LIFE MANAGEMENT OF SG FOR WWER PLANTS

Trunov N.B., Dragunov Yu.G., Banyuk G.F.,
OKB “Gidropress”,
21 Ordzhonikidze Str., Podolsk, Russia
trunov@grpress.podolsk.ru

ABSTRACT

Nowadays, 252 steam generators (SG) of horizontal type are in operation at WWER plants constructed by the Russian designs. In connection with end of the specified service life of the reactor plant equal to 30 years the activities are performed on service life extension of the main equipment including the SG.

At some Units, throughout the design service life of SG there were problems resulting in necessity of SG replacement. At the same time the SGs at some Units are in successful operation above the design service life. This report deals with the peculiarities of operation of the horizontal SGs and the problems to be highlighted as the most important for service life extension.

The main component to determine possibility for SG service life extension is the SG tubing. As the operating experience shows it is water chemistry of the secondary circuit that is the main factor influencing operability of the SG tubing. Therefore, differences in water chemistry organization leads to significant differences in operability of the SG tubing at various Units and in some cases within one Unit. Owing to the fact that the cases of water chemistry disturbance and the process of tubes fouling with the corrosion products of the main condensate system are not excluded, the damages continue to occur.

Tube integrity shall be inspected by eddy current method using the various instrument complexes. This method has certain disadvantages but allows to estimate the degree and direction of degradation processes. The results of eddy current test (ECT) can be used to determine the plugging criterion for defective tubes. The significant number of defective tubes at some Units makes a choice of the plugging criterion to be an important problem, on which solution the SG safety, reliability and service life depends.

The report deals with directions of activities in service life management for the SG at WWER plants. Main activities are improvement of water chemistry and non-destructive tests.

1 INTRODUCTION

The horizontal SGs applied at WWER plants differ in their structural concept from the vertical SG used at NPP of the main western countries. Their design features are the horizontal cylindrical vessel, horizontal coils of the heat exchange surface being embedded in the vertical collectors of the primary coolant, and also use of the vessel upper part for gravitational separation. Design of SG WWER-440 shown on Fig 1. Essential design feature is also application of stainless steel 08X18H10T as material of the SG tubing. Such a type of SG has a number of essential advantages before the SG of other types both as regards reliability and convenience of operation, and concerning the safety properties of the Unit as a whole.
Now, 252 SGs of horizontal type are in operation at WWER plants constructed by the Russian designs. The SGs of this type operate at all two-loop NPPs in Russia, Ukraine as well as in Bulgaria, Czechia, Slovakia, Hungary, Finland, Armenia. The SGs of some Units are in operation for more than 30 years (NV NPP, Units 3&4, KNPP, Unit 1).

At present, service life extension of NV NPP, Units 3&4 and KNPP, Unit 1 has been substantiated for an additional period of operation equal to 15 years. However, service life extension for the SG tubing of these Units requires additional confirmation with account of the necessary corrective measures. Activities on service life extension for WWER –1000 plants are started.

2 PROBLEMS OF SG OPERATION AND WAYS OF THEIR SOLUTION

2.1 Solution of the operational problems

Presently, the SGs of PGV-440 and PGV-1000 types are used at WWER plants. Their structures as compared with the design one have been changed and modified in the course of operation. Design of SPS, feedwater distribution unit, separation devices, blowdown water outlet units, surge tanks and other units were changed. With this, it is necessary to take into account that these changes for various Units were realized differently and in various scope. The process of improvement of the SG under operation is going on. The main technical characteristics of SG and the process of their structural development were considered for example in /2,3/. The horizontal SG design for WWER plants were compared with the vertical SGs used at PWR plants. The advantages and disadvantages of various structural solutions were singled out. As a result of the analysis it is shown that solution of the operational problems is within a framework of the structural concept for horizontal SG.

The main problems arisen during SG operation can be briefly characterized as follows:

- structural integrity of the PGV-440 and PGV-1000 collectors;
- structural integrity of the PGV-440 flange joints;
- corrosion-erosive deterioration of the feedwater distribution collector;
- cracks in area of welds No.111 (PGV-1000);
• corrosion degradation of the tubing.

