20th International Conference on Structural Mechanics in Reactor Technology (SMiRT 20)
Espoo, Finland, August 9-14, 2009
SmiRT 20-Division 8 Paper 1650

Reactor plant equipment ageing management using SACOR residual life automated control system

A.V.Bogachev , V.Ya.Berkovich , B.N.Dranchenko , D.B.Muravin , V.P.Semishkin

OKB "GIDROPRESS", Podolsk, Russia, -mail: tombulatov@grpress.podolsk.ru

Key words: service life, equipment, stresses, calculation, NPP, operation

1 ABSTRACT

The paper covers the main approaches to ageing management of reactor equipment and pipeline materials using SACOR residual life automated control system.

So far, Generation I SACOR-M system, developed in 2001, has been introduced at 6 power units with VVER-1000. Generation II SACOR-320, developed and adapted for RP V-320 design is being introduced at Rostov Unit 2 to be further introduced at newly built NPPs with VVER. SACOR-320 is characterized by considering the actual steam generator displacements, usage of surface temperature resistance thermometers in a number of units for coolant supply into RP circulation system, additional usage of brittle and ductile strength mechanisms as the limiting states.

For the new generation designs (AES-2006 and the Belene NPP) in the course of SACOR system elaboration the problems were solved of the choice of reference point that take into consideration the possible mechanisms of material degradation, calculation of the loading factors on the basis of the standard sensor readings and stresses in response to the loading factors, as well as the assessment of the limiting states for stresses in the course of operation.

A possibility of SACOR adaptation for the operating power units with VVER reactor was analysed and methods were proposed to restore the information for the elapsed period.

On the basis of the actual events from the experience of NPP operation examples of different situations are considered that can use the results of SACOR system operation.

2 FUNCTIONS TO CALCULATE STRESSES USED IN SACOR

When solving the tasks of in-service life characteristics management it is necessary to take into consideration the actual equipment loading and the presence of initial defectiveness using to the utmost available information in design thermal hydraulic and strength calculations.

The task is offered to be solved by creating and introducing the residual service life automatic control system for RP with VVER based on a calculational assessment of fatigue damage from the actual recorded in-service loading.

The residual life automated control system (SACOR) is designed to control and monitor the service life of components for each type of VVER reactor equipment in the most loaded (reference) points chosen in accordance with the design checking strength calculations, operating experience and the results of non-destructive testing. SACOR assesses the cumulative damage from different mechanisms by actual thermo-force loading that is controlled by sensor readings. The solution of the task of choosing the reference points, determination of the loading parameters, calculation of the loading parameters from the standard sensors and calculation of coefficients in functional dependences of stresses is specific for each reactor design.

Stress calculation is performed using the basis of functional stress versus loading factor dependences. The loading factors imply pressure, temperature, temperature moments and displacements in different areas of reactor plant. The formula of stress versus loading factor dependence was deduced at SACOR-M development for Rostov NPP Unit 1 and is not empirical but was deduced from general equations of heat conductivity and thermoelasticity. With this, the assumptions are shown that have been made at problem linearization and particular tasks required to be solved to obtain each of the coefficients in stress versus loading factor functional dependencies and in the

calculations of the loading factors. Formula deduction and its justification is given in /1/ and it can be presented as follows:

$$\sigma_L = G + A_1 \cdot p_1 + A_2 \cdot p_2 + \sum_{i=1}^{I} B_i \cdot T_i^{\tilde{n}\partial} + \sum_{j=1}^{J} S_j \cdot u_j + \sum_{n=1}^{N} D_n \cdot M_n^{\tilde{n}\partial} + \\ + \sum_{k=1}^{K} \left[C_k \cdot T_k + \int_{t-\Delta t}^{t} \sigma_k (t-\tau) \cdot \frac{\partial T_k(\tau)}{\partial \tau} \cdot d\tau \right] \quad (1)$$

where the loading factors that are calculated on the basis of the readings of the temperature and force monitoring are: p_1, p_2 – primary and secondary pressure; $u_j(t)$ – displacement vector components in some points; T_i , $_n$ (t) - integral temperatures and temperature moments; $T_k(\tau)$ – temperature values of coolant that directly washes the unit surfaces; I, J, N, K – number of sections with different loading factors. G, A_1, A_2, B_i, S_j , D_n, C_k, - governing coefficients, i.e. a set of constants that is specific for each reference point, σ_k (t) – base function of Duamel integral that is approximated by analytical function and is assigned by a set of constants, t and Δt - current time and characteristic time for stresses to reach the steady-state conditions in the base function. These constants including the base function shall be obtained at the stage of SACOR-320 development.

Duamel integral that is part of the structure of approximating function reflects the change in the reference points of thermal stresses at transients with coolant temperature change. Knowing the base function for each reference point using the Duamel integral stress value can be obtained in the point at any law of temperature change versus time. Stress calculation considers the loading factors from the primary and secondary pressure, temperature compensation of pipelines, off-design displacement of equipment, thermal pulses and stratification of coolant in transient and emergency conditions.

Simplified conservative approaches were used in SACOR-M (Rