VVER STEAM GENERATOR PERFORMANCE AND EUROPEAN COMMISSION SUPPORT

R. Ahlstrand, M. Bièth, C. Rieg and P. Trampus
Institute for Energy, EC DG JRC
P. O. Box 2, NL-1755 LE Petten

Steam generators are one of the most critical components of VVER nuclear power plants due to both their high safety significance and their importance in plant availability. In case of VVER-440s, moreover, the steam generators may be life-limiting components because their replacement is, as a consequence of the plant layout, practically impossible. The European Commission continues to improve the safety of nuclear facilities in Central and Eastern Europe via its TACIS and PHARE programs, and the Institute for Energy provides technical and scientific expertise in all areas of these programs. The paper summarizes the main technical and scientific achievements of the above European Commission support. SENUF (Safety of Eastern European Nuclear Facilities), a new network type initiative of the Institute for Energy, is also introduced. SENUF is now focussing on plant maintenance, which provides a framework for some emerging steam generator related topics.

1. INTRODUCTION

In commercial pressurized water reactor (PWR) nuclear power plants (NPPs), the steam generator tubes represent more than half of the total pressurized surface of the primary circuit, and their failure can lead to a small break loss of coolant accident (SB LOCA). The tubes are part of the containment as one of the physical barriers to radioactive release, which means that a tube failure, which may result in primary coolant leakage into the secondary side, could lead to a radioactive release into the environment. Structural integrity of the heat exchanging tubes is a serious safety issue not only during design basis accidents like a main steam line break but risk assessment studies show that a significant portion of the risk due to steam generator tube failures is associated with tube failures due to severe accidents, during which tube temperatures can increase to 650-700 °C [1].

Steam generator performance is clearly important from the point of view of plant availability and becoming much more important in case of ageing NPPs. Steam generators have been described as the weak link in the PWR design. Considering exclusively the tubing problems, this statement is not valid for VVER steam generators. The load bearing capability of heat exchanging tubes in VVER steam generators exceeds that of the PWR steam generators, thanks on one hand to the structural material (titanium stabilized stainless steel) used, and on the other hand to the greater wall thickness in relation to tube diameter. Taking into consideration the heat transfer capacity, the VVER steam generators have larger in-built reserve than vertical steam generators. These benefits are, however, counterbalanced by the primary circuit layout of the VVER-440 NPPs, which in fact makes any steam generator replacement impossible (or economically impractical). Consequently, VVER-440 steam generators play as significant a role in determining the limit of plant service life as the reactor pressure vessel [2]. Table 1 summarizes some of the main features/parameters of the VVER steam generators. For the sake of comparison, the corresponding PWR steam generator features are also included.

Table 1

Main features/parameters of VVER and PWR steam generators

	VVER-440	VVER-1000	PWR
Type	Horizontal	Horizontal	Vertical
Heat transfer coefficient, kW/m^{2}K	4.7	6.1	6.7 – 8.5
Recirculation number	4 - 6	1.5 – 1.9	3 - 6
Barrier between primary and secondary circuit	136 mm tube collector wall	171 mm tube collector wall	600 – 1000 mm plate
Water separation	One step	One step	Two steps
Heat exchanging tube material	08H18N10T	08H18N10T	Alloy-600, 690 or 800
Collector/Plate	08H18N10T	10GN2MFA, 08H18N10T cladding	Low-alloyed steel, tube material cladding
Shell	22K	10GN2MFA	Low-alloyed steel
Supports	08H18N10T	08H18N10T	Carbon- or stainless steel

2. VVER STEAM GENERATOR PROBLEMS AND PERFORMANCE

Major problems related to VVER steam generators have included the following:

- *Primary collector ligament cracking of VVER-1000 steam generators.* The cold collector has suffered from stress corrosion problems and severe collector cracking has been observed. The reason for the cracking was mainly originating from manufacturing process: explosion welding was used for fastening the tubes to the collectors and the small ligaments between the tube holes were plastically deformed when fastening the tubes. As a consequence the material properties in the ligament changed and the collector was partly bent due to asymmetric deformation. At present most of the steam generators of operating VVER-1000 plants have been replaced and in new steam generators, the tubes are fastened to the collector walls using hydraulic compression. The allowance in the upper part of the collector and the steam generator body was also increased in order to avoid collector contact with the steam generator frame.
- *Intergranular and/or transgranular stress corrosion cracking (IGSCC, TGSCC) on the heat exchanging tubes of both VVER-440 and VVER-1000 steam generators.* The main contributors to this degradation are the iron corrosion products and the copper and copper compounds from feed water and condensate systems and their deposition on the tubes. The use of corrosion-resistant materials for high-pressure and low-pressure pre-heater tubing as well as for elbows or T-joints of piping, which are known to be subject to erosion/corrosion, can help to reduce iron transport to steam generators. Using stainless steel or titanium rather than copper-based alloys as a condenser tube material will help to prevent copper transport to steam generators and to reduce oxygen intake into the condensate system.

- *Loss of primary collector integrity due to cracking of threaded holes on the flange area or cover lift-up as a consequence of bolt rupture in VVER-440 steam generators.* The degradation mechanism for both failure types is stress corrosion accelerated by specific lubricant materials additions. Preventing, detecting and mitigating measures will be discussed later in this paper.
- *Feed water distribution header erosion (at T-joints and distribution nozzles) of VVER-440 steam generators.* Redesign and replacement of the whole part within the steam generator was carried out in most steam generators.

It can be seen that there are different factors that affect VVER steam generator performance in general such as construction (design), structural materials and water chemistry regime. Ideally, a harmony should exist among these factors in the entire steam, condensate and feed water system because the impurities and corrosion products accumulating in the steam generator originate from these systems. Theoretically, it means the following:

- The construction (design) should ensure that zones of high local stresses, stagnant and disordered flows and high local heat fluxes are avoided.
- Concerning the structural materials, the mass rate of general corrosion should be as low as possible and they should not be sensitive to local corrosion.
- As for the water chemistry, the concentration of stress corrosion activators should be minimal and dosed chemicals must provide for minimal corrosion of the selected materials [3].

3. EUROPEAN COMMISSION SUPPORT AT A GLANCE

Member States of the European Union (EU) have been making a sustained effort, spanning several decades, to enhance nuclear safety through a number of technical and legislative actions and, consequently, have been decreasing the environmental and health risk related to the production of nuclear energy and to the management of irradiating materials such as radioactive waste and spent nuclear fuels. The TACIS and PHARE programs were established in 1991 along with other European Commission (EC) programs as support mechanisms through which projects could be identified and addressed satisfactorily.

One priority for TACIS and PHARE funding is nuclear safety. In the nuclear safety area, the countries mainly concerned are Armenia, Kazakhstan, Russia and Ukraine for TACIS, and Bulgaria, Czech Republic, Hungary, Lithuania, Romania, Slovakia and Slovenia for the PHARE program. The TACIS and PHARE programs concerning NPPs consist of on-site assistance and operational safety improvement, design safety improvement, regulatory authority assistance and waste management issues. The assistance is focused on reactor safety issues contributing to the improvement in the safety of operating (mainly Russian designed) NPPs in Central and Eastern Europe through technology and safety culture transfer. Between 1991 and 2003, the TACIS funding used amounted to € 940 million and that of PHARE was € 240 million.

In the framework of the TACIS and PHARE programs, the Institute for Energy, one of the seven institutes of the Joint Research Center (JRC-IE), a Directorate General of the EC, has a unique role: it provides the policy Directorates General of the EC with the necessary technical and scientific support totally independently from any vested or commercial interests, and it has been performing this role since 1997.

In regard to VVER steam generators 32 projects have been implemented in the past decade or so. The beneficiary countries were: Armenia (1), Bulgaria (1), Czech

Republic (3), Hungary (1), Russia (16) and Ukraine (10). In case of the three Czech Republic projects, Hungary and Slovakia were co-beneficiaries. The distribution of the steam generator related projects among topical areas were:

- Water chemistry regime (9)
- In-service inspection, non-destructive examination (7)
- Replacement of safety and control valves (10)
- Erosion/corrosion (2)
- Primary to secondary leakage (1)
- Stud tensioning technology (1)
- Steam generator replacement (1)
- Leak detection system (1).

To illustrate the achievements of the EC funded projects, selected projects from the areas of water chemistry regime improvement, handling large primary to secondary leakage, in-service inspection (ISI) of the tubes and steam generator replacement strategy and methods, will be briefly summarized in the following sections.

4. WATER CHEMISTRY REGIME IMPROVEMENT

In operating NPPs, where construction and materials are given and their modification, even if it is possible, has limitations, the water chemistry regime can provide the best opportunity to maintain the harmony mentioned in the introduction. The projects were primarily dedicated to the Kalinin NPP in Russia and to the South Ukraine NPP in Ukraine (both VVER-1000) with the objectives of preserving steam generator integrity by minimizing corrosion risk in the secondary side and of optimizing primary coolant and thus reducing the production of liquid radioactive waste. The major project tasks for both plants were:

- Analysis of steam generator secondary side water chemistry.
- Application of proven computer code to collect data on chemical environment in steam generator crevices.
- Feasibility study for replacement of ammonia by morpholine.
- Definition of comprehensive and coherent set of monitoring and analyzing equipment (for both primary and secondary regime).
- Review of primary side water chemistry specifications.
- Definition of associated corrective actions.
- Assessing possible substitution of ammonia by hydrogen.
- Feasibility study for condenser tube cleaning.
- Associated equipment supply.

Improvement of the secondary water chemistry by adapted specifications and enhanced control as a consequence of on-line monitoring means and accurate laboratory analysis is certainly the most visible result achieved at Kalinin NPP confirmed by the proper status of the steam generators. The result was obtained through a very close collaboration between the parties involved [4]. In the South Ukraine NPP, the implementation of morpholine water chemistry regime has contributed to steam generator integrity improvement. The number of unplanned unit shutdowns due to primary to secondary coolant leakage has fallen [5].

5. HANDLING OF LARGE PRIMARY TO SECONDARY LEAKAGE

Large primary to secondary leakage (defined as PRISE) is a major concern of the VVER-440 units. The primary collector is known to be a sensitive item of these reactors. Rupture of one or more tubes or loss of primary collector integrity (collector break or cover lift-up) cannot be totally excluded. Such events can lead to an uncontrolled overfilling of the steam generator, a pressure increase, and then, safety valve opening and radioactive release. During the accident mitigation, due to possible loss of the emergency core cooling system water recovery features, PRISE can also increase the core melt probability. PRISE was considered by the designer as a postulated accident only after the primary collector cover lift-up at Rovno NPP (Ukraine). In Paks NPP (Hungary) cracks were detected around the threaded holes of the primary collector flange during a routine ISI see Fig. 1.

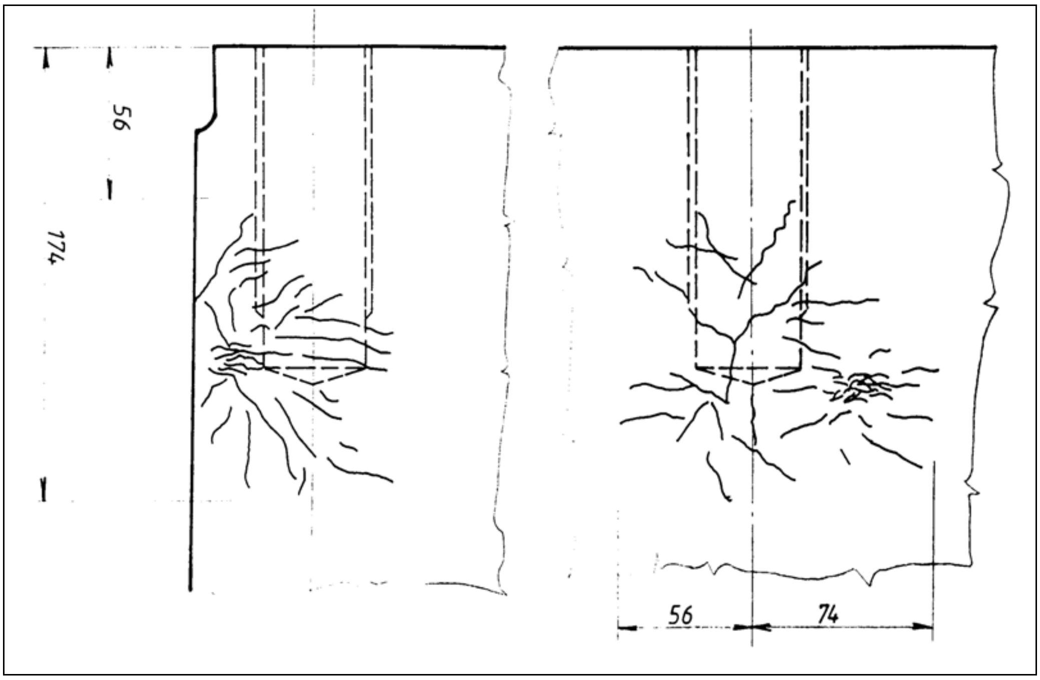

Fig. 1. Cracks detected in the primary collector flange

This event led to the establishment of a PHARE project for Hungary. The project objectives were to decrease PRISE occurrence probability, to ensure that radioactive release criteria were respected for those breaks with the highest probability, and to decrease core melt probability for the breaks with lower occurrence probability but having more severe consequences. A concept based on defense-in-depth principles was proposed and implemented: improvements were recommended in the field of prevention of the event, detection of the leak and mitigation. Table 2 shows the summary of the project recommendations.

6. ISI OF HEAT EXCHANGER TUBES

ISI on steam generator is crucial for the assessment of fitness-for-service and safe operation of the NPP on a long-term basis. TACIS and PHARE have funded several projects concerning ISI and NDE of steam generators. For VVER-440 plants, improvements to the ISI of transition welds (to both secondary collector and feed water nozzle) and primary collector (associated with PRISE) were the aim of two of the PHARE projects. These projects covered the following:

- Assessment of the current inspection technology by a round-robin-test (preparation of a steam generator collector with real cracks, determination of the acceptance criteria, implementation of the trial with international participation and evaluation of the results).
- Elaboration of procedures for the NDE qualification process and of drawings and specifications for the purchase of qualification test blocks.

Table 2

Defense-in-depth concept for PRISE

	Level 1	**Level 2**	**Level 3**
Prevention	To avoid leakage ▪ Chemical treatments improvements	To detect leakage ▪ Inspection, maintenance recommendations ▪ Sensitive detection of steam line activity	To limit consequences ▪ Recommendations for Tech. Specs. ▪ Collector cover design improvement
Detection		▪ Continuous monitoring of secondary activity (in condenser, in steam line – N16) ▪ Sampling (blow down)	▪ Optimized diagnosis (Symptom-based Emergency Operation Procedures)
Mitigation	AVOID SG OVERFILLING	No → AVOID LOSS OF SEC. INTEGRITY	No → LIMITATION OF RADIOLOGICAL CONSEQUENCE

Design Basis Case | *Beyond Design Basis Case*

One of the biggest issues in steam generator ISI is the eddy current examination of the heat exchanging tubes. The active degradation mechanism, i.e. stress corrosion cracking initiation and growth from the tube outer surface mainly beneath the support plates, leads to tube failure. In extreme cases the cracks propagate through the wall and the radioactive primary coolant medium leaks into the secondary side. Although eddy current examination has become a daily routine in almost every plant, inspection strategies (scope), plugging criteria and level of inspection quality differ throughout the industry. Sometimes the cause of the limited inspection scope is obviously the lack of funding. Several TACIS projects were aimed at improving this situation. In the framework of these projects, among others, complete inspection equipment with remote-controlled manipulators and data evaluation software was delivered, and training of inspection personnel was carried out. A special project to establish a center for training, qualification and certification of personnel of the Ukrainian nuclear power industry NDE was completed. Fig. 2 shows the qualification process recommended for the tube inspections as an example of the project outcomes.

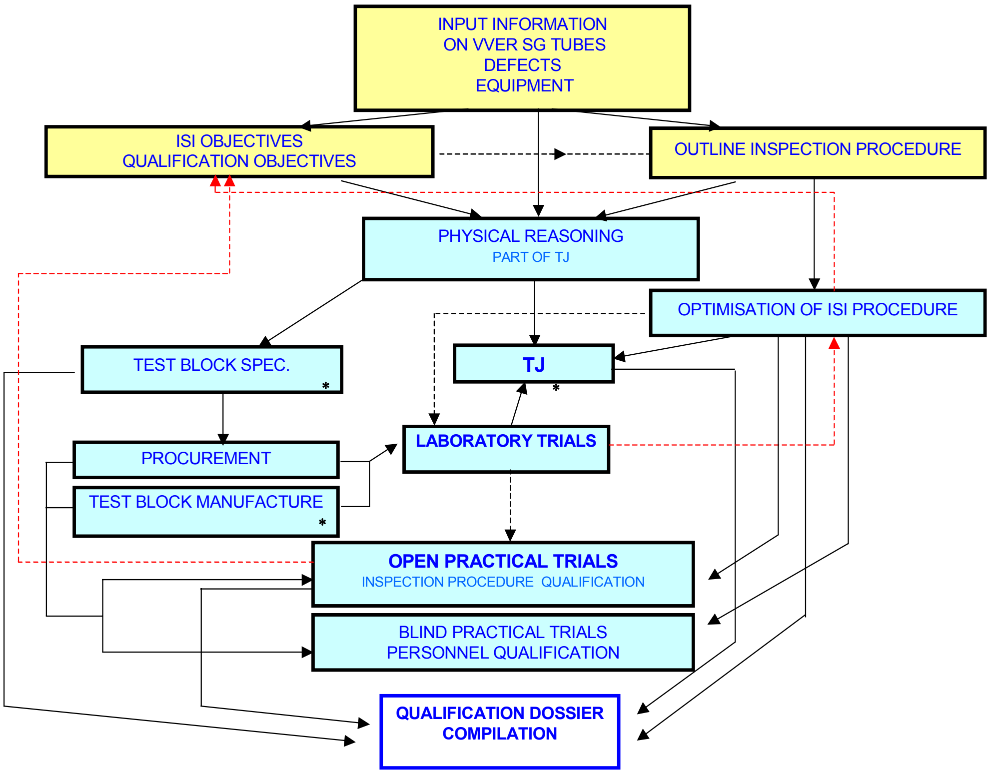

Fig. 2. Flowchart for the qualification process for eddy current examination of steam generator tubes

7. IMPLEMENTATION OF STEAM GENERATOR REPLACEMENT SYSTEM

Since VVER-1000 steam generator replacements cannot be excluded in the future, a special project was launched, dealing with replacement strategy and methodology to optimize eventual replacement actions. The beneficiary country of the project was Ukraine. The expected results of the project were an increased efficiency and reliability of processes, reduction in outage time as well as reduction in radiation doses. The basic concept of the strategy recommended consists of the conservation of the original design and minimization of impact stress status on the reactor coolant loop. The main elements of the replacement methodology were:

- Clamping of the primary piping before cutting.
- Matching of the new steam generator and piping supported by optical survey and calculation.
- Accurate machining of steam generator nozzles and pipe ends.
- Reliable welding (automatic narrow-gap welding technology).
- Radiation dose prediction.

8. SENUF

The main actors of the TACIS and PHARE programs are spread around several countries, whereas the NPPs are mainly of the same design, i.e. VVER and RBMK, and the safety related topics are generic. The creation of a horizontal and integrated project concerning nuclear safety of NPPs in Eastern Europe has been the best solution to bring together all stakeholders: the beneficiaries, end users, Eastern and Western nuclear industries, and thus, to favour fruitful technical exchanges and feedback of experience. The specific objective of this horizontal project called "Safety of Eastern European Type Nuclear Facilities" (SENUF), integrated into the JRC-IE's existing nuclear safety related SAFELIFE action [6], is to facilitate:

- the harmonization of safety cultures between the Candidate Countries (CCs) and the EU,
- the understanding of needs to improve the nuclear safety in CCs,
- the dissemination of JRC-IE nuclear safety institutional activities to CCs.

Within SENUF, it was decided to concentrate first on NPP maintenance. A specific Working Group has been established on NPP maintenance and to date nine institutions (mainly utilities or NPPs) from Western as well as Central and Eastern Europe have signed an agreement with JRC-IE to collaborate. One of the major tasks in 2004 is to prepare a status report on advanced strategies for optimisation of NPP maintenance. This task covers the analysis of the existing optimisation strategies (e.g. predictive maintenance based on monitoring component condition, reliability centred maintenance, risk informed maintenance), and has an interface with the overall life management programs of the plants. Nowadays, many VVER plants have decided to extend their service life and thus component ageing management, modernization, refurbishment or replacement actions became much more important. Steam generators are always on the agenda of the life management programs, consequently, SENUF results may also contribute to maintaining overall steam generator performance.

9. CONCLUSIONS

It has been described that VVER steam generator performance depends on various factors such as construction, structural materials and water chemistry regime. In operating NPPs, where construction and materials are already given and their modification even if possible has limitations, the water chemistry regime seems to be the most effective tool for maintaining and/or improving performance. The EC's TACIS and PHARE programs in the field of nuclear safety have been a useful instrument in relation to steam generator performance improvement.

REFERENCES

[1] SGTR Severe Accident Working Group, "Risk Assessment of Severe Accident-Induced Steam generator Tube Rupture", NUREG-1570, US NRC, Washington DC, 1998

[2] F. Gillemot: Technical risk considerations for a VVER plant, Proc. IAEA Technical Meeting on Risk Informed Aspects of NPP Life management – Emphasis on Integrity of Primary Circuit Components, Budapest, 2001, p. 211-220

[3] J. Osz: Decrease of Degradation Risk Factors of WWER Steam Generators, Proc. Joint WANO Moscow Centre – IAEA Regional Workshop "Optimisation of Steam Generator Performance", Rovno, 2002

[4] V. Balashov, J.-P. De Cook: Water Chemistry Control Improvement Projects in the Framework of the TACIS Nuclear Safety Programme at Kalinin NPP, Proc. Int. Conf. "10th Anniversary of the TACIS Nuclear Safety Programme", Kiev, 2002, p. 70-72

[5] A. Arkhipenko: Water Chemistry Control Improvement Projects in the Framework of the TACIS Nuclear Safety Programme at Ukrainian NPPs, Proc. Int. Conf. "10th Anniversary of the TACIS Nuclear Safety Programme", Kiev, 2002, p. 73-76

[6] Report EUR 20984 EN on Int. Seminar "Networking for Effective R&D", Petten, 2003