As it is shown in /4/, a number of the structural and technological measures allowed to solve practically the first three of the above problems. The most urgent for today are the problems of structural integrity of welds No.111 and corrosion of the tubing. The ways of solving these problems are considered herein below.

2.2 Study of the causes of weld No.111 cracking

A problem of metal cracking in area of the collector-to-SG vessel joint (weld No.111) occurred for the first time in 1998 at NV NPP, Unit 5. Further the same damages to three SGs more were revealed that forced to consider the problem as the common-cause one. A significant scope of research was performed /5/ to reveal the factors resulting in cracking. In particular, the following has been done till now:

• detailed calculation analyses of the stressed state caused by the operational factors;
• experimental studies of the stressed state of unit;
• assessment of residual stresses caused by the manufacturing process;
• analysis of manufacturing process and metal properties;
• determination of the critical crack size;
• measurements and analysis of displacements of the RP equipment during thermal expansion.

The results of studies allow to single out the main factors to determine the process of damages such as:

• technological heredity after explosive expansion, welding and heat treatment;
• off-design stressed state in case of obstacles to free displacement of SG.

It is planned to continue complex studies of the causes and mechanisms of damage in the following directions:

• calculation analyses of residual stresses after explosive expansion, welding and heat treatment;
• study of equipment displacements;
• improvement of the methods for in-service inspection and others.

Presently, the bench tests have been completed and trial implementation of the devices for deposits washing out of the “pockets” during PM is under way which allows to decrease corrosion effect of medium upon metal.

The unfavourable factors leading to this type of damages are excluded for the SG new designs. This relates to the cracking problem of coolant collector as well.

2.3 Assurance of reliable operation of the tubing

The reliable operation of SG heat-exchanging tubes is the most important problem for different NPP types all over the world. Practically all vertical SGs of the first generation with tubes of alloy 600MA have been replaced or put out of operation because of damage to the heat-exchanging tubes before expiration of the design service life. The average actual service life for SG of 122 Units is 25 years. /6/. This problem for the Russian-manufactured SG is not so acute, however, damages to the heat-exchange bundle take place in a various degree at all NPP Units and are now the main factor to determine the residual service life of SG. In Russia, replacement of steam generators because of corrosion in the heat-exchanging tubes was made only at Balakovo NPP, Unit 2. Two SGs were also replaced at South-Ukrainian NPP for this particular reason.

As an operating experience shows the main factor exerting influence upon operability of the SG tubing is water chemistry of the secondary circuit. So, significant differences in operability of the SG tubing are observed at various Units, and in some case within one Unit. In /7/ on the basis of analysis of tube damageability it is shown that a determinative factor resulting in tube failures is the inadmissibly high
value of SG tubing fouling with the insoluble products of corrosion. Already at an early stage of operation, it has resulted in development of multiple corrosion failures in the heat-exchanging tubes of some SG. The main mechanisms are as follows:

- development of the primary pitting damages as a result of significant amount of copper in the deposits;
- high concentration of corrosive impurities in the thick porous deposits;
- development of corrosion cracks in the most cases starting from the initial pitting tips up to the through failure of tubes.

First of all, it’s worth noticing that in the designs of WWER-440 and WWER-1000 plants of the first generation a choice of structural materials for the equipment and pipelines of the secondary circuit (presence of copper-bearing alloys and carbon steels), water purification and treatment systems does not allow to organize optimum water chemistry of the secondary circuit from the viewpoint of SG and, as a consequence, it has negative influence upon SG reliability and lifetime.

At present, six steam generators of PGV-1000 type have been replaced because of corrosion in the heat-exchanging tubes. Analysis of SG state at the Russian NPP /8/ shows that the SGs have different states even within one Unit that testifies to various operating conditions of these SGs. The process of intensive degradation for some SGs continues, so confirmation is required for residual service life of heat-exchanging tubes, for example for 3SG-4 of Balakovo NPP and 3SG-4 of Novovoronezh NPP. At the same time the SGs are in good state after being in operation for about 140000 hours (for example, 2SG-1 and 2SG-2 of Kalinin NPP). At some SG we observe stability and even improvement of state. As a rule, it is relates to quality of water chemistry maintenance and realization of chemical washing. Despite of the significant operating time, the SG tubing at NPP “Loviisa”, NPP “Kozloduy” Unit 6, Khmelnitsky NPP Unit 1 and some other NPPs are in excellent state.

Tightness check of the SG heat-exchanging tubes at WWER plants is performed, mainly, using the hydraulic or pneumohydraulic aquarium methods and the hydraulic tests proper. The heat-exchanging tubes with the through flaws detected in them shall be plugged. Recently the eddy current testing (ECT) became the main method of inspection. By the ECT results they perform preventive plugging of the defective tubes that allows to avoid possible opening of the available flaw up to the through one during operation and, respectively, off-schedule shutdown of the reactor plant. The overwhelming number of heat-exchanging tubes, especially on the steam generators with significant corrosion damages to the SG tubing, have been plugged by the results of this inspection. The problems of application of this method are considered herein below.

As it is specified in /7/, the main causes resulting in damage to the significant number of SG heat-exchanging tubes are:

- imperfection of the secondary systems (presence of the equipment made of insufficiently corrosion-resisting materials, intakes and quality of cooling water in the turbine condensers, absence of the automatic system for chemical control, deficiencies in blowdown system) that resulted in imperfection of water chemistry;
- high level of deposits on the heat-exchanging tubes before the first chemical washings up to filling of the inter-tube space that in combination with earlier disturbances in water chemistry of the secondary circuit has resulted in creation of conditions for concentration of the corrosive impurities and occurrence of initial corrosion damages to metal of the SG heat-exchanging tubes;
- absence of reliable eddy current testing that prevents from development of optimum strategy for inspection of the SG tubing and tools for processing and visual interpretation of the ECT results. The specified circumstance did not allow to reveal beginning of the negative processes on SG in time and to estimate their consequences.
3 BASIC TRENDS OF SERVICE LIFE MANAGEMENT

3.1 Improvement of water chemistry

Basic direction of R&D aimed, presently, at increasing SG reliability and service life is improvement of the secondary water chemistry.

In compliance with requirements of PNAE G-01-011-97 «General provisions for ensuring safety of nuclear power plants OPB-88/97» secondary water chemistry shall be arranged so that to provide integrity of the third protective barrier i.e. of “reactor coolant pressure boundaries” (heat-exchanging tubes and primary steam collector of steam generator).

With this, it is necessary to consider two safety aspects pertaining to provision of integrity of the third protective barrier:

- corrosion processes causing direct failure of protective barrier;
- corrosion processes weakening a protective barrier so that though it remains intact during operation, its possible damages could raise the level of accident situation during transients.

When choosing this or that water chemistry and setting up quality standards of the secondary working medium, complex consideration of technology of water chemistry management is necessary to be made with regard for provision of SG and secondary-side equipment reliable operation. The following general criteria shall be taken into account when setting up the standards:

- maximum permissible concentration of water impurities shall be determined on the basis of available experimental data on conditions of corrosion behaviour of structural materials of SG and other secondary components;
- penetration of impurities into SG shall be maintained at a minimum possible level with regard for system’s capabilities for maintaining water chemistry;
- actually achievable accuracy of chemical analyses using laboratory or automatic monitoring instruments shall provide a reliable determination of concentration of controlled impurities within the assigned interval.

For setting up controlled parameters of SG water quality and their values it is necessary to evaluate corrosion activity of water at working parameters for SG structural materials, first of all, for material of heat-exchanging tubes - stainless chromium-nickel austenitic steel 08\(\times\)18\(\times\)10\(\times\) and material of primary steam collectors - steel of pearlitic class 10\(\Gamma\)Н2МФА.

Nowadays, there are no reliable calculated methods which make possible to evaluate effect of SG corrosive impurities of water on the rate of corrosion failures extension of steel 08\(\times\)18\(\times\)10\(\times\).

General principles of effect of water medium quality on the rate of corrosion cracks extension are reduced to the following:

- process of removal of reaction products from the crack apex is governing process in crack extension. In very pure media the rate of crack extension is insignificant;
- the rate of crack growth increases with pH lowering of water medium;
- under improvement of water quality, growth of the crack, having already been formed, stops;
- presence of oxidizers (oxygen, copper oxides and higher oxides of iron) in water containing chlorides results in formation of acid medium in pittings even if the basic solution remains alkaline;
- not only chlorides but also other anions are capable to cause steel corrosive damage.

Decrease in standard of content of corrosive impurities in SG blowdown water down to the level of standards accepted at PWR plants (USA, France) is held due to the following reasons:

- tube systems of turbine condensers are made of copper-bearing alloys that does not make possible to provide their integrity in the water side below 0,001 % that corresponds to cooling water leak of...
36 L/h. At foreign PWR plants having condenser tube systems made of titanic alloys, the leak amounts to less than 0,05 L/h that makes possible to standardize content of chlorides, sulphates and sodium in SG blowdown water not more than 20 µg/kg and cation conductivity at the level of 0,8-1,0 µS/cm.

- presence of copper-bearing materials (condensers of turbines, LPH, boilers) in the secondary circuit does not make possible to raise pH value of feedwater above 9,2 to minimize carrying-away of corrosion products of iron from the main condensate system. At the majority of PWR plants, pH value of feedwater amounts to 9,4-9,8, and actual contents of iron - less than 5 µg/kg.

To increase SG reliability and durability of WWER-1000 plants it is necessary to perform work in the following trends:

- turbine condenser tube system made of copper-bearing alloys shall be replaced with titanic alloys or stainless steel, and LPH and HPH tube system - with corrosion- resistant steels. It will enable to reduce considerably the level of intakes of cooling water in turbine condensers, will give possibility to raise pH value of feedwater up to 9,4-9,8 and bring quality of SG feedwater and blowdown water up to the level of western standards. Finally, it will enable to reduce considerably carry-away of corrosion products from the main condensate system, to decrease noticeably the rate of accumulation of deposits, to reduce damageability of heat-exchanging tubes and, as a whole, to simplify SG operation. It is important, especially, for the Units under construction;

- justification and pilot-commercial test of alternative water chemistry of the secondary circuit: - lithium, octadecylamine, ethanolamine and morpholine water chemistry. It also will make possible to minimize carry-away of corrosion products of iron and copper from the main condensate system;

- modernization of blowdown and purification system of blowdown water with the aim of increasing the SG blowdown flowrate and refining the blowdown specifications;

- development and introduction of automatic system of the chemical control of the secondary water chemistry with the inventory of up-to-date instrumentation;

- routine and qualitative chemical washing of SG tubes from deposits (starting from the first years of SG in operation), including local washing of sections with maximum deposits.

3.2 Modernization of inspection and maintenance means

Improvement of inspection, monitoring and maintenance means is an important element in strategy of service life management. The modern level of development of robotics means enables nearly to exclude presence of the man in the areas with ionizing radiation. The operational experience shows low effectiveness of inspection of tubing deposits using the method of deposits scraping from accessible places. These methods shall be replaced with calculated methods of evaluation as well as eddy-current testing method of deposits. Examination of tubing can be performed also remotely without unsealing the secondary-side hatches.

As to maintenance from the primary side, necessary remote means of inspection and repair are available. There is necessity only in their improvement in terms of quality and capacity. The positive experience in application of mechanical plugs in heat-exchanging tubes is noteworthy as they make possible to reduce considerably repair time.

As operational experience shows, inspection means applied nowadays do not provide a reliable identification of flaws for decision making about repair. It is confirmed to be true by heat-exchanging tube leaks with large flowrate due to opening of available flaws /10/. There is a crucial need for improvement of the applied inspection methods. What concerns instrumentation, it is, first of all, application of sensors for improved assessment of flaw geometry /7/. Such sensors of rotation type, array and others are widely applied abroad for spot checking of the most critical areas. Such sensors have been developed also for SG of WWER plants, however, up to now they have not found a wide practical application. Development of regulatory-and-methodical base of inspection as applied to design features of
SG of WWER plants is necessary. Methods of independent expert judgement of the inspection results shall be implemented into practice.

Perfection of ultrasonic inspection methods is required. Practice has shown that the existing methods do not always make possible to reveal cracks which could be formed in the area of weld No. 111.

A great scope of work on certifying the applied inspection methods is in prospect. In Russia the regulatory documents on certification have been brought into force which require application of specimens with real and realistic defects. Actually, the base of such specimens has already been formed by the results of work related to cutting the tubes from the dismantled SG of SU NPP /11/. The acting IAEA program pursues the same objective [12].

3.3 Development of inspection and repair strategy

Development of SG inspection and repair means shall be of tradeoff nature - between sufficient effectiveness and reduction in costs and personnel’s dose commitment. Achievement of the assigned criteria on reliability and safety of operation shall be understood as sufficient effectiveness. As applied to tubing, it is permissible probabilities of heat-exchanging tube rupture as well as provision of the assigned availability factor in case of shutdown because of leak. As it is shown in [13] in practice, the last of the criteria appears to be decisive. The specified probabilities are determined on the basis of the probabilistic approach using methods of fracture mechanics. The surface margin in terms of provision of the required thermal-hydraulic parameters of SG as a part of RP is also considered.

As studies show there are significant reserves on the ways of optimizing the costs for inspection and maintenance. For example, costs for tubing inspection are very high. However, now they are poorly connected to SG actual state, meanwhile, for SG in good state they can be essentially reduced. On the other hand, economy in improving the equipment of the main condensate system inevitably shall turn into increase in inspection scopes and costs for downtimes of the Unit because of leaks and repair of heat-exchanging tubes.

The problem of choosing the value of plugging criterion of defective heat-exchanging tubes by the ECT results (by the depth of corrosion crack - "shortage of material") is remaining important. This value is different in different countries of the world and for various RP. The foreign approaches, however, cannot be transferred to SG of WWER plants, having considerably higher load-carrying ability of heat-exchanging tubes because of greater ratio of wall thickness to diameter. Practice of application of the fixed plugging criteria against thinning depth by indications of bobbin probe shows that the given approach is not optimum. Most leaks are found in those places where the flaw has not been detected before whereas the extension of the majority of the recorded flaws is insignificant [8]. Recently, the tendency prevails of setting up plugging criterion against the type of the flaw and its location with regard for peculiar features of degradation processes in each separate steam generator. In Russia, work on development of plugging criteria considering flaw parameters [10] is also under way. So, in choosing plugging criteria at SG of NV NPP, Unit 3, the following rejection symptoms were considered:

- plugging criterion (recommended) based on the value "shortage of material", proceeding from design estimations amounts to 70 %;
- for flaws located in the range of 60-70 %, the rate of flaw growth according to the data of several EC inspections is more than 10 % per year;
- close location of defects in the critical area (up to 15 mm between indications);
- newly generated indications in the critical area (where intensive degradation was observed).

On the basis of these conditions an analysis of unsoundness for all the Unit steam generators was performed and heat exchange tubes to be plugged were determined.

In 2003 about 600 tube sections were cut out of the dismounted SG at the South-Ukrainian NPP /11/. The area of cutting-out is located in semicircle II between the spacing grids 1 and 4 out of 25 lower rows of tubes. At present the following testing of the cutout specimen performance is under way:
• correlation is being determined between the linear dimensions of actual flaws and the parameters of EC signals;
• certification testing facility is being built;
• detectability thresholds for different EC hardware is being determined;
• detection of through defects with the method of gas leak detection;
• pressure tests are being carried out to justify the plugging criteria.

Optimization of the plugging criteria with account for the EC signal amplitude (the amplitude is proportional to the volume of discontinuity) and an individual approach to each defect (location, geometrical dimensions) will permit to reduce considerably the number of plugged tubes and extend the service life of the problem SGs.

