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The Study of Multiaxial Loading and Damage to the Structure and Materials in the PWR Steam Generator of Nuclear Reactor

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A B S T R A C T

In Pressurized Water Reactor (PWR) Nuclear Power Plants (NPPs), the steam generator is crucial for transferring heat from the primary to secondary cooling systems, vital for steam production to drive turbines, and central to nuclear power safety. This study explores recent research on multi-axial loading, structural integrity, and material durability in PWR steam generators, shedding light on key factors affecting these systems. Common corrosion-related degradation in steam generators often arises from design, material, and water chemistry factors. However, the shift to All Volatile Treatment (AVT), the development of advanced material alloys, and enhanced water quality control in primary and secondary systems have significantly reduced instances of steam generator degradation. These findings promise to enhance the reliability and safety of steam generators in future nuclear applications.

1. INTRODUCTION

The growing need for clean and sustainable energy sources has led to the exploration of nuclear reactors as a promising option. By harnessing thermal energy through nuclear reactions, nuclear reactors have gained attention as a means to meet global and national energy demands, including Indonesia's goal of achieving Net Zero Emissions (NZE) by 2060. As a signatory of the Paris Agreement, Indonesia has pledged to independently decrease its greenhouse gas emissions by 29% by the year 2030, and with the aid of international support, potentially achieve a reduction of up to 41% [1].

The steam generator (SG) is an essential component within the Pressurized Water Reactor (PWR) Nuclear Power Plants (NPPs). The steam generator serves as a pivotal element in power generation by facilitating heat transfer from the primary cooling system to the secondary cooling system, resulting in the production of steam for the purpose of driving turbines [2]. Subsequently, this steam is channeled to the turbine to propel the electrical generator.

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The performance of SG is of utmost importance concerning the safety aspects of nuclear power generation. This aligns with IAEA TECDOC number 1668, which addresses the assessment and management of aging components in nuclear reactors, specifically the SG [3]. The assessment of heat generation, structural integrity, materials, and the performance of fluid-structure interactions occurring within the steam generator process is of vital significance. Stress corrosion cracking (SCC) and pitting are eventually identified as the predominant mechanisms contributing to Steam Generator Tube Rupture (SGTR). Other data show that during periodic inspections, SGs exhibit issues such as localized corrosion and mechanical wear in certain SG tubes, resulting in a reduced lifespan of SGs [4].

Meanwhile, other issues associated with steam generators in NPPs encompass tube denting, thinning, corrosion, fluid-induced vibrations, cracking, and bending deformation in U-shaped tubes or support plates, tube leaks, and fractures. One of these significant accident risks may stem from operational transients and rare events involving degraded steam generator tubes, potentially leading to core meltdown scenarios [5].

The SG technology continues with advancements in the nuclear power industry. This development aims to enhance nuclear power plant systems efficiency, reliability, and safety. Some ongoing innovations include the utilization of new heat-resistant materials, optimization of fluid flow, and improvements in temperature and pressure control [6]. Therefore, a profound understanding of the factors influencing damage in SGs becomes exceedingly crucial.

To advance the goal of making nuclear energy safe and efficient, extensive research into multi-axial loading, structural integrity, and material wear in PWR nuclear steam generators is essential. This study will delve into recent research findings and data collection efforts to uncover key insights into how nuclear reactor steam generators in PWR systems deteriorate. The knowledge gained from this study has the potential to significantly improve the reliability and safety of SG operations in the future.

2. THEORY

In the early 20th century, the fundamental design of shell-and-tube heat exchangers in PWR was introduced in response to the power generation needs, which required extensive heat exchange surfaces for condensers and feedwater heaters capable of operating under relatively high pressure. Although both applications continue to be in use, the design of shell-and-tube heat exchangers has made significant advancements and has become highly specialized, with specific standards and codes related to heat exchanger applications.

Heat exchangers have a long history in facilitating heat exchange between fluids at different temperatures. These equipment have been vital in energy production and management, where about 90% of heat energy relies on their use. Widespread applications span across industries like power generation, chemicals, petroleum, food, aerospace, and nuclear. Their significance grew significantly after the 1973 oil crisis, prompting a stronger focus on saving energy and exploring new energy sources. This led to extensive research, covering areas like predicting performance, optimizing design, improving heat transfer methods, and enhancing their structure. Heat exchangers are now also seen as an avenue for reducing material usage in their manufacturing [7, 8].

