Steam Generators for the Small and Medium Nuclear Power Plants (NPPs). Experience in Design Development and Advanced Innovative Solutions

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ABSTRACT

Recently, the world has once again revealed its strong interest in such energy sources as small and medium NPPs. Despite the variety of designs offered for this niche of reactor technologies, the most mastered and developed for implementation are reactor technologies based on the use of reactor plants with PWRs. One of the key components of such reactor plants is the steam generator.

The report highlights a brief analysis of the design, layout and conceptual solutions on the steam generators both for the land-based NPPs and those used in the transport, nuclear ship building industries. Moreover, advanced solutions are presented in the report that best meet the requirements of small and medium NPPs, including floating nuclear power plants and finally, attractiveness of Russian ship technologies is demonstrated regarding their application in the small and medium nuclear power plants.

1. INTRODUCTION

During the last years, a stable interest in such energy sources as small and medium NPPs has arisen in the world. Today, developers offer various reactor technologies for this niche, including land-based and floating options. The most mastered and developed for near term implementation are reactor technologies based on the use of reactor plants (RP) with PWRs. These RPs are used in majority of NPPs (roughly 75% of all world's NPPs). Today, the nuclear shipbuilding industry utilizes only this RP type.

The key component of any RP is a steam generator (SG). The configuration of the SG largely depends on the RP type. On the other hand, this or that concept of the RP can be implemented depending on the SG design.

The configuration of PWR plants for small and medium NPPs is influenced by the experience in land-based NPPs and those used in the transport, nuclear shipbuilding industries. Evidently, the nuclear shipbuilding industry experience is surely most applicable for the SG being a component of the small NPP with account of such regional power industry features as the power level and requirements for autonomy.

All first marine nuclear propulsion plants and PWR NPPs had loop-type RPs, wherein the SG was connected to the reactor and reactor coolant pump (RCP) via the primary piping (nuclear icebreaker *Lenin*, first-in-the world Obninsk NPP and Siberian NPP in the Soviet Union, USS *Nautilus*, nuclear-powered cargo-passenger ship *Savannah*, Shippingport NPP in the USA).

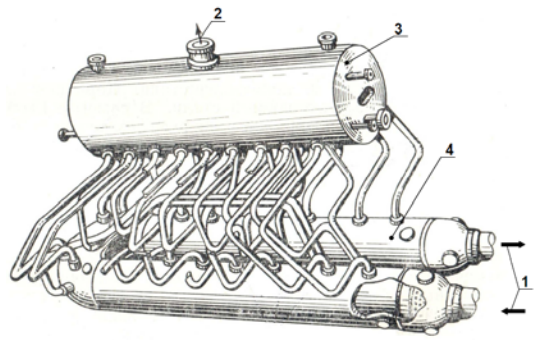

Fig. 1. Shippingport NPP SG:
(1) primary inlet/outlet; (2) steam outlet; (3) separator drum; (4) evaporator

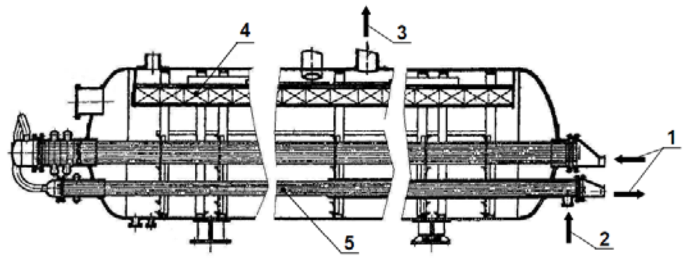

Fig. 3. Low-head SG in the Siberian NPP:
(1) primary inlet/outlet; (2) feedwater outlet; (3) steam outlet; (4) separation device; (5) heat-exchange tubes

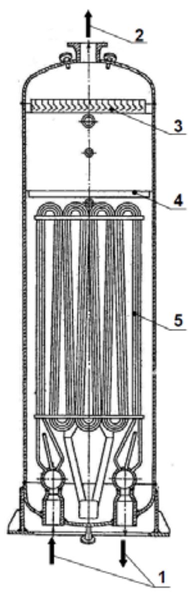

Fig. 2. SG evaporator in the first-in-the world NPP:
(1) primary inlet/outlet; (2) steam outlet; (3) separator; (4) submerged perforated sheet; (5) heat-exchange tubes

The primary coolant was on the tube side in the SG; the secondary medium, on the shell side.

This design solution – "the medium under the higher pressure is on the tube side" – was for many years one of the main design postulates for SG designers. It was considered that the solution makes it possible to design an SG shell for lower secondary pressure.

Another significant design solution is the SG type (recirculation or once-through) and configuration of heat-transfer tubes.

The first nuclear plants in the U.S. (USS *Nautilus*, nuclear-powered cargo-passenger ship *Savannah* and Shippingport NPP) utilized recirculation SGs with horizontal heat-exchange U-tubes (Fig. 1).

The SG evaporator in the first-in-the world NPP was also the recirculation type; however, it had vertical heat-transfer tubes in the form of vertical flat coils joined together via horizontal headers (Fig. 2). The Siberian NPP SG was the recirculation type as well. However, it had straight heat-transfer tubes horizontally placed in the horizontal shell (Fig. 3).

The SG in the nuclear icebreaker *Lenin* essentially differed from the above-mentioned counterparts, because it was a vertical once-through SG with spiral heat-transfer tubes (Fig. 4).

Austenitic steels 18-8, 18-9 and 18-10 were used as a structural material for heat-transfer tubes in all the above-mentioned SG designs.

The operation experience in the above-mentioned SGs can be briefly summarized as follows.

2. RECIRCULATION SGs

All first recirculation SGs demonstrated quite varied reliability levels. It is known that multiple failures of heat-exchange tubes were reported for horizontal SGs in USS *Nautilus* and Shippingport NPP. At the same time, two other SGs in the Shippingport NPP operated without failures. SGs in the nuclear-powered cargo-passenger ship *Savannah*, Russian SGs in the first-in-the world Obninsk NPP and Siberian NPP showed a high level of operational reliability as well.

Further development of recirculation SGs had the following features. Despite the positive operating experience with the vertical SGs in the first-in-the world Obninsk NPP, Russian designers selected horizontal SGs for their NPPs. Reasons for this decision are detailed in [1]. Later on, all Russian VVER NPPs have utilized only horizontal recirculation SGs with 08Cr18Ni10Ti stainless steel heat-exchange tubes (Fig. 5).

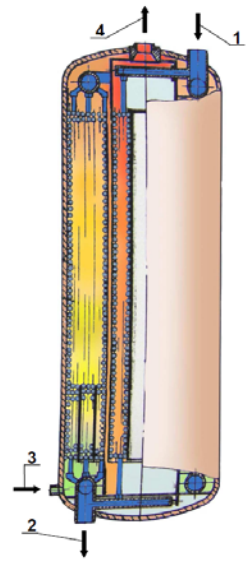

Fig. 4. Icebreaker *Lenin* SG: (1) primary inlet; (2) primary outlet; (3) feedwater inlet; (4) steam outlet

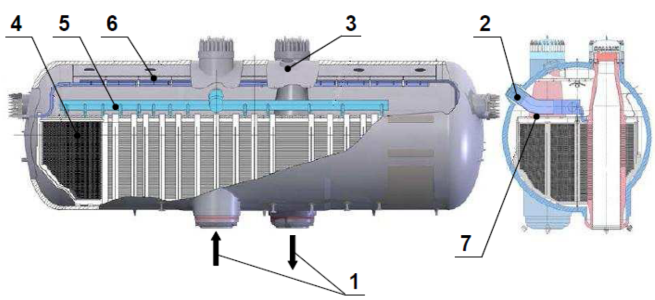

Fig. 5. Horizontal recirculation SG: (1) primary inlet/outlet; (2) feedwater outlet; (3) steam outlet; (4) heat-exchange tubes; (5) feedwater supply header; (6) steam-receiving perforated sheet; (7) submerged perforated sheet

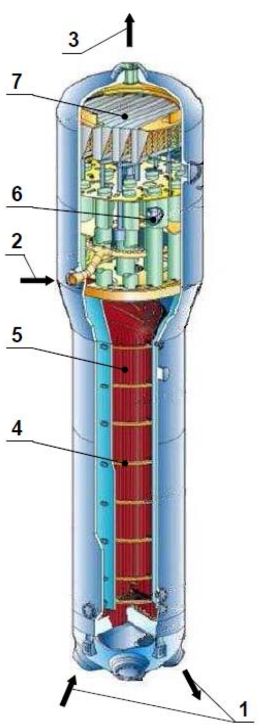

Fig. 6. Vertical recirculation SG: (1) primary inlet/outlet; (2) feedwater inlet; (3) steam outlet; (4) spacing grids; (5) heat-exchange tubes; (6) primary separator; (7) secondary separator

Outside Russia, the development of recirculation SGs for land-based and marine NPPs went in the opposite direction. While having generally positive operating experience with first horizontal SGs, designers selected vertical SGs.

Among disadvantages of first U.S. horizontal marine SGs are large dimensions and difficulties with monitoring the SG level in pitching and listing. In fact, these circumstances provided for future transition to vertical recirculation SGs in the nuclear power industry outside Russia (Fig. 6).

Nevertheless, while transition to vertically arranged SGs significantly improved the general RP layout, it also produced a variety of corrosion and vibration-induced wear problems in SGs themselves. Inconel 600 used instead of stainless steel for heat-exchange tubes did not improve the situation. According to the opinion of some competent specialists outside Russia, the vertical recirculation SG turned into a real "corrosion machine" [2]. Transition to alloys 800 and 690 slightly reduced the acuteness of the corrosion problem, but the vibration damage problem still remained.

It is amazing why designers of recirculation SGs are persistent in trying to keep the traditional vertical SG layout despite the apparent problems with this SG design.

3. ONCE-THROUGH SGs

Experience in once-through PWR SGs outside Russia is known by B&W developments. Once-through straight-tube SGs with the primary medium circulating on the tube side have been utilized in several U.S. NPPs, in particular in the Oconee NPP (Fig. 7). Operation of this type SGs was also accompanied by corrosion and vibration-induced wear problems as in case with the recirculation SGs. Note that transition from alloy 600 to 690 did not reduce plugging rate for faulty heat-exchange tubes [3].

At the same time, operating experience with the once-through SG in the NPP of the German nuclear-powered cargo vessel *Otto Hahn* was very successful because there was no failure in 10 years of operation. The SG was built into the integral reactor vessel; the secondary medium was inside spiral coil tubes; the material of heat-exchange tubes was Inconel 690 (Fig. 8).

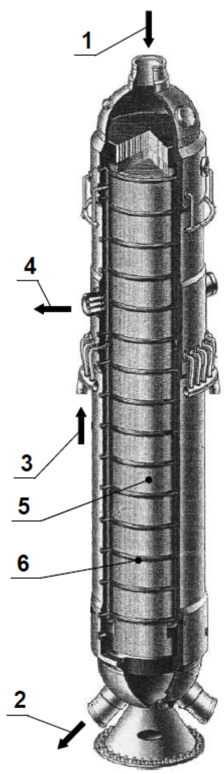

Fig. 7. Once-through straight-tube SG in the Oconee NPP:
(1) primary inlet; (2) primary outlet; (3) feedwater inlet; (4) steam outlet; (5) heat-exchange tubes; (6) spacer grids

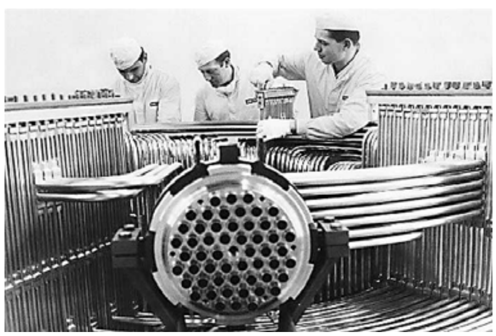

Fig. 8. Assembling the SG for the nuclear-powered cargo vessel *Otto Hahn*

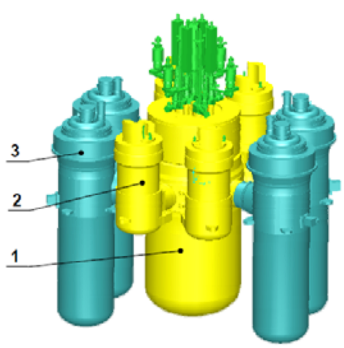

Fig. 10. Modular arranged RP:
(1) reactor; (2) reactor coolant pump; (3) once-through SG

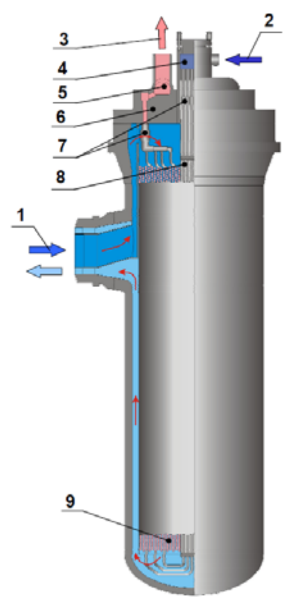

Fig. 9. Once-through SG with the secondary medium circulating on the tube side:
(1) primary inlet/outlet; (2) feedwater inlet; (3) steam outlet; (4) feedwater header; (5) steam header; (6) SG head; (7) adapters; (8) feedwater tubes; (9) heat-exchange tubes

Operating experience in first once-through SGs in the nuclear icebreaker *Lenin* showed that austenitic stainless steels could not be used as a structural material for heat-exchange tubes in once-through SGs. These steels turned out to be susceptible to stress corrosion cracking in the environment with a high content of chlorine ions. In once-through SGs, chlorine ions extensively concentrate at the end of the evaporation area, which is characterized by high vapor content. During the icebreaker *Lenin* operation period 1959–1966, SGs were replaced twice. These circumstances absolutely demonstrated the problem of selecting the acceptable structural material for once-through SGs.

Resulting from the series of material science studies, a titanium alloy was selected as the material for the SG heat-transfer tubes. Later on, this decision made it possible to practically solve the corrosion resistance and reliability problems generally for marine once-through SGs.

Simultaneously, work was in progress to upgrade the SG design. As a result, a conceptually new design of the once-through SG was developed where the secondary medium circulated on the tube side. At the same time, a higher reparability level was implemented in the SG, which made it possible to detect and plug if necessary a separate leaky SG section, as well as replace the entire SG tubing system without removing the SG shell (Fig. 9).

The new SG design was developed mainly due to the requirements related to a new modular design RP. Transition from the loop-type RP to the modular RP was an outstanding event in the nuclear shipbuilding industry. The modular layout predetermined the overall image of the Russian nuclear shipbuilding industry for the forthcoming period of more than 40 years (Fig. 10).

Further 19 years of SG operation in the new modular RP on the nuclear icebreaker *Lenin* from 1970 to 1989 demonstrated a high reliability level of these SGs. During this period, the SG operating time was achieved of more than 100,000 hr exceeding the initial design lifetime for these SGs by more than 3 times. Note that most SGs had no failures, and only two SGs had one plugged section each. Similar SGs on the nuclear icebreaker *Arktika* achieved the operating time of approximately 180,000 hr with the service life of 34 years, which exceeded the initial design lifetime by nearly 6 times. The total operating time of all once-through titanium SGs in modular RPs exceeds 20,000 SG-years.

4. MATERIALS FOR HEAT-EXCHANGE TUBES

Selection of the material for SG heat-exchange tubes has always been the key issue in the design of SGs and remains to be topical these days.

The SGs outside Russia utilized stainless steels 304, 316, 347, Monel 400 copper-nickel alloy, Inconel 600MA, 600TT and Incoloy 800 chromium-nickel alloys. The experience in application of stainless steels, Monel 400 and Inconel 600 alloys in vertical SGs was unsuccessful primarily due to corrosion problems. To date, all vertical SGs with stainless steel heat-exchange tubes have been replaced. Vertical SGs with alloy 600 tubes are being replaced with SGs with alloy 690 and 800 tubes. It was necessary to untimely replace around 350 SGs due to substantial, primarily, corrosion damage to heat-exchange tubes.

Russian horizontal SGs have always utilized heat-exchange tubes made of stainless steel 08Cr18Ni10Ti. Despite similar corrosion problems, these problems, though being important and acute, were not critical due to horizontal arrangement of tubes. Because of substantial damage to heat-exchange tubes, only 6 SGs had to be untimely replaced out of the total of 278 horizontal

SGs being in operation. In this connection, indicative is the opinion of G. P. Karzov, the furthermost Russian authority in the area of nuclear material science, "Horizontal SGs are an absolutely successful and lucky case in the world's practice. Up to date, these SGs have successfully utilized steel 08Cr18Ni10Ti that is generally a simple stainless steel. As for heat-exchange tubes in horizontal SGs, the use of stainless steel 08Cr18Ni10Ti is the justified, reasonable and profitable engineering solution" [4].

Russian marine once-through SGs utilize titanium alloys. Titanium alloys for SG tubes have several unique qualities and properties. First of all, they have high corrosion resistance to practically all corrosion types; titanium is practically unsusceptible to corrosion cracking. High corrosion resistance of titanium is explained by fast formation of the passive oxide film on its surface that is toughly connected to the base metal and excludes the metal-to-medium contact. Because of permanent protecting film, titanium and titanium alloys are stable in a variety of corrosion media. Another positive factor is that linear thermal expansion and the elasticity modulus of titanium alloys are by ~ 2 times lower than those of stainless austenitic steels and alloys. Because of these properties, titanium structures have temperature stresses by ~ 4 times less than the same austenitic material structures at similar temperature pulsations and temperature differences. As a result, in combination with high fatigue properties, titanium alloys allow designing SGs with the high level of cyclic strength. Titanium alloys are low activated. Due to this property, the significantly lower dose rates are ensured during SG repair and replacement.

At the same time, titanium alloys have certain disadvantages. First, there is tendency towards hydrogen pickup in long-term operation and, consequently, towards possible hydrogen embrittlement at reduced temperatures. Hence, this phenomenon has to be taken into account in the design and operation of SGs. Use of titanium also requires highly reliable "steel-titanium" adapters in the SG design. It should be noted that the problem of steel-titanium adapters was reliably solved for marine once-through SGs.

5. DAMAGING FACTORS AND ENGINEERING SAFETY CONCEPT

The basic damaging factors for recirculation SGs are corrosion cracking and vibration wear processes of which evolution can hardly be predicted. Crack formation and propagation up to a through crack take place in SGs under tensile operation stresses (the primary circuit is on the tube side). When the through crack propagates further, there is an actual risk of a large break of the heat-transfer tube (or several tubes) with abnormal operation scaling up into LOCA that requires that the power unit be scrammed. These circumstances and operating experience in recirculation SGs shaped a certain type of the engineering safety concept:

- Periodical inspections are conducted on the condition of heat-exchange tube metal throughout operation (eddy current testing (ET)).

- Faulty heat-exchange tubes are plugged based on ET results when cracks in heat-exchange tubes reach the critical size.

- SG blowdown water is periodical monitored for activity to check on the absence of SG inter-circuit leaks.

- The power unit is shut down at reaching safe operation limits (critical value of the inter-circuit leak).

All the above-mentioned items are also applicable for once-through SGs, where the primary medium is on the tube side.

For once-through SGs, especially with titanium heat-exchange tubes, where the secondary medium circulates on the tube side, the engineering safety concept is cardinally different and better. First of all, it relates to the nature of damaging factors.

In once-through SGs of this type, corrosion-induced factors are excluded from the factors that have an effect upon the SG reliability and lifetime. This is achieved through applying highly corrosion-resistant titanium alloys, as well as through optimal flow aerodynamics in SG spiral tubes and steam-generating components that prevents noticeable sludge deposition in operation.

Absence of low-frequency elements in the SG design in the feedwater path excludes the risk of vibration-induced damage. The issues of spacing the heat-exchange tubes are also reliably solved in the SG design with guaranteed tuning out of resonance frequencies.

Basic factors that have a considerable effect upon operability of these once-through GSs are thermal and barometric pressure cyclic loads upon SG units and components in operation.

The effect of cyclic thermal and barometric pressure loading is quite correctly predicted by calculational methods. The cyclic strength of units and components in SG modules is representatively verified by accelerated lifetime testing.

Compressing stresses acting on SG tubes from the primary side prevent both propagation of possible hidden flaws and formation of a large through crack, which ensures an absolutely new higher safety level for NPPs.

All these circumstances and operating experience in once-through SGs with secondary medium on the tube side made it possible to develop our own genuine type of the engineering safety concept:

- Highly sensitive continuous monitoring of the steam activity is ensured downstream of the SG that allows on-line detection of the inter-circuit micro-leaks.

