected to a large crossbeam.

When steam was introduced into a cylinder, the pressure of the steam raised the piston. The process was then reversed by spraying cold water into the cylinder, condensing the steam and lowering the piston back in the cylinder. This up and down.

1.2.1. Nuclear steam generator design/ specification

Before beginning the design process, it is essential to have full specifications of the design requirements. The steam generator will receive reactor coolant at flow rate, temperature, and pressure requirements which are determined from the reactor system analysis. The steam generator must produce steam at a prescribed flow rate and pressure as required by the steam system.

Design conditions must be specified which are consistent with overall plant safety criteria. All plant operating transients must be fully described in the specifications to be consistent with all anticipated operating cycles over the life of the plant. However, the main criteria required to get the design process underway are:

- Full power reactor coolant flow (kg/s), and fluid (heavy or light water)
- Full power reactor coolant pressure (MPa)
- Full power reactor coolant temperature at the steam generator Inlet (°C)
- Full power reactor coolant outlet temperature from the steam generator (°C) (or alternately
- heat transferred at full power)
- Steam pressure at full power (MPa)
- Variation in steam pressure with power level (MPa)
- Full power steam flow rate (kg/s)
- Feedwater temperature (°C)

The steam generator will be designed from the inside outward. At the heart of the steam generator is the tube bundle. It is necessary to decide:

- number of tubes
- tube size

– tube material

– tube heating surface

Total heat flow rate from the reactor coolant to the boiling water outside the tubes is determined by simple thermodynamics: For a total mass flow M, Heat flow

$$Q = M\,(h_{inlet} \_ h_{outlet}) \qquad (1.2)$$

where h represents fluid enthalpy. This is calculated and also used to verify that the same heat flow rate will generate sufficient steam on the outside of the tubes.[2]

Figure 1.4 - Steam generator tube installation

1.2.2 PWR VVER steam generator

VVERs, transliterated from water-water energetic reactors, are a series of PWRs developed in Russia. In addition to Russia, countries operating VVERs include Armenia, Bulgaria, China, Czech Republic, Finland, Hungary, India, Iran, Slovakia, and Ukraine. Unique features of VVERs include hexagonal fuel assembly cassettes and horizontal SGs. The SGs used in the WWER-440 and WWER-1000 plants are horizontal shell-and-tube heat exchangers manufactured by Gidropress (Russia) and Skoda Vitkovice (Czech Republic).

They consist of a SG vessel, a horizontal heat exchange tube bundle, two vertical primary collectors and a feedwater piping system, moisture separators, and a steam collector. A sketch of a WWER-1000 SG. Primary coolant enters the SG through a vertical collector, travels through the horizontal U-shaped submerged stainless-steel tubing, and exits through a second vertical collector.

The tube ends penetrate the collector wall, which performs the same function as the tube sheet in a PWR SG, and are expanded using either a hydraulic or explosive expansion process and then welded at the collector inside wall surface. The WWER-440 collectors are made of Ti-stabilized austenitic stainless steel. The WWER-1000 collectors are made of low-alloy steel cladded with stainless steel.

The WWER-440 tubes are arranged in line (corridor), while the WWER-1000 tubes are staggered. Tube supports are made of stainless-steel bars and stamped wave-like plates, with a typical distance between the tube supports being 700–750 mm. The SG vessel is made of a carbon steel (WWER-440) or low-alloy

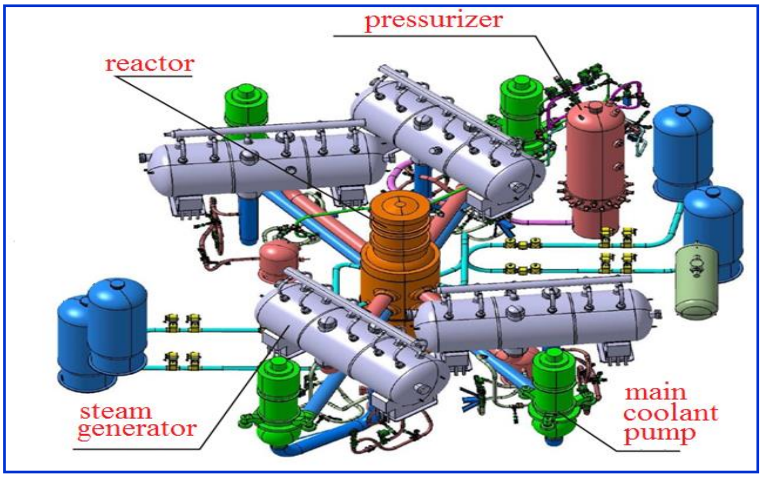


Figure 1.5- Primary circuit of VVER 1000 with 4 Unit of SG

Bainitic steel (WWER- 1000) designed as horizontal cylinder consisting of forged shells, stamped elliptical ends and stamped branch pipes and hatches welded together. The vertical hot and cold primary coolant collectors penetrate the vessel near its mid-point. Feedwater is supplied to the middle of the WWER-400 tube bundle by perforated piping. In the WWER-1000 SGs, the feedwater is supplied from the top of the hot leg of the tube bundle under a submerged perforated sheet.

The tube bundle is completely submerged in both designs. The WWER-440 and WWER-1000 SG designs are similar except for the (a) size (the WWER-1000 SG is about 4 m longer), (b) tube arrangement (corridor vs staggered), (c) collector material, (d) feedwater supply location, (e) submerged perforated top plate (WWER-1000 only), (f) steam dryer arrangement, (g) emergency feedwater distribution system (WWER-1000 only), (h) steam header arrangement, and (i) vessel material.

The most recent design of the WWER-1200 SG (PGV- 1000MKP) is similar to PGV-1000 M except its bigger vessel diameter (4200 mm) and corridor tube bundle arrangement (IAEA, 2011).Many similarities can be drawn between the VVER and Western PWRs such as the use of low-enriched uranium oxide fuel, and their light water coolant and moderator.

Even though similar in many ways, early designs of VVERs plants lack a number of safety features that are standard for the Western PWRs, such as a fire protection system, an emergency core cooling system, and a strong containment system (Trunovet al., 2008). Nevertheless, some of the advantages of using horizontal rather than vertical SGs in VVER have been exemplified over many years of operating experience. Advantages include:

- moderate steam load (steam outflow rate from the evaporation surface of around 0.2–0.3 m/s)
- moderate velocity of the medium within the second loop (up to 0.5 m/s) which prevents danger of vibrations of the heat exchanger tubes
- validated serviceability of 08Kh18N10T austenitic steel tubes for up to 38 years in a PGV- 440 and 23 years in PGV-1000
- vertical arrangement of the first-loop collectors, preventing accumulation of sludge deposits on their surfaces, reducing the danger of corrosion damage to the heat exchanger (Trunov et al., 2008).

There are currently two large issues with horizontal SGs in operation: defects in weld joints and SG tube degradations. It is important to note that these issues affect vertical PWRs as well, and to an even larger magnitude. VVER SG tubes have been plugged in almost an order of magnitude than that of vertical SG counterparts (Trunovet al.,) 2008.

1.3 Water chemistry in NPP steam generator

Water chemistry regime is the combination constructional and operational measures that are taken to provide optimum physical chemical characteristics of working fluid in all the parts of a steam-water channel. There are various avenues with which impurities are sent into condenser-feedwater channel:

- Makeup water after chemical water purification;
- Air inflow through clearances in vacuum region of the condenser duct;
- Leakages of cooling water through clearances in turbine condensers;
- Corrosion products of constructional materials of devices and pipelines of secondary circuit.
- Condensate of drainage tanks.

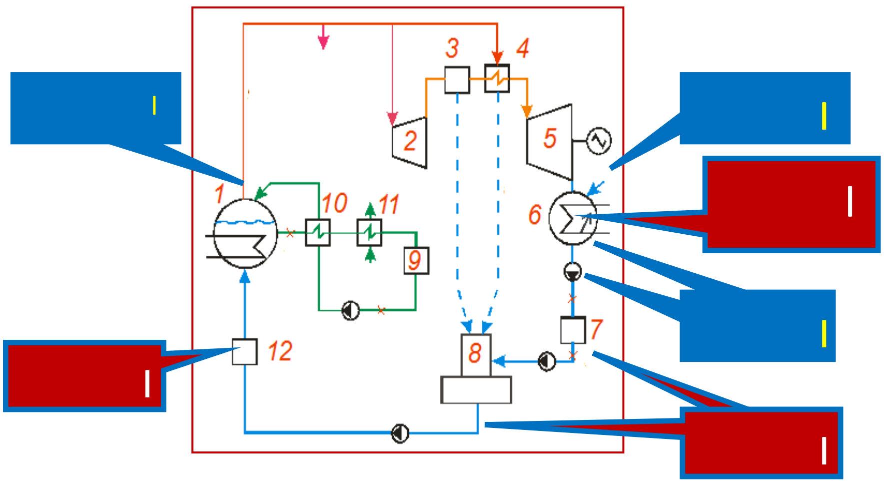


Figure 1.6 – Channels of impurities into SG

Where;

1 – steam generator;

2, 5 – turbine;

3, 4 – separator and steam superheater;

6 – condenser;

7, 12 – regenerative heaters:

7 – of low pressure;

12 – of high pressure

8 – deaerator;

9 – filters (ion-exchange);

10, 11 – cooler and aftercooler of blowdown

1.4 Deposits on heat-exchange tubes in WWER SGs

During heating seasons heat transfer characteristics of WWER SGs drop by 1…3%. Consequently, steam-generating efficiency of SGs and thermal output of the unit decreases. Main reason of the decline in SG's heat transfer characteristics is coverage of SG tube bundle on the secondary side with copper ferrum oxide deposits (Cu and Fe oxides). Total weight of deposits can reach 0.6…1.2t, from which Fe_2O_3 comprises 50…80%.

Operating practice has shown that 80-90% of ferrum compounds is carried over in the first high pressure feedwater heater in which feedwater is heated up to 160-190^{o}C. When water reaches the temperature of 160-190^{o}C, the speed of oxide film formation is lower than the speed of its destruction, which leads to ferrum compounds carryover from high pressure feedwater heater to SG. Furthermore, significant erosive processes take place in collector coil-type high pressure heaters, which results in increased deposits carryover in SG.

1.5 Corrosion problems affecting steam generator tubes in commercial water-cooled nuclear power plants (VVER NPP)

This type of steam generator is used in all of the Russian design VVER PWRs, including the 440 and 1000 MWe size units. The steam generators are horizontal units with horizontal U-bent tubes that attach to hot and cold vertical collectors (large pipes that are also called headers). The collector walls take the place of the tube sheet in vertical PWR and PHWR recirculating steam generators.

The tubing material in these units is titanium-stabilized austenitic stainless steel with the designation 08X18Nl0T and is similar to AISI Type 321 stainless steel.

The main corrosion problems that have affected the tubing in VVER steam generators are as follows (Miroslav and Stefan, 1994; Rucsak et al., 1998; Kadenko et al., 2003; Trunov et al., 2010; Yurmanov et al., 2010; Kukushkin, 2010; IAEA, 2007):

Figure 1.7 - Deposits on heat-exchange tubes in WWER SGs

- Pitting and SCC associated with deposit buildup on tubes as a result of corrosion product (Cu and Fe) ingress from the secondary system. The SCC often starts from the base of a corrosion pit.
- Pitting and SCC at support straps.
- The above pitting and SCC occur predominantly in the region near the hot collector (also known as the hot header) and is generally attributed to chlorides aggravated by oxidizing conditions associated with ingress of copper.

Limited general corrosion.

1.6 Deterioration of WWER SG tubes

Operating practice of WWER and PWR NPP SGs reveals that the main element that determines their actual lifetime is heat-exchange tubes. To eliminate the possibility of primary coolant leakage into the secondary circuit, all SGs undergo regular eddy current testing of heat-exchange tubes.

The testing results can be used for preventative tube plugging. All the cases of massive corrosive damage of heat exchange tubes refer to SGs that had been in long-term continuous operation without chemical washing and proper observance of water chemistry standards. In operating SG damages occur both in free regions and underneath the spacing grids of heat-exchange tubes. Metal graphic analysis of removed damaged tubes shows that the defects are mostly of pitting character or represent corrosive cracks developed under the deposit layer.

It has been stated that corrosive defects both in free regions and under spacing grids tend to develop primarily in the lower part of SG tube bundles. Defects in free regions are localized mostly near the hot collector. Defects under the spacing grids are located in most cases in the lower part of a SG but are more evenly distributed over the tube bundle length.

1.6.1 Factors that affect the speed of corrosion processes

- Structure and condition of metal surface
- Value and character of stresses in metal (tensile, compressive)
- Water composition
- Temperature
- Aggregate state of water and pressure
- Flow velocity of the medium
- Severity of radiation exposure

1.6.2 Calculation scheme of impurities balance in secondary circuit of WWER NPP

Considering the case when there is no condensate purification in SG, we can say:

$$q \cdot S_{охл} + \alpha_{д.в} \cdot S_{д.в} + (1+\alpha_{пп}) \cdot S_{п} + p \cdot S_{пг.оч} = (1+\alpha_{пп}) \cdot S_{п} + \alpha_{ут} \cdot S_{п} + p \cdot S_{пг} \tag{1.3}$$

In the case when there is 100 % condensate purification

$$q \cdot S_{к.оч} + \alpha_{д.в} \cdot S_{д.в} + (1+\alpha_{пп}) \cdot S_{п} + p \cdot S_{пг.оч} = (1+\alpha_{пп}) \cdot S_{п} + \alpha_{ут} \cdot S_{п} + p \cdot S_{пг} \tag{1.4}$$

- a – flow rate in relative units (in fractions of steam flow rate in turbine);
- *S* – concentration of impurities;
- p – flow rate for blowdown in relative units;
- q – leakage in condenser in relative units;

- «пп» – steam and superheater drainage;
- «п» – fresh steam;
- «ут», «дв» – leakage, makeup water;
- «к» – exhausted steam and main condensate;
- «ох.в» - cooling water in condenser;
- «пг», «пг.оч» - blowdown and purified water;
- «к.оч» - purified condensate

From mass of deposits on heat surface of once-through SGs, we can say:

$$\Omega^{отл}_{общ} = 3,6\cdot10^{-3}\, D\,\tau_{м.п.}\left(S^{общ}_{пв} - S^{общ}_{п}\right), \tag{1.5}$$

Where: **Ω** is cumulative quantity of deposits, kg;

D is steam production capacity of SG, kg/s;

τ is duration of inter-washing period, h;

$S_{пв}$, $S_{п}$ is content of impurities in feedwater and steam, mg/kg

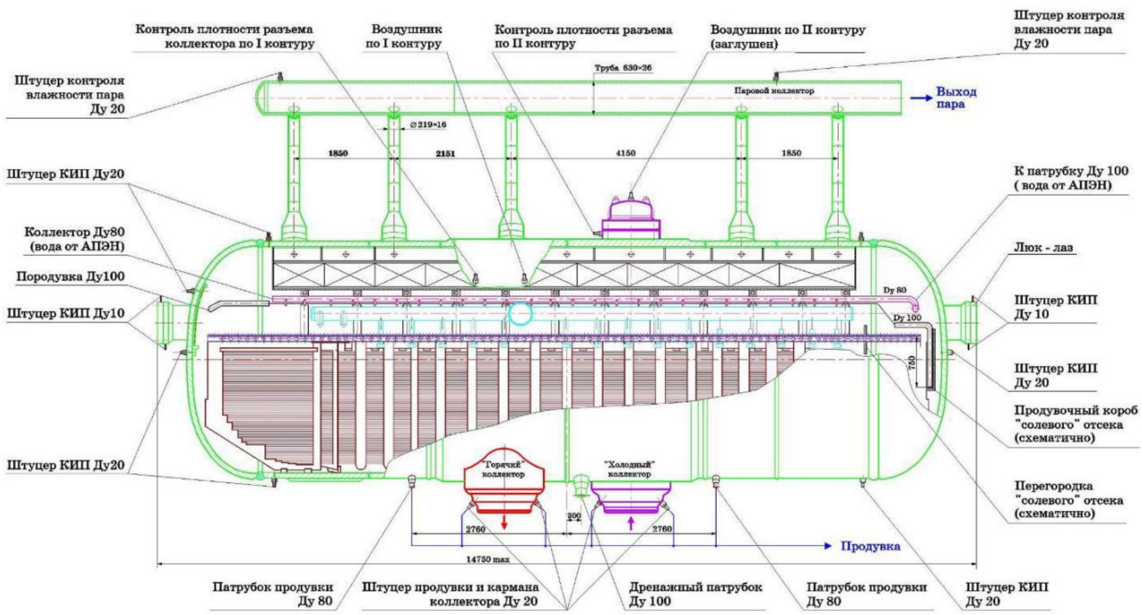


Figure 1.8 - Schematic diagram of blowdown water ejection from WWER SG

1.7 Nuclear steam generator tube inspection tools

The bulk of SG tube inspections are carried out using ET probes. Inspection systems consist of ET probes connected to digital, computer-controlled, multichannel, multifrequency instruments that are paired with probe-drive systems, probe manipulators, and mass data-storage units. Occasionally, additional techniques such as ultrasonic testing (UT) and profilometry probes are deployed for reinspection and characterization.

Chapter 2.0 – Steam generators inspection analysis

2.1 SG equipment technology

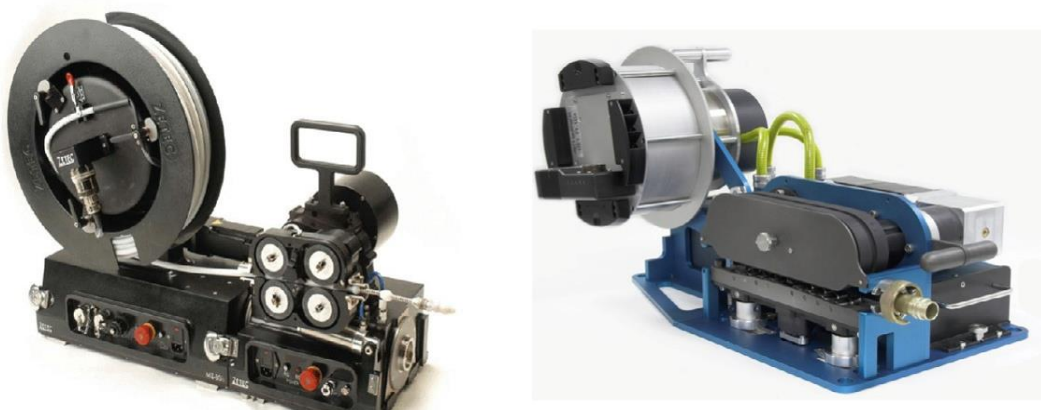
The majority of SG inspections are carried out with modern inspection systems having high degree of automation, integration, and versatility. These systems consist of light and compact parts that easily assemble into an integrated single-box system comprising probe pusher, coil reel, probe drive, power supply, electronics, and powerful ET instruments

These systems communicate with the acquisition computer via standard Ethernet connection. They require plant air supply for cooling and/or to assist in probe push operation, and electric power. Shows two examples of state-of-the-art Zetec MIZ-80iD system (Burnett et al., 2016) and Core Star OMNI-200-TIP (Core Star International Corp, n.d.). These ET instruments are fully digital, support simultaneous or multiplexed multifrequency operation, and use of multiple probes or array probes with channel capabilities of up to 512, 640, or 1024 channels, depending of the configuration.

Their high digitation rates permit inspection speeds as fast 40 in./s. The enhanced capabilities of current equipment address the need to continuously reduce inspection costs, shorten outage times, and improve inspection quality. Also, the increase automation aids in reducing levels of radiation exposure for the personnel involved in installing and operating probe manipulators and data acquisition equipment to comply with ALARA (as low as reasonably achievable) objectives.

However, it should be mentioned that, in some cases, SG inspections are still being conducted using legacy inspection systems. These systems consist of multiple heavy and awkward-to-carry individual components, i.e., ET instrument, probe drive and probe-drive controller, power supply, communication system, and manipulator controller. Typically, this equipment is transported into the reactor building by several people.

Communication with the computers that are located outside the reactor building requires a large number of cables and adapters, many of them a few hundred meters long. In these cases, inspection systems comprising multiple probe drives operating simultaneously are often used to reduce inspection time, which, in turn, multiplies the overall complexity, time, and dose needed for setup.



(A) (B)

Fig. 2.1 - Images of state-of-the-art integrated inspection systems. (A) Zetec MIZ-80iD (Burnett et al., 2016) and (B) CoreStar OMNI-200-TIP (CoreStar International Corp, n.d.).

2.1.1 Probe manipulators

Because of the high radiation fields inside a SG head, data acquisition systems rely on robotics to deliver the probes remotely. The manipulator technology has significantly evolved over the years. Early versions required substantial human intervention as the operator needed to enter the SG head to install and relocate them to cover areas where the manipulators could not reach, called exclusion zones. Also, other manipulators were sometimes needed to perform repairs. This resulted in a very high cost in terms of radiation exposure. The design of state-of-the-art probe manipulators have addressed many of these issues and, as a result, reduced considerably the radiation exposure of the personnel. They are denoted as minimum-entry or nonentry robots as they are typically installed without the need for the operators to enter the SG. However occasionally, the operators might need to introduce their arms inside the SG head.

Their design eliminates the need to relocate the robot within the generator in order to inspect all tubes and therefore, reduces inspection time. This generation of robots, when coupled with advanced software and hardware, can perform inspections in fully automatic mode.

They use vision systems to accurately locate the tubes, ET data to determine probe position and tube end, encoders and information from the robot to go from tube to tube following the inspection plan without the intervention of the operator. Shows pictures of the Westinghouse ROSA III and AREVA Non-Exclusion Zone RANGER (Westinghouse Nuclear Services, 2016; Wilson,2011) and BWXT PRIMA 3 Axis Robotic Arm (for inspection of CANDU1 SGs). Moreover, the robust designs of these robots allow them to perform ET inspections.

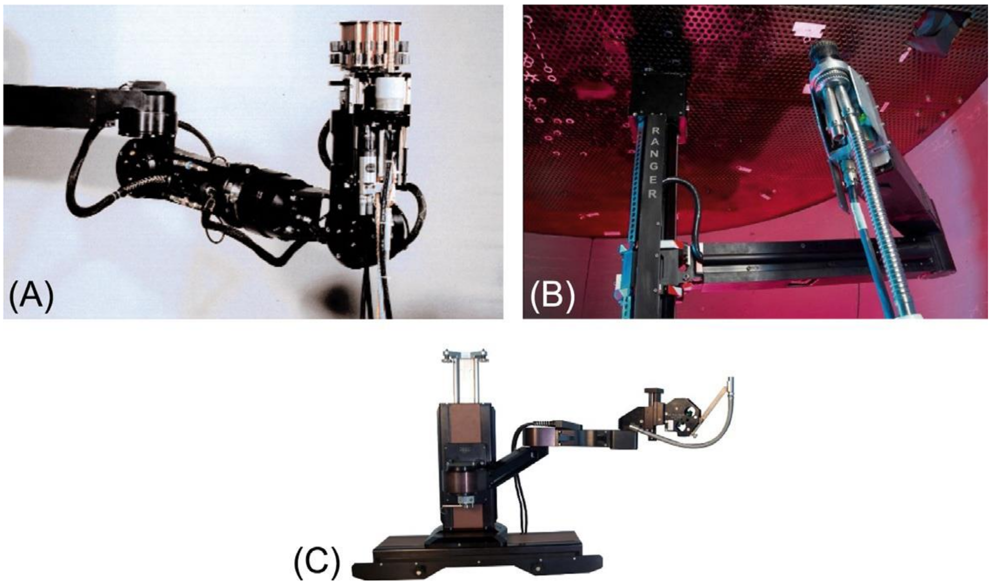


Figure 2.2 - Examples of nonentry manipulators (A) Westinghouse ROSA III (Westinghouse Nuclear Services, 2016), (B) AREVA Non-Exclusion Zone RANGER (Wilson, 2011), and (C) BWXT PRIMA 3.

