Possible in-service damages of steam generators at VVER-1000 and VVER-1200 NPP units and their impact on long-term operation

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Abstract. Specific features of corrosion-mechanical damages of primary circuit header to steam generator vessel branch welds at VVER-1000 NPPs and their impact on safety and economic efficiency during long-term operation are analysed. Measures to avoid the damages for similar zones of VVER-1200 steam generators are discussed.

Keywords. VVER-1000& VVER-1200 reactor facilities, long-term operation, steam generator, weld of primary circuit header to steam generator branch, corrosion-mechanical damage in operation.

1 Introduction

One of serious issues during VVER-1000 NPP operation is damage of primary circuit header (collector) to steam generator (SG) vessel branch welds. The welds under consideration are conventionally indicated as SS-111 for both “hot” and “cold” SG headers.

VVER-1000 NPP Units are significant part of the existing Russian NPP fleet and are also the basis for development of domestic nuclear energy in the future and essential component of nuclear technologies export abroad.

Analysis of the operating experience of the VVER-1000 NPP is important both for long-term operation of existing power units and for future effective operation of new NPPs with VVER-1200 and VVER-TOI reactor facilities with a design life of 60 calendar years.

The analysis is of rather high importance due to lack of clearly established root causes of damages in SS-111 zones. It can be used for the VVER-1200 NPP units under construction and under design to clarify the requirements for diagnostics of technical state parameters of the SS-111 zones both at the stages of commissioning and long-term operation.

2 Operation experience of VVER-1000

The operation of the VVER-1000 NPPs was not perfect, in particular, because of damages revealed on the primary circuit collectors and forced replacement of a significant amount of SGs at NPP Units in Russia and Ukraine [1]. The next problem area turned out to be the SS-111 zone.

Specific design features of SS-111 zones under consideration are shown in Fig.1 [2]. SG branches connected to headers are oblique ones having long and short forming lines. A typical view of the SS-111 zone "pocket" is shown in the right part of Fig.1.

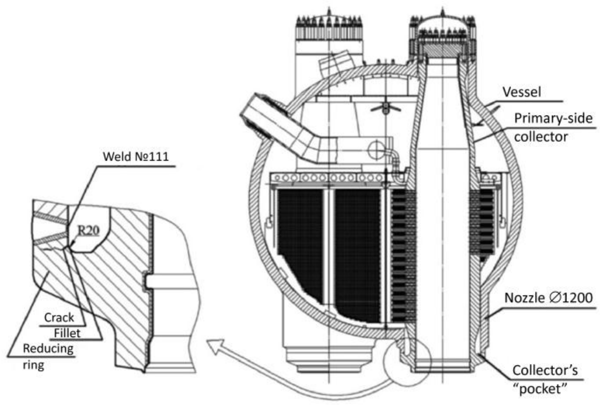

Fig.1. Steam generator PGV-1000M [2]

Damage of SS-111 starts on the inner surface from the "pockets" under corrosion impact of the secondary circuit coolant. Water chemistry parameters inside the "pockets" (Fig.1) may differ for the worse with accumulation of corrosion products and increased content of impurities.

For the first time, SS-111 damage was detected in 1998 at unit No. 5 of Novovoronezh NPP due to a leak. Subsequently, damages of SS-111 welds of "hot" and "cold" SG headers were detected at the Russian NPP units (unit No. 5 of Novovoronezh NPP, units No.No.1, 2 and 4 of the Balakovo NPP), as well as at the

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https://doi.org/10.1051/e3sconf/202020903005

Ukrainian NPPs (South Ukrainian NPP and Zaporozhye NPP).

3 In-service damage mechanism assessment

Examinations of metal cut from damaged SS-111 zones revealed corrosion-mechanical damage in form of cracks initiating from the inner surface of the "pocket" in contact with secondary side coolant.

Damage in the SS-111 zone of cold SG collector of Kalinin NPP unit No.1 had specific features as long chains of pitting (Fig.2).

Fig.2. Pitting areas in the **SS-111** zone of cold SG collector of Kalinin NPP unit No.1 [3]

Mechanism of crack initiation and growth in the SS-111 zones was defined as delayed deformation corrosion cracking [1,4]. Studies performed in Ukraine have confirmed the same nature of damage of defective SS-111 zones of "hot" and "cold" headers [8]: "comprehensive studies and data obtained earlier suggest that the nature of destruction of welded joints in the steam generators of the South Ukrainian and Zaporozhye NPP is the same, despite the fact that the cracks were formed on the "hot" header in the first case, and on the "cold" – in the second".