- The leaky SG or leaky SG section are isolated with double feedwater and steam stop valves designed for primary pressure.

- The plant can operate further on without a shutdown at the reduced power level with the isolated leaky SG.

- SG operability can be restored by plugging a leaky SG component in the cooled-down plant without opening the primary circuit cavity.

- There is no need to periodically inspect heat-exchange tube metal (ET).

The last point is the most important. This type SGs do not require in-service maintenance and make it possible to implement the advanced concept of small NPPs without reactor refueling for the entire design service life.

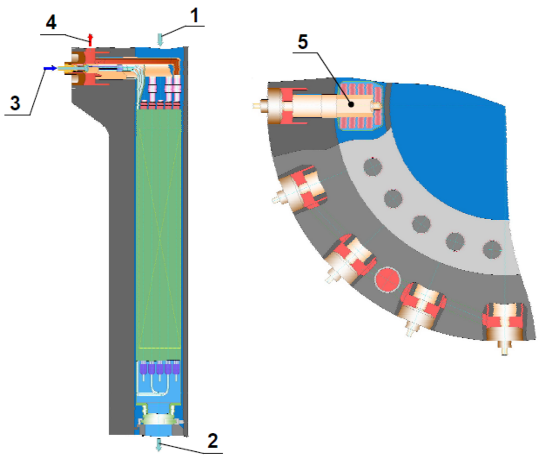

Fig. 11. ABV once-through SG:
(1) primary inlet; (2) primary outlet; (3) feedwater inlet; (4) steam outlet; (5) SG cassette

Fig. 12. Once-through VBER SG:
(1) primary inlet/outlet; (2) steam-generating modules; (3) feedwater headers

The Russian experience in development and operation of once-through marine SGs has been implemented in such small and medium NPP designs as KLT-40S, ABV-6 and VBER-300 [5].

The heat-exchange surface of the KLT-40S RP steam generator is formed of spirally coiled tubes making a single tube bundle (Fig. 9). A modular concept is implemented in the ABV and VBER SGs. Note that ABV steam generators (Fig. 11) utilize straight tube steam-generating elements, while VBER steam generators, spirally coiled tubes (Fig. 12).

The floating cogeneration NPP with the KLT-40S reactor plant has undergone all licensing stages, and is now under construction. All reactor plant equipment, including SGs, has been manufactured and delivered to the shipyard.

The Russian experience in development and operation of once-through marine SGs with straight tube steam-generating elements is unique and prospective experience. The said SGs are characterized by high compactness and efficiency. Specific thermal power generated by the volume unit of the heat-exchange surface in such SGs can be 60 MW/m^3. Low hydraulic resistance on the primary side in such SGs makes them especially attractive for integral RPs with 100% natural circulation of the coolant (for example, ABV reactor plant).

6. CONCLUSION

Resultant from the analysis of feasible steam-generating technologies for marine and land-based NPPs, the technology based on once-through SGs with the secondary medium circulating in titanium heat-exchange tubes shaped as spiral coils or straight-tube steam-generating elements that do not require in-service maintenance is proposed as the most prospective one for steam generators in small and medium NPPs, especially for portable SG designs.

REFERENCES

[1] Lukhasevich, B.I., Trunov, N.B., Dragunov, Yu.G., Davidenko, S.E., Steam generators of VVER reactor plants for NPPs, 2004

[2] Bergunker, V.D., Issues of selecting materials for PWR RP*s*, 5th ISTC Ensuring safety of VVER NPPs, Podolsk, Russia, 2007

[3] Klarner R., Boyd, J. T., Keck M., Once through times two, *Nuclear Engineering International*, April 2004, pp. 14-19

[4] Karzov, G.P., Issues and perspectives of applying structural materials for horizontal steam generators, Paper for the 8th International Conference on Horizontal Steam Generators, Podolsk, Russia, May 19–21, 2010

[5] Bykh, O.A., Petrunin, V.V., Experience in designing steam generators for nuclear power plants developed by JSC “Afrikantov OKBM”, Paper for the 6th CNS International Steam Generator Conference “Management of Real-Life Equipment Conditions & Solutions for the Future”, November 8–11, 2009, Toronto, Ontario, Canada