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ScienceDirect
Nuclear Energy and Technology 3 (2017) 92–97
www.elsevier.com/locate/nucet

Design and experimental assessment of thermal stratification effects on operational loading of surge line of Unit 5, Novovoronezh NPP

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Available online 18 May 2017

Abstract

One of the key tasks in substantiating NPP service life extension consists in detailed examination of all factors affecting the remaining lifespan of critical NPP components. Particular attention must be paid to studying the phenomenon of thermal stratification (TS) which is the effect of coolant lamination into the “cold” and “hot” layers in horizontal pipelines when flows with different temperatures propagate at slow velocities. Special importance of this issue is explained by the fact that cyclic loads caused by TS contribute in accumulation of metal damage due to thermal fatigue and can provoke formation and accelerated growth of defects.

This study is dedicated to implementing complex analysis of coolant TS observed in horizontal sections of the surge line (SL) on WWER-1000 units from the viewpoint of assessment of TS effects on the stressed-deformed conditions of metal and accumulation of cyclic damages. The experimental data on the distribution of temperature fields in horizontal SL sections, as well as cyclic loading history during several reactor fuel residence campaigns were recorded by the on-line diagnostic monitoring system put into operation on Unit 5 Novovoronezh NPP. Certain distinguishing features of TS in SL of Unit 5 were identified as the result of data analysis depending on operational modes. The most significant TS effects were observed in the control cross-section located within the first horizontal section from the pressurizer.

Calculation and experimental assessment of effects of thermal loading factors on the stress-deformed state of SL demonstrated that effects of thermal stratification and thermal fatigue significantly affect the operational loading of the pipeline. It is noted that zones with maximum accumulated damage determined according to the results of calculations coincide with places where factual operational defects were detected. Procedure involving treatment of SL welded joints by the method of surface plastic deformation is suggested as the compensatory measure aimed at extending the SL residual lifespan.

Keywords: Thermal stratification; Surge line; Thermal fatigue; Thermomechanical load; On-line monitoring; Stressed-deformed state.

Operation of power units of nuclear power plants (NPPs) is not infrequently accompanied with detection of phenomena and processes not anticipated in the plant design which produce significant impact on the operational damage rate of metal of pipelines of the reactor facility (RF) [1,2]. One of such phenomena is the coolant thermal stratification (TS) representing the effect of lamination of the flow along the height into the “cold” lower layer and the “hot” upper layer in pipeline horizontal sections. As a rule, TS takes place in horizontal pipeline sections in the cases when two different layers within the flow travel separately, i.e. without pronounced intermixing of fluid layers, because of the temperature difference and, as the consequence, because of the difference between the densities of the upper and lower layers. Development and stabilization of the laminated flow depend on the temperature difference and the relative velocity between the fluid flows. TS results in the appearance in the pipelines of

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Peer-review under responsibility of National Research Nuclear University MEPhI (Moscow Engineering Physics Institute).
Russian text published: Izvestiya vuzov. Yadernaya Energetika (ISSN 0204-3327), 2017, n.1, pp. 5–16.

http://dx.doi.org/10.1016/j.nucet.2017.05.001

additional cyclic loads contributing in the intensive accumulation of metal fatigue damages.

Special importance of investigation of TS phenomena is explained by the fact that additional thermal mechanical loads emerging as the result of TS were not accounted for in the design strength calculations of pipelines of power units designed and put into operation during the seventies–eighties of the last century. This negatively affects the level of safety of first generation NPPs because of the insufficient substantiation of cyclic strength of certain critical pipelines. On NPPs equipped with pressurized water power reactors (WWER) it is the pipelines of the pressurization system, reactor core emergency cooling system, separate sections of pipelines of "hot" and "cold" legs of the main circulation pipeline and steam generator feedwater pipelines which are subjected to thermal stratification [3–5]. Accelerated development of operational defects caused by TS can potentially lead to failures during operation of process circuits of the RF which is confirmed by the experience of NPP long-term operation [6,7]. For instance, more than 10 penetrating fractures were detected in pipelines of NPPs in the USA, the cause of which was recognized to be the effects of TS. Similar cases of pipeline damages caused by TS were also detected on NPPs in Germany, Belgium, France, Finland and Japan. Until the present moment no such cases were detected on NPPs in Russia but, however, effects of TS as one of significant factors contributing in beyond design loading of RF pipelines must be thoroughly investigated and taken into consideration during implementation of measures for substantiating extension of operational life of NPP power units [8].

This study was implemented during 2013–2015 on Unit 5, Novovoronezh NPP for the purpose of calculation and experimental assessment of TS effects on operational loading of the surge line operated as part of the pressurization system of WWER-1000 RF [9,10]. Pressurization system (PS) is intended for creating and maintaining pressure in the primary cooling loop in steady-state operation modes and limitation of pressure surges during transients and emergency operation modes [11]. The main PS elements include pressurizer intended for maintaining pressure and compensation of volume in the primary cooling loop and surge line (SL) connecting water volume of the pressurizer with coolant in the "hot" leg of the main circulation pipeline (MCP) loop.

With changing coolant temperature in the primary cooling loop in transient modes of RF operation (reactor heating up, shut-down cooling, variation of power) part of the coolant flows from the pressurizer in the MCP or from the MCP into the pressurizer along the surge (connection) Ø 426×40-mm pipeline. Because of temperature differences in the pressurizer and the MCP when coolant flows with low flow rates stratification (lamination) of the coolant flow along the pipeline cross-section into the "hot" and "cold" layers takes place in the pressurizer. TS effects are the cause of development of time-dependent temperature fields along the pipeline wall thickness and, as the consequence, of additional thermal mechanical loads which may serve as the cause of initiation and development of operational damages.

Reliable experimental data on the distribution of temperature fields in horizontal pipeline sections for different operational modes are required for the assessment of potential TS contribution in the SL metal damage rate. The system for monitoring thermal stratification (TSMS) intended for performing the following main functions was implemented on Power Unit 5, Novovoronezh NPP:

- Monitoring of temperature fields in control cross-sections of the SL during the whole fuel residence period of the RF;
- Calculation and experimental analysis of stressed-deformed state of the SL for different RF operation modes using the data of TS monitoring;
- Determination of the list of process operations and operational modes resulting in the maximum temperature gradients in the SL and additional operational loads not accounted for in the design.

TSMS consists of specialized electronic units, commutation boxes and measuring thermocouples combined to form the unified digital data transfer network using cable lines [12]. Structural schematic diagram of the TSMS is represented in Fig. 1.

Data collection and processing unit consisting of the set of measuring thermometering modules is located directly within the containment in the vicinity of the SL. Data storage and transmission unit representing the commercial high-capacity server with connected auxiliary equipment is installed inside the manned premises of the power unit. Temperature monitoring is implemented in four control cross-sections of the SL located in horizontal pipeline sections. Five thermocouples were arranged on the pipeline external surface along the cross-section perimeter in each control cross-section. All monitoring data were automatically recorded and were transferred along the network communication lines to the remote analytical center for processing and detailed analysis.

Sufficient volume of statistical data allowing establishing general regularities of development of TS processes in different operational modes was collected according to the results of TS monitoring in the SL during two fuel residence campaigns from 2013 until 2015 [13,14]. Taking into consideration long time intervals for the collection of the data and fast processes involved it is difficult to judge the specifics of flow lamination based solely on the graphs representing absolute temperature values. In such cases, it is necessary to possess information on the temperature gradients in the SL control cross-section in order to subsequently analyze the pipeline stressed-deformed conditions. Temperature difference ΔT between the maximum and minimum temperature values along the pipeline cross-section is used in the analysis for simplified quantitative assessment of the TS value.

Comparative analysis of monitoring data recorded during the RF heating up period to reach the "hot" state demonstrated that significant pulsation laminations of the flow are observed in the whole surge line while temperature difference between the "hot" and "cold" flows in control section no. 4 reached