In [2] based on results of computational substantiation of strength of the header and its connection zone with the SG branch, using refined three-dimensional finite element models and taking into account the significant factors (pressure environments of the first and second circuits; temperature field during facility operation at nominal parameters, loads from piping of the main circulation circuit (MCC)), it was noted "powerful" impact of MCC on the area of damage in combination with improper work of SG supports PG due to their jamming and additional resistance to SG movement via supports.

In the report of JSC OKB “Gidropress” [6] on the SS-111 zone, it was stated that "the highest level of loading of the zone is realized during hydraulic testing of SG secondary circuit (at yield strength level) and when cooling via blowdown lines, and high loading is also possible during improper operation of the SG supports".

Characteristically, the position of the primary damages in the SS-111 zones of "cold" headers is also close to so-called "MCC line" as for “hot” headers (Fig.3) both on VVER NPP Units of "small" series, and on VVER NPP Units of the project V-320 (according to JSC NPO "CNIITMASH" reports [4, 7]).

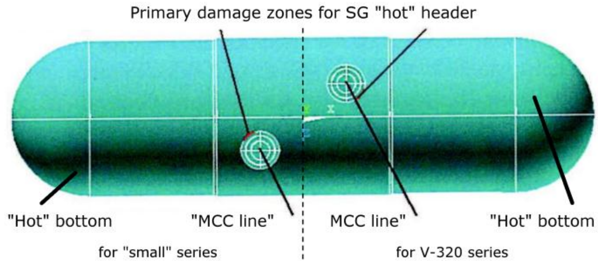

Fig.3. Zones of primary damages for VVER-1000 of “small” series and V-320 series from [8]

The results are consistent with the hypothesis that there is a directed mechanical impact of the MCC piping on the SS-111 zones, which should be considered as the main factor in the formation and growth of primary cracks in the direction of the "MCC line" (Fig.4-6). Fig.4 shows caption comments that are common to Fig.4-6.

Other factors (technology of rolling heat exchange tubes, presence of deposits in the "pockets" of SG, actual parameters of the secondary circuit water chemistry, etc.) should be considered as concomitant, despite their possible influence on crack initiation under delayed deformation corrosion cracking mechanism.

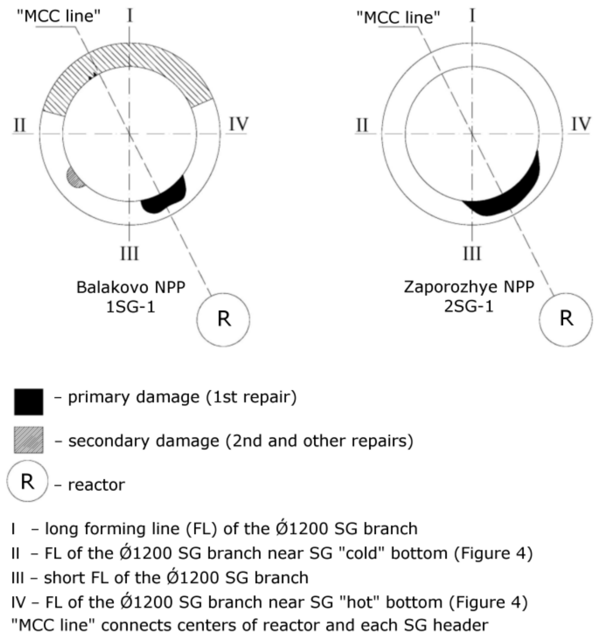

Fig.4. Zones of primary and repeated defects in **SS-111** of VVER NPP Units of the project V-320 ([2])

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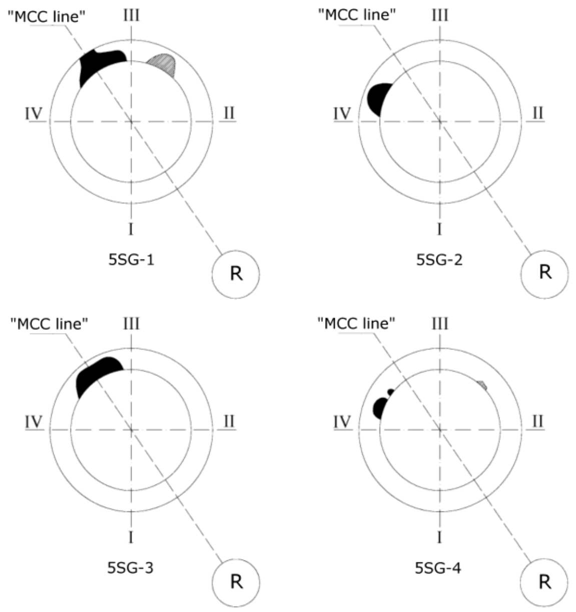

Fig.5. Zones of primary and repeated defects in **SS-111** of the unit No. 5 of Novovoronezh NPP ([2])

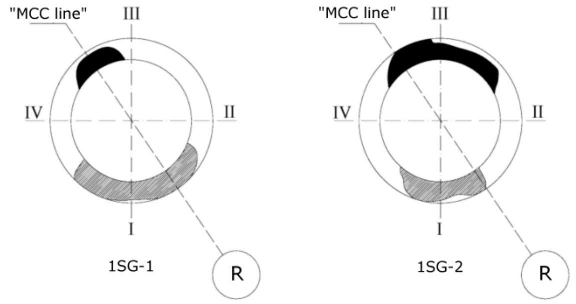

Fig.6. Zones of primary and repeated defects in **SS-111** of the unit No. 1 of South Ukrainian NPP ([2])

Layouts of MCC piping of VVER NPP Units of "small" series and VVER NPP Units of the project V-320 are shown on Fig.7 and 8 from [2].

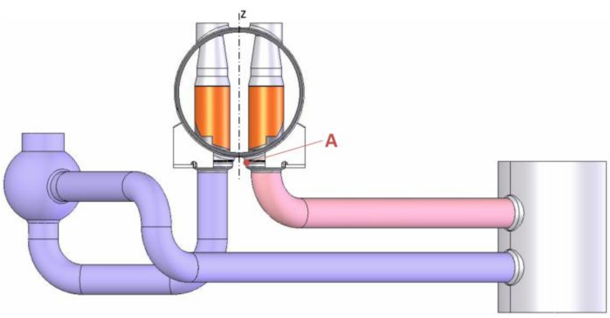

Fig.7. Layout of MCC piping of VVER NPP Units of "small" series ("hot" MCC piping in rose color)

Points A (Fig.7) and B (Fig.8) show maximum loaded zones located near short forming line of SG branches and "MCC line" (Fig.3).

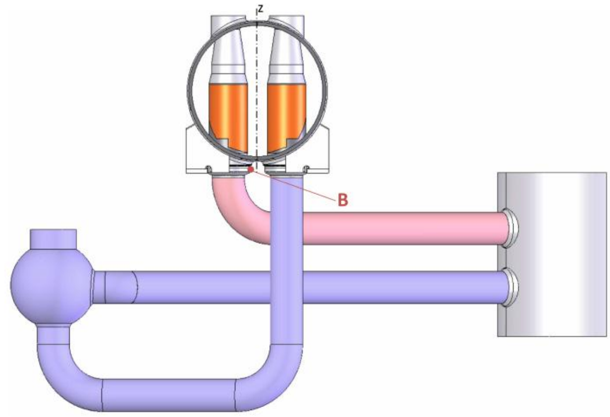

Fig.8. Layout of MCC piping of VVER NPP Units of the project V-320 series ("hot" MCC piping in rose color)

4 Damage cause analysis

Additional resistance to SG movement via supports due to their jamming generates extra loads for the SS-111 zones during start-up and shut-down of NPP unit.

Table 1 provides information on repairs of the SS-111 zones at all NPP units with VVER-1000 reactor facility according to [4, 6, 9]: the intense yellow background highlights the primary damage of the SS-111 zones of the "hot" headers, and the blue background highlights the "cold" headers. The "+" symbols indicate the number of repeated damages in different years. Information on absence of cracking of the SS-111 zones at several VVER-1000 NPPs was confirmed in the speeches of representatives from Ukraine (Rivne and Khmelnitsky NPPs), Bulgaria (Kozloduy NPP) and the Czech Republic (Temelin NPP) at the WANO MC seminar held in Yerevan (Armenia) in May 2015 [10].

Information on repeated damages of the SS-111 zones are shown in Table 2: the intense yellow background highlights the primary damage of the SS-111 zones of the "hot" headers, (the cases of repeated damages are highlighted in light yellow background), and the blue background highlights the "cold" headers. Through-wall damages are marked by "▲" symbols. Negative assessment of the dynamics of damage in 2010-2014 is too pessimistic, since many of these damages are repeated, that is, after the use of repair technology with through-thickness metal removal and subsequent volume filling by welding. However, the repeat leakages in almost the same place (Fig.4) of the 5SG-1 hot collector at unit No. 5 of Novovoronezh NPP, first ~9 years after the replacement of the SG, and then ~15 years after the repair of this defective zone by welding, show that the main factors that led to through-wall damage were not identified and eliminated during the period from 1998 to 2013.