As well as the follow-up maintenance and repairs such as tube pulling, plugging, or welding of sleeves with rapid changes of the tool head, minimizing radiation exposure, and total time needed for SG maintenance activities. A newer generation of nonentry, non-exclusion zone robots are lightweight crawlers such as Westinghouse PEGASYS and Zetec ZR-100.

These robots are designed to be mounted on the tube sheet and to navigate it using tube-walking technology. They are lighter and easier to assemble than the previous models, but they can only perform light repairs and consequently are optimal for inspection of replacement SGs that should require very little or no repairs.

Specifically, designed versions of older manipulators such as the Zetec SM-23 and ZR-1 are still being used frequently to inspect the CANDU SGs. These smaller SGs require specifically designed robots.

The SM-23 mounts on the man-way and is typically dedicated to perform the ET inspections only. It has a computer interface that allows remote semiautomatic operation using specific software. A video camera located on the arm assembly allows the operator to continuously view the guide tube and tube sheet on the remote station monitor and aid in the final tuning of the guide-tube location before inserting the probe in the tube (Zetec Products Alphabetical Listing, 2007).

2.1.2 Probe technology

Bobbin probes have been the industry standard for general inspection of SG and heat exchanger tubes for many years. They are quite reliable and provide good general-purpose inspection of the tubes, being able to reliably detect and size volumetric flaws such as fretting wear and pitting corrosion. With the new instrumentation their typical scanning speed is up to about 40 in./s.

However, one of the major limitations of bobbin probes is their inability to detect circumferentially oriented cracks because the induced current in the tube wall circulates parallel to the coil windings and is inherently unaffected by the presence of

such cracks. Illustrates the limitation of the probe for detecting circumferential cracks. These probes are sensitive to axial cracks at straight tube sections; however, at TTS and the U-bend transition regions, the large signals generated by geometrical tube-wall distortions significantly reduce detectability (Cecco et al., 1981; Cecco and Van Drunen, 1985; Sullivan et al., 1998). Reliable detection of SCC and further characterization of flaws often requires the use of additional inspection probes. Motorized rotating pancake coil (MRPC) probe and Plus Point probes are widely used as either reinspection probes or to inspect crack-prone regions such as the TTS.

These surface-riding probes are connected to motor units that rotate the probe inside the tube in a helical pattern. They overcome the limitations of bobbin probes since they can detect both axial and circumferential cracks and can also provide information about flaw morphology. Illustrates the distortion to the ET pattern generated by a pancake coil in the presence of a circumferential crack. It is this distortion of the magnetic field that gives the ability to detect circumferential cracks. The Plus Point probe comprises two orthogonal coils connected in differential mode crossing at a point so that they are affected simultaneously by material and geometric distortions such as lift-off. This probe has the ability to detect circumferentially and axially oriented cracks as well as discriminate between them. The figure below illustrates the coil configuration of a Plus Point probe.

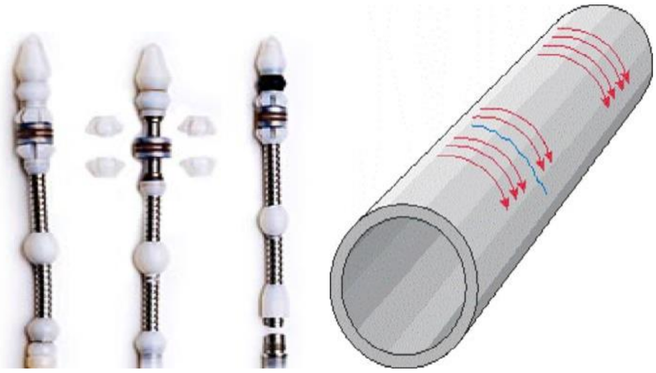


Figure 2.3 - Bobbin probes (A) view of typical bobbin probes for SG tubing inspection and(B) illustration of ET pattern generated by bobbin probes, demonstrating the limitations for detection of circumferential cracks.

Figure 2.4 - X-probe for axial and circumferential crack detection (A) view of an X-Probe for 22.3 mm diameter tubing and (B) view of an X-Probe for 12.9 mm diameter tight-radius U-bend tubing.

In many cases rotating probe heads might incorporate both pancake and Plus Point probes. The main limitation of rotating probes is, however, their speed. In spite of the use of high speed and high torque motors, rotating probes scanning speed is _80 times slower than that of bobbin probes. Also, these probes are usually spring loaded to minimize lift-off, which makes them prone to failure. This is especially evident in

CANDU reactors where the presence of internal magnetite deposits reduces probe life significantly, and the small diameter of the motors make them more fragile. For that reason, the time required for inspections and thus the cost is significantly higher for stations that are required to inspect a large number of tubes with the plus point probe to address detection of SCC.

Transmit/receive (T/R) array probes were developed in the 1990s, to address specific inspection needs of CANDU SG tubes. These probes take advantage of the superior properties of T/R technology compared to impedance probe technology. They offer a fivefold to tenfold improvement in signal-to-noise ratio, in the presence of lift-off caused by geometrical tube distortions such as U-bend deformations or the tube sheet transition.

The array feature makes it unnecessary to have moving parts, which leads to increased probe reliability (Sullivan et al., 1998). Since T/R probes have directional properties, being sensitive primarily to defects in-line with the T/R coil pairs, the probe design can be optimized to maximize response for different crack orientations (Obrutsky et al., 2001). The X-Probe2 is a fast single-pass T/R array probe that is currently used world-wide for inspection of SG tubing as a fast alternative to rotating probes. It combines coil pairs aligned for circumferential flaw detection and for axial flaw detection in a single probe-head as shown in the number of coils in each row varies from 8 to 19 depending on the tube diameter. Electronic circuits at the probe head allow the coilpairs to discriminate between axial, circumferential, and volumetric flaws in a single.

Figure 2.4 - View of the Mitsubishi Intelligent probe (EPRI, 2007). scan.

The X-Probe has shown performance equivalent to rotating probes but can run full-length inspections at scanning speeds up to 40 in./s (Davis, 2005). A special design of this probe, shown in Fig. 16.5B, can negotiate tight radius U-bends. When, combined with a bobbin probe, inspection times can decrease significantly, since the need to revisit the tubes with different probes is virtually eliminated (Obrutsky et al., 2001; Davis, 2005).

There are also various versions of T/R array probes becoming available in the market based on similar coil arrangements to that of the X-Probe. Examples of these new probes are the Tecnatom T probe (Ribes et al., 2014) and the Eddyfi DefHi3 probe (Renaud, 2014). Another array probe available in the market is the Mitsubishi Intelligent probe shown in Fig. 16.6. This is also a high-speed, high-performance alternative to rotating probe inspections. The Intelligent Probe combines bobbin and array coil technologies to detect all flaw types in a single pass.

The non-surface riding probe design is durable, reliable and allows fast pull speeds. This probe technology combines an inclined drive coil arrangement and thin film pickup coils with traditional bobbin capabilities into one probe. By design, the probe coils are sensitive to all flaw types and provide characterization of indications. Each probe has a build-in electronic preamplifier circuit that optimizes the signal-to-noise ratio and EMI (electromagnetic interference) shielding (ZetecProducts Alphabetical Listing, 2007).

Probe technology and the ET instruments progressed hand-in-hand. The availability of multiple inputs, large number of channels, fast acquisition rates, simultaneous or timeslot multiplexing, and greater bandwidths makes it possible to operate these array probes at high acquisition speeds similar to bobbin probes. Although the initial goal of probe development was to address the need for reliable detection of SCC, the current probe technology not only fulfills that goal but also widens the scope of ET inspections.

Current probe technology, in combination with advanced software and hardware, has the ability to characterize flaw types and their morphologies. This information is often used in tube-integrity assessments and root-cause analysis to help identifying degradation mechanisms. UT probes and inspection systems are occasionally used as reinspection tools. Given the slower scanning speed, scope of inspections is typically limited to a reduced number of tubes and only at the area of interest. The superior sensitivity and sizing accuracy of UT (quoted to be _3% TW for normal beam) makes it an excellent tool to obtain accurate information about flaw sizes and flaw characterization. It is also often used to detect flaws that are below ET detection to obtain ET "misses" in support of probability of detection (POD) studies (Chen et al., 2008).[3]

2.1.3 VVER SGs with stabilized stainless-steel tubes

This type of steam generator is used in all of the Russian design VVER PWRs, including the 440 and 1000 MWe size units. The steam generators are horizontal units with horizontal U-bent tubes that attach to hot and cold vertical collectors (large pipes that are also called headers). The general arrangement is shown in. The collector walls take the place of the tube sheet in vertical PWR and PHWR recirculating steam generators. The tubing material in these units is titanium-stabilized austenitic stainless steel with the designation 08X18Nl0T and is similar to AISI Type 321 stainless steel.

The main corrosion problems that have affected the tubing in VVER steam generators are as follows (Miroslav and Stefan, 1994; Rucsak et al., 1998; Kadenko et al., 2003; Trunov et al., 2010; Yurmanov et al., 2010; Kukushkin, 2010; IAEA, 2007):

- Pitting and SCC associated with deposit buildup on tubes as a result of corrosion product (Cu and Fe) ingress from the secondary system. The SCC often starts from the base of a corrosion pit.
- Pitting and SCC at support straps.
- The above pitting and SCC occur predominantly in the region near the hot collector (also known as the hot header) and is generally attributed to chlorides aggravated by oxidizing conditions associated with ingress of copper.
- Limited general corrosion.

2.1.4 Denting

The term "denting" is used to describe the situation where expansion of carbon steel corrosion products on the outside of a tube results in inward deformation of the tube. This type of denting occurs most readily if the hole in the tube support plate is a round drilled hole. However, denting has also occurred at broached hole supports and at lattice bar and flat plate supports.

2.1.5 Locations where denting has occurred

Locations where denting has occurred include:

- Drilled hole carbon steel tube support plates
- At the top of carbon or low alloy steel tube sheets in steam generators with part depth rolled tubes, i.e., where there are deep tube sheet crevices, and also in some steam generators with full depth expanded tubes
- At carbon steel lattice bar, scallop bar, and flat bar supports
- At carbon steel broached hole tube supports
- In sludge piles at the top of the tube sheet where carbon steel foreign material such as shot used for blasting has collected and corroded

2.1.6 Types of steam generators affected by denting

The steam generators that have been most severely affected by denting are those with Alloy 600MA tubes. This is not a result of the tube material but rather the result of using carbon steel supports in these steam generators and the types of water chemistry used in these plants. There have been lesser amounts of denting in plants with 600TT, 800NG, and 690TT tubing. This is a result of the use of stainless-steel supports in these units, together with improved water chemistry in the plants with these types of steam generators.

2.1.7 Materials and design features required for denting to occur

The essential features required for denting of a tube to occur include:

- A readily corrodible material such as carbon or low alloy steel in close proximity to the tube

– A crevice between the tube and the corrodible material in which impurities can concentrate and lead to aggressive conditions fostering corrosion of the carbon or low alloy steel

– Sufficient heat flux to cause boiling and concentration of chemicals in the crevice

– Water chemistry conditions conducive to the concentration of impurities to aggressive levels in occluded areas of the steam generators coupled with the presence of oxidants such as copper oxide. These adverse chemistry conditions were most commonly the result of condenser leaks at plants with salty cooling water, but also occurred in a few freshwater-cooled plants, e.g., as the result of ingress of condensate polisher resins

The most effective ways to prevent or minimize denting are to (1) use design features that minimize susceptibility, e.g., use stainless steel supports and design features that minimize crevices at the OD of tubes, such as lattice bar supports; (2) control of water chemistry conditions to minimize factors that aggravate denting, such as minimizing ingress of chlorides, copper, and resin particles; and (3) ensuring that reducing conditions are achieved early during start-ups. In addition, it is necessary to ensure that foreign materials such as iron shot from blasting operations are not allowed to enter the steam generators.

2.1.8 Consequences of denting and likelihood of future occurrence

The main consequences of denting are:

– The strains and stresses developed in the tube at the dents increase the likelihood of SCC occurring from both the primary and secondary sides of the tubes.

– The deformation can interfere with inspection of the tube and require it to be plugged for that reason. As noted earlier, steam generators with 600TT, 800NG, and 690TT tubes have experienced less denting than units with 600MA tubes.

The lower amount of denting, together with the increased resistance to cracking of these alloys, has resulted in there being relatively little or no denting caused SCC, and it is expected that this relative freedom from denting-induced SCC will continue in the future. However, since the tube sheet is low alloy steel, denting can and has occurred in these types of steam generators as a result of corrosion at the top of the tube sheet crevice between the tube and tube sheet. In addition, denting could occur if iron foreign material is introduced into the steam generators and collects in the sludge piles on the tube sheet, e.g., as the result of blasting elsewhere in the secondary system. Thus, ensuring that denting does not occur requires good control of water chemistry conditions and effective foreign material exclusion practices.

2.1.9 Pitting in vertical PWR steam generators

The most seriously affected PWRs with vertical steam generators were Indian Point 3, Millstone 2, and Kori 1, all of which had 600MA tubing and salty cooling water (EPRI, 1994; Hwang et al., 2003). The pitting affected both the hot and cold legs but generally was worse on the cold leg. The pitting was attributed to development of sludge piles on the tube-sheets coupled with ingress of aggressive chlorides and sulfur species and also with the ingress of oxidants such as copper oxides. Susceptibility to this type of pitting has been resolved by:

- Significant upgrades to plant secondary systems to minimize ingress of corrosion products, aggressive anions, and oxidants
- Use of mechanical and chemical cleanings to remove accumulated deposits
- Replacement of steam generators

It is judged that pitting is unlikely to seriously affect any of the currently operating vertical PWR steam generators, assuming that current stringent water chemistry practices are maintained. In this regard, it should be understood that all of the tubing alloys, including 600MA, 600TT, 600SR, 690TT, 800NG, and stabilized stainless steel are susceptible to pitting if aggressive conditions are allowed to develop on the secondary side as the result of ingress of corrosion products, aggressive anions, and oxidants.

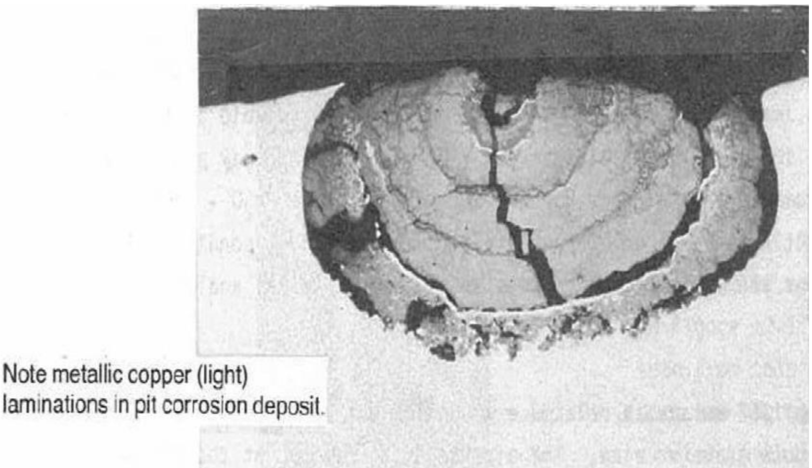


Figure 2.5 - Photomicrograph of pit from Indian Point 3 (EPRI, 1997)

2.1.10 Pitting in horizontal VVER steam generators

Early VVERs experienced significant amounts of pitting on the secondary side of the stabilized stainless-steel tubing used in these units. This pitting sometimes led to development of stress corrosion cracks emanating from the base of the pits (Trunov et al., 2010).

This mode of attack was generally most severe near the hot collector. The pitting was attributed to development of deposits and sludge piles on the horizontal tubes, coupled with ingress of aggressive chlorides and sulfur species and also the ingress of oxidants such as copper oxides. Susceptibility to this type of pitting has been largely resolved by:

– Significant upgrades to plant secondary systems to minimize ingress of corrosion products, aggressive anions, and oxidants

– Use of mechanical and chemical cleanings to remove accumulated deposits

– Replacement of steam generators at some plants.

The above measures are reported to have brought the pitting and associated SCC situation under control such that they are unlikely to limit the lifetime of the steam generators. However, these modes of degradation remain active at low levels and require that current water chemistry, maintenance, and inspection practices be maintained at effective levels.

2.2 Horizontal steam generators with stabilized stainless-steel tubing

IGA/SCC is reported to have initiated from pits in many VVER steam generators and to have affected enough tubes at a few plants to lead to steam generator replacement (Trunov et al., 2010). An example of pitting and associated IGA/SCC. This pitting and IGA/SCC have primarily occurred close to the hot collector and is reported to have occurred under heavy sludge deposits and at supports. Improved water chemistry controls coupled with periodic chemical and mechanical cleaning of the tubes is reported to have resulted in this problem currently affecting only small numbers of tubes and to not be a life limiting problem although continued attention to water chemistry and control of deposits is required.

2.3 Causes of secondary side IGA/SCC and methods to minimize its occurrence

The main cause of secondary side IGA/SCC is, with one exception, considered to be the accumulation of aggressive species to high concentrations in occluded areas as a result of boiling in the occluded areas. (The one exception to this rule seems to be that of cracks developed in Alloy 600MA tubes in cold legs of preheat units at lines of severe abrasion, where the cracking appears to have occurred in non-concentrated secondary coolant.) While there is general agreement that secondary side IGA/SCC is

Figure 2.6 - Pitting and associated IGA/SCC in a VVER steam generator tube (IAEA, 2007).

Mainly caused by the accumulation of aggressive species in occluded areas, there is uncertainty regarding what specific species are involved and regarding what other factors such as pH, ionic strength, or ECP are involved. In a few cases, the causes of secondary side IGA/SCC have been firmly identified, such as cases associated with ingress of large amounts of lead.

However, for the most part, and despite many years of extensive research, firm conclusions have not been reached regarding the specific chemical species that have been involved in the IGA/SCC that has affected Alloy 600MA tubing. Despite there being uncertainty regarding the chemical species involved in the secondary side IGA/SCC of 600MA tubing, some useful general observations have been developed regarding how to minimize its occurrence, as follows:

– Observation of strict limits on water chemistry during power operation and shutdown/start-up periods have successfully limited the rate of occurrence of secondary side IGA/ SCC although they have not prevented continuing slow rates of occurrence. These limits include limits on ingress of species such as chlorides, sulfur species and sodium, and also limits on the ingress of oxidants such as oxygen and copper oxides.

– It has been found necessary to ensure that reducing conditions are maintained in steam generators when temperatures are over about 120°C. During power operation this is generally accomplished by addition of oxygen scavengers to the feedwater. During and following layup periods steps are taken to minimize the oxidation of species such as copper that could raise the potential during subsequent power operation (again using oxygen scavengers) and to reduce any oxides that did develop during the outage during the return to power phase of the start-up.

– Minimizing ingress of lead into steam generators is essential and requires strict observance of foreign material exclusion practices and minimizing the concentration of lead in materials used in components where wear or corrosion could result in the ingress of lead into the steam generators.

– Minimizing the presence of occluded areas where concentration of impurities can occur is important. This involves use of design features such as lattice bar supports that minimize built-in crevices and minimizing ingress and accumulation of deposits in the steam generator that can result in development of occluded areas.[4]

2.4 VVER SG components

Steam generator PGV-1000MKP with supports comprises the following components: steam generator, steam header, supports, shock absorbers, one- and two-chamber surge tanks, embedded components for supports and shock absorbers. The steam generator itself is a single-vessel heat exchange apparatus of horizontal type with submerged heat-transfer surface and comprises the following components:

- a vessel with different-purpose nozzles;
- a heat-exchange bundle with fastener and spacer components;
- primary coolant collectors;
- feedwater supply and distribution systems;
- emergency feedwater supply and distribution systems;
- distribution perforated plate;
- submerged perforated plate;
- chemicals feeder.

The application of the horizontal type steam generators makes it possible to reduce the height of the building, thus improving its seismic resistance.SG vessel is a 13820 mm long welded cylindrical vessel with a 4200 mm internal diameter. Elliptic bottoms are welded to its both edges. The SG vessel houses the primary collectors, heat-transfer surface and the internals. The vessel is made of 10GN2MFA steel. The primary coolant collector is a thick-walled cylinder of variable diameter and thickness.

The total height (without the cover and displacer) is 5100 mm, the maximum diameter is 1176 mm at wall thickness 171 mm. The collector is made of electroslag remelting 10GN2MFA steel. The internal surface has protective corrosion-resistant cladding. There are 10978 holes of 16.25 mm nominal diameter in the central cylindrical part of the collector. The holes are

positioned in a staggered order: the vertical pitch of the holes is 44 mm and the horizontal pitch of the holes is 30.8mm (on the external surface).

The joint in the top part of the collector connects to 500 collector flange with threaded seats and a flat cover with a displacer. 20 joint studs of M60 type are made of steel 38KhN3MFA and the nuts are made of steel 25Kh1MF.There are two pipe sleeves on the reducing ring for continuous and periodic blow down out of the collector pockets and for flushing device installation and one D nom 30 pipe sleeve to attach flushing devices.

The pipe sleeves for continuous and periodic blow down out of the collector pockets and for flushing device installation are provided with detachable flange joints that are sealed with expanded graphite gaskets and fixed with six bolts. The D nom 30 pipe sleeve to attach the flushing device is also provided with a detachable flange joint that is sealed with expanded graphite gaskets and fixed with six bolts, too.

The heat-transfer surface consists of 10978 tubes 16x1.5 mm (08Kh18N10T U steel). The heat-exchange tubes are U-coils, assembled into a heat-exchange tube bundle. The tubes in the bundle are placed in a staggered order: the vertical pitch is 22 mm and the horizontal pitch is 24 mm. The coils are slanting towards the collectors (20 mm on the coil length) to provide a possibility for complete drain of the tubes. The tubes are fixed in the collectors by welding the edges over with the internal surface of the collector (the penetration depth is not less than 1.4 mm). The tubes are hydraulically expanded with additional mechanical expansion on the outside surface until the gap (slot) is completely closed. The tubes are spaced with bent and flat plates that provide a regular corridor tube positioning in the heat exchange bundle. The sub-slime corrosion in the gap between the tube and the spacers is prevented due to the venting slots in the plates that are designed to avoid the gap stagnation.[5]

2.5 Calculation for steam generators of capacity 150 kg / s.

The calculation is used to find the heat transfer coefficient, heat flux density, heat transfer coefficient and heat transfer surface area of steam generator modules for economizer and evaporator. The area of heat transfer surface and the entire steam generator, the length of its pipes is also determined.

Using following steel grades:

- For pipes of heat transfer surface - 12X18H10T;
- For the coolant collector - 10GN2MFA, clad on the side washed by the coolant, steel 12X18H10T;
- For case elements - 10ГН2МФА.

Calculation of wall thickness of heat transfer pipe

Wall thickness of heat transfer surface, mm:

$$\delta_p = \frac{P_{1p} \cdot d_H}{2 \cdot \phi \cdot [\sigma] + P_{1p}} + C; \qquad (2.1)$$

Calculated coolant pressure:

$$P_{1P} = 0,9 \cdot 1,25 \cdot P_1 = 0,9 \cdot 1,25 \cdot 15 = 16,9 \text{ МПа}. \qquad (2.2)$$

We translate the calculated pressure of the coolant to other units of measurement:

$$P_{1P} = 16,9 \cdot 0,102 = 1,72 \text{ кгс/мм}^2. \qquad (2.3)$$

The calculated temperature of the pipe wall in the inlet section in the first approximation can be calculated by the formula:

$$t'_{CT.P} = 0,5 \cdot (t'_1 + t_{S2}) = 0,5 \cdot (320 + 270) = 295\ °C \qquad (2.4)$$

For steel 12X18H10T we take, rated allowable voltage

$\left[\sigma_H\right]=12$ кгс/мм$^2 \approx 118$ МПа. Since the heat exchange surface tubes are stainless, the strength factor.