Nowadays the regulatory documents define the scopes and periodicity of inspection, as well as the criteria of heat exchange tubes plugging in PGV-1000 SG. However, the given documents deal with SGs, that show no salient signs of heat exchange tube degradation. For problem SGs in each particular case special corrective activities are worked out that incorporate an increase in the scope of inspection and plugging criteria revision. At present inspection strategy is being developed in Russia supported by an engineering and economic substantiation to be followed by a regulatory document issuance and a revision of operational documentation.

3.4 A forecast for tubing service life

To extend RP lifetime the task of capital equipment service life extension up to 45 years needs to be solved. As for steam generators the issue of its service life extension depends on the lifetime of its heat exchange tubes. The assessment of the tubing residual life is made on the basis of the probabilistic approaches covered in [13]. When applying the methods we face major difficulties in assigning the input data on the initial condition of the tubing and the dynamics of its deterioration. The extension of service life for the steam generators at Novovoronezh and Kola NPPs has been implemented with considerable uncertainty of the heat exchange tubes residual life, because so far there is no procedure to determine lifetime of heat exchange tubes with corrosion defects that takes into consideration all the operational factors. As the value of ECT uncertainty is not determined there exists considerable error when determining the probability of SG heat exchange tube rupture or leak, that is the principal criterion when calculating the value of residual life of SG tubing. By the results of the analysis carried out, intensive tubing degradation in a number of SGs is under way. Due to the above uncertainty of SG tubing residual life, OKB “Gidropress” has added to the terms of SG 15-year service life extension a list of compensatory activities and a requirement of mandatory confirmation of the residual life of SG heat exchange tubes every 5 years with account for the above activities.

Thus, one of the main tasks of the study is the description of the model of tube damageability with account for all the operational factors and, first and foremost, the factors of corrosion. Studies need to be done with this aim in view both with models and in autoclaves as well as the analysis of operating experience. Modeling of the actual conditions of heat exchange tube operation is sufficiently difficult and time-consuming so the elaboration of the model shall be based, first and foremost, on a study of SG operating experience. For this purpose processing and analysis of a large amount of data is required, beginning with the stage of SG manufacturing. They are properties of materials, results of non-destructive testing, water chemistry parameters and operating conditions. Such work is impossible without applying contemporary information-analytical systems that are being developed at present [14], [15].

The main bulk of information at present consists of ECT results. They permit to obtain numerical characteristics connected with the state of each heat-exchange tube and make integral assessments on the basis of these data. Software has been created for simple and easy work with these data arrays. All the information obtained from the Russian NPPs is accumulated in a single data bank that is upgraded on a regular basis [8]. One-type processing of information on a large scale has permitted to master the process and methodology of analysis, a possibility appeared to follow, if necessary, not only the dynamics of changes in the state of each SG, but also that of each individual defect. A number of criteria have been revealed, their value and variation permitting to assess the state of SG, the trends of its changes, the
influence and efficiency of corrective activities. New criteria and correlations between the operating parameters (thermal, chemical and dynamic) and these criteria are being studied.

The morphology of defects and the dynamics of corrosion mechanisms is investigated both on heat exchange tube specimens cut out of the operating SGs, and in the course of studies on corrosion mock-ups and in autoclaves [16].

A study of tubing corrosion is directly connected with a substantiation of the hydrodynamics of water space. So far positive results have been achieved in the mathematical modeling of mass transfer on the secondary side [17]. However, experimental data are not sufficient for a reliable verification of computer codes. It is necessary to continue the studies both at the newly commissioned Units and on the mock-up that is supposed to reproduce the main hydrodynamic phenomena on the secondary side.

The forecasts for the SG service life on the basis of statistical estimation of SG operability at a number of power Units [15] show a possibility to extend the lifetime up to 50 years.

4. CONCLUSION

The work to increase SG reliability at the operating Units is mainly directed at meeting state-of-the-art requirements for the secondary-side water chemistry.

An increase in the engineering level as well as an improvement of the methodological provisions of SG in-service inspection hardware and their certification is required.

A possibility to extend the SG service life above the design one is stipulated, first and foremost, by the state of tubing, which depends on the conditions of operation. For a number of power Units a possibility has been demonstrated to extend service life to as long as 50 years on condition of a high technical level of operation and water chemistry management.
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