In [11], it is erroneously stated that the time before appearance of through-thickness defect in the metal of the 5SG-1 hot collector at unit No. 5 of Novovoronezh NPP was 24 years.

Table 1. Information on repairs of the **SS-111** zones at all NPP units with VVER-1000

NPP	Unit	SG-1		SG-2		SG-3		SG-4	
		"Hot"	"Cold"	"Hot"	"Cold"	"Hot"	"Cold"	"Hot"	"Cold"
Novovoronezh NPP	5	+++		+		+		++	
Kalinin NPP	1						+		
	2								
	3								
	4								
Balakovo NPP	1	++							+
	2			++					
	3								
	4		+						
Rostov NPP	1								
	2								
	3								
South Ukrainian NPP	1	++		++					
	2								
	3	*	**				**		
Zaporozhye NPP	1								
	2	+	+		+				
	3								
	4					+			
	5								
	6								

Note: at Unit No.3 of South Ukrainian NPP sub-surface flaws were revealed by In-service Inspection [13] and repaired in 2012 (*) and 2014 (**)

Table 2. Information on repeated damages of the **SS-111** zones

NPP	№SG	Replaced	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Novovoronezh NPP	5SG-1	1989_{3}	▲															▲		
	5SG-2	1987_{3}																		
	5SG-3	1990_{3}																		
	5SG-4	1989_{3}																		
Kalinin NPP	1SG-3	no																		
Balakovo NPP	1SG-1	1990_{3}																		
	1SG-4	1990_{3}																		
	2SG-2	2000_{3}																		
	4SG-1	no																		
South Ukrainian NPP	1SG-1	1989_{3}																		
	1SG-2	1989_{33}				▲														
Zaporozhye NPP	2SG-1	1990_{3}																		
	2SG-2	1990_{3}																		
	4SG-3	no																		

Note: ▲ - damage revealed by leak.

As can be seen from table 1, the damage of the SS-111 zones affects mainly the group of SGs replaced at NPP units due to damage of the headers and/or due to plugging of the heat exchange tubes over the limit. Of the 15 damaged units, only 3 were damaged on SGs operating on the units since installation. Information on SG replacements is provided in the report [12] based on several sources [1, 13-14].

When replacing the SGs on an NPP unit in operation, one of the welded joints SS-111 of "hot" or "cold" header becomes the closing one, whereas when installing SG to MCC at construction stage both welded joints SS-111 of the "hot" and "cold" headers to Dn850 pipelines are never the closing ones.

Thus, it seems acceptable to assume that part of the SGs was installed with the presence of implicit mounting preload during replacement (tables 1 and 2), which was not detected after repair and was not recorded in the reporting documentation. A similar hypothesis assumed presence of implicit mounting preload during the installation of part of the SGs in the MCC on newer blocks also seems realistic, since table 1 shows that the percentage of damaged SGs (from the number of not replaced) is significantly lower than among the sample of replaced SGs.

In the future, implicit mounting preload during the installation/repair could lead to restrictions (jamming) when SG moving via supports, taking into account the specifics of design solutions for MCC of VVER NPP Units of "small" series, and VVER NPP Units of the project V-320.

Therefore, the main cause of primary cracks in the SS-111 zones is the interaction of several factors that were excluded earlier from the analysis of the causes of damage in [15], namely: «4.1 Preload of the Du850 MCC piping during the replacement of the SGs», «4.3. Jammed roller and/or ball bearing supports of SG and/or MCC», «4.4 SG jammed for other reasons», which can be combined into a common cause: "shortness (jamming) of SG displacement on the supports". The crack growth rates depend to a significant extent on water chemistry inside the SG "pockets".

5 Conclusion

So primary damages in the SS-111 zones did not lead to extensive propagation along the circumferential weld perimeter, and the correlation of their location with the "MCC line" indicates the role of mechanical loads in the process of damage that does not pose a threat of complete break. However, for long-term cost-effective operation of the SG, it is necessary to improve load monitoring system for the SS-111 zone (for early detection of prerequisites for cracking initiation) and SG maintenance and repair/replacement technology.

Measures to monitor the thermomechanical loading of the SS-111 zone (especially after weld repair or/ and SG replacement) will allow to get an early warning for NPP personnel about non-project loading and the need for compensative actions in the form of an extraordinary preventive maintenance of SG supports and more frequent ISI of the SS-111 zone.

It should be noted that in-service damages of the SS-111 zone lead to decrease of NPP unit availability rather than safety. Operation experience should be also taken into account for VVER-1200 NPP Unit design to avoid in-service damages of the SS-111 zone during long-term operation.

The reported study was funded by RFBR according to the research project № 19-07-00455.

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