Then:

$$\delta_p - C = \frac{1,72 \cdot 16}{2 \cdot 1 \cdot 12 + 1,72} = 1,071. \tag{2.5}$$

The value of C is defined as: $C = C_1 + C_2 + C_3 + C_4$. Thickness increase at minus tolerance:

$$C_1 = 0,11 \cdot \left(\delta_p - C\right) = 0,11 \cdot 1,071 = 0,118 \text{ мм} \tag{2.6}$$

The increase in thickness for thinning due to corrosion is accepted. $C_2 = 0$The required thickening δ_P for technological, installation and other reasons, designing or manufacturing enterprises accept. $C_3 = 0$. The wall thinning in the place of bends will be determined by the following formula, while we assume that the pipe i $a = 12\%$and the wall thickness in the first approximation we take:

$$C_4 = \left[\frac{1,5\left(\dfrac{a}{100} - \dfrac{\delta_p}{d_н}\right)}{1,5\dfrac{a}{100} + \dfrac{\delta_p}{d_н}}\right]\delta_p = \left[\frac{1,5\left(\dfrac{12}{100} - \dfrac{1,4}{16}\right)}{1,5\dfrac{12}{100} + \dfrac{1,4}{16}}\right] \cdot 1,4 = 0,205; \tag{2.7}$$

Thus, the total increase to will be determined from the relationship:

$$\begin{gathered} C = C_1 + C_2 + C_3 + C_4 = 0,118 + 0 + 0 + 0,205 = 0,32 \text{ мм}; \\ \delta_p = 1,07 + 0,32 = 1,39 \text{ мм}. \end{gathered} \tag{2.8}$$

From the standard series, we take the nearest greater value of the tube thickness of the heat exchange surface. $\delta_p = 1,4$ мм.

Internal diameter of pipes:

$$d_B = d_H - 2 \cdot \delta = 16 - 2 \cdot 1,4 = 13,2 \text{ мм}. \tag{2.9}$$

The area of the living section of the pipe can be defined by:

$$f_{TP} = \frac{\pi \cdot d_B^2}{4} = \frac{\pi \cdot 0,0132^2}{4} = 1,368 \cdot 10^{-4}\ \text{м}^2. \quad (2.10)$$

2.6 The number of heat transfer surface in SG pipes

The range variation of velocity heat pump in the tubes of heat transfer surface is 3/5, m/s. Take the speed of coolant at entrance to the tube $\omega_{1BX} = 3$ м/с. The average density of the coolant at the inlet tube:

$$\overline{\rho} = \text{f}(t'_{TH}, P_1) = 725,55\ \text{кг/м}^3. \quad (2.11)$$

From the continuity equation, we determine the number of pipes of the heat transfer surface:

$$F \cdot \omega_{1BX} = \frac{G}{\overline{\rho}}; \quad (2.12)$$

Where:

$$F = n_{TP} \cdot \frac{\pi \cdot d_{BH}^2}{4} - \quad (2.13)$$

area of the living section of all tubes SG, m^2; $d_{BH} = 0,0132$ - inner tube diameter, m;

$G = 1283,56 -$ coolant consumption, kg / s

Then the number of tubes:

$$n_{TP} = \frac{4 \cdot G}{\omega_{1BX} \cdot \overline{\rho} \cdot \pi \cdot d_{BH}^2} = \frac{4 \cdot 1283,56}{3 \cdot 725,55 \cdot \pi \cdot (0,0132)^2} = 4309,1 \approx 4309\ \text{шт}. \quad (2.14)$$

2.6.1 Calculating the heat-transfer surface area of evaporator in SG section

Initial data:

$$Q_{EV} = 235,2\,\text{МВт};\ t'_{1EV} = t'_1 = 320\ °C;\ t''_{1EV} = 280\ °C;\ t'_{2EV} = t''_{2EV} = t_{S2} = 270\ °C. \quad (2.15)$$

The area of heat transfer surface is calculated by the formula:

$$S_{EV} = \frac{Q_{EV}}{\overline{k_{EV}} \cdot \overline{\Delta t_{EV}}}; \quad (2.16)$$

Where; $\overline{\Delta t_{EV}}$ – average temperature pressure in the evaporation area;

$\overline{k_{И}}$ – average heat transfer coefficient in the evaporation area.

$$\overline{\Delta t_{EV}} = \frac{(t'_{1И} - t''_{2И}) - (t''_{1И} - t'_{2И})}{Ln\left[\frac{(t'_{1И} - t''_{2И})}{(t''_{1И} - t'_{2И})}\right]} = \frac{(320-270)-(280-270)}{Ln\left[\frac{(320-270)}{(280-270)}\right]} = 24,89\ °C. \quad (2.17)$$

So how is the attitude

$$\frac{d_н}{d_в} = 1,21 \le 2, \quad (2.18)$$

then the coefficient of heat calculated by the formula.

$$k = \left[\frac{1}{\alpha_1} + \frac{\delta_{ст}}{\lambda_{ст}} + 2 \cdot R_{ок} + \frac{1}{\alpha_2}\right]^{-1} \quad (2.19)$$

Since the material of the heating surface tubes is austenitic stainless steel, grade 12X18H10T, the thermal resistance is oxides.

Heat transfer coefficient from the heat carrier to the wall:

$$\alpha_1 = 0,021 \cdot \frac{\lambda}{d} \cdot \mathrm{Re}^{0.8} \cdot \mathrm{Pr}^{0.43} \cdot C_t \cdot C_l \quad (2.20)$$

where the correction factors C_t and C_l in the calculation can be taken equal to one. For the accuracy in calculation, the heat transfer at the evaporator will be considered for the inlet and outlet sections (for TH), i.e. We consider the heat transfer coefficient in the inlet section of the evaporator ($k_{ВХ}$) and in the output ($k_{ВЫХ}$).The coefficients $k_{ВХ}, k_{ВЫХ}$ should differ by no more than 25%. Otherwise, it will be necessary to split the evaporator section of steam generator in half and count the heat transfer coefficients for the three sections of the inlet, outlet and middle. $d_Г = d_В$. The coolant moves inside the tubes, so the hydraulic diameter is equal to the inner diameter of the heating surface tube.

Calculate the velocity of coolant at the inlet and outlet of tube:

$$\omega_{1ВХ} = \frac{G}{\rho_{1ВХ} \cdot n_{тр} \cdot f_{тр}} = \frac{1283,56}{678,76 \cdot 4309 \cdot 1,368 \cdot 10^{-4}} = 3,2 \text{ м/с};$$
$$\omega_{1ВЫХ} = \frac{G}{\rho_{1ВЫХ} \cdot n_{тр} \cdot f_{тр}} = \frac{1283,56}{763,57 \cdot 4309 \cdot 1,368 \cdot 10^{-4}} = 2,85 \text{ м/с}, \quad (2.21)$$

Where:

$$\rho_{1ВХ} = f(\mathrm{P}_1; \mathrm{t'}_1) = 678,76 \text{ кг/м}^3 \quad (2.22)$$

- density TH at the entrance to the tube of the evaporator;

$\rho_{1ВЫХ} = f(\mathrm{P}_1; \mathrm{t''}_{1И}) = 763,57 \text{ кг/м}^3$ - the density of the heat pump at the outlet of the evaporator tubes. Determine the Reynolds number for the input and output sections:

$$\mathrm{Re}_{ВХ} = \frac{\omega_{1вх} \cdot d_Г}{\nu_{1ВХ}} = \frac{3,2 \cdot 13,2 \cdot 10^{-3}}{1,18 \cdot 10^{-7}} = 3,58 \cdot 10^5;$$
$$\mathrm{Re}_{ВЫХ} = \frac{\omega_{1вых} \cdot d_Г}{\nu_{1ВЫХ}} = \frac{2,85 \cdot 13,2 \cdot 10^{-3}}{1,26 \cdot 10^{-7}} = 2,98 \cdot 10^5, \quad (2.23)$$

Where;

$$\nu_{1ВХ} = f(\mathrm{P}_1; \mathrm{t'}_1) = 1,18 \cdot 10^{-7} \text{ м}^2/\text{с} \quad (2.24)$$

- Kinematic viscosity at the inlet area;

$$\nu_{1ВЫХ} = f(\mathrm{P}_1; \mathrm{t''}_{1И}) = 1,26 \cdot 10^{-7} \text{ м}^2/\text{с} \quad (2.25)$$

- kinematic viscosity at the exit section. Heat transfer coefficients and Prandtl criteria:

$$\lambda_{1ВХ}(P_1, t'_{1И}) = 0,517\ \frac{\text{Вт}}{\text{м}\cdot\text{к}}; \quad \lambda_{1ВЫХ}(P_1, t''_{1И}) = 0,592\ \frac{\text{Вт}}{\text{м}\cdot\text{к}};$$
$$\Pr_{ВХ}(P_1, t'_{1И}) = 0,959; \qquad \Pr_{ВЫХ}(P_1, t''_{1И}) = 0,827. \tag{2.26}$$

We find; $\alpha_{1ВХ}$ and $\alpha_{1ВЫХ}$

$$\alpha_{1ВХ} = 0,021\cdot\frac{0,517}{13,2\cdot 10^{-3}}\cdot\left(3,58\cdot 10^5\right)^{0.8}\cdot 0,959^{0.43}\cdot 1\cdot 1 = 22434,25\ \text{Вт/м}^2\cdot\text{К};$$
$$\alpha_{1ВЫХ} = 0,021\cdot\frac{0,592}{13,2\cdot 10^{-3}}\cdot\left(2,98\cdot 10^5\right)^{0.8}\cdot 0,827^{0.43}\cdot 1\cdot 1 = 20807,76\ \text{Вт/м}^2\cdot\text{К}. \tag{2.27}$$

Heat transfer from the wall to working fluid in evaporator SG occurs under boiling conditions in a large volume. The following formula is calculating in the heat transfer coefficient of working fluid ($\alpha_{2ВХ}$).

We define the $\alpha_{2ВХ}$ formula CKTI:

$$\alpha_{2ВХ} = \frac{10,45}{3,3 - 0,0113\cdot\left(T_s - 373\right)}\cdot q^{0.7}, \tag{2.28}$$

Where:

q – is the heat flux density, W / m^2;

T_S – saturation temperature of working environment, 0^{C}.

This equation is solved by the method of successive iterations. Approximately, determined by the value calculated value $q = q'$, then determined α'_2, k'_2. If the condition is met $q'' = k'\cdot\Delta t$, the calculation ends. If the condition is not met $0,95 \le \frac{q'}{q''} \le 1,05$, the calculation continues and is accepted as q the new value q''. For the first iteration q', the value can be taken equal to:

$$q' = \left(0,7 \div 0,8\right) \cdot \Delta t \cdot \left(\frac{1}{\alpha_1} + \frac{\delta_{cm}}{\lambda_{cm}} + 2R_{o\kappa} \right)^{-1}, \tag{2.29}$$

λ_{CT} – Thermal conductivity coefficient, determined by wall temperature;

Δt – Temperature pressure in the corresponding section of the evaporator, 0C.

The wall temperatures in the inlet and outlet sections of the evaporating section can be taken equal to:

$$t_{CT}^{BX} = t_s + 0,3 \cdot \left(t'_{1И} - t_s\right) = 270 + 0,3 \cdot \left(320 - 270\right) = 285\ °C;$$
$$t_{CT}^{ВЫХ} = t_s + 0,3 \cdot \left(t''_{1И} - t_s\right) = 270 + 0,3 \cdot \left(286,1 - 270\right) = 274,8\ °C. \tag{2.30}$$

The coefficients of thermal conductivity of the wall in the inlet and outlet sections of the evaporative;

$$\lambda_{CT}^{BX} = 18,605\ \text{Вт/м} \cdot \text{К}; \quad \lambda_{CT}^{ВЫХ} = 18,47\ \text{Вт/м} \cdot \text{К}.$$

Temperature head at the inlet and outlet of the evaporating section:

$$\Delta t_{BX} = t'_1 - t_{S2} = 320 - 270 = 50\ °C;$$
$$\Delta t_{ВЫХ} = t''_{1И} - t_{S2} = 286,10 - 270 = 16,1\ °C. \tag{2.31}$$

The heat transfer coefficient at the inlet of the evaporator:

Where,

$$\alpha'_{2BX} = \frac{10,45}{3,3 - 0,0113 \cdot \left(270 + 273,15 - 373\right)} \cdot \left(234,8 \cdot 10^3\right)^{0.7} = 43595,63\ \text{Вт/м}^2 \cdot \text{К};$$
$$k'_{BX} = \left[\frac{1}{22434,25} + \frac{1,4 \cdot 10^{-3}}{18,605} + 2 \cdot 2 \cdot 10^{-5} + \frac{1}{43595,63} \right]^{-1} = 5471,6\ \text{Вт/м}^2 \cdot \text{К};$$
$$q'' = k'_{BX} \cdot \Delta t_{вх} = 5471,62 \cdot 50 = 273,8\ \text{кВт/м}^2.$$

(2.32)

Because, $\frac{q'}{q''} = 0,858$ it is necessary to make the second iteration. Will take

$$\alpha'_{2BX} = \frac{10,45}{3,3-0,0113\cdot\left(270+273,15-373\right)}\cdot\left(273,8\cdot10^{3}\right)^{0.7} = 48543,27\ \text{Вт/м}^2\cdot\text{К};$$

$$k'_{BX} = \left[\frac{1}{22434,25}+\frac{1,4\cdot10^{-3}}{18,605}+2\cdot2\cdot10^{-5}+\frac{1}{48543,27}\right]^{-1} = 5542,52\ \text{Вт/м}^2\cdot\text{К};$$

$$q'' = k'_{BX}\cdot\Delta t_{вх} = 5542,52\cdot50 = 277,31\ \text{кВт/м}^2.$$

(2.33)

Because, $\frac{q'}{q''} = 0,987$ then we finish the calculation and accept.

Similarly, we define for the output section:

$$q' = 0,75\cdot16,14\cdot\left(\frac{1}{20807,76}+\frac{1,4\cdot10^{-3}}{18,47}+2\cdot2\cdot10^{-5}\right)^{-1} = 73,85\ \text{кВт/м}^2. \quad (2.34)$$

Where,

$$\alpha'_{2ВЫХ} = \frac{10,45}{3,3-0,0113\cdot\left(270+273,15-373\right)}\cdot\left(73,85\cdot10^{3}\right)^{0,7} = 19401,21\ \text{Вт/м}^2\cdot\text{К};$$

$$k'_{ВЫХ} = \left[\frac{1}{20807,76}+\frac{1,4\cdot10^{-3}}{18,47}+2\cdot2\cdot10^{-5}+19401,21\right]^{-1} = 4642,51\ \text{Вт/м}^2\cdot\text{К};$$

$$q'' = k'_{ВЫХ}\cdot\Delta t = 4642,51\cdot16,1 = 74,91\ \text{кВт/м}^2.$$

(2.35)

Because, $\frac{q'}{q''} = 0,986$ then we finish the calculation and accept,

$$k_{ВЫХ} = 4642,51\ \text{Вт/м}^2\cdot\text{К}. \quad (2.36)$$

Coefficients k_{BX} and $k_{ВЫХ}$ should differ by no more than 25%, i.e

$$\frac{k_{BX}-k_{ВЫХ}}{k_{BX}}\cdot100\% = \frac{5542,52-4642,51}{5542,52}\cdot100\% = 15,15\,\%. \quad (2.37)$$

Determine the average heat transfer coefficient:

$$\overline{k_И} = \frac{k_{ВХ} + k_{ВЫХ}}{2} = \frac{5471,62 + 4642,51}{2} = 5057,06 \text{ Вт/м}^2 \cdot \text{К}. \quad (2.38)$$

Determine the area of heat transfer surface of the evaporation area:

$$S_И = \frac{Q_И}{\overline{k_И} \cdot \overline{\Delta t_И}} = \frac{235,17 \cdot 10^6}{5057,06 \cdot 24,89} = 1868,06 \text{ м}^2. \quad (2.39)$$

Table 1. Parameters of the evaporator section of the NG

Thermal power plot, $Q_И$, МВт	235,17
Temperature head Δt, $°C$ at the entrance $\Delta t_{ВХ}$: at the exit $\Delta t_{ВЫХ}$:	50,0 16,1
Heat transfer coefficient from TH to the wall α, кВт/м$^2 \cdot$К. at the entrance $\alpha_{1ВХ}$: at the exit $\alpha_{1ВЫХ}$:	22,43 20,81
Heat transfer coefficient from wall to RT α, кВт/м$^2 \cdot$К. at the entrance $\alpha_{2ВХ}$: at the exit $\alpha_{2ВЫХ}$:	48,54 19,40
Heat flux density for RT q, кВт/м^2. entrance area $q_{ВХ}$: output section $q_{ВЫХ}$:	277,31 74,91
Heat transfer coefficient k, Вт/м$^2 \cdot$К. entrance area k_{IN} : output section k_{OUT} :	5542,52 4642,51
Heat transfer surface area of the evaporator area, м^2	1868,06

Calculation of the heat-transfer surface area of the gas generator

Initial data:

$$Q_Э = 42{,}9\ \text{МВт};\ t'_{1Э} = t''_{1И} = 286{,}1\ °C;\ t''_{1Э} = t''_1 = 280\ °C;$$
$$t'_{2Э} = t_Ц = 260{,}5\ °C\ \ (\text{при}\ k_Ц = 6);\ t''_{2Э} = t_{S2} = 270\ °C. \qquad (2.40)$$

Water is heated to the economizer section of the SG to boil. Since the temperature of the coolant in the whole area $t_{1Э} > t_S = 270\,°C$, and the under heating of the working fluid is relatively small, the heat transfer from the pipe wall to the working fluid is possible under conditions of washing with non-boiling water, if the temperature of the outer surface of the pipe wall $\overline{t}_{CT} < t_S$ and under conditions of surface boiling under heated from t_S water, if $\overline{t}_{CT} > t_S$. the heat transfer in the economizer section is considered for the average temperatures of the coolant and working fluid. Determine the average temperature of RT

$$\overline{t}_{1Э} = \frac{t''_{1Э} + t'_{1Э}}{2} = \frac{280 + 286{,}1}{2} = 283{,}05\,°C;$$
$$\overline{t}_{2Э} = \frac{t''_{2Э} + t'_{2Э}}{2} = \frac{270 + 260{,}5}{2} = 265{,}2\,°C;$$
$$\overline{t}_{CT} = \frac{\overline{t}_{1Э} + \overline{t}_{2Э}}{2} = \frac{283{,}05 + 265{,}2}{2} = 274{,}1\,°C; \qquad (2.41)$$
$$274{,}1 > 270\ \ т.е.\ \overline{t}_{CT} > t_S\ \Rightarrow$$

Heat transfer from the pipe wall to the working medium occurs under conditions of superficial boiling of water under heated to the saturation temperature of water. The heat transfer coefficient of the heat pump is considered for the heat transfer mode in case of surface boiling of the water under heated to the temperature in the annular space of the steam generator. The algorithm of its calculation is the same as in the evaporating section. The area of the heat transfer surface is calculated by the formula.

$$S_Э = \frac{Q_Э}{k_Э \cdot \overline{\Delta t_Э}}; \qquad (2.42)$$

Where,

$\overline{\Delta t_Э}$ – Average temperature pressure in the economizer section of SG;

$\overline{k_Э}$ – Average heat transfer coefficient on the economizer section of the steam generator;

Average temperature head:

$$\overline{\Delta t_Э} = \frac{(t'_{1Э} - t''_{2Э}) - (t''_{1Э} - t'_{2Э})}{Ln\left[\dfrac{(t'_{1Э} - t''_{2Э})}{(t''_{1Э} - t'_{2Э})}\right]} = \frac{(286,1 - 270) - (280 - 260,5)}{Ln\left[\dfrac{286,1 - 270}{280 - 260,5}\right]} = 17,8\ °C. \qquad (2.43)$$

So, $\dfrac{d_н}{d_в} = 1,21 \leq 2$, then the heat transfer coefficient is calculated by the formula:

$$k_Э = \left[\frac{1}{\alpha_1} + \frac{\delta_{CT}}{\lambda_{CT}} + 2 \cdot R_{OK} + \frac{1}{\alpha_2}\right]^{-1}; \qquad (2.44)$$

Since the material of the heating surface tubes is austenitic stainless steel, grade 12X18H10T, we will take the thermal resistance of oxides, can be expressed as

$$R_{OK} = 2 \cdot 10^{-5}\ \text{м}^2 \cdot \text{К/Вт} \qquad (2.45)$$

Heat transfer coefficient from coolant to the wall,

$$\alpha_1 = 0,021 \cdot \frac{\lambda}{d} \cdot \mathrm{Re}^{0.8} \cdot \mathrm{Pr}^{0.43} \cdot C_t \cdot C_l\,. \qquad (2.46)$$

where the correction factors C_t and C_l in the calculation can be taken equal to one.

The coolant moves inside the tubes, so the hydraulic diameter is equal to the inner diameter of the heating surface tube ($d_Г = d_В$).

Determine the average speed of the coolant:

$$\overline{\omega_{1Э}} = \frac{G}{\overline{\rho_{1Э}} \cdot n_{тр} \cdot f_{тр}} = \frac{1283,55}{758,17 \cdot 4309 \cdot 136,85 \cdot 10^{-6}} = 2,871 \text{ м/с.}, \qquad (2.47)$$

where

$$\overline{\rho_{1Э}} = f(\text{P}_1; \overline{t_{1Э}}) = 758,17 \text{ кг/м}^3 \qquad (2.48)$$

The average density of the SG on the economizer section of the SG. Thermo physical properties of TH for average temperature. $\overline{t}_{1Э} = 283,05\ {}^0C$:

$\lambda_1 = 0,557$ Вт/м·К – coefficient of thermal conductivity;

$\nu_1 = 1,25 \cdot 10^{-7}$ м^2/с – kinematic viscosity;

$\text{Pr}_1 = 0,831$ - Prandtl number.

Determine the Reynolds number:

$$\text{Re}_{1Э} = \frac{\overline{\omega_{1Э}} \cdot d_Г}{\nu_1} = \frac{2,871 \cdot 13,2 \cdot 10^{-3}}{1,25 \cdot 10^{-7}} = 3,021 \cdot 10^5; \qquad (2.49)$$

We can find, $\alpha_{1Э}$:

$$\alpha_{1Э} = 0,021 \cdot \frac{0,557}{13,2 \cdot 10^{-3}} \cdot \left(3,021 \cdot 10^5\right)^{0.8} \cdot 0,831^{0.43} \cdot 1 \cdot 1 = 20898,57 \text{ Вт/м}^2 \cdot \text{К}; \qquad (2.50)$$

Heat transfer from the wall to the working fluid in the economizer section of the SG occurs in boiling conditions in a large volume. The following formula is used for calculating the heat transfer coefficient of working fluid ($\alpha_{2Э}$).

We define the $\alpha_{2Э}$ formula:

$$\alpha_{2Э} = \frac{10,45}{3,3 - 0,0113 \cdot \left(T_S - 373\right)} \cdot q^{0.7}, \qquad (2.51)$$

q -is the heat flux density, W / m^2;

T_S – Saturation temperature of working environment, 0C.

This equation is solved by successive iterations. Roughly set by value $q = q'$, calculated value, then determined. If the condition is met, the calculation ends $q'' = k' \cdot \Delta t$. If the condition $0,95 \le \dfrac{q'}{q''} \le 1,05$ is not met, the calculation continues and is accepted as q the new value q''. For the first iteration, the value can be taken equal to:

$$q' = \left(0,7 \div 0,8\right) \cdot \Delta t_Э \cdot \left(\frac{1}{\alpha_{1Э}} + \frac{\delta_{CT}}{\lambda_{CT}} + 2R_{OK} \right)^{-1}, \tag{2.52}$$

Where,

λ_{CT} –thermal conductivity coefficient, determined by wall temperature, $Вт / м \cdot К$

Δt – temperature pressure, 0^C.

