

DEFECTS IN THE METAL OF WELDED JOINTS OF COLLECTORS TO STEAM GENERATORS IN NUCLEAR POWER PLANTS

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Abstract

This article presents a study of the metal of coolant collectors' welded joints to steam generators in nuclear power plants. During the operation of nuclear power plants of the VVER-1000 type, metal defects were found in the collectors' welds to the steam generator body. The general cause for the defects' occurrence and development is the combination of: 1) the influencing stresses, and 2) the corrosively aggressive working environment. The specific manifestation and development of defects differs across different NPPs. This study focuses on examining the on-site working conditions. It describes observations on the occurrence and development of defects in the metal of the welded joints and possible facility degradation scenarios. The resulting data come from actual observations spanning a 30-year-period. This information is important for the safe operation of steam generators in NPPs. The data can be used for probabilistic safety analyses at NPPs as well as for NPP lifetime extension.

Key words: nuclear power plants (NPPs), steam generators, defects, long term operation

Introduction. In the first decades of the 21st century, people operate numerous safety related facilities, components and systems that are at the end of their design life period, or run under extended service life of nuclear power plants. The facilities lifetime extension occurs after obtaining positive results of tests and

analyses of their operability. This is especially relevant due to the high standards and requirements of the authorities, as well as public expectations for the safe operation of nuclear power units. As of 2024, of all the nuclear reactors in operation worldwide, 164 reactors have been in operation for 40 years or more [1]. The degradation mechanisms of the metal mechanical properties, typical for nuclear installations, are well-known [2]. However, the synergistic effect of several influencing factors has not been studied yet. It turns out that under the influence of operating conditions and after 35–40 years of operation, areas with potential for metal degradation and destruction occur in great part of the metal used on the facilities. Metallographic tests are carried out periodically by means of various non-destructive methods. The data obtained are indicative of the integrity of the metal on the facilities and can be used in the probabilistic analysis of a nuclear power unit safety. It is necessary to conduct strength calculations, for which data on the mechanical characteristics of the metal of the equipment are used.

Materials and methods. The steam generator (SG) is part of the VVER-1000 reactor plant. It is a horizontal evaporator with a submersible U-shaped tube bundle of heat exchange tubes. The body of the steam generator is a cylindrical vessel with an inside diameter of 400 cm, with two elliptical end plates. The cylindrical part of the steam generator housing consists of a central ring and two side rings. In the lower part of the central ring, two nozzles with a diameter of DY 1200 are welded to connect the coolant manifolds at the primary circuit (“hot” and “cold” nozzles/collectors), as shown in Fig. 1a. The primary circuit coolant collectors have the same devices and are vertical vessels, as shown in Fig. 1b. The

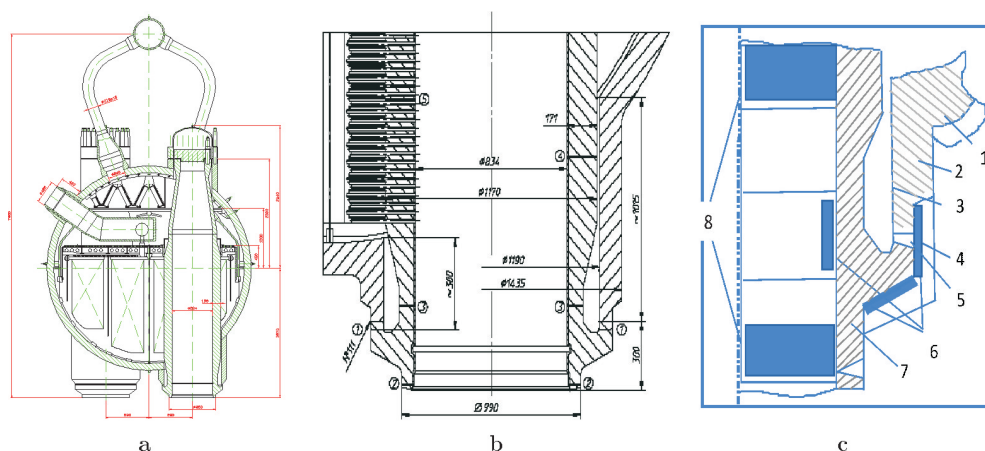


Fig. 1. a) Cross-section of a steam generator type PGV 1000M; b) Nozzle DY 1200 for the SG collector; 1 – section of the collectors’ welded joints to the SG housing, 2 – section of the main circulation pipe-lines, 3 – section of the collector; c) Diagram of the weld between the manifold and the DY 1200 nozzle. 1 – SG body with insulation, 2 – gland; 3 – “pocket”; 4 – thermal insulation; 5 – welded joint; 6 – heating elements; 7 – collector; 8 – thermal insulation plugs

parts are made of high-quality ferrite-pearlite steel 10GN2MFA. On the inside of the collectors there is an anti-corrosion overlay. The welded connection between the SG collector and the DY 1200 nozzle has a complex geometry resembling a “pocket” (Fig. 1c).

The SG operating conditions are determined by the different power unit operating modes and states. The data on thermal and structural stresses originate from the strength analysis of the steam generator collector [3], and are shown in Table 1.

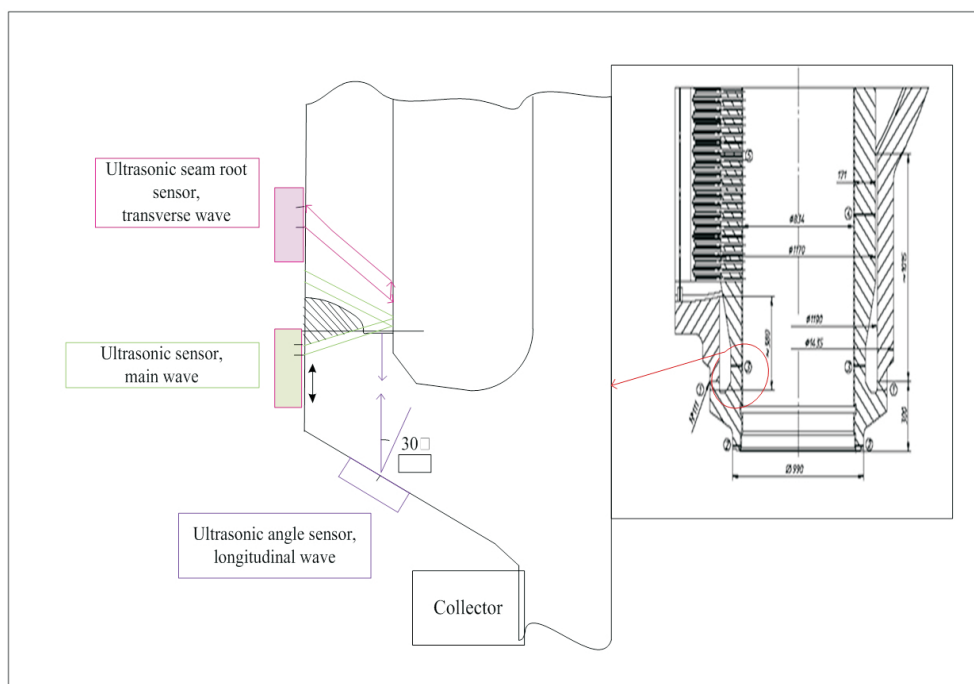
T a b l e 1

Operating conditions of steam generators – values for pressure, temperature and voltage

Parameter	Values	
	Primary circuit	Secondary circuit
Pressure at the primary coolant side	15.6 MPa	–
Generated steam pressure	–	6.18 MPa
Rated working pressure	17.6 MPa	7.85 MPa
Pressure in hydrostatic strength tests	24.5 MPa	10.8 MPa
Pressure in hydrostatic leak tests	17.6÷19.6 MPa	7.85÷8.6 MPa
Generated steam temperature	–	278.5 °C
Coolant temperature at the SG inlet	320 °C	–
Coolant temperature at the SG outlet	289 °C	–
Design temperature	350 °C	300 °C
Temperature in hydrostatic tests	70–119-dg	70-dg
Local circular (bending) stresses	132.8 MPa	
Local meridional stresses	91.1 MPa	
Total meridional stresses	136.8 MPa	
Total bending stresses	117.3 MPa	

The working medium of the welded joints is air, and that of the collectors is the primary circuit fluid. The welded joints metal examination was carried out by non-destructive ultrasonic testing [4, 5]. The test equipment was an ultrasonic multi-channel flaw detector TOMOSCAN III, SPH-pipeline scanner and sensors. Appropriate scanning of the objects through various sensors was carried out (Fig. 2).

Results. During periodic ultrasonic inspection of the welded joints, the presence of discontinuities (defects) was found. The cracks grow from the inner surface of the nozzle into the weld metal. Defects originate in the inner surface of the welded joint and the base metal in the radius transitional area. The observation period lasted about 30 years. No defects were found at the beginning of the SG operation. The incubation period is defined as the time of operation of the facility during which the defect will develop from a micro level to a minimum detectable



size of about 1 mm; this value depends on the sensitivity of the test equipment. The shortest incubation period is estimated at 14–15 years. Once the defects have been identified, the sites must be inspected every year in order to ensure the safe operation of the steam generator. The inspection periods are then shortened from 4 years to 1 year. Two possible orientations of the defects are defined. The first group of defects are oriented along the axis and parallel to the axis of the weld within the limits $\pm 15^\circ$ to the axis of the seam, starting from the inner surface. The second group of defects are located at the root and along the lines of fusion of the welded joint with the base metal – close to 90° . The length values of defects in the welded joints are presented in Fig. 3 for two steam generators (A and B).

Discussion. In order to produce high-quality welding seams for the safety important steam generators, collectors and nozzles, mandatory systematic and strict quality control of the welded joints has been introduced in the production process. During welding, various metallurgical defects can arise and develop such as microcracks in the seam, holes, uneven layering, lack of seam tightness, large stresses and deformations, and many others. Throughout the operation of steam generators in NPPs, under the operating conditions impact, defects start to develop in the objects under consideration. This is due to the specific design of the welded joints, the acting thermo-hydraulic stresses, tensile stresses from other equipment in the circuit and the corrosive-aggressive working environment [6, 7].

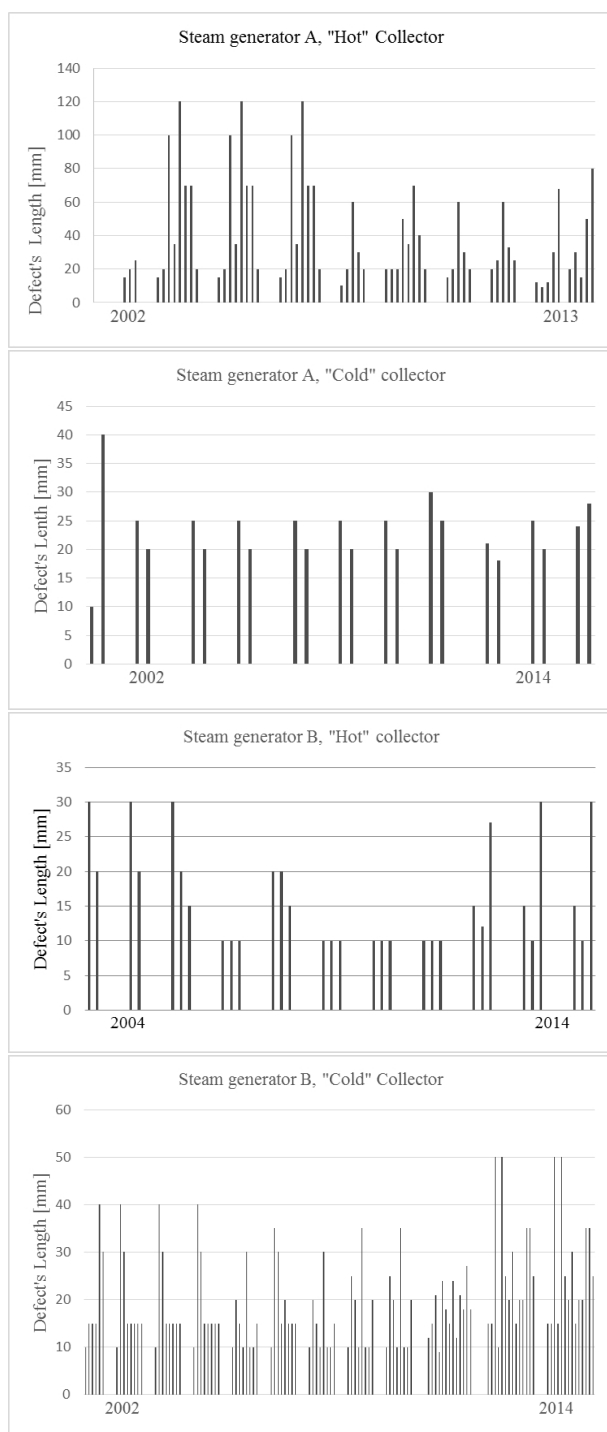


Fig. 3. Length of defects [mm] vs. years of steam generators operation. Development of defects in the welded joints for two steam generators (A and B). Each vertical line indicates a defect

The first stage of the defects formation at the root of the suture and in the peri-suture zone is caused by stress corrosion. The further development of the defect to a depth of up to 2–3 mm is along the radius transitional line – we conditionally refer to this as the second stage of defect development. The mechanisms of metal destruction in the second stage are stress corrosion cracking and corrosion fatigue of the metal. The best case scenario in practice is absence of (substantial) development of defects during the operation of steam generators, Fig. 3, point 1. In case of stress corrosion cracking and corrosion fatigue of the metal, a rapid growth in the number of defects is observed, as well as an increase in their length, Fig. 3, points 2 and 3. These are the worst case scenarios of defect development – the material becomes porous, and a fatal destruction may occur due to stress corrosion cracking. In cases of a large number of defects, there is a danger of fast fracture of the material. In the process of extending a steam generator life it is necessary to assess the metal condition according to two criteria – the material brittle fracture toughness and the resistance of the metal to defects development. It is important to note that the described cases have been observed under the same operating conditions of the steam generators and, therefore, the influencing load factors are equivalent.

Conclusions. The welded joints metal condition is assessed in accordance with the requirements of strength standards [8]. Defects can be assessed as acceptable or unacceptable. In the first case, steam generator operation is allowed, provided that the defects will be monitored annually. In case of unacceptable defects, the equipment must be repaired. The most dangerous ageing mechanisms registered in the welding area are stress corrosion and corrosion fatigue, which, under certain factors, can cause the development of a through-hole crack due to delayed deformation-corrosion cracking. The results of ultrasonic testing show the presence of local corrosion (pitting) on the inside surface of the “pockets” of the DY1200 nozzles, which at a certain stage of operation becomes a dominant ageing mechanism. No crack-type indications have been recorded. Preventive measures are taken at NPPs to reduce the corrosion products and the rate of corrosion in steam generators. The copper-containing equipment along the secondary part is being replaced, a highly alkaline water-chemistry regime is maintained, the system for constant and periodic purging of steam generators is being modernized. When extending the steam generator service life, it is necessary to conduct strength assessments of the condition of the steam generators.

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