The thermal design of PWR shell-and-tube heat exchangers typically involves an iterative process that often relies on computer programs provided by institutions such as the Heat Transfer and Fluid Flow Service (HTFS) or Heat Transfer Research Incorporated (HTRI) [9]. Nevertheless, engineers need to grasp the fundamental principles underlying these calculations. To compute heat transfer coefficients and pressure drop, initial determinations must be made regarding fluid allocation on both sides, as well as determining the type of front and rear headers, shell type, baffle type, tube diameter, and tube arrangement. Tube length, shell diameter, baffle pitch, and the number of tube passes are also selected, with these parameters often subject to modification in each iteration to optimize overall heat transfer within acceptable pressure drop limits.

Mechanical design considerations for shell-and-tube heat exchangers encompass calculations related to shell thickness, flange thickness, and other structural aspects. These calculations are performed by pressure vessel design codes such as the Boiler and Pressure Vessel Code established by the American Society of Mechanical Engineers (ASME) (ASME), along with the British Master Pressure Vessel Standard, BS 5500 [9]. While Section VIII (Pressure Vessels) of the ASME code is most pertinent to heat exchangers, Sections II (Materials) and V (Nondestructive Testing) also hold relevance.

Advantages of Shell and Tube Steam Generators (SG) for PWR

While ASME and BS5500 are widely used and accepted worldwide, some countries have requirements to use their national codes.

International standard organizations are currently working on developing new codes that are internationally recognized, but widespread acceptance may take some time.

Shell and tube SGs offer several advantages. Firstly, they efficiently transfer heat between the primary and secondary systems. This design allows the hot fluid flow within the tubes, surrounded by the secondary coolant in the shell, facilitating effective heat transfer. Additionally, these SG can maintain the integrity of the reactor pressure boundary. The tubes in the SG serve as a crucial part of the reactor cooling system's pressure boundary, preserving both pressure and fluid inventory in the primary system [10]. The SG of one type of PWR is depicted in Fig. 1.

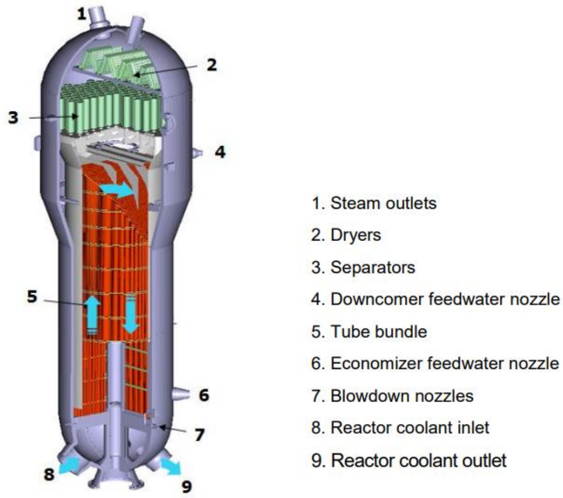

Fig. 1. APR 1000 Steam Generator Schematic [10]

Shell and tube SG can also isolate radioactive fission products in the primary coolant from leaking into the secondary system. The tubes in these SG can prevent the spread of radioactive contaminants generated from nuclear fission into the secondary system [11]. Furthermore, the design of the shell and tube SG offers ease of maintenance and replacement. If there is damage to the tubes, they can be replaced individually without affecting the overall SG system. However, it should be noted that the time required for tube repair or replacement can lead to significant reactor downtime [3].

Another advantage of shell and tube steam generators is their high reliability. Their design has proven effective in maintaining stable and long-term reliable performance. However, it should be remembered that the risk of leaks can disrupt reactor operations and reduce system efficiency.

Furthermore, shell and tube SG can handle sudden heat surges. Their design allows the system to accommodate rapid temperature and pressure changes, maintaining reactor operation stability. However, it should be noted that there is potential for sudden temperature changes in the secondary system that can affect system performance and reliability.