Determine the temperature head:

$$\Delta t_Э = \overline{t_{1Э}} - t_S = 283{,}05\text{-}270{=}13{,}05\ °C.$$

The coefficient of thermal conductivity of the wall for the average temperature.

$$\overline{t}_{1Э} = 283{,}05^0 C : \lambda_{CT} = 18{,}6\ \text{Вт/м} \cdot \text{К}$$

Heat transfer coefficient in the first iteration:

$$q' = 0,75 \cdot 13,05 \cdot \left(\frac{1}{20898,57} + \frac{1,4 \cdot 10^{-3}}{18,6} + 2 \cdot 10^{-5} \right)^{-1} = 60{,}16\ \text{кВт/м}^2. \tag{2.53}$$

Where,

$$\alpha_{2Э} = \frac{10,45}{3,3 - 0,0113 \cdot (270 + 273,15 - 373)} \cdot \left(60,16 \cdot 10^3\right)^{0.7} = 16806,6 \text{ Вт/м}^2 \cdot \text{К};$$

$$k_Э = \left[\frac{1}{20898,6} + \frac{1,4 \cdot 10^{-3}}{18,6} + 2 \cdot 2 \cdot 10^{-5} + \frac{1}{16806,6}\right]^{-1} = 4492,0 \text{ Вт/м}^2 \cdot \text{К}; \qquad (2.54)$$

$$q'' = k_Э \cdot \Delta t = 4492,0 \cdot 13,1 = 58,77 \text{ кВт/м}^2, \frac{q'}{q''} = 0,981 \Rightarrow$$

So, $k_Э = 4492,0 \text{ Вт/м}^2 \cdot \text{К}$. then we finish the calculation and determine the area of heat transfer surface economizer area:

$$S_Э = \frac{Q_Э}{k_Э \cdot \overline{\Delta t_Э}} = \frac{42,9 \cdot 10^6}{4492,0 \cdot 17,76} = 537,76 \text{ м}^2.$$

(2.55)

Table 3. Parameters of economizer section of SG.

Thermal power plot, $Q_Э$, МВт	42,9
Temperature head Δt, $°C$:	17,76
Heat transfer coefficient from TH to the wall α, кВт/м$^2 \cdot$К	20,90
Heat transfer coefficient from the wall к PT α, кВт/м$^2 \cdot$К	16,81
Heat flux density for RT q, кВт/м^2	58,77
Heat transfer coefficient k, Вт/м$^2 \cdot$К	4492,0
Heat transfer surface area of the evaporator area,	537,76

2.6.2 Calculation for heat transfer area of gas generator and tubes length

Since in the course of SG operation, the formation of deposits is possible. The formation of leaks in individual tubes and their plug, the actual area of the heat transfer surface is calculated with a certain margin, which is taken into account by the safety factor. The value of the safety factor is taken from the interval 1.1/ 1.25. Take the margin of heat transfer surface $k_з = 1,15$

2.6.3 Calculated heat transfer surface area:

$$S_P = S_И + S_Э = 1868,06 + 537,76 = 2405,82 \text{ м}^2. \quad (2.56)$$

Heat transfer surface area,

$$S = S_P \cdot k_З = 2405,82 \cdot 1,15 = 2766,70 \text{ м}^2. \quad (2.57)$$

The length of pipe heat transfer surface SG

$$L = \frac{S}{\pi \cdot d_{CP}} = \frac{2766,70}{\pi \cdot 14,6 \cdot 10^{-3}} = 60,32 \cdot 10^3 \text{ м}. \quad (2.58)$$

One pipe length:

$$l = \frac{L}{n_{TP}} = \frac{60,32 \cdot 10^3}{4309} = 13,9985 \approx 14 \text{ м}. \quad (2.59)$$

Next, we will perform variant calculations in order to assess the influence of the pressure of the working fluid on its parameters.

2.7 Effect of working fluid pressure on steam humidity volume of a steam generator

The purpose of theoretical studies is an analytical effect in assessment of pressure of the working fluid (steam) on its basic parameters, as well as the moisture content of the steam entering the louvered separator or steam receiving ceiling. The obtained values will allow to estimate the preliminary capital costs for the design and creation of a steam generator. A preliminary assessment of heat exchange surface area, the number of heat exchange tubes; the presence or absence of a louvered separator. In assessing the change in humidity of the generated steam in the steam volume, the following parameters were used, which are characteristic of steam generators operating as part of the power generating units of nuclear power plants:

D - Steam production, kg / s;

P_2 - pressure of working fluid, MPa;

t_I, t_{II} is the coolant temperature in the hot and cold collectors, respectively, 0^C;

$t_{fw} = t_{2S}$ is the saturation temperature of the working fluid at a pressure of P_2, 0^C;

k, 55 = 5500-6000 W / (m^2.K) is the heat transfer coefficient, (by analogy with VVER-1000);

$F_{d\cdot a}$. = 30 m^2 is the surface area of the evaporation mirror (by analogy with VVER-1000);

h_{mass} = 0.4 m is the weight level for working fluid in the steam generator.

The thermal power of the steam generator was determined by the formula

$$Q_{sg} = (h_{II2}s-h_{fw}), \tag{2.60}$$

where h_{fw} f (P_2, t_{fm}) is the feed water enthalpy, kJ / kg, h_{II2s}. f (P2) is the enthalpy of the working fluid, kJ / kg.

Average temperature head in steam generator

$$\overrightarrow{\Delta t} = \frac{(t_I^I - t_{2s)}^{II}) - (t_I^{II} - t_{2s}^I)}{\ln\frac{(t_I^I - t_{2s)}^I}{(t_I^{II} - t_{2s)}^I}} \tag{2.61}$$

where $t^{II}{}_2s$ is the temperature of the working fluid (steam) in a state of saturation, $0^c{}_,t^I{}_{2s}$ is the temperature of the working fluid (feed water) in a state of saturation, 0^C

The surface area of heat transfer and surface area of heat exchange tubes is determined for the purpose of prognostic analysis of the geometric parameters of the steam generator, m^2:

$$F_{S.G.} = \frac{Q_{S.G.}}{\bar{k} \cdot \Delta \bar{t}} \tag{2.62}$$

The reduced steam velocity when passing through the evaporation mirror

$$w_0'' = \frac{D}{\rho'' \cdot F_{зи}} \tag{2.63}$$

where ρ'' is the density of saturated steam at pressure, p_2 kg / m³.True volumetric steam content during steam bubbling through a layer of water

$$\varphi = \frac{w_0''}{w_0'' + \left(0,65 - 0,039 \cdot p_2\right)} \tag{2.64}$$

Actual water level in the steam generator, m

$$h_{fact} = \frac{h_{mass}}{1-\varphi} \tag{2.65}$$

The height of the steam volume, m

$$h_S = 1,6 - h_{fact} \tag{2.66}$$

$$Y = \left(2,05 - 3,049 \cdot p_2 + 0,9614 \cdot p_2^2\right) \cdot 10^{-4} \cdot \frac{\left(w_0''\right)^{2,76}}{h_S^{2,3}} \tag{2.67}$$

where p_2 в MPa.

The process of transferring thermal energy from the coolant to the working fluid is represented graphically in the form of a T-Q diagram.

2.8 T-q chart

Minimum temperature pressure, ° C,

$$\Delta t_{MIN} = t_I^{II} - t_{2s}^{I} \tag{2.68}$$

Note that, from the information for water to water type steam generators, the minimum temperature difference is from 10 to 20 0^C. So, this range will be one of the criteria for evaluating the influence of the working body pressure on steam humidity. The following are alternative calculations of the parameters of the steam generator at various pressures of the working fluid. The pressure range studied is 5-7 MPa.

a) Investigating the influence of working fluid pressure P_2 = 5.0 MPa on the parameters of steam generator and the medium in the steam volume.

Thermal power of the steam generator:

$$Q_{sg} = 150.\ (2794\text{-}1155) = 240.93\ \text{MW}, \tag{2.69}$$

Average temperature pressure in the steam generator:

$$\overrightarrow{\Delta t} = \frac{(325-263{,}9)-(295-263{,}9)}{\ln\frac{(325-263{,}9)}{(295-263{,}9)}} = 44{,}4\,^{o}\text{C}. \tag{2.70}$$

The surface area of heat transfer and surface area of heat exchange tubes is determined for prognostic analysis of geometric parameters of the steam generator, m^2:

$$F_{S.G.} = \frac{240{,}93\cdot 10^3}{5500\cdot 44{,}4} = 986{,}08\ \text{m} \tag{2.71}$$

The reduced steam velocity when passing through the evaporation mirror, m / s:

$$w_0'' = \frac{150}{25{,}35\cdot 30} = 0{,}197\ \text{m/s}. \tag{2.72}$$

True volumetric steam content during steam bubbling through a layer of water

$$\varphi = \frac{0{,}197}{0{,}197+\left(0{,}65-0{,}039\cdot 5\right)} = 0{,}302. \tag{2.73}$$

Actual water level in the steam generator, m

$$h_{fact} = \frac{0{,}4}{1-0{,}302} = 0{,}57. \tag{2.74}$$

The height of the steam volume, m. Humidity of steam in front of a steam receiver louvered separator / steam ceiling,

$$Y = \left(2{,}05-3{,}049\cdot 5+0{,}9614\cdot 5^2\right)\cdot 10^{-4}\cdot \frac{\left(0{,}197_0\right)^{2{,}76}}{1{,}03^{2{,}3}} = 1{,}156\%, \tag{2.75}$$

The process of transferring thermal energy from the coolant to the working fluid is represented graphically in the form of a T-Q diagram.

Minimum temperature pressure, °

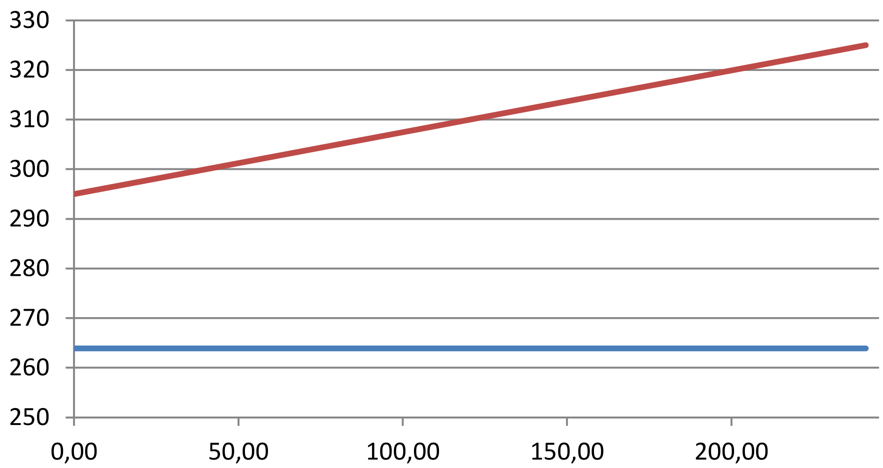


Figure 2.7 - T-Q diagram of a steam generator with a working fluid pressure of 5.0 MPa

$$\Delta t_{MIN} = 295 - 263{,}9 = 31{,}1\ 0^{c} \tag{2.76}$$

Analytical calculations were performed to assess the main parameters of the working fluid in steam volume of steam generator. It has been established that, with a pressure value of the working fluid of 5.0 MPa, the thermal power of the steam generator is 240.9 MW, while the heat exchange surface area does not exceed 1000 m^2 (986.1 m^2). The reduced steam velocity at the “evaporation mirror-vapor volume” boundary and the volumetric steam content at a vapor volume height of 1.03 m is 0.197 m / s and 0.303%, respectively. The humidity value of steam has a value of 1.147%, which allows us to conclude that it is necessary to use a louvered separator in the design of a steam generator. At the same time, the minimum temperature pressure is equal to 31.1 0^C, the value does not correspond to the required range for water-water steam generators (10-20 0^C). Thus, the efficiency of the heat exchange process between the coolant and the working fluid will be ineffective.

b) Investigating the influence of working fluid pressure P_2 = 5.5 MPa on the parameters of steam generator and the medium in steam volume. Thermal power of the steam generator:

$$Q_{sg} = 150.\ (2790\text{-}1185) = 235.94\ \text{MW}, \qquad (2.77)$$

Average temperature pressure in the steam generator:

$$\overrightarrow{\Delta t} = \frac{(325-270)-(295-270)}{\ln\frac{(325-270)}{(295-270)}} = 35{,}4\ ^{o}\text{C}. \qquad (2.78)$$

The surface area of heat transfer and surface area of heat exchange tubes is determined for prognostic analysis for geometric parameters of steam generator, m^2:

$$F_{S.G.} = \frac{235{,}94\cdot 10^{3}}{5500\cdot 35{,}4} = 1212{,}08\ \text{m}^2. \qquad (2.79)$$

To reduced steam velocity when passing through the evaporation mirror, m / s:

$$w_0'' = \frac{150}{28{,}06\cdot 30} = 0{,}178\ \text{m/s}. \qquad (2.80)$$

True volumetric steam content during steam bubbling through a layer of water

$$\varphi = \frac{0{,}178}{0{,}178+\left(0{,}65-0{,}039\cdot 5{,}5\right)} = 0{,}282. \qquad (2.81)$$

Actual water level in the steam generator, m

$$h_{fact} = \frac{0{,}4}{1-0{,}282} = 0{,}56. \qquad (2.82)$$

The height of the steam volume, m

$$h_S = 1{,}6-0{,}56 = 1{,}04. \qquad (2.83)$$

Humidity of steam in front of a steam receiver (louvered separator and steam ceiling)

$$Y = \left(2{,}05-3{,}049\cdot 5{,}5+0{,}9614\cdot 5{,}5^{2}\right)\cdot 10^{-4}\cdot\frac{\left(0{,}178_0\right)^{2{,}76}}{1{,}04^{2{,}3}} = 1{,}115\%, \qquad (2.84)$$

The process of heat transfer from the coolant to the working fluid is represented graphically in the form of a T-Q diagram.

Minimum temperature pressure, ° C

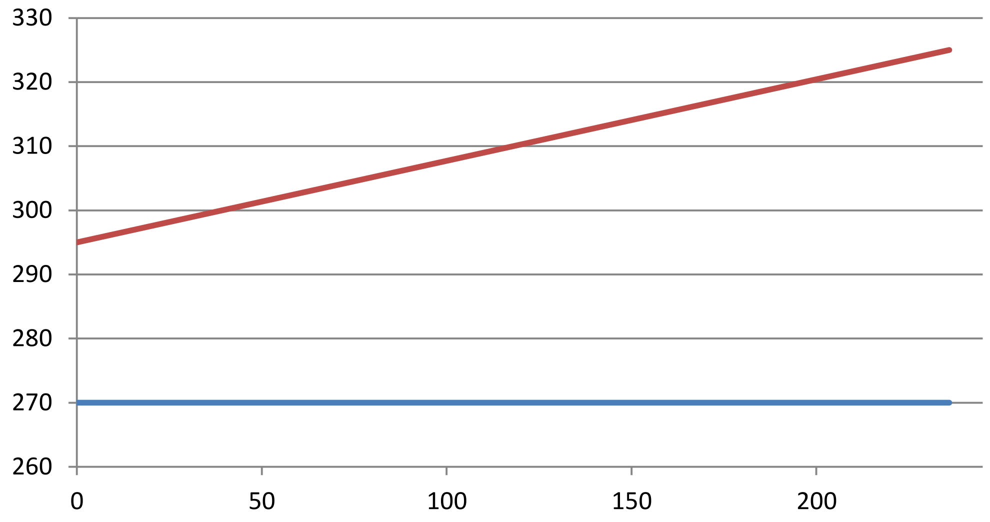


Figure 2.8. T-Q diagram of a steam generator with a working fluid pressure of 5.5 MPa

Minimum temperature pressure, ° C

$$\Delta t_{MIN} = 295 - 270 = 25\ ^{o}\mathrm{C}. \qquad (2.85)$$

Analytical calculations were performed to assess the main parameters of the working fluid in the steam volume of the steam generator. It has been established that with the pressure of the working fluid of 5.5 MPa, the thermal power of the steam generator is 235.9 MW, while the surface area of heat exchange exceeds 1000 m^2 (1127.4 m^2). The reduced steam velocity at the “evaporation mirror – vapor volume” boundary and the volumetric steam content at a vapor volume height of 1.04 m is 0.178 m / s and 0.282%, respectively.

The humidity value of steam has a value of 1.123%, which makes it possible to conclude that it is necessary to use a louvered separator in the design of a steam generator. At the same time, the minimum temperature pressure is equal to 25.0 ° C, the value does not correspond to the required range for water-water steam generators

(10-20 ° C). Thus, the efficiency of the heat exchange process between the coolant and the working fluid will be ineffective

c) Investigating the influence of working fluid pressure P_2 = 6.0 MPa on the parameters of steam generator and the medium in steam volume. Thermal power of steam generator can be calculated by:

$$Q_{sg} = 150 \cdot (2785-1214) = 230,94 \text{ MW} \quad (2.86)$$

The average temperature pressure in the steam generator:

$$\overrightarrow{\Delta t} = \frac{(325-275,6)-(295-275,6)}{\ln\frac{(325-275,6)}{(295-275,6)}} = 32,1\ ^{o}\text{C}. \quad (2.87)$$

The surface area of heat transfer and surface area of heat exchange tubes is determined for prognostic analysis of geometric parameters of steam generator, m^2:

$$F_{S.G.} = \frac{230,94 \cdot 10^3}{5500 \cdot 32,1} = 1308,19 \text{ m}^2 \quad (2.88)$$

To reduced steam velocity when passing through the evaporation mirror, m / s:

$$w_0'' = \frac{150}{30,82 \cdot 30} = 0,162 \text{ m/s}. \quad (2.89)$$

True volumetric steam content during steam bubbling through a layer of water

$$\varphi = \frac{0,162}{0,162 + (0,65 - 0,039 \cdot 6)} = 0,273. \quad (2.90)$$

Actual water level in the steam generator, m

$$h_{fact} = \frac{0,4}{1 - 0,273} = 0,55. \quad (2.100)$$

The height of the steam volume, m

$$h_S = 1,6 - 0,55 = 1,05. \quad (2.101)$$

Humidity of steam in front of steam receiver louvered separator and steam ceiling

$$Y=\left(2,05-3,049\cdot 6+0,9614\cdot 6^{2}\right)\cdot 10^{-4}\cdot\frac{\left(0,162_{0}\right)^{2,76}}{1,05^{2,3}}=1,085\%, \quad (2.102)$$

The process of transferring thermal energy from the coolant to the working fluid is represented graphically in the form of a T-Q diagram.

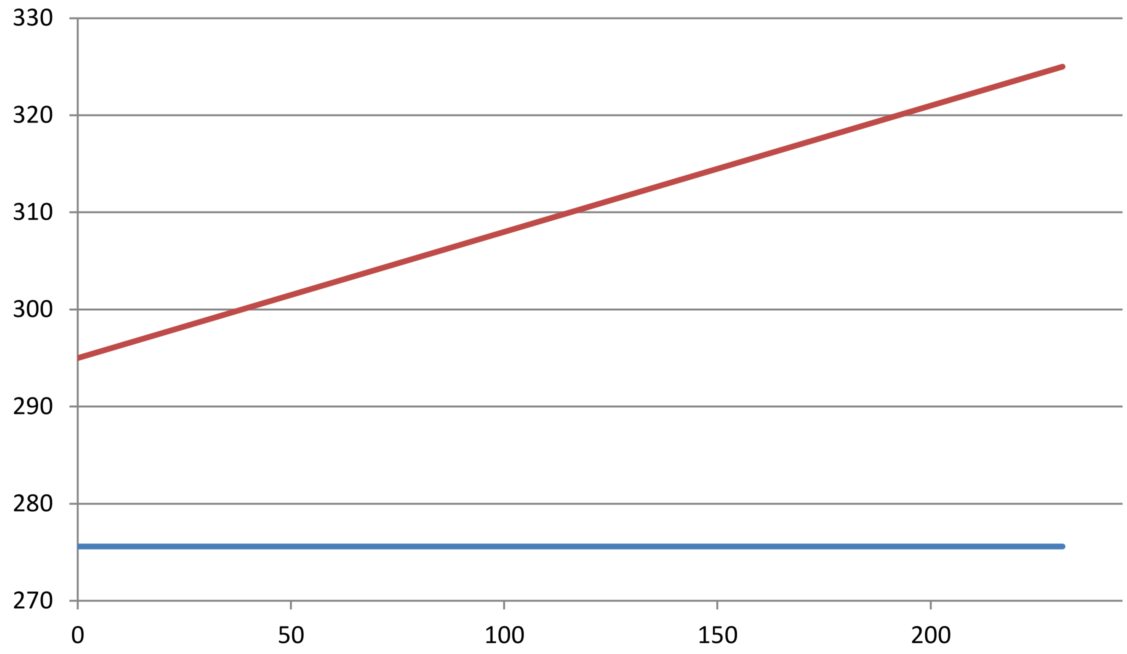


Figure 2.9 - T-Q diagram of a steam generator with a working fluid pressure of 6.0 MPa

Minimum temperature pressure, ° C

$$\Delta t_{MIN}=295-275,6=19,4\ ^{o}\mathrm{C} \quad (2.103)$$

Analytical calculations were performed to assess the main parameters of the working fluid in the steam volume of the steam generator. It was established that when the pressure of the working fluid is 6.0 MPa, the heat power of the steam generator is 230.9 MW, and the heat exchange surface area exceeds 1000 m^2 (1308.2 m^2). The reduced steam velocity at the “evaporation mirror-vapor volume” boundary and the volumetric steam content at a vapor volume height of 1.05 m are 0.162 m / s and 0.273%, respectively. The value of steam humidity is 1.08%, which allows to conclude that there is no need to use a louvered separator in the design of the steam generator. At the same time, the minimum temperature head is equal to 19.40 0^c, the value corresponds to the required range for water-cooled steam generators (10-20 0^c).

d) Investigating the influence of working fluid pressure P_2 = 6.5 MPa on the parameters of steam generator and the medium in the steam volume. Thermal power of the steam generator:

$$Q_{sg} = 150 \cdot (2779 - 1241) = 226{,}09 \text{ MW}, \tag{2.104}$$

Average temperature pressure in the steam generator:

$$\overrightarrow{\Delta t} = \frac{(325-280{,}9)-(295-280{,}9)}{\ln\frac{(325-280{,}9)}{(295-280{,}9)}} = 26{,}3\ {}^{o}\text{C}. \tag{2.105}$$

The surface area of heat transfer and the surface area of heat exchange tubes is determined for prognostic analysis for geometric parameters of steam generator, m^2

$$F_{S.G.} = \frac{226{,}09 \cdot 10^3}{5500 \cdot 26{,}3} = 1562{,}44 \text{ m}^2. \tag{2.106}$$

True volumetric steam content during steam bubbling through a layer of water

$$\varphi = \frac{0{,}149}{0{,}149 + (0{,}65 - 0{,}039 \cdot 6{,}5)} = 0{,}266. \tag{2.107}$$

Actual water level in the steam generator, m,

$$h_{fact} = \frac{0{,}4}{1 - 0{,}266} = 0{,}54. \tag{2.108}$$

The height of the steam volume, m

$$h_S = 1{,}6 - 0{,}54 = 1{,}06. \tag{2.109}$$

Humidity of steam in front of a steam receiver (louvered separator / steam ceiling)

$$Y = \left(2{,}05 - 3{,}049 \cdot 6{,}5 + 0{,}9614 \cdot 6{,}5^2\right) \cdot 10^{-4} \cdot \frac{\left(0{,}149_0\right)^{2{,}76}}{1{,}06^{2{,}3}} = 1{,}06\%, \qquad (2.110)$$

The process of transferring thermal energy from the coolant to the working fluid is represented graphically in the form of a T-Q diagram.

Minimum temperature pressure, ° C

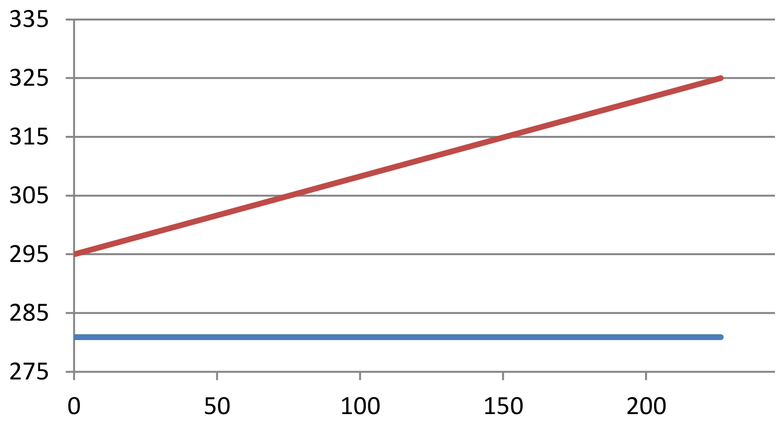


Figure 2.10 - T-Q diagram of a steam generator with a working fluid pressure of 6.5 MPa Minimum temperature pressure, ° C

Analytical calculations were performed to assess the main parameters of working fluid in steam volume of steam generator. It has been established that, at a pressure working fluid of 6.5 MPa, the heat power of steam generator is 226.1 MW, and the heat exchange surface area exceeds 1000 m^2 (1562.4 m^2). The reduced steam velocity at the “evaporation mirror-vapor volume” boundary and the volumetric steam content at a vapor volume height of 1.06 m is 0.149 m/s and 0.266%, respectively.

The humidity value of steam has a value of 1.05%, which allows us to conclude that there is no need to use a louvered separator in the design of the steam generator. At the same time, the minimum temperature pressure is 14.4 0^C, the value corresponds to the required range for water-to-water steam generators (10-20 0^C).

$$\Delta t_{MIN} = 295 - 280{,}9 = 19{,}4\ {}^{o}C. \qquad (2.111)$$

e) Investigating the influence working fluid pressure P_2 = 7.0 MPa on the parameters of steam generator and the medium in the steam volume. Thermal power of the steam generator:

$$Q_{sg} = 150\cdot(2773-1267) = 221{,}38\ \text{MW}, \qquad (2.112)$$

Average temperature pressure in the steam generator:

$$\overrightarrow{\Delta t} = \frac{(325-285{,}8)-(295-285{,}8)}{\ln\frac{(325-285{,}8)}{(295-285{,}8)}} = 20{,}7\ ^{o}\text{C}. \qquad (2.113)$$

The surface area of heat transfer and surface area of heat exchange tubes is determined for prognostic analysis of geometric parameters of steam generator, m^2:

$$F_{S.G.} = \frac{226{,}09\cdot 10^3}{5500\cdot 20{,}7} = 1986{,}09\ \text{m}^2. \qquad (2.114)$$

To reduced steam velocity when passing through the evaporation mirror, m / s:

$$w_0'' = \frac{150}{36{,}52\cdot 30} = 0{,}137\ \text{m/s}. \qquad (2.115)$$

True volumetric steam content during steam bubbling through a layer of water

$$\varphi = \frac{0{,}137}{0{,}137+\left(0{,}65-0{,}039\cdot 7\right)} = 0{,}261 \qquad (2.116)$$

Actual water level in the steam generator, m

$$h_{fact} = \frac{0{,}4}{1-0{,}261} = 0{,}53. \qquad (2.117)$$

The height of the steam volume, m

$$h_S = 1{,}6-0{,}53 = 1{,}07 \qquad (2.118)$$

Humidity of steam in front of a steam receiver louvered separator and steam ceiling

$$Y = \left(2{,}05-3{,}049\cdot 7+0{,}9614\cdot 7^2\right)\cdot 10^{-4}\cdot\frac{\left(0{,}137_0\right)^{2{,}76}}{1{,}07^{2{,}3}} = 1{,}01\%, \qquad (2.119)$$

The process of transferring thermal energy from the coolant to the working fluid is represented graphically in the form of a T-Q diagram.

Minimum temperature pressure, ° C

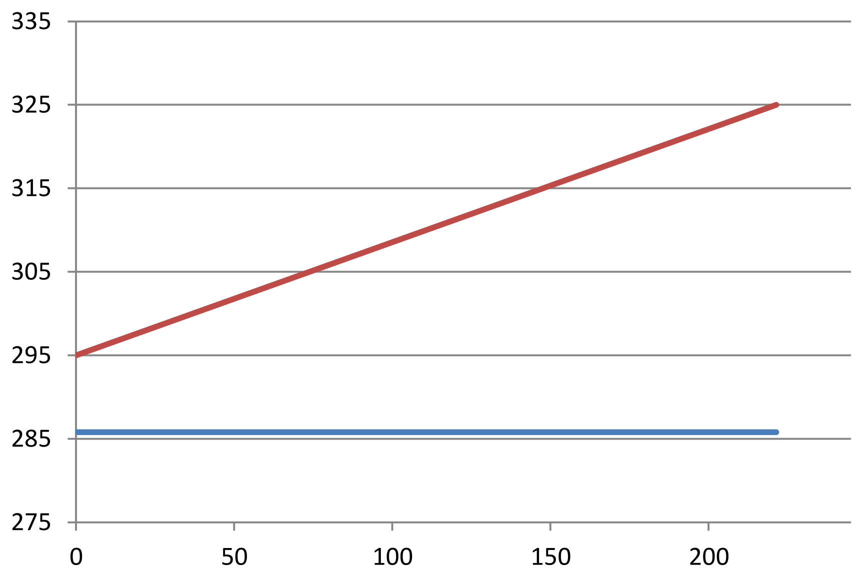


Figure 2.11—T-Q diagram of a steam generator with a working fluid pressure of 7.0 MPa Minimum temperature pressure, ° C

$$\Delta t_{MIN} = 295 - 285{,}8 = 9{,}2\ ^{o}\mathrm{C}. \quad (2.120)$$

Analytical calculations were performed to assess the main parameters of the working fluid in steam volume of the steam generator. It was established that when the pressure of working fluid is 7.0 MPa, the thermal power of the steam generator is 221.4 MW, while the surface area of heat exchange exceeds 1000 m^2 (1944.8 m^2). The reduced steam velocity at the "evaporation mirror-vapor volume" boundary and the volumetric steam content at a vapor volume height of 1.06 m is 0.137 m / s and 0.261%, respectively. The value of steam humidity is 1.01%, which allows to conclude that there is no need to use a louvered separator in the design of the steam generator. At the same time, the minimum temperature head is equal to $9.2{,}0^{C}$, the value does not correspond to the required range for water-cooled steam generators

(10-20 0^C). The conducted studies allow us to draw several conclusions. First, with an increase in the pressure of working fluid from 5.0 to 7.0 MPa, the surface area of heat exchange increases more than twofold from 986.1 m^2 to 1944.8 m^2. At the same time, the heat capacity of the steam generator is reduced by 20 MW from 240.9 MW to 221.4 MW.

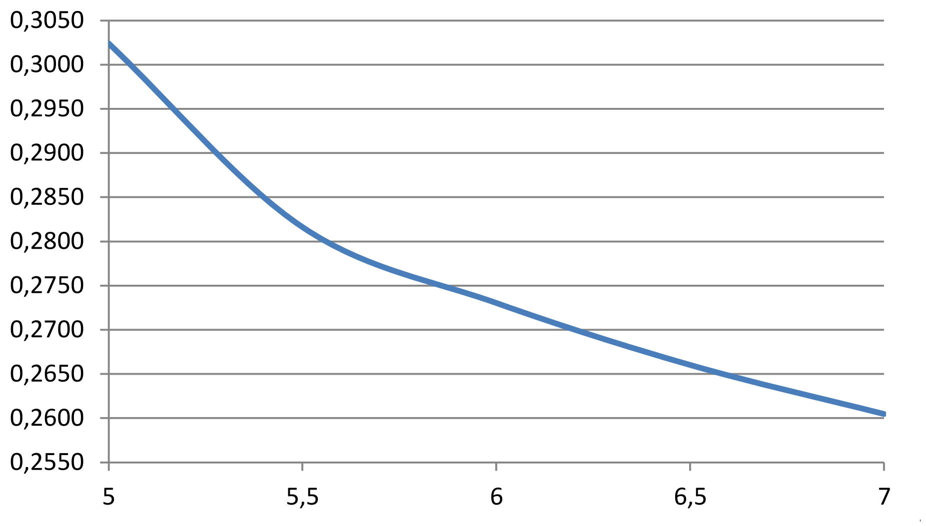


Figure. 2.12. The change in volumetric content in the steam volume

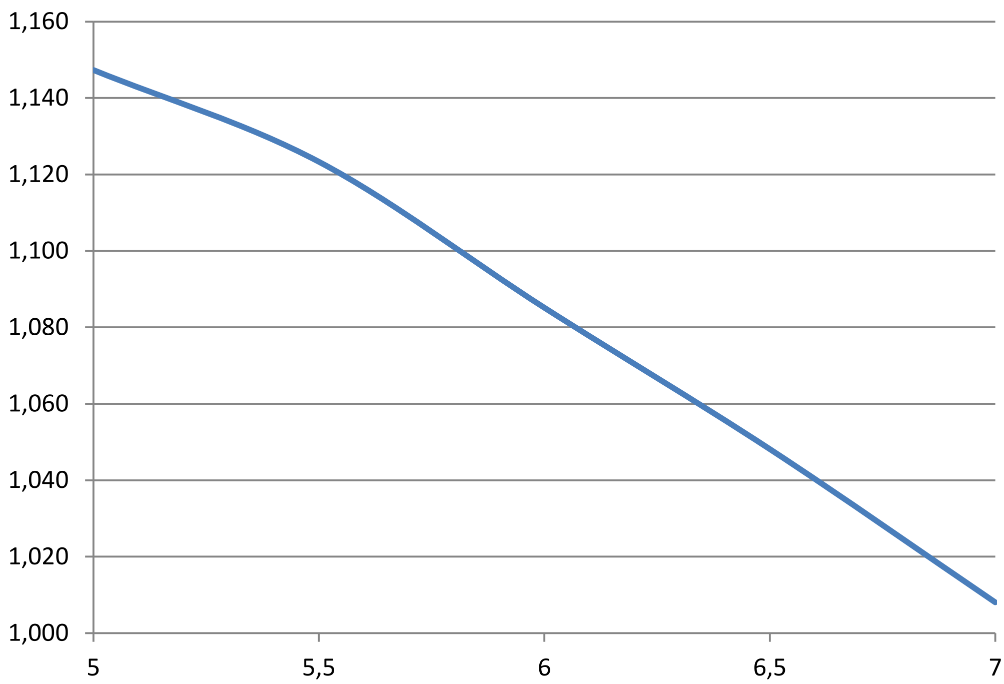
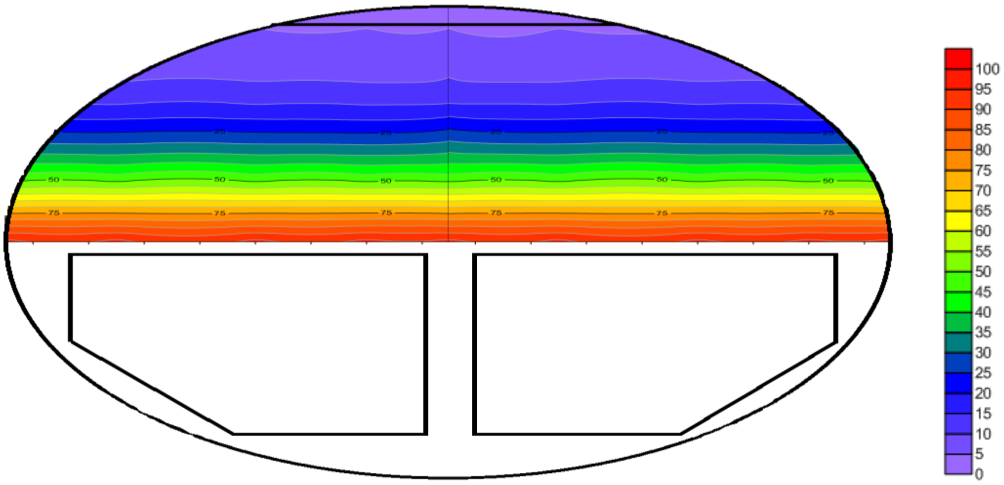
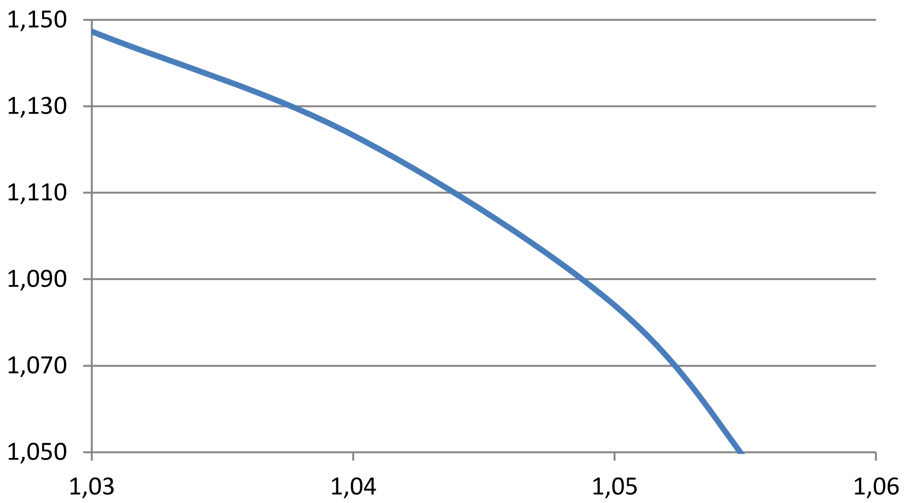


Figure 2.13 - Change in steam moisture in steam volume

The obtained dependences illustrate the nonlinear dependence of the volumetric steam content and moisture content in the vapor volume of a water-water steam generator. It can be concluded that increasing the pressure of the working fluid up to 6.0 MPa makes it possible not to use a louvered separator in the design of a steam generator. The required value of steam at the boundary of the steam volume and the louvered separator is achieved by gravity separation.



(A)



(B)

Figure 2.14 - The change in steam moisture volume of the steam generator at the height of the steam volume

2.9 SGs degradation

The mechanisms of corrosion degradation of WWER SGs heat exchange tubes are the same or similar with vertical SGs, and they are described in many articles. Influence of bulk water chemistry on corrosion degradation was studied in depth, e.g., in Nuclear Research Institute, Rez (NRI), VI´TKOVICE plc, and another research institutes. Based on performed research results, requirements on feedwater chemistry were refined and, at present, integrity of SGs tubing is relatively trouble free. But, as will be shown later, nor the best feedwater chemistry guarantee sufficient condition for no initiation and grows of corrosion cracks. Erosion-corrosion damage of SGs feedwater distribution system occurred at all WWRE 440 NPPs. The feedwater tubing was originally manufactured from carbon.

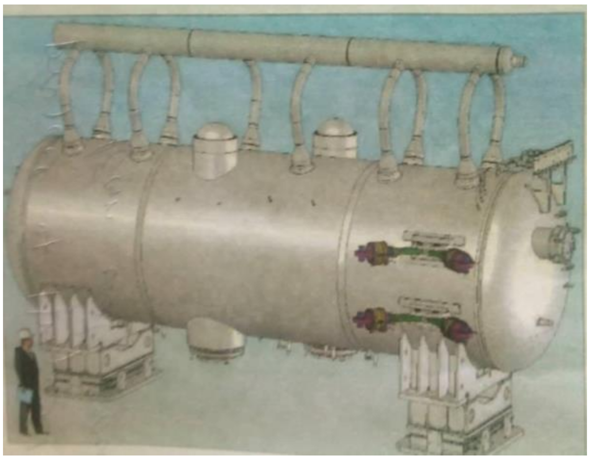


Figure 2.15 - WWER steam generators (SGs) side view

Table 4 Basic parameters of WWER steam generators

Parameters	SG440	SG1000
Thermal power (MWt)	229	750
Steam capacity (kg s_1)	125	408
Steam pressure (MPa)	4.61	6.27
Steam temperature (°C)	258.9	278.5
Coolant temperature	297/270	320/289
(inlet/outlet) (°C)	12.26	15.7

Coolant pressure (MPa)	7100	21.200
Coolant flow rate ($m^3\ h^{-1}$)	164-223	164-220
Feedwater temperature (°C) Vessel internal diameter (m)	3.2	4.0
Vessel length (m)	11.6	13.4
Evaporation surface (m^2)	24	40
Vessel material	22k	10GN2MFA
Collector material	08Ch18N10T	10GN2MFA
Heat exchange tube material	08Ch18N10T	08Ch18N10T
Tube diameter (mm)	16	16
Tube thickness (mm)	1.4	1.4
Number of tubes	5536	11,000

Steel, and a feedwater was distributed from central pipe to center of heat exchange bundle via many rectangular turnings. The damaged feedwater systems were removed, and they were replaced using stainless steel pipes. At Loviisa and Paks (GIDROPRES solution) feedwater is distributed above tube bundles; at Dukovany, Bohunice, and Temelin submerged distribution (similar as original design) was implemented. After these modifications, the feedwater distribution system seems to be trouble free. Corrosion cracks in collectors threaded holes (sealing of covers) occurred at many power plants. This damage requires replacement of the collector upper part which is a time-consuming operation. High level of tensile stress and splash of secondary water to holes are the basic reasons for this problem.

The level of secondary water around HC is above the steam separators—Fig. 5.2A. Level at the cold side of SG is uniform and sufficiently low—Difference in levels is given by different average void fraction in tube bundles. The average void fraction around HC is approximately 0.2 and around cold one is lower than 0.07 (Papp, 1996). Difference between steam-water mixture levels near hot and CCs results from uneven steam performance along the heat exchange tubes—heat flux exponentially decreases with distance from HC. The problem of level measurement can be explained using simplified model of SG shown. Static equilibrium of two-phase mixture in SG.

(A) (B)

Figure 2.16 - (A) Trace of level, hot collector (HC), (B) trace of level, cold collector (CC).

2.10 WWER SGs modifications

Modifications of SGs were started after damage of WWER 440 SGs collectors' upper part and especially after damage of WWER 1000 collectors. Removed WWER 1000 SGs were cut, and extreme impurities concentration around collectors were confirmed—dry crystalline salt deposits were found between heat exchange tubes of hot leg tube bundle (Trunov et al., 2001). The reason why only CCs were damaged was explained, too. Due to intensive heat flux near tube—HC crevices (250 kW m_2), these crevices are plugged by salt, i.e., corrosion medium free. Heat flux in CC area is approximately 45 kW m^2. Calculations and sampling of secondary water on operated WWER 1000 power plants (Trunov et al., 2001) have shown that the highest concentration of impurities is around HC and is approximately three times higher than the concentration in blowdown.

This value is questionable—it depends on time of sampling from time of sludge blowdown, on height of sampling point, etc. In places with dry deposits, the concentration was not measured. The problem of impurities distribution in WWER SGs is specific problem of horizontal SGs and can be explained using Fig. 5.7A and B. In these figures are shown the extreme variants of WWER SGs blowdown strategy. The concentration of impurities in blowdown in case of Fig. 5.7A is given by equation

$$C_b = C_F : M_F / M_b \tag{2.121}$$

(the salt content in steam is neglected)

Where:

– Cb is the concentration of impurities in blowdown

– CF is the concentration of impurities in feedwater

– Mb is the blowdown flow rate (kg s_1)

– MF is the feedwater flow rate (kg s_1)

For usual value of M_F/M_b =0:5%, the concentration of impurities in blowdown will be Cb =200:C_F

2.11 Integrity of heat exchange tubes

Integrity of WWER SGs heat exchange tubes is up to now trouble free. The summary of ECT inspection results at Dukovany NPP for time period 1985–2000 is reported in Berezanin (2001). The maximum number of plugged tubes on 1 SG after 13 years of operation was 43, i.e., 0.78% of total number of SG tubes. At 168 operated SGs up to 1999 0.65% of tubes were plugged (Trunov et al., 2001). Especially for WWER 440 NPP with 15% projected reserve of heat exchange tubes, these values are negligible. Nevertheless, each leakage of primary water generates significant economic loss for NPP. To reduce this loss, the following issues have to be studied:

- accuracy of corrosion cracks detection
- burst pressure for tubes rupture
- probability of cracks detection
- crack growth rate

The eddy current method (ECT) is the basic method for heat exchange tubes testing. Tests of accuracy with laboratory prepared cracks, using bobbin coil and x-probe coils, were performed in 1996, and comparison of results is shown.[6]

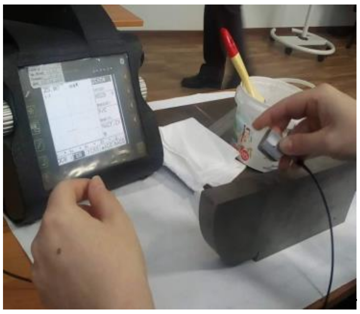


Figure 2.17 - Image capillary testing of VVER SG in ROSTOV 2019

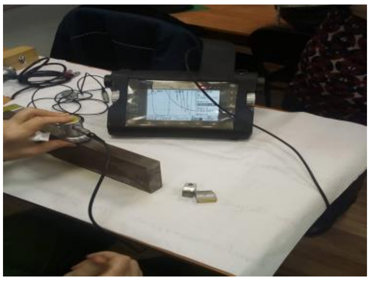


Figure 2.18 - Experiment detecting defect in VVER

2.12 Models for failure of U-bends with a single axial EDM notch

Limited tests have been conducted on U-bends with circumferential notches. Most tests and modeling of U-bends have concentrated on axial notches. Test experience has shown that circumferential notches are inherently more resistant to rupture than axial notches. Consequently, to achieve rupture at normal operation or MSLB pressures, the circumferential cracks have to be unrealistically long (>180°). Production of such long circumferential notches by machining has turned out to be a challenge.

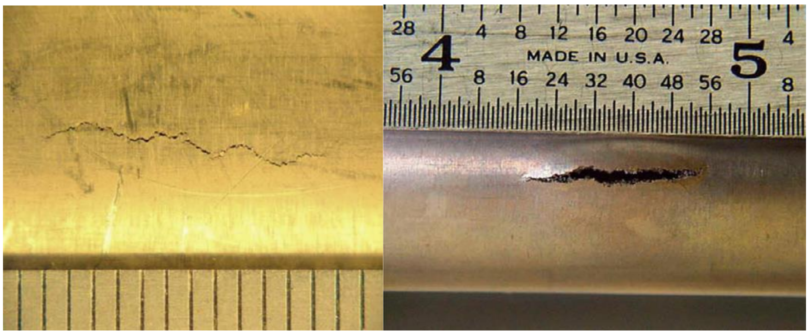


Figure 2.19 - Surface appearance of stress corrosion cracks in SG tubes after ligament rupture.[8]

2.13 Repair criteria for steam generator tubes

Steam generator tubes may be repaired or removed from service by sleeving or tube plugging when levels of degradation exceed allowable limits established by repair/ plugging criteria. Repair/plugging criteria are often expressed in terms of the through wall extent of the degradation. For example, the American Society of Mechanical Engineers (ASME), Boiler and Pressure Vessel Code (BPVC), Section XI, Rules for Inservice Inspection of Nuclear Power Plant Components (American Society of Mechanical Engineers, 2015a) considers degradation with depths in excess of 40% of the wall unacceptable unless there is a degradation mechanism specific repair criteria, which has been accepted by the regulatory authority, demonstrating that deeper flaws will not impact the integrity of the affected tube(s). The same criterion has been adopted by the Canadian Standards Association (CSA) Standard, N285.4, Periodic inspection of CANDU nuclear power plant components (Canadian Standards Association, 2014) and other international standards and practices.

While the 40% through wall criterion has generally been effective in preventing tube ruptures during normal operation and under accident conditions, as inspection technologies improved and flaw sizing has become more accurate it has been recognized that the 40% criterion is often overly conservative, particularly for volumetric forms of degradation such as support plate fretting or pitting. In such cases, implementing the 40% through wall criterion can result in an unnecessary operational penalty if large numbers of tubes are repaired/plugged.

Industry has expended significant effort to develop location and degradation mechanism specific repair criteria resulting in deeper allowable flaws as an alternative to the 40% criterion. This criterion may also be difficult to implement for some forms of degradation that cannot be readily characterized in terms of depth using existing inspection methods. The 40% through wall criterion or other general wall loss criteria are typically established based upon the assumption that the wall loss is uniformly distributed around the circumference of the tube.

A plastic limit load analysis is carried out using margins against tube burst of 3 for normal operating loads and 1.43 for design loads (International Atomic Energy

Agency, 2011).Industry has developed location and defect specific criteria that can provide accurate evaluations of the structural integrity of steam generator tubes subjected to localized forms of degradation to take advantage of detailed information provided by nondestructive examination (NDE) techniques and steam generator design features.[9]

2.14 Performance trends: Steam generator tube integrity

Although the new TS requirements have only been in place since 2005–07, depending on the plant, all PWR licensees have been implementing the basic performance-based elements of these requirements since 1999–2000 following their commitment to the industry's NEI 97-06 initiative. The NEI 97-06 initiative was an evolutionary change in licensee programs for ensuring tube integrity since the effectiveness of these programs have been constantly evolving and improving since the 1970s.

Industry guidelines relating to secondary water chemistry control and in-service inspection have been available since this period and have been frequently updated to reflect research findings, technology developments, and operating experience. In the late 1980s, licensees became sensitized to the need to monitor operational primary-to-secondary leakage on as close to a real-time basis as possible to provide added assurance of plant shutdown before rupture of a leaking tube. Industry guidelines for monitoring and responding to operational primary-to-secondary leakage have been available since the mid-1990s.

Another trend dating to the 1970s was an ever-increasing awareness among licensees of the need for their SG programs to address tube integrity in addition to satisfying TS surveillance requirements. Industry guidelines for tube integrity assessment became available in the mid-1990s and led to improved consistency, rigor, and completeness of licensee tube integrity assessments. In parallel with these SG programmatic improvements, tube integrity reliability appears to have improved significantly since the 1970s. This is evidenced by the sharply declining trends in frequency of forced shutdowns due to SG leakage, and in SGTR frequency.

The forced outage data in Fig. 18.1 were developed from industry data in Steam Generator Progress Report (2000) (which covers forced outages through 1999) and from unpublished NRC staff data for forced outages after 1999. The SGTR data were compiled from NUREG/CR-6365 (1996) and also include the SGTR event at Indian Point 2 in 2000 (NRC Special Inspection Report, 2000), which occurred after publication of NUREG/CR-6365 (1996). The use of tubing that is more resistant to stress corrosion cracking (i.e., TT alloy 600 and 690 tubing in lieu of MA alloy 600 tubing used in SGs manufactured through the late 1970s) in new (post-1970s) and replacement SGs has been responsible for some of this improvement as is indicated in these figures. However, as also can be seen in these figures, even plants with alloy 600 MA tubing have experienced sharply improved performance trends in forced outage and SGTR.[10]

2.15 Fluid Loading

Turbulence and fluid elastic excitations are considered in this analysis. Random turbulence excitation is a significant vibration mechanism in tubes subjected to cross-flow. The interior tubes within a tube bundle are excited by the turbulence generated within the bundle. In general, fluid excitation due to turbulence is modeled as randomly distributed forces.

To implement this approach, the empirically based bounding spectra of turbulence excitation are obtained using the flow velocity, the tube diameter, and the array geometry. The bounding spectra proposed by Oeng€oren and Ziada are used to simulate the random excitation forces. Depending on the flow velocity and the tube's diameter, the power spectral density (PDS) curve of the turbulence excitation is obtained. Finally, this PSD curve is transformed into a force-time record. For each element, two force-time records are generated and applied in the lift and the drag directions.

The fluid elastic instability model utilized in this work is the flow-cell model described in detail by Hassan et al. in a series of papers. Briefly, the entire flow inside the tube bundle is divided into a number of layers, each of which is associated with a tube finite element. The flow inside each layer can be idealized by a series of flow channels. The area of these flow channels is decomposed into a steady state component and a perturbation component. The area perturbation is set to the tube lift displacement along the tube-flow channel contact length. The response history is required in order to calculate the area perturbation in the channel.

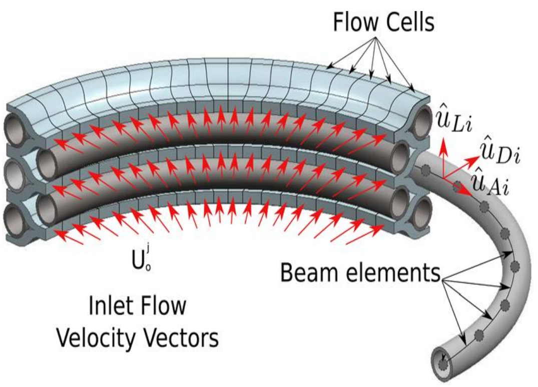


Figure 2.20 - Flow cell model in the U-bend region

2.16 Water conditions

Water conditions both at the primary and secondary side of the steam generator are of primary importance. Water conditions are intended to define the conditions under which the steam generator will operate properly. The condition of the boiling water should be tested by sampling at least once a day or as required by the operating instructions. The values of alkalinity and solids in excess of those specified may cause scaling of the steam generator tubes.

Feed water must be maintained as free from impurities as possible. This requirement involves careful attention to the entire system through which the water flows, either in the form of steam or water, for even though water is used as feed water be pure at the same time of its entry into the system, it may absorb impurities from the various parts of the installation. Specific attention should be directed to possible points of water leakage from the service water system, as in the main and auxiliary condensers. Feed water must be treated to maintain the required water conditions. The parameters to observe are, for the primary side:

– Impurity content, not considering the presence of inhibitors and chemical additives, which are necessary to the operation of the plant.

– Total dissolved solid, which is one of the causes of performance degeneration.

– pH.

– Hydrogen.

– Dissolved oxygen.

– Chlorides.

– Boric acid (with chemical shim1 or without chemical shim).

Steam entering the main header from the steam off take nozzle will have a moisture content not exceeding a determinate value (usually a percentage of the steam flow under certain conditions, like constant power steam generation, or power increasing or decreasing up to a percent of full power). In pressurized water reactor nuclear power plants, it is necessary to filter corrosion products transported by the main flow, as well as radioactive particulate.

Activity must be controlled: fission products must be detected, as well as noble gases and iodine's or activation products. Gamma spectra are acquired at many locations along the circuit. Gas borne activity is measured by means of coolant samples (e.g. fission gases isotopes of krypton and xenon). In the composition of primary coolant activity monitoring system, there are devices to detect Iodine volume activity. Isotopic composition of contamination inside primary circuit components comprises: C-14, Cs-137, Co-60, Ni-59, Ni-63, Sr-90, U-234, 235, 238, Transuranic, and, to a small degree, Nb-94, Cl-36, Tc-99, I-129 (figure 5). For purifying primary coolant, ion exchange resins are utilized, as well as demineralizers.

Spent ion exchange resins constitute the most significant fraction of the wet solid waste produced at power reactors. They are wet solid waste arising during operation of a nuclear power plant. The main wastes arising during the operation of a nuclear power plant are components which are removed during refueling or maintenance (mainly activated solids, e.g. stainless-steel containing cobalt-60 and nickel-63) or operational wastes such as radioactive liquids, filters, and ion-exchange resins which are contaminated with fission products from circuits containing liquid coolant. Powdered resins are used in PWRs, but are commonly used in BWRs with pre-coated filter demineralizers. The make-up water for the steam generation system is similar to fossil fuel power plants: pre-treatment is followed by reverse osmosis system.

2.17 Ruptures and maintenance

Problems associated with Steam Generators in nuclear power plants are tube denting (denting results from the corrosion of the carbon steel support plates and the corrosion product in the crevices between tubes and the tube support plates), wastage, thinning, corrosion, flow-induced vibrations, cracking and deformation of U-tube bend, or of support plates, tube leakage, fractures. Considering a leakage, which would compromise the integrity of separation between radioactive and not-radioactive fluid, the main symptoms are:

- Low level alarm for primary circuit pressurizer.
- Low pressure alarm for primary coolant.
- Low level alarm for low pressure expansion tank.
- High level alarm for activity in steam generator purge line.
- High level alarm for activity in turbine condenser void pumps discharge line.
- High level alarm in the steam generator.
- Imbalance between steam flow and feedwater.

The Steam Generator should be then insulated, and the part of system discharged, when needed, and maintenance operations must be carried out. When a certain percent of the tubes has been plugged as described above, heat transfer deteriorates too much and a final intervention is needed. Typically, it requires up to 60 days to replace a Steam Generator Replacement of Steam Generators is a practice followed by nuclear power stations across the world to ensure longer life to the plant.

During the 40-year initial license period of a power plant, normally steam generation replacement is not considered. To achieve license extension, and extend operating life, this practice has become of wide application all over the world. Some examples are the reactors of: Three Miles Island Unit 1 (U.S.A.), Angra 1 (Brasil). Referring to French power plants, localized corrosion and mechanical problems are observed on some SG tubes (Bezdikian 2009). During the 80's, the thermal aging phenomenon was confirmed, so French Utility and the Manufacturer decided to take measurements to predict the metallurgical aging mechanism to assess for:

- 1st step 40 years evaluation,
- 2nd step 60 years prediction

The objectives were to assess the ability of the cast elbows in existing plants to withstand continued and to maintain components in operating respect safety requirements. The strategy applied was to combined Elbows replacement with Steam Generators replacement. After studies based on economic and technical criteria, EDF set up a Steam Generator replacement program in compliance with the safety rules. These operations are classified into exceptional maintenance operations (all maintenance operations programmed nationally, on large number of NPPs usually carried out once during the lifetime of units), and have therefore significant cost and impact on availability.

They are integrated in new routine maintenance program. All units in study were classified into groups:

- Group 1. Units with SG affected by important degradations and Steam Generator replacement will be carry out in future;
- Group 2. Units with SG lifetime evaluation is within certainties, evolution of

degradations are unknown;

- Group 3. Units with SG Lifetime equal to Plant lifetime.

2.18 Decontamination and decommissioning of steam generators

When approaching end of life, decontamination and decommissioning of Steam Generators must be planned. Decommissioning is the end of life of a facility. It implies many issues: strategic, technological and scientific, measurement, environmental, legislation, and economic issues. In this chapter we focus just on

Steam Generators decommissioning issues. Steam Generators are one of the big metal components in decommissioning nuclear power plants. Their material should be managed with an eye toward reuse, recycling and clearance of all material and scrap (Anigstein et al., 2001; IAEA, 2004; IAEA 2000; NEA, 2008; Nieves et al, (1998). Surface contamination and volume activity must be controlled.

When activity decreases below clearance levels, then legal constraints on material can be eliminated (IAEA, 2004; IAEA, 2000). Clearance levels are a set of requirements on radionuclides concentrations below which radioactive waste is no longer considered a radioactive hazard. Levels for unrestricted release of material are not internationally harmonized, but in any case, have to comply with radiation protection principles. Clearance levels are recommended by EC (European Commission) and other international organizations.

Although some cost-effective options to clearance exist, in the long-term clearance is the best waste management choice internationally accepted (NEA, 2008). When decontamination is possible and justified, metal material will undergo decontamination process in order to fit clearance levels or to reduce occupational exposure of workers, limiting potential releases and exposures, or to allow material reuse and make its management easier. The remaining metal will undergo the process of characterization as radioactive waste. During the decommissioning of nuclear power plants large metallic components like steam generators (or reactor pressure vessels) play a relevant role.

Depending on their radiological properties a disposal or a recycling is possible. Different strategies are used. These strategies are planned considering economic costs, radiological protection or the site situation. A relevant aspect is the possible clearance of the waste material which can be achieved after decay storage if necessary or after a decontamination process. Based on these conditions different strategies are resulting.

Large components can be dismantled on site with the objective of a final storage. Another strategy is achieving the clearance of at least a part of the large component’s material. This can typically be achieved by treatment of the fragmented or entire large components, eventually including decay storage before or after fragmenting.

Three main strategies for big metal components are usually considered:

– transport to an external treatment facility (option number 1)
– transport to an interim storage on site and treatment after decay (option number 2)
– in situ treatment (option number 3)

As an example of in situ treatment (option number 3) we can cite Gundremmingen nuclear power plant. The Steam Generators were filled with water, frozen and cut in situ by a band saw. The main advantage is that the pieces could be treated directly on site, avoiding the transport of heavy parts. On the other hand, it took a time of several years. As an example of transport to an external treatment facility (option number 1) we can cite the Steam generator of the nuclear power plant Stade (Germany). They have been transported to Studvik Radwaste (Sweden) for: dismantling, melting and clearance of material. The large components are leaving the plant at an early stage, allowing the use of the empty place for the dismantling of other parts. Moreover, the decommissioning will be accelerated. In any case, the transport has to be planned very carefully, considering national law prescriptions, and it is cost intensive.

An example of transport to an interim storage on site and treatment after decay is the Decay storage of several reactor pressure vessels and steam generators in the interim storage Nord (Lubmin / Germany) (option number 2). The aim is to achieve the clearance of these components after cutting but without melting. In fact, the decay storage reduces the activity and allows an easier clearance of material without decontamination or other treatment.

It avoids component transport. This strategy is very sensitive for changes in clearance regulations during the decay time (Bauerfeind & Feinhals 2010).

2.19 Decontamination techniques

Decontamination is the removal of contamination from surfaces of facilities or equipment. It can be performed by washing, heating, chemical or electrochemical action, mechanical cleaning, or other techniques. Decontamination is one of the main decommissioning activities. The objectives of decontamination are:

- reduce radiation exposure;
- reduce the volume of equipment and materials requiring radioactive waste
- management;
- remove loose radioactive contaminants and fix the remaining contamination in place in preparation for further activities;
- reduce the magnitude of the residual radioactive source.

Decontamination process will produce much secondary waste, thus a facility for secondary waste treatment is needed (processing chemical solutions, debrides, etc…). Liquid waste and, in general, concentrated waste, must be solidified for disposal, or treated for waste reduction or recycling.

When a treatment is undertaken, there may be an increase in: occupational exposure rates, potential for a release or uptake of radioactive material. These may be higher than to those due to removing, packaging and disposal of the radioactive material without decontamination treatment. All interventions must be defined after an economic / technical / environmental assessment of treatment.

Prior to performing actions, the appropriate knowledge on the presence, kind and distribution of radioactivity inside the item should be known. This stage is the radiological characterization step.

Radiological characterization and radioactivity inventory for decommissioning purpose is an evaluation of systems internal contamination and activation in order to plan the best procedure of intervention. Radiological characterization of a that could lead to accidental contaminations. Representative components for each system can be identified and the materials belonging to these systems can be grouped into: contaminated/ activated/not contaminated or activated.

This first classification is followed by dose rate measurement campaign and radiochemical analysis campaign on representative components in order to detect the level of specific contamination, its isotopic composition, and correlation factors between easily-measured radionuclides and other critical nuclides. Dose rate measurements should be performed on each component, with radiometric survey to detect superficial removable contamination lying on outer surfaces.

To evaluate the deposition of contamination on components inner surface, calculation codes are applied. SGs are typically the primary circuit components which the greater contaminated surface belongs. A complete description of decontamination techniques may be found in literature (IAEA 2006, NEA 1999). For our purpose, just a brief introduction to the available techniques will be presented. After that, a practical example will be provided.

Washing, swabbing, foaming, abrasive blasting, grinding, scarifying, are some examples of physical (mechanical) decontamination techniques. These last techniques are most applicable to the decontamination of structural surfaces. Usually give very high decontamination factors. Decontamination factor is used to express the capability of a process to remove decontamination. It is defined as the ratio of radiation level of the material or component prior to the treatment, and the level of the same measured immediately after decontamination. These techniques are not applicable for complicated surfaces. Chemical decontamination is based on the use of chemical reagents in contact with the contamination layer to remove, in this case, to dissolve. Generally, the process may be continued or repeated until the required decontamination factor is achieved, taking care of the material involved.

Chemical decontamination is often carried out by circulating the selected reagents in the system, while segmented parts may be decontaminated by immerging them into the reagent. Application of specific chemical decontamination depends on many factors, e.g., complexity of shape and dimensions of the item to be treated, kind and characteristics of the chemical reagents, type of material and contamination, availability of proper process equipment, and so on. It may be mild or aggressive, which involves the dissolution of the base metal.

Chemical flushing is recommended for remote decontamination of intact piping systems. It is also suitable for use on complex geometries as well as for a uniform treatment of piping surfaces. These techniques, however, require efficient recycling of reactive chemicals. Compliance with basic health and safety practices regarding chemical agents is required, in addition to the radiological safety aspects. As a minimum, workers – suitably trained – will be equipped with the proper DPI (individual protection devices) such as glasses, full-body protective coveralls, impermeable gloves and foot covers. Additional safety equipment depends on the toxicity of contaminants.

When a chemical decontamination is assisted by an electrical field, we speak about an electrochemical decontamination. It usually involves the immersion of the item in electrolyte bath or using a pad. The electric current causes an anodic dissolution and removal of metal and oxide layer from the surface in treatment. It may be only applied to conductive surfaces.

Melting may also be considered as a decontamination method, although generally limited by specific national law constraints. It homogeny a number of radionuclide's in the ingots and concentrating others in the slag. It is used often for complex geometries, avoiding the problem for inaccessible surfaces. Also, many hybrid technologies between those cited above are in use (Kinnunen 2008).[12]

2.20 Managing the SG service life.

At present, work has been carried out on extending the service life of the first generation power units operating at NPSs equipped with VVER 440 reactors and VVER 1000_based Unit 1 at the Novovoronezh NPS5; work is also being conducted on extending the service life of other power units constructed on the basis of VVER_400 and VVER_1000 reactors. SG tubes are the main critical element that determines the SG service life [for PGV_1000 steam generators, these are the cold headers and the zone of joint through which the header is welded to the shell (the one of weld joint No. 111)]. Repair methods have been developed for all these joints; however, the possibilities of this repair have certain limitations. In parallel, safe operation of SGs is substantiated provided that flaws are revealed from the moment of their incipience to the moment at which they reach critical sizes.[13]

2.21 Description of the transient in VVER 1000-SG

From beginning of the accident. the thermal power was 3120 MW. The initiating event is instantaneous break with equivalent diameter of 100 mm of SG2 cold collector in the area of lower row of heat exchanging tubes. It results in abrupt primary pressure and pressurizer water level decreasing, initiated by the leak of the primary coolant to secondary side of affected steam generator through break of steam generator cold collector. As a result of increase in boiler water level in affected SG by 200 mm from the nominal value, RCP set of loop 2 is tripped at 9,75 s. Loss of coolant in the primary system results in pressure decrease in it up to the set point of reactor scram at 11,2 s of the transient (pressure decrease at the core outlet to 14,7 MPa at reactor power more than 75 % against the nominal one). Coolant leak from the primary system into the affected steam generator results in signal generation at 10 s by the fact of increase in gamma - background in the affected SG steam line. Level in affected SG2 increases by 300 mm from the nominal value at 10,5 s and at 11,75 s (1,0 - time of signal generation, 0,25 s - the time of signal passing in electrical circuits) of the transient, a signal “ primary-to-secondary leak” is generated when two process parameters reach the established values.[14]

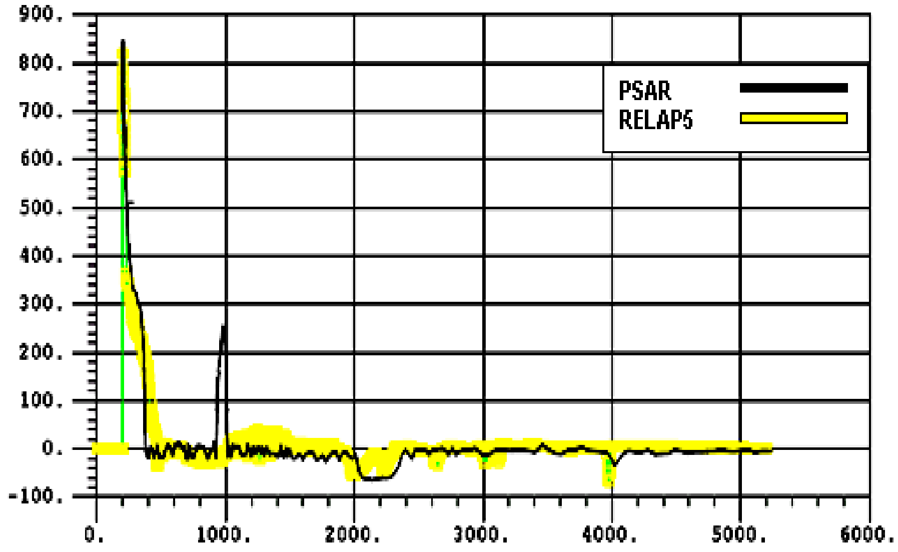


Figure 2.21 - primary to secondary coolant in VVER 1000 SG

2.22 Prospective RP designs of large power and alternative design VVER-1200A (V-501)

The design and construction of VVER SG has various significant features. The SG does not contradict the idea of reducing the basement area. Allows for compact arrangement of the equipment, easy maintenance and simplifies withstanding of seismic loads;

The following are advantages of VVER SG design:

- Reliability (absence of vibrations, damages from foreign objects, no accumulation of sludge at the tube sheet).
- Safety (reliable natural circulation, effective gas removal, water inventory, “thick” tube).
- Convenience of maintenance and repair (easy access on the primary and secondary sides, low irradiation).[15]

2.23. Simulation Methods

In the calculation of primary side flow, the heat exchanger is divided into various of section of tubes. An average flow velocity is evaluated for each group. The primary results of the calculation are the velocity distribution in the header and the flow velocities in the tubes. Model representation of the primary side pressure drops takes into account pressure drops in the inlet and outlet tubes connecting the steam generator with the hot and cold legs of the circulation loops, in both collectors and in the heat exchanger tubes[16]

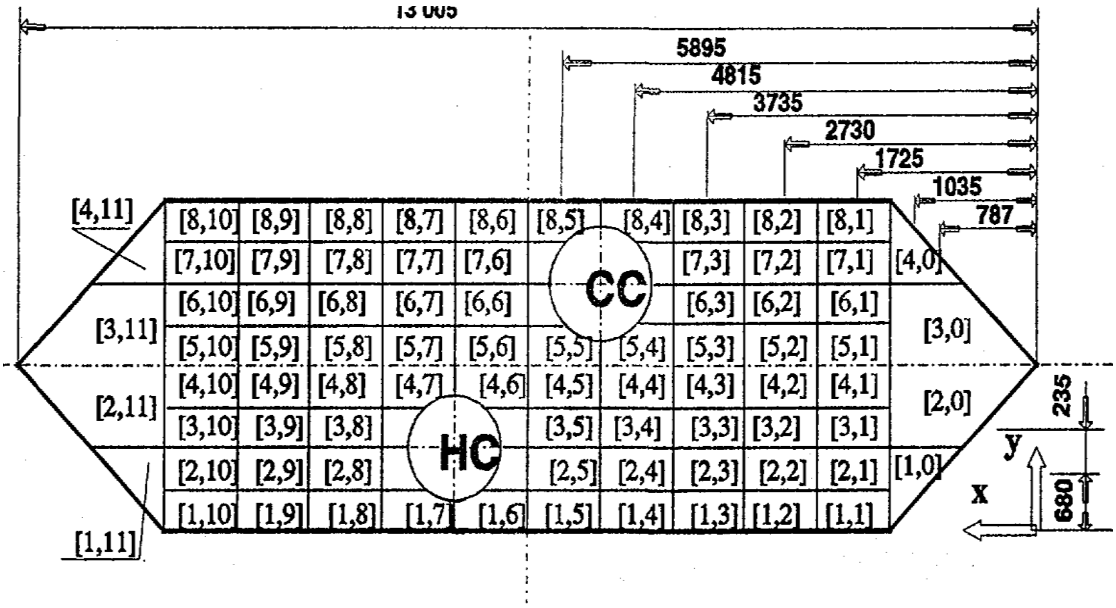


Figure 2.22 - perforated Sheet Division. Dimension [mm].

2.24 Deposit accumulation in PWR steam generators

Due to frequent undesirable consequences of deposit accumulations (e.g., thermal performance penalties, corrosion, thermal hydraulic instabilities, interference with inspections, etc.), utilities employ a variety of means to periodically remove deposit accumulations from SGs. The specific deposit management activities that are chosen by a utility can include a combination of any or all of the available deposit removal services that are available from vendors. Some deposit removal processes are likely to be used during each and every refueling outage, e.g., tube sheet sludge lancing, while others may only be performed once in the life of the plant, e.g., chemical cleaning. The approach to deposit management depends first and foremost upon the utility's goals. The goals that often provide a basis for the strategy include

- Maintain or maximize heat transfer (plant output)
- Reduce risk of secondary side corrosion
- Reduce risk of unwanted thermal hydraulic issues
- Reduce the potential for tube wear and vibration cause by changes in flow patterns or tube fixity conditions [17]

2.25 Regulation and control

There is various way to achieve normal steam generator operation. Variety of parameters that are subjected to regulations. To maintain these aim, steam and feedwater flows need to be balanced; otherwise, the SG would overfill (if the feedwater flow is larger than the steam flow) or dry out (in the case the steam flow is larger than the feedwater flow). The amount of steam leaving the steam generator depends on the electrical load demand by the consumers. The turbine power is a linear function of the reactor coolant average temperature. The reactor temperature regulation system maintains the temperature by adjusting the position of the reactor control rods taking into account the signal of the turbine power. For the fast load changes, the excess steam is directed directly into the turbine condenser, thus bypassing the turbine. In that way, the steam generator pressure is being kept below the safety limits. Additionally, for the SG pressure control, power operated relief and safety valves, mounted on the steam lines, are used. The relief valves are motor-operated valves, while safety valves are passive components.

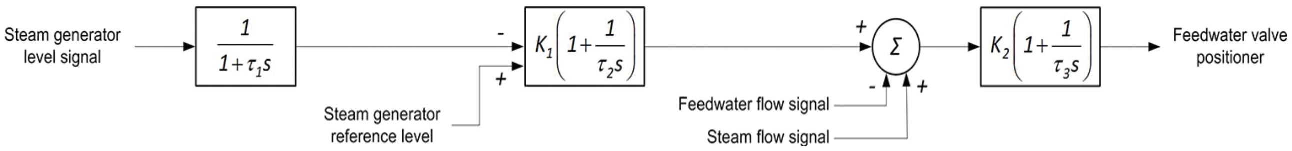


Figure 2.23. Functional diagram of the SG level control system.

Chapter 3 – Financial aspects

3.1 Financial management, resource efficiency and resource saving

The purpose of this section is to design and create competitive developments and technologies that meet the requirements in the field of resource efficiency and resource saving.

Achieving the purpose is provided by solving problems:

- development of a common economic project idea, formation of a project concept;
- organization of work on a research project;
- identification of possible alternatives for research;
- research planning;
- assessment of the commercial potential and prospects of research from the point of view of resource efficiency and resource saving;

– the definition of resource (resource saving), financial, budget, social and economic efficiency of the study [26].

This dissertation paper presents the definition of the BREST nuclear fuel campaign. The fast lead coolant reactor (BREST) was developed as a medium-sized serial power reactor and as an experimental demonstration reactor designed to accumulate operational experience, develop and test technical solutions determining the safety and economy of fast lead coolant reactors, and create a closed nuclear fuel cycle.

The development of BREST reactors is based on the following considerations:

- full reproduction of plutonium in the core without uranium-containing screens;

– natural safety of the reactor with the deterministic elimination of the most dangerous accidents of rapid acceleration, loss of coolant, fires, steam and hydrogen explosions with the destruction of fuel and radioactive emissions of a catastrophic level;

– reduction of radiation hazard of radioactive waste due to transmutation of the most dangerous long-lived actinoids and fission products in the reactor and deep purification of radioactive waste from them with the achievement of the radiation balance between disposed waste and uranium extracted from the earth;

– exclusion of the possibility of using the production of a closed fuel cycle to extract plutonium from irradiated fuel

3.2 Analysis of competitive technical solutions

The VVER 1000 steam generator is a Russian designed heat exchanger which produces saturated steam with pressure of about 6.4Mpa with moisture of 0.2. Due to its durability and longer life spam. it is best of its kind among other leading reactors among other NPP industries. VVER (SG) is only horizontal designed SG across the globe with good safety and anti-built corrosive materials that can stand the test of time. The use of secondary side ethanolamine water chemistry and elimination of copper-bearing components on the secondary side, enable an expected service life of

60 years to be achieved. Many countries across the globe mostly few African nations like Nigeria and Ghana are keying into this technology because of its efficiency and long-life spam.

Analysis of competitive technical solutions is determined by the formula:

$$C = \sum B_i \cdot \text{Б}_i \, , \qquad (3.1)$$

where C is the competitiveness of scientific research or a competitor;

W_i– weight of the indicator (in fractions of a unit);

P_i - point i-th indicator.

The following parameters were chosen as technical criteria: energy efficiency, reliability, safety and functional power. Energy efficiency is determined by the efficiency of the installation and is an important parameter.

The reliability of installations is also one of the important criteria due to the fact that a nuclear reactor is a source of electrical and thermal energy, and in the event of a breakdown, large areas can be left without heat and power supply.

Safety is the most important criterion for nuclear power plants, since a nuclear reactor is a potentially dangerous device that, in the case of emergency situations, can cause a large-scale disaster. An equally important criterion is the functional capacity of the installation, the value of which characterizes the area of the population that the installation can provide with electric and heat energy.

Table 3.1 - Evaluation map for comparison of competitive technical solutions (developments)

Criteria for evaluation	Weight criterion	Points			Competitiveness		
		P_f	P_{c1}	P_{c2}	C_f	C_{c1}	C_{c2}
1	2	3	4	5	6	7	8

Technical criteria for evaluating resource efficiency							
1. Energy efficiency	0.1	4	5	4	,5	0,5	0,4
2. Reliability	0.26	4	4	4	1,22	1	1
3. Safety	0.2	4	4	5	1,2	1	1
5. Functional power	0.2	3	3	3	0,7	1	0,7
Economic performance evaluation criteria							
1. Development cost	0.05	4	4	4	0.26	0.2	0.2
2.Market penetration rate	0.03	5	5	5	0.05	0.15	0.16
3. Estimated lifetime	0.1	5	4	3	0.5	0.4	0.2
4. After-sales service	0.02	5	4	3	0.1	0.06	0.07
Total	**0.96**	**34**	**33**	**31**	**4.53**	**4.31**	**3.73**

Above is an analysis of the competitiveness of nuclear power facility presented in this paper among domestic developments of BN-600 and BN-800. From the analysis it can be seen that the advantage of the developed NPF is especially noticeable in safety and reliability, which is one of the main reasons for successful market entry, since the consumer is primarily prone to choosing safe energy. The performance of the nuclear power facility under consideration is not inferior to that of competitors. The developed facility will allow to get rid of accumulated SNF by other installations.

3.3 SWOT analysis

SWOT analysis is a complex analysis of a research project that is used to study the external and internal environment of the project. Strengths are factors that characterize the competitive side of a research project. In other words, strengths are the resources or capabilities that a project management has and that can be effectively used to achieve their goals.

Weakness is the lack, omission or limitation of a research project that impedes the achievement of its goals. This is something that is bad at the project or where it has insufficient capabilities or resources compared to its competitors. Opportunities include any present or future preferred situation arising in the project's environmental conditions, such as a trend, change, or perceived need that supports demand for project results and allows project management to improve its competitive position.

A threat is any undesirable situation, tendency or change in the environmental conditions of a project that are destructive or threatening to its competitiveness in the present or future. The threat may be a barrier, restriction or anything else that may cause problems, destruction, damage or damage to the project [27].

The full table of the SWOT analysis is presented in Table 3.2.

Table 3.2 - SWOT Analysis

	Strengths of a research project:	**Weaknesses of a research project:**
	S1. The uses of a body scheme increase the safety of the facility; S2. Understanding the	W1. Challenges of timely defection of defect in NPP material W2. Inadequate uses of

	hydrodynamics of heat transfer in SG; S3. Analysis of heat exchanger.	PPE within the facilities in the process of performing capillary testing such as (safety shoes)
The possibility: P1. A huge amount of material separated from spent nuclear fuel reactors, which is now practically not used; P2. Providing additional jobs place; P3. Transition from fissile materials to "raw materials"; P4. Reduced electricity prices.	1. Reducing the cost of electricity due to the deep burning and long campaign of fuel; 2. The closure of the NFC will lead to the use of “raw” material as fuel, as a result, there will be no need to use fissile material obtained using current technologies.	1. The possibility of closure of nuclear fuel cycle in reactors of this type can lead to cheaper nuclear power, and can also reduce the cost of mining and enrichment of uranium; 2. Qualified specialists can contribute to the improvement of the quality of work of a nuclear power plant and its safety.
Threats: T1. Natural disasters: earthquakes, tsunamis, tornadoes, accidents; T2. Reducing the interest of the state in the development of nuclear energy and the	1. The body type reactor serves as a protective sheath to prevent the release of radioactive substances in an accident. 2. The advantages of NPF will not attract actions of a terrorist and sabotage	1. Economic uncertainty of the project, pilot-demonstration reactor. This is precluded by the allocation of additional resources for research and experimentation; 2. The occurrence of an

introduction of new capacities; T3. The threat of sabotage and terrorist actions against nuclear power facility.	nature, since the fuel produced in the reactor cannot be used to create weapons.	accident will reduce the interest in projects of this kind, but using features of fuel and coolant can minimize the probability of an accident.

After analyzing the result, we can conclude that the most optimal strategy for entering the development of a market is a strategy of joint business activities.

3.4 Project Initiation

As concerned parties, there are organizations or stakeholders that are actively participating in the project, or which interests are considered to be both positively or negatively in duration of the projects shortly after it is finished. These parties could be customers, sponsors, public sphere among others. Information's relating to both parties are listed below in Table 3.3.

Table 3.3 - Stakeholders of the project

Project stakeholders	**Stakeholder expectations**
ROSATOM'	Design and development of good materials that can stand corrosion and **degradation** such as heat exchange tube material 08Ch18N10T and collector material 10GN2MFA respectively**.** Hence the above-mentioned fact as big challenges associated with the operation of steam generator

Table 3.3.1 provides information on the hierarchy of project objectives and criteria for achieving purpose.

Table 3.3.1 - Purpose and Results of the Project

Purpose of project:	To study the mechanics and working fluid process in VVER 1000 horizontal steam generator with saturated steam.
Expected results of the project:	Sustainable construction and design scheme of the steam generator used in VVER reactor
Criteria for acceptance of the project result:	The result for selection SG materials was the optimal in other to maintain safe and good working environment during operation
Requirements for the project result:	**Demand:**
	Consideration of various SG efficiencies.
	Investigating the durable of the strength of material use in the design of SG
	Evaluation of the results and comparison of their effectiveness.

3.5 The organizational structure of the project.

At this stage of work, it is necessary to solve the following questions: who will be part of the working group of this project, determine the role of each participant in this project, and also prescribe the functions performed by each of the participants and their labor costs in the project.

This information is presented in table 3.4.

Table 3.4 - Project Working Group

	Full name, main place of work, position	Role in the project	Functions	Labor costs, hours.
	Gvozdyakov.D.V. TPU, Associate Prof	Supervisor	Expert advisory	32
	Nnodi Chinweikpe Akelachi, TPU, engineer	Project contractor	Implementation of calculations	498

3.6 Limitations and assumptions of the project

Project limitations are all factors that can serve as a restriction on the degree of freedom of the project team members, as well as “project boundaries” —the parameters of the project or its product that will not be implemented under this project.

Project limitations are listed in table 3.5.

Table 3.5 - Project limitations

Factor	Limitations / Assumptions
3.1. Project's budget	180333
3.1.1. Source of financing	TPU
3.2. Project timeline:	08.03.19 - 31.07.19
3.2.1. Date of approval of the project management plan	08.02.19
3.2.2. Completion date	29.07.19

3.7Planning of research project

3.7.1 Project plan

As part of planning a research project, a calendar schedule was built using a Gantt chart. Gantt chart is a type of bar charts (histograms), which is used to illustrate the project schedule, where the work on the topic is represented by lengthy segments, characterized by the dates of the beginning and end of these works.

Table 3.6 – Project Schedule

Job Code	Title	Duration, working days	Start date	Date of completion	List of participants
Development of technical task					
1	Drafting and statement of technical specifications	1	01.02.19	3.02.19	A.C Nnodi
Choosing the direction of research					
2	Selection and study of materials on the topic	4	3.02.19	8.02.19	A.C Nnodi. D.V Gvozdyakov
3	Scheduling work on the topic	1	7.02.19	10.02.19	A.C Nnodi
Theoretical and experimental studies					
4	Study of the design features of the reactor and software under consideration	21	10.02.19	10.03.19	A.C Nnodi
5	Development of the calculated model of the reactor under investigation	14	11.03.19	28.03.19	A.C Nnodi
6	Making calculations	14	21.03.19	21.04.19	A.C Nnodi
Summary and evaluation of results					
7	Evaluation of the effectiveness of the results	2	19.04.19	23.04.19	A.C Nnodi,

Filling out of master's thesis					
8	Drafting an explanatory note	22	18.04.19	26.05.19	A.C Nnodi
9	Checking the work performed on compliance with all state standards	4	12.05.19	31.05.19	A.C Nnodi,Gvozdyakov.D.V.
Total:		**83**			

Table 3.6.1 presents the calendar schedule for conducting scientific research.

Table 3.6.1 – Calendar schedule of scientific research

	Type of work	Performers	к, al. days	Duration of work											
				February			March			April			May		
	Drafting and statement of technical specifications	Project leader													
	Selection and study of materials on the topic	Project leader, engineer													
	Scheduling work on the topic	Project leader													
	Study of the design features of the	Engineer	7												

	reactor and software under consideration														
	Development of the calculated model of the reactor under investigation	Engineer	7												
	Making calculations	Engineer	3												
	Evaluation of the effectiveness of the results	Project leader, engineer													
	Drafting an explanatory note	Engineer	2												
	Checking the work performed on compliance with all state standards	Project leader, engineer													

– Project leader, Engineer

3.8 Research Budget

When planning a research budget, a full and reliable reflection of all types of expenses related to its implementation should be provided. In the process of budgeting, the following grouping of costs by items is used:

- material costs;
- costs of special equipment for scientific (experimental) work;
- basic salary of the performers of the topic;
- additional salary for the performers of the topic;
- deductions to extra-budgetary funds (insurance deductions);
- overhead.

3.9 Calculation of material costs

Values of prices for material resources can be set according to data posted on relevant websites on the Internet by manufacturers (or supplier organizations). Material costs required for this development are recorded in table 3.9. The absence in the table of the division into sources of financing indicates that there is only one source. The source of finance in this work is the engineer [28].

The main work for the final qualifying work was carried out for a laptop in the room of a residential house. The time spent at the laptop will be equal to 498 hours. Laptop power: 0.065 kW. Electricity costs are calculated by the formula:

$$C = T_{el} \cdot P \cdot F_{eq}, \qquad (3.2)$$

C =5.8.0.065.498= 187.74 rubbles

where $Ц_{эл}$ – tariff for industrial electricity (5.8 rubles per 1 kW·h);

P – equipment power, kW;

$F_{об}$ – equipment usage time, h

The cost of electricity amounted 187.74 rubles.

Table 3.7 – Material costs

Name	unit of measurement	amount	Price per unit, rub.	The cost of materials, (C_m), rub.
1. Electricity	kW·h	498	5.8	187.74
2. Internet access	month	4	250	1000.00
Total				1270.35

3.10 Basic salary

This article includes the basic salary of workers directly involved in the implementation of work on this topic. The value of salary costs is determined based on the labor intensity of the work performed and the current salary system [28]. The basic salary (S_b) is calculated according to the following formula:

$$S_{\text{b}} = S_a \cdot T_{\text{w}}, \qquad (3.3)$$

where W_b – basic salary per employee;

T_{w} – the duration of the work performed by the scientific and technical worker, working days;

Wa - the average daily salary of an employee, rub.

The average daily salary is calculated by the formula:

$$S_d = \frac{S_m \cdot M}{F_{\text{v}}}, \qquad (3.4)$$

where S_m – monthly salary of an employee, rub.;

M – the number of months of work without leave during the year:

– at holiday in 24 slave. M day = 11.2 months, 5-day week;

F_v – valid annual fund of working time of scientific and technical personnel.

The actual annual working time fund for scientific and technical personnel is presented in Table 3.7.1.

Table 3.7.1 - Actual annual Fund of working time

Working time	
Calendar number of days	365
The number of non-working days: – weekend; – red-letter day	66 104 14
Loss of working time: – holiday; – absences due to illness	 24 –
Valid annual working time fund	223

Monthly salary of an employee:

$$S_m = S_s \cdot (k_p + k_s) \cdot k_d \,, \qquad (3.5)$$

where S_s – base salary, rub.;

k_p – premium ratio;

k_s – the coefficient of surcharges and allowances;

k_d – district coefficient

The calculation of the basic salary is given in table 3.7.2

Table 3.7.2 - Calculation of basic salary

Monthly position salary is calculated as follows:

$$S_m = S_{em} \cdot k_r \qquad (3.6.2.4)$$

where S_{em} – monthly position salary, rub.;

k_p – regional salary coefficient (1,3 for Tomsk).

Performers	S_{em}, rub	k_r	S_m, rub	S_d, rub	T_w, w.days.	S_{base}, rub	S_{bon}, rub
Scientific advisor	33664	1.3	43763.2	1569	8	12552	1255
Engineer	12664	1.3	16463.2	590	83	48970	489

The base salary for a scientific advisor from TPU is calculated based on industrial remuneration. In TPU this remuneration considers next content for salary:

- emolument, determined by the enterprise;
- incentive payments, determined by the head of departments for efficient work, the accomplishment of job duties and etc.;
- other payments;
- regional salary coefficient [18].

Additional salary equals to 10% from the base salary. According to calculations, the additional salary for an engineer is 489 rubles and scientific advisor is 753 respectively.

3.11 Taxes for non-budget funds

This part of costs shows the necessary taxes according to laws of the Russian Federation about social assurance, pension fund and medical insurance from costs on salary.

Contributions are calculated as follows:

$$S_{soc} = k_{contr} \cdot (S_{base} + S_{bon}), \qquad (3.6.3.1)$$

where k_{contr} – the coefficient for taxes in non-budget funds

Besides, taxes in non-budget funds are not required for scholarships. At the moment of the 2019 year, the insurance fees are 30%, however, for education enterprises, there is a reduced rate equal to 27,1%.

Table 3.7.3 - **Taxes for non-budget funds**

	Scientific advisor	Engineer
Base salary, rub.	12552	48970
Additional base salary, руб.	1255	489
Coefficient for non-budget taxes, %	27,1	
Total, rub.	1595.1	13404

3.12 Formation of budget costs

The calculated cost of research is the basis for budgeting project costs.

Determining the budget for the cost of scientific research for each version is given in Table 3.7.6.Table 3.7.6 – Items expenses grouping

Name	Material costs	Basic salary	Additional salary	Labor tax	Overhead	Total planned cost
Cost, rubles	5630	61522	6152	14999	20302	108605

3.13 Project Risk Register

The identified risks of the project include possible uncertain events that may occur in the project and cause consequences that will entail undesirable effects. Information about this is entered in the project risk register.

The project risk register is presented in table 3.8.

Table 3.8 - Risk register

	Risk	Potential impact	Probability of occurrence (1-5)	Risk impact (1-5)	Risk level *	Ways to mitigate risk	conditions of occurrence
	Laptop hard disk crash	impossibility to carry out further work	1	5	low	Storage of information on external media or in the "cloud"	Mechanical damage or large amount of data stored on the hard disk
	Software failure at a certain stage of calculation	The lose of additional time for recalculation	2	3	average	Do not allow the inclusion of third-party programs during the calculations	No result or stop calculation at a certain point for a long time

3.14 Evaluation of the comparative effectiveness of the study

Determination of efficiency is based on the calculation of the integral indicator of the effectiveness of scientific research. Its finding is associated with the definition of two weighted average values: financial efficiency and resource efficiency.

The integral indicator of the financial efficiency of a scientific study is obtained in the course of estimating the budget for the costs of three (or more) variants of the execution of a scientific study. For this, the largest integral indicator of the implementation of a technical problem is taken as the calculation base (as a denominator), with which the financial values are correlated for all execution options [30].

The integral financial indicator of the development is determined by:

$$I_{\mathrm{f}}^{p} = \frac{F_{pi}}{F_{\max}}, \tag{3.9}$$

where $I_{\mathrm{f}}^{\mathrm{ex.i}}$ – integral financial index of development;

F_{pi} – the cost of the i-th version;

$F_{\max}$ – the maximum cost of execution of a research project (including analogues).

The obtained value of the integral financial indicator of development reflects the corresponding numerical increase in the budget of development costs in times (the value is greater than one), or the corresponding numerical reduction in the cost of development in times (the value is less than one, but greater than zero).

Since the development has one execution, that $I_{\mathrm{f}}^{\mathrm{ex.i}}$ = 1.

The integral indicator of the resource efficiency of the variants of the research object can be determined as follows:

$$I_{m}^{a} = \sum_{i=1}^{n} a_i b_i^{a}\ ,\ I_{m}^{p} = \sum_{i=1}^{n} a_i b_i^{p} \qquad 3.10)$$

where I_m – integral indicator of resource efficiency for the i-th version of the development;

a_i – the weighting factor of the i-th version of the development;

b_i^a, b_i^p – score in points of the i-th version of the development, set by an expert on the selected rating scale;

n – number of comparison parameters.

The calculation of the integral indicator of resource efficiency is presented in the form of table 3.9.

Table 3.9 - Evaluation of project performance characteristics

Criteria	Weight coefficient parameter	Evaluation
1. Energy efficiency	0.1	4
2. Reliability	0.26	4
3. Security	0.2	4
4. Functional power	0.2	3
Economic performance evaluation criteria		
	0.05	4
	0.03	4
	0.1	4
	0.02	3
Total	1	36

$I_m = 0.1{\cdot}4+0.26{\cdot}4+0.2{\cdot}4+0.20{\cdot}3+0.05{\cdot}4+0.03{\cdot}4+0.1{\cdot}4+0.02{\cdot}5= 4.16$

The integral development efficiency indicator (I_f^d) is determined on the basis of the integral indicator of resource efficiency and the integral financial indicator using the formula:

$$I_f^d = \frac{I_m^d}{I_f^d}, I_f^a = \frac{I_m^a}{I_f^a} \text{ etc } I_{ex.2} = \frac{I_{d-ex2}}{I_f^{ex.2}} \text{ etc} \qquad (3.11)$$

Comparison of the integral indicator of the effectiveness of the current project and analogues will determine the comparative efficiency. Comparative effectiveness of the project:

$$S_{av} = \frac{I_f^d}{I_f^a}. \qquad (3.12)$$

Table 3.9.1 - Development Efficiency Indicators Evaluation

Integrated financial management	1
Integral indicator of development resource efficiency	4,71
Integral performance	4,71

Comparison of the values of integral performance indicators allows us to understand and choose a more effective solution to the technical problem from the standpoint of financial and resource efficiency. But since the task has strict conditions, the solution has only one option.

Chapter 4 - Social responsibility

In recent time, the main ways for radical improvement for prophylactic work referred to reduce total Incidents rate and occupational morbidity is the widespread implementation of an integrated occupational safety and health management system. That means combining isolated activities into a single system of targeted actions at all levels and stages of the production process.

Occupational safety is a system of legislative, socio-economic, organizational, technological, hygienic and therapeutic and prophylactic measures and tools that ensure the safety, preservation of health and human performance in the work process [19].

Rules for labor protection and safety measures are introduced in order to prevent accidents, ensure safe working conditions for workers and are mandatory for workers, managers, engineers and technicians.

A dangerous factor or industrial hazard is a factor whose impact under certain conditions leads to trauma or other sudden, severe deterioration of health of the worker [31]. A harmful factor or industrial health hazard is a factor, the effect of which on a worker under certain conditions leads to a disease or a decrease in working capacity

4.1 Analysis of hazardous and harmful factors

The working conditions in the workplace are characterized by the presence of hazardous and harmful factors, which are classified by groups of elements: physical, chemical, biological, psychophysiological. The main elements of the production process that form dangerous and harmful factors are presented in Table 4.1.

Table 4.1 – The main elements of the production process, forming hazardous and harmful factors

Parameters used within the plant during production process	FACTORSGOST 12.0.003-74 Occupational safety standards system		Documents
	harmful	Dangerous	
Working within the NPP industries is associated with a lot of hazard. During the student internship program, precautions were taken in other to	—	Electricity	GOST 12.1.038-82 Occupational safety standards system. electrical safety
	The impact of radiation (HF, UHF, SHF, etc.)	—	SanPiN 2.2.2 / 2.4.1340-03 Sanitary-epidemiological

avoid accident within the facility. Putting on personnel protection equipment (PPE) played very crucial rule in ensuring accident free atmosphere during our practice at the Rostov NPP manufacturing facility.			rules and regulations. "Hygienic requirements for personal computers and organization of work"
Individual capillary testing was carried out during practical section and the chemicals involved where very dangerous to health. Both chemicals as listed below were use to detect defect in SG, reactor among others components of VVER reactor. The names are stated below: a. Developers b. Penetrant	—	Fire	Fire and explosion safety of industrial installations GOST R12.1.004-85 SSBT

Students were taught on how to protect themselves by wearing various safety equipment as part of safety precaution as listed in 4.5.This is part health and safety requirement in line with Russia federation and global best practice. The practice took place at ROSTOV.			

a. physical:
- temperature and humidity;
- noise;
- static electricity;
- electromagnetic field of low purity;
- illumination;
- presence of radiation;

b. psycho physiological:
- psychophysiological dangerous and harmful factors are divided into:
- physical overload (static, dynamic)
- mental stress (mental overstrain, monotony of work, emotional

overload).

4.2 Justification and development of measures to reduce the levels of hazardous and harmful effects, and eliminate their influence

4.2.1 Organizational arrangements

All personnel are required to know and strictly observe the safety rules. The training of personnel in occupational safety and industrial sanitation consists of introductory briefing and briefing at the workplace by the responsible person.

The commission responsible for the work place checks the knowledge of safety rules after training at the workplace. After that, commission assign the safety qualification group corresponding to the employee’s knowledge and experience of work and issue a special certificate.

Persons serving electrical installations must not have injuries and illnesses that interfere with manufacturing activity. The state of health is established by medical examination before being employed.

4.2.2 Technical Activities

The rational layout of the workplace provides for a clear order and permanent placement of objects, means of labor and documentation. Object, what is required to perform the work more often, should be located in the easy reach of the workspace, as shown in Fig. 4.1.

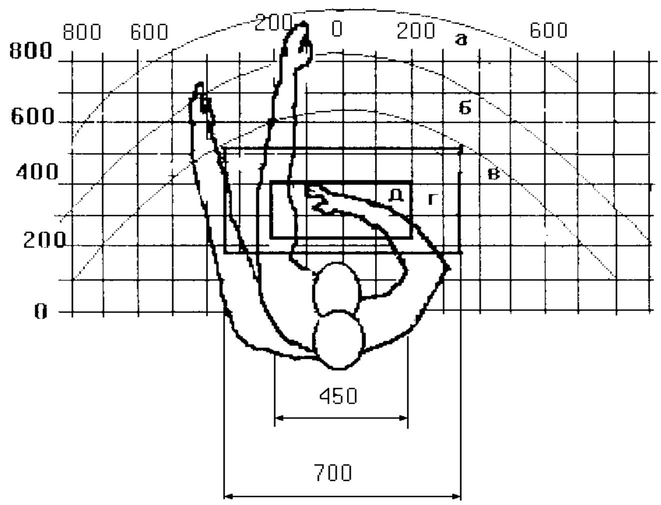


Figure 4.1 - Hand reach zones in the horizontal plane

- Zone of maximum reach of hands;
- reach zone of fingers with outstretched arm;
- easy reach zone of the palm;
- Optimum space for fine handmade work
- the optimum space for rough manual work;

Optimal placement of objects of labor and documentation in the reach of hands:

- the display is located in zone a (in the center);
- keyboard - in the area of e / d;
- the system unit is located in zone b (on the left);
- the printer is in zone a (right);

The documentation is placed in the easy reach of the palm - in (left) - literature and documentation necessary for work; In the drawers of the table - literature that is not used constantly. When designing a desk, the following requirements must be taken into account.

The height of the working surface of the table should be within 680-800 mm. The height of the working surface with the keyboard should be 650 mm. The working table must be at least 700 mm wide and at least 1400 mm long. There should be a legroom of not less than 600 mm in height, a width of at least 500 mm, a depth at the knee level of at least 450 mm and at the level of elongated legs - not less than 650 mm.

The work chair must be lift able and adjustable in height and angle of inclination of the seat and backrest, as well as the distance of the backrest to the front edge of the seat. It is recommended that the height of the seat be above the floor level of 420 to 550 mm. The design of the working chair should ensure: the width and depth of the seat surface is not less than 400 mm; Seat surface with recessed front edge.

The monitor should be located at the eye level of the operator at a distance of 500 - 600 mm. According to the norms, the viewing angle in the horizontal plane should be no more than 45º to the normal of the screen. It is better if the viewing angle is 30 °. In addition, it should be possible to select the level of contrast and brightness of the image on the screen. It should be possible to adjust the screen:

- height +3 cm;
- slope from 10 to 20 degrees with respect to the vertical;
- in the left and right directions.

The keyboard should be placed on the surface of the table at a distance of 100 - 300 mm from the edge. The normal position of the keyboard is at the elbow level of the operator with an angle of inclination to the horizontal plane of 15º.It is more convenient to work with keys that have a concave surface, a quadrangular shape with rounded corners. The key design should provide the operator with a click sensation. The color of the keys should contrast with the color of the panel.

It is recommended to choose soft, low-contrast floral shades that do not disperse attention (low-saturated shades of cold green or blue colors) in the case of monotonous mental work requiring considerable nervous tension and great concentration. Shades of warm tones are recommended at work, which requires intense mental or physical tension, due to excitation of human activity.

4.2.3 Safe work conditions

The main parameters characterizing the working conditions are microclimate, noise, vibration, electromagnetic field, radiation, illumination. The air of the working area (microclimate) is determined by the following parameters: temperature, relative humidity, air speed. The optimum and permissible values of the microclimate characteristics are established in accordance with [20] and are given in Table 4.2.

Table 4.2 – Optimal and permissible parameters of the microclimate

Period of the year	Temperature, ^{o}C	Relative humidity,	Speed of air

		%	movement, m / s
Cold and changing of seasons	23-25	40-60	0.1
Warm	23-25	40	0.1

The measures for improving the air environment in the production room include: the correct organization of ventilation and air conditioning, heating of room. Ventilation can be realized naturally and mechanically. In the room, the following volumes of outside air must be delivered:

- at least 30 m^3 per hour per person for the volume of the room up to 20 m^3 per person;
- natural ventilation is allowed for the volume of the room more than 40 m^3 per person and if there is no emission of harmful substances.
- The heating system must provide sufficient, constant and uniform heating of the air. Water heating should be used in rooms with increased requirements for clean air. The parameters of the microclimate in the laboratory regulated by the central heating system, have the following values: humidity 40%, air speed 0.1 m / s, summer temperature 20-25 °C, in winter 13-15 °C. Natural ventilation is provided in the laboratory. Air enters and leaves through the cracks, windows, doors. The main disadvantage of such ventilation is that the fresh air enters the room without preliminary cleaning and heating.

Noise and vibration worsen working conditions, have a harmful effect on the human body, namely, the organs of hearing and the whole body through the central nervous system. It results in weakened attention, deteriorated memory, decreased response, and increased number of errors in work. Noise can be generated by operating equipment, air conditioning units, daylight illuminating devices, as well as spread from the outside. When working on a PC, the noise level in the workplace should not exceed 50 dB.

The screen and system blocks produce electromagnetic radiation. Its main part comes from the system unit and the video cable. According to [32], the intensity of the electromagnetic field at a distance of 50 cm around the screen along the electrical component should be no more than:

- in the frequency range 5 Hz - 2 kHz - 25 V / m;
- in the frequency range 2 kHz - 400 kHz - 2.5 V / m.

The magnetic flux density should be no more than:

- in the frequency range 5 Hz - 2 kHz - 250 nT;
- in the frequency range 2 kHz - 400 kHz - 25 nT.

There are the following ways to protect against EMF:

- increase the distance from the source (the screen should be at least 50 cm from the user);
- the use of pre-screen filters, special screens and other personal protective equipment.

When working with a computer, the ionizing radiation source is a display. Under the influence of ionizing radiation in the body, there may be a violation of normal blood coagulability, an increase in the fragility of blood vessels, a decrease in immunity, etc. The dose of irradiation at a distance of 20 cm to the display is 50 μrem / hr. According to the norms [21], the design of the computer should provide the power of the exposure dose of x-rays at any point at a distance of 0.05 m from the screen no more than 100 μR / h.

Fatigue of the organs of vision can be associated with both insufficient illumination and excessive illumination, as well as with the wrong direction of light.

4.3 Electrical safety

Depending on the conditions in the room, the risk of electric shock to a person increases or decreases. Do not operate the electronic device in conditions of high humidity (relative air humidity exceeds 75% for a long time), high temperature (more than 35 ° C), the presence of conductive dust, conductive floors and the possibility of simultaneous contact with metal components connected to the ground and the metal casing of electrical equipment. The operator works with electrical devices: a computer (display, system unit, etc.) and peripheral devices. There is a risk of electric shock in the following cases:

- with direct contact with current-carrying parts during computer repair;
- when touched by non-live parts that are under voltage (in case of violation of insulation of current-carrying parts of the computer);
- when touched with the floor, walls that are under voltage;
- Short-circuited in high-voltage units: power supply and display unit.

Measures to ensure the electrical safety of electrical installations:

- disconnection of voltage from live parts, on which or near to which work will be carried out, and taking measures to ensure the impossibility of applying voltage to the workplace;
- posting of posters indicating the place of work;
- electrical grounding of the housings of all installations through a neutral wire;
- coating of metal surfaces of tools with reliable insulation;
- inaccessibility of current-carrying parts of equipment (the conclusion in the case of electroporating elements, the conclusion in the body of current-carrying parts) [22].

4.4 Fire and explosive safety

According to [34], depending on the characteristics of the substances used in the production and their quantity, for fire and explosion hazard, the premises are divided into categories A, B, C, D, E. The room belongs to category B according to the degree of fire and explosion hazard. It is necessary to provide a number of preventive measures.

Possible causes of fire:

- malfunction of current-carrying parts of installations;

- work with open electrical equipment;
- short circuits in the power supply;
- non-compliance with fire safety regulations;
- presence of combustible components: documents, doors, tables, cable insulation, etc.

Activities on fire prevention are divided into: organizational, technical, operational and regime.

Organizational measures provide for correct operation of equipment, proper maintenance of buildings and territories, fire instruction for workers and employees, training of production personnel for fire safety rules, issuing instructions, posters, the existence of an evacuation plan. The technical measures include: compliance with fire regulations, norms for the design of buildings, the installation of electrical wires and equipment, heating, ventilation, lighting, the correct placement of equipment.

The regime measures include the establishment of rules for the organization of work, and compliance with fire-fighting measures. To prevent fire from short circuits, overloads, etc., the following fire safety rules must be observed:

- elimination of the formation of a flammable environment (sealing equipment, control of the air, working and emergency ventilation);
- use in the construction and decoration of buildings of non-combustible or difficultly combustible materials;
- the correct operation of the equipment (proper inclusion of equipment in the electrical supply network, monitoring of heating equipment);
- correct maintenance of buildings and territories (exclusion of the source of ignition - prevention of spontaneous combustion of substances, restriction of fireworks);
- training of production personnel in fire safety rules;
- the publication of instructions, posters, the existence of an evacuation plan;
- compliance with fire regulations, norms in the design of buildings, in the organization of electrical wires and equipment, heating, ventilation, lighting;

- the correct placement of equipment;
- well-time preventive inspection, repair and testing of equipment.
- In the case of an emergency, it is necessary to:
- inform the management (duty officer);
- call the Emergency Service or the Ministry of Emergency Situations - tel. 112;
- take measures to eliminate the accident in accordance with the instructions.

4.5 Safety with working with chemicals

The following chemicals and precaution were taken to ensure healthy and safety working conditions in accordance with GOST 12.1.007-76 Occupational safety standards system as enshrined in Russian federation law. Harmful substances used while carrying out the testing are stated below:

- Uses of safety hand gloves
- Helmet
- Safety glasses
- Lab coat

4.6 Conclusion

From my research, studies and analytical effect in assessment of pressure of the working fluid (steam) on its basic parameters, as well as the moisture content of the steam entering the louvered separator or steam receiving ceiling was calculated and achieved. However, comparison shows that, conducting research within the University premises is less cost effective than performing it in the industry. The purpose of this course of action is to achieve good financial efficiency.

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MITIGATION STRATEGY AGAINST NUCLEAR AND RADIATION TERRORISM IN NIGERIA

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СТРАТЕГИЯ СНИЖЕНИЯ РИСКОВ ПРОТИВ ЯДЕРНОГО И РАДИАЦИОННОГО ТЕРОРИЗМА В НИГЕРИИ

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***Аннотация**. Распространение оружия массового поражения несёт угрозы миру и национальной безопасности каждого государства. Террористическая активность в мире ставит новые требования к обеспечению физической безопасности ядерных и радиоактивных веществ для развитых государств. Нигерия – член МАГАТЭ, развивающий ядерные технологии для образования и промышленности, использование ядерных материалов для выработки электроэнергии так же входит в планы дальнейшего развития государства. Действия террористической исламистской секты «Боко Харам» в северо-восточной части страны вынуждают серьёзно рассматривать угрозу атаки на объекты ЯТЦ с целью завладеть ядерными материалами и радиоактивными веществами. В этой работе проведён анализ угроз террористических атак в различных частях страны с учётом местоположения объектов и маршрутов перемещения ЯМ и РВ между ними. Предложены действия, которые Нигерия должна совершить на международной арене и внутри государства, чтобы обеспечить физическую безопасность и гарантии нераспространения. Рассмотрена деятельность группировки «Боко Харам», национальное законодательство Нигерии в области обращения с ЯМ и РВ, а также участие в международных договорах и соглашениях по нераспространению.*

Introduction. An attack by terrorist on radiological or nuclear facilities could result in the release of radiation and/or possible loss of control of radioactive material; this in turn, could result in harm to the public and the environment. Considering the activities of the radical Islamic sect "Boko Haram" north eastern Nigeria and their affiliation to the terror group al-Qaeda, there is a need to secure and safeguard nuclear facilities and radiation sources. Appropriate plans aimed at ensuring that terrorist groups do not gain possession of radioactive materials that could be used in the production of weapon of mass destruction WMD need to be implemented.

This paper seeks to highlight the security challenges to nuclear technology applications in Nigeria. The use of nuclear and radioactive source in the country is on the increase. This paper will identify applications of Sources in education and industry within Nigeria. The Sources used, industry and application of this Sources are highlighted. Furthermore, the paper demonstrates Nigeria's commitment to the safety, security and safeguards of nuclear and radioactive facilities and activities. Strategies aimed at bolstering security and eliminating threats to nuclear facilities were discussed.

Brief overview of Nigeria. Nigeria is the most populous nation in Africa with over 170 million, situated on the Gulf of Guinea, with capital city-Abuja,36 states,6 geopolitical zones, with 3 major languages comprises of (Hausa, Igbo, and Yoruba),the country has four major International Airport through which goods and services are imported into the country, namely: (Abuja, Lagos, Port-Harcourt and Kano) with major sea ports (Port-Harcourt, Calabar, Lagos and Warri) the country also has neighboring countries (Benin, Niger, Cameroon and Chad). Figure 1 shows the Maps of Nigeria.

Brief history of boko haram terrorism in Nigeria. Nigeria is the most populous black Nation of Africa that has been known to be relatively peaceful and free from terrorism until the rise of Boko Haram in 2009 after the death of their leader Mr Mohammad Yusuf Mohammed who was killed by Nigerian police. Since then, the group has been fighting the government; his death took a different magnitude through an increase of bomb detonation in many locations such as villages, towns, religious gathering and market places amongst others [23].

Boko Haram was discovered to have an international affiliation with the broader al-Qaeda network. Members of Boko Haram are also believed to have trained in Afghanistan with the help of al-Qaeda [24]. In 2002, Osama bin Laden send one of his aides to Nigeria to distribute the sum of $3 million to sympathetic Salafi groups, among the recipients was late Mohammed Yusuf who was the Boko Haram's founder [25]. Intelligent data gathered by the United States Government, suspects there could be communications training, and weapons links among the group known as Boko Haram, and al-Qaeda in the Arabian Peninsula in Yemen, al-Shabaab and al-Qaeda in the Islamic Maghreb (AQIM) [26]. "The activities of Boko Haram pose enormous threat to Nigeria's high-risk nuclear facilities."

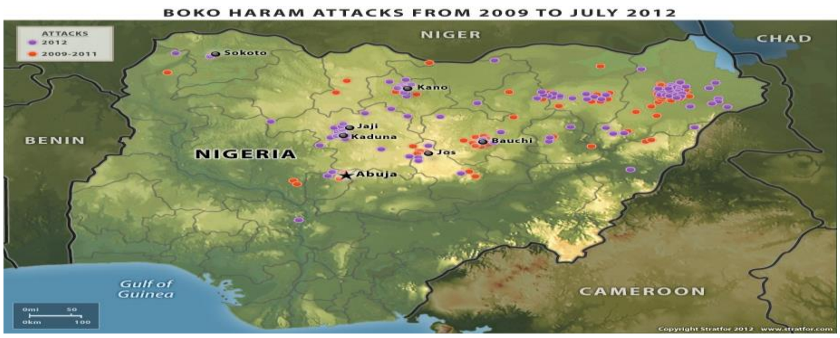

Fig. 1. Area of Boko Haram terrorist attack in North east Nigeria [27]

Uses of radioactive source and nuclear materials in Nigeria. Nuclear applications are growing fast in Nigeria. Currently, there are over four thousand radioactive sources used in various applications in the country. Radioactive sources mostly used are Cs-137, Co-60, Am-241, Tc-99 among others. Nuclear materials are widely used for oil exploration in the southern region for oil explorations and non-destruction testing NDT. Also, Nigeria has a 30kw tank in pool miniature neutron source reactor MNSR known as NIRR-1 built by China which uses 1085 kg and 90% of highly enriched uranium HEU as fuel. NIRR-1 is used for research and training, neutron activation analysis and for the production of isotopes.

In October 30th 2017, the Government through the Nigeria Atomic Energy Commission (NAEC) signed a memorandum of understanding with the ROSATOM to build Russian design nuclear reactor VVER 1000 [6].

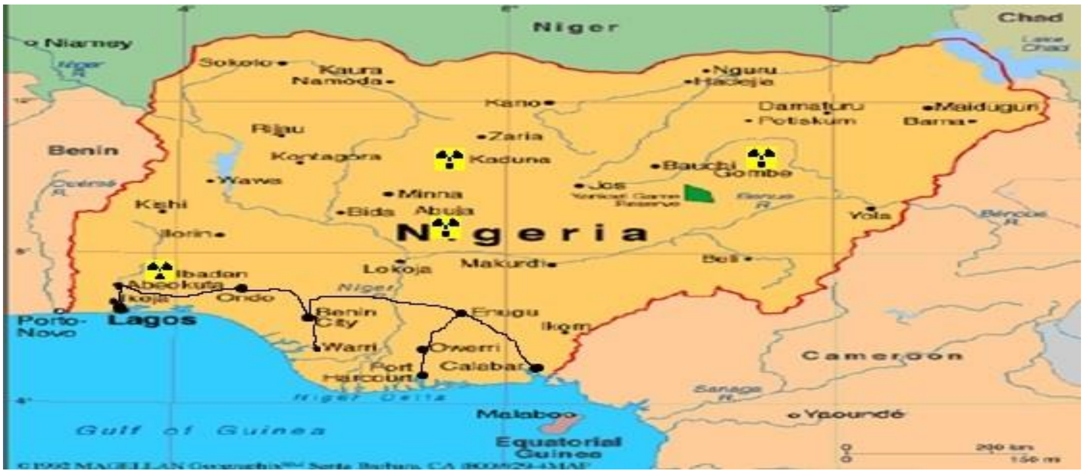

Fig.2. Map showing locations and transport routes of radioactive sources

Nuclear security and safeguards in Nigeria. Regulatory oversight is one of the core functions of the Nigerian Nuclear Regulatory Authority (NNRA) as provided by the Act of 1995, which establishes the Authority [28].Nigeria signed and ratified the Convention on Physical Protection of Nuclear Material and Nuclear Facilities (CPPNM/NF) which came into force in May 2016. In order to domesticate the provisions of the CPPNM, the NNRA commenced the development of Regulations on Physical Protection of Nuclear Material and Nuclear Facilities in 2013. In year 2013/2014 and 2015/2016 under review, the NNRA conducted depleted Uranium (DU) survey across Nigeria as part of country's commitment with respect to its obligation to the IAEA on nuclear material accounting and control (NMAC) [29].

National and international legal framework. Nigerian Government has made a decision to generate electricity from nuclear power plant and also has ratified necessary instruments and is committed to international best practices and requirements for nuclear safety, security, safeguards and liability regimes.[30]

Mitigation strategy against nuclear and radiation terrorism attack by Nigeria government. The following effort made by the government of the above:

“Existence of effective and independent regulatory body, sustained implementation of return to supplier principle, acceptance of replacement of HEU with LEU for the research reactor, establishment of portal monitoring at the ports, continued training of staff, frontline officers, the lawyers and the Press, maintenance of regular inspections and sustaining the licensing process”

Conclusion. There has been existence of effective and independent regulatory body. Nigeria has signed and rectified various conventions and treaties of the (IAEA). The Government of Nigeria has signed MOU with the (U.S.DOE), in collaboration with the IAEA and the Chinese government for core conversation of NIRR-1 from HEU to LEU as a means to minimize the possible risk of terrorist attack in the facility. Physical security upgrades are also carried out quarterly with the help of U.S DOE in Nigeria high risk nuclear facilities.