Shell and tube SG can also withstand temperature fluctuations, minimizing temperature fluctuations and reducing the risk of system damage, thus maintaining optimal performance. However, it should be noted that there is a potential for temperature imbalances between the primary and secondary systems, which can reduce heat transfer efficiency.

Lastly, shell and tube SG benefit from the availability of an adequate supply of raw materials. The materials used in the manufacture of the tubes and shells are relatively easy to obtain, simplifying component production and replacement. However, there is a risk of potential raw material supply limitations that may occur in the future.

Weaknesses of Shell and Tube Steam Generators (SG) for PWR

One of the weaknesses of nuclear reactor SG with a shell and tube design is the potential for leakage at the connection between the tubes and the shell. This leakage can occur due to high pressure, high temperature, and rapid temperature changes within the system. Such leakage can result in the loss of coolant water and the potential spreading of radiation contamination of the surrounding environment [12, 13].

Additionally, this model is susceptible to corrosion. Although the materials used in making the tubes and shell have good corrosion resistance, prolonged exposure to radiation and extreme operational conditions can still lead to corrosion. Corrosion can weaken the structure of the steam generator and cause serious damage. The shell and tube model also faces the risk of solid substance buildup inside the tubes (fouling). Fouling can occur due to mineral deposits or other contaminants in the coolant water. The buildup of solid substances can impede the flow of heat and reduce heat transfer efficiency, necessitating regular maintenance and cleaning [14].

In PWR systems, the vertical positioning of SG presents certain limitations compared to their horizontal counterparts, which are considered more resilient to degradation than the U-tube vertical designs. Specifically, the orientation of the tubes plays a crucial role in heating dynamics and the occurrence of heating crises, leading to varying behaviors under different pressure conditions [11]. From extensive operational experience, horizontal SG offers notable advantages over their vertical counterparts, including handling moderate steam loads (steam flow rate from the evaporation surface at 0.2–0.3 m/s) [15, 16].

Furthermore, shell and tube SGs also feature relatively large dimensions, necessitating a substantial amount of space. This can present challenges during installation and placement within nuclear reactors that have space limitations. Additionally, there is the potential for efficiency loss due to heat dissipation in the heat transfer process. Although shell and tube models are typically efficient in heat transfer, some heat losses remain unavoidable during the process. Shell and tube SG are also vulnerable to excessive vibrations and high pressures. Excessive vibrations can lead to wear and damage to components, while high pressure can result in stress and material fatigue. Another weakness is the potential for radiation contamination in the coolant water.

3. METHODOLOGY

This research aims to investigate multi-axial loading and the resulting structural and material damage in shell and tube-type PWR SGs in nuclear reactors. The study seeks to comprehend the causes of damage, identify contributing factors, and evaluate their impact on the performance of the SG. The selection of samples in this study will be based on relevant criteria such as the age of the SG, the type of materials used, and its operational history. Samples will be carefully chosen to encompass sufficient variation in pertinent characteristics.

Data will be collected from various sources, including scientific journals, books, standard codes, and the internet. These data will be analyzed to identify the types and levels of damage occurring in the structure and materials of SG. The analysis results will be interpreted to draw research findings. These findings will be compared with relevant literature and previous experiences in the nuclear industry. The study will conclude by summarizing the analytical results and key findings. These conclusions will offer insights into the issues of damage in the structure and materials of shell and tube SG in nuclear reactors.

4. RESULTS AND DISCUSSION

Various degradation mechanisms occur in circulation-type PWR shell and tube SGs, resulting in various issues [17–19]. These extensive mechanisms affect both the primary and secondary sides, with secondary-side degradation being a major concern. Additionally, numerous SG replacements are required, incurring costs related to repair work, radiation exposure for personnel, and power loss [20, 21]

Several explanations regarding degradation mechanisms have been published [22–24]. They are summarized in Fig 2, which identifies the degradation locations for PWR SG. Table 1 lists the degradation mechanisms for PWR SG, their locations, triggers, failure modes, and inspection methods for tubes and tube sheets. Most degradation mechanisms in SG stem from chemical agents (corrosion).

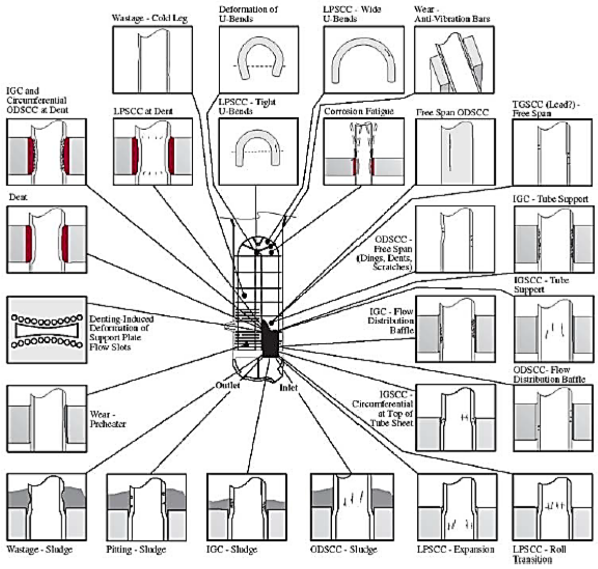

Fig. 2. Failure types that have occurred in recirculation SG [25]

In the 1970s, pipe damage emerged as a significant issue extensively reported by numerous utilities across various units in the United States, as depicted in Table 1. The Electric Power Research Institute (EPRI) established one of two Steam Generator Owner Groups to address these challenges. These groups were formed to tackle pipe damage and associated problems, focusing on widespread pipe denting.

Currently, the most prevalent form of malfunction is intergranular cracking, frequently denoted as stress-corrosion cracking. This particular failure mode accounts for roughly 60 to 80 percent of all tube imperfections resulting in blockages. Additionally, fretting and pitting make up approximately 15 to 20 percent of all tube defects. The residual cases of failure can be ascribed to diverse factors, encompassing mechanical damage, erosion, dents, and fatigue cracking [26].

Table 1. Summary of PWR Recirculating Steam Generator Tube Relevant Degradation Processes [25]

Rank	Degradation Mechanism	Stressor	Degradation Sites	Potential failure mode
1	ODSCC	Tensile stresses, Impurity concentrations sensitive materials	• Tube to tube sheet crevices • Sludge pile • Tube support late • Free span	• Axial or circumferential crack • Circumferential crack • Axial crack
2	PWSCC	Temperature, residual tensile stresses, sensitive materials (low mill anneal temperature)	• Inside surface of U bend • Roll transition without kiss rolling • Roll transition with kiss rolling • Dented tube regions	• Mixed Crack • Axial Crack • Circumferential Crack
3	Fretting Wear	Flow induced vibration aggressive chemicals	Contact points between tubes and the AVBs, or tubes and the preheater baffles Contact between tubes and loose parts Tube to tube contact	• Local wear • Depends on loose part geometry • Axial Wear
4	High cycle fatigue	High mean stress level and flow induced vibration initiating defect (crack, dent. pit. etc)	At the upper support late If the tube is clamped	Transgranular circumferential cracking
5	Denting	Oxygen, copper oxide, chlorides, temperature pH, crevice condition deposits	At the tube support plates, in the sludge pile, in the tube sheet crevices	Flow blockage in tube, may lead to circumferential cracking (see PWSCC). decreases the fatigue resistance
6	Pitting	Brackish water, chlorides sulphates, oxygen, copper oxides	Cold leg in sludge pile or where scale containing copper deposits is found under deposit pitting in hot leg	Local attack and tube thinning may lead to hole
7	Wastage	Phosphate chemistry, chloride concentration resin leakage	Tubesheet crevices, sludge pile. tube support plates, AVBs	General thinning

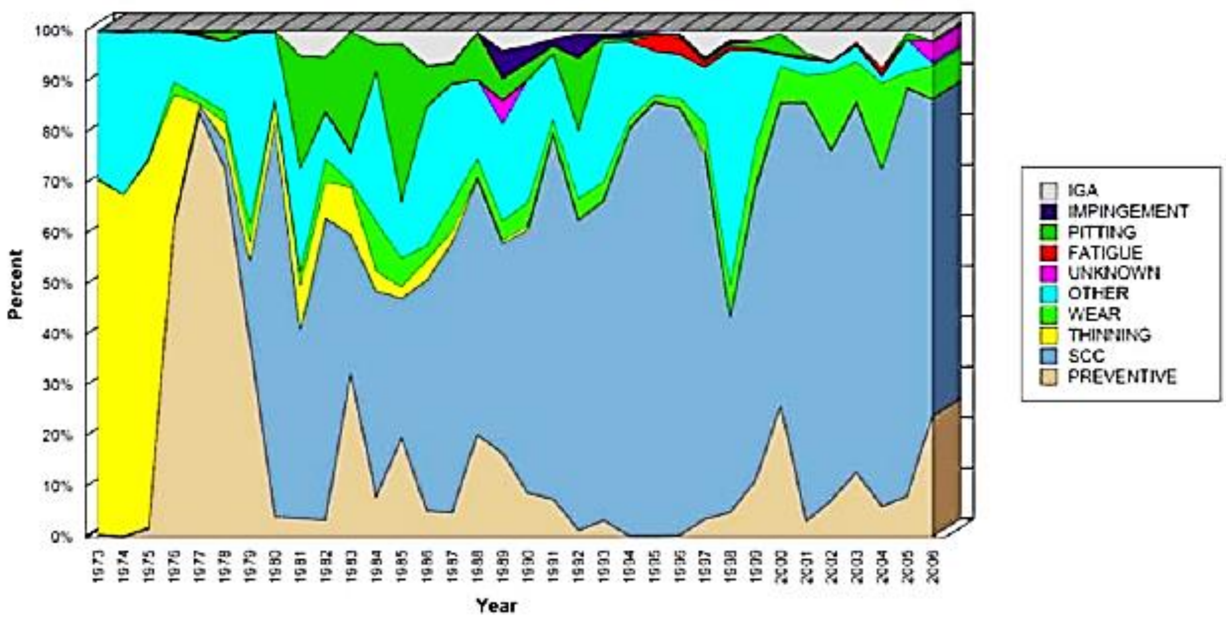

Fig. 3. Worldwide causes of steam generator plugging [25]

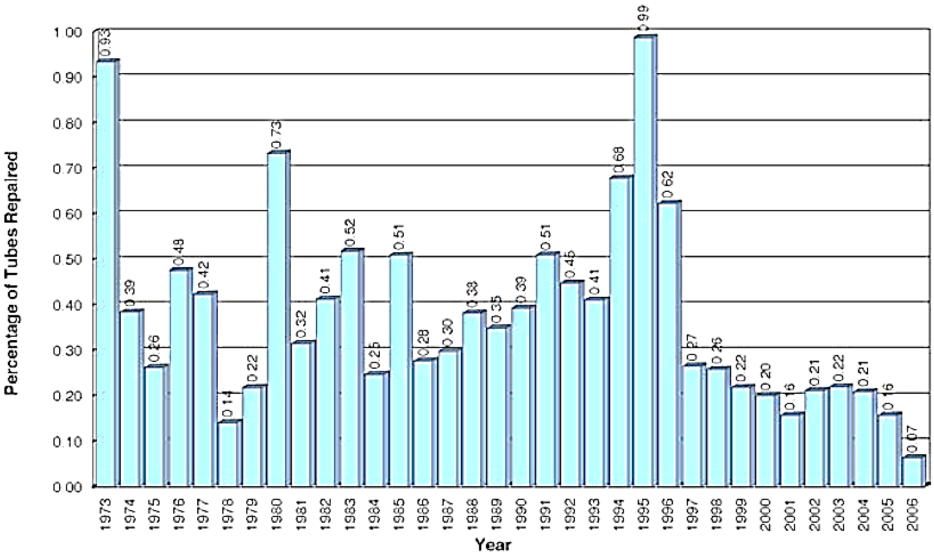

Fig. 4. Worldwide percentage of plugged tubes [25]

The influence of tube degradation mechanisms on the performance of PWR steam generators varies over time. Fig. 3 provides a visual representation of the proportion of total tube failures attributed to each major degradation mechanism from 1973 to 2008. According to an IAEA report, a total of 175 plants globally underwent SG replacements [4]. Failures of recirculating SG tubes and once-through SG tubes, both of which are of the PWR-type, have been summarized globally. Up until approximately 1976, the predominant cause of tube failures in PWR steam generators was common corrosion, primarily resulting from the chemical reaction of phosphate residue in areas with low water flow. From around 1976 to about 1979, denting emerged as the primary cause of failure in PWR steam generator tubes. Fretting damage became increasingly noticeable after approximately 1983, with more than 50% of PWR units worldwide reporting instances of fretting and tube wear. Nevertheless, some manufacturers reported no issues, even after five years of operation. The impact of these degradation mechanisms on tube plugging rates is depicted in Fig 4.

Tube degradation observed in earlier years is clearly related to the tube material. However, optimizing SG performance is the result of a combination of several factors, including plant design, material concepts, and chemistry. Variations in SG performance can be elucidated by considering not only the material of the SG tubes but also several design features and other chemical factors at play.

The primary reason for the deterioration of SGs is the corrosion of their tubes. Therefore, it is crucial to give special attention to the chemical aspects related to this degradation. SG tube corrosion depends on the simultaneous influence of three factors, as illustrated in Fig 5..

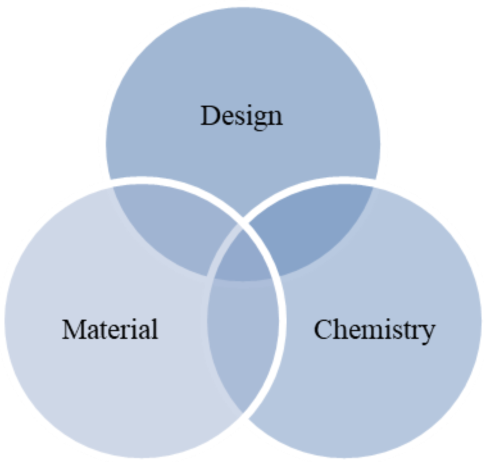

Fig. 5. Factors affecting corrosion [20]

The most frequently occurring cases of SG degradation are attributed to the mismatch among the three factors illustrated in Fig. 5. Even plants with well-designed features and sound material concepts may encounter less stringent chemical processes that can result in material damage. In this context, a portion of the secondary-side chemical processes also influences the optimal plant design and material selection.

As elaborated in the previousections, most widespread and severe degradation issues stem from the mismatch of these three simultaneous factors mentioned earlier. Significantly improving design, materials, and operational chemistry is, therefore, imperative to substantially enhance SG performance. Nevertheless, the persistent degradation of SGs remains a concern, necessitating the adoption of preventive and corrective measures. These measures are essential for the development and construction of new units, as well as for ensuring the safe and dependable operation of existing facilities.

5. CONCLUSION

The performance of steam generators is of utmost importance for the safety aspects of nuclear power generation. This aligns with IAEA TECDOC number 1668, which addresses assessing and managing the aging of key reactor components, namely steam generators. According to various sources, the failures of tubes caused by primary degradation mechanisms from 1973 to 2008, specifically in recirculating SGs of the PWR-type and once through PWR steam generators, indicate that common corrosion resulting from the chemical reaction of phosphate acid residues in low flow rate areas is the primary cause of tube failures in PWR SGs. Most common corrosion-related degradation cases in SG occur due to three key factors: design, material, and the chemical factors of water. However, with the transition to All Volatile Treatment (AVT), the advancement of the material alloy, and improved water quality control in both primary and secondary systems, the incidence of SG degradation has significantly diminished.

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AUTHOR CONTRIBUTION

All authors equally contributed as the main contributors of this paper. All authors read and approved the final version of the paper.

REFERENCES

1. The Ministry of Environment and Forestry of the Republic of Indonesia *FOLU Net Sink: Ministry of Environment and Forestry Indonesia's Climate Actions T owards 2030*. 2023.
2. Pioro I., Duffey R. Nuclear Power as a Basis for Future Electricity Generation. Journal of Nuclear Engineering and Radiation Science. 2015. **1**(1)
3. IAEA *Methodologies for Assessing Pipe Failure Rates in Advanced Water Cooled Reactors*. 2023.
4. IAEA *Heavy Component Replacement in Nuclear Power Plants: Experience and Guidelines*. Vienna: 2008.
5. Sollier T. Nuclear Steam Generator Inspection and Testing. in: *Steam Generators for Nuclear Power Plants*.Elsevier; 2017. pp. 471–93.
6. Riznic J. Steam Generators for Nuclear Power Plants. 2017.
7. Zhang J., Zhu X., Mondejar M.E., Haglind F. A Review of Heat Transfer Enhancement Techniques in Plate Heat Exchangers. Renewable and Sustainable Energy Reviews. 2019. **101**:305–28.
8. Anxionnaz Z., Cabassud M., Gourdon C., Tochon P. Heat exchanger/reactors (HEX Reactors): Concepts, Technologies: State-of-the-art. Chemical Engineering and Processing: Process Intensification. 2008. **47**(12):2029–50.
9. Emarah E., Kasban H. Efficient Evaluation of Heat Exchangers Behaviour in Nuclear Power Plants. Arab Journal of Nuclear Sciences and Applications. 2021. **54**(2):126–36.
10. IAEA *Advanced Large Water Cooled Reactors*. 2020.
11. Egorov M.Yu. Vertical steam Generators for VVER NPPs. Nuclear Energy and Technology. 2019. **5**(1):31–8.
12. Suthar A., Kumar M. Critical Accident Scenario Analysis of Pressurized Water Reactor. in: *Twelve International Conference on Thermal Engineering: Theory and Applications*. 2019.
13. Udiyani P.M., Setiawan M.B. Source Term Assessment for 100 MWe Pressurized Water Reactor. Jurnal Teknologi Reaktor Nuklir Tri Dasa Mega. 2020. **22**(2):61.

14. Zhang T., Qiu G., Yu H., Zhou P., Wang S., Zhang K., et al. The Fouling Behavior of Steam Generator Tube at Different Positions in the High-Temperature Water. Metals (Basel). 2021. **11**(5):684.
15. Bahmanyar M.E., Taheranpour N., Talebi S. Applying Second Law of Thermodynamic for Optimization of Horizontal Steam Generator. Progress in Nuclear Energy. 2021. **133**:103636.
16. Le T.T., Melikhov V.I., Melikhov O.I., Blinkov V.N., Nerovnov A.A., Nikonov S.M. Investigation of the Equalization Capability of Submerged Perforated Sheets under Thermal–hydraulic Conditions of a Horizontal Steam Generator. Ann Nucl Energy. 2020. **148**:107715.
17. Suat O., Nordmann F. PWR and VVER Secondary System Water Chemistry.Advanced Nuclear Technology International; 2010.
18. Carroll L.B. Nuclear Steam Generator Fitness-for-service Assessment. in: *Steam Generators for Nuclear Power Plants*.Elsevier; 2017. pp. 511–23.
19. Gorman J.A. Corrosion Problems Affecting Steam Generator Tubes in Commercial Water-cooled Nuclear Power Plants. in: *Steam Generators for Nuclear Power Plants*.Elsevier; 2017. pp. 155–81.
20. EPRI *Steam Generator Management Program: Steam Generator Integrity Assessment Guidelines Revision 3*. 2008.
21. IAEA *Basic Principles Objectives IAEA Nuclear Energy Series Stress Corrosion Cracking in Light Water Reactors: Good Practices and Lessons Learned*. 2011.
22. Zhao Q.-S., Chu Y.-J., Luo W., Wu W.-R., Kong Y.-Y. The Research of Steam Generator Thermal Performance Degradation in Nuclear Power Plant. in: *2020 IEEE Far East NDT New Technology & Application Forum (FENDT)*. 2020. pp. 140–4.
23. Rodríguez M.A. Corrosion Control of Nuclear Steam Generators under Normal Operation and Plant-outage Conditions: a Review. Corrosion Reviews. 2020. **38**(3):195–230.
24. Huang X. *Theoretical and Experimental Study of Degradation Monitoring of Theoretical and Experimental Study of Degradation Monitoring of Steam Generators and Heat Exchangers Steam Generators and Heat Exchangers*. 2003.
25. IAEA *Assessment and Management of Ageing of Major Nuclear Power Plant Components Important to Safety: Steam Generators*. Vienna: 2011.
26. Hoseyni S.M., Di Maio F., Zio E. Condition-based Probabilistic Safety Assessment for Maintenance Decision making Regarding a Nuclear Power Plant Steam Generator Undergoing Multiple Degradation Mechanisms. Reliab Eng Syst Saf. 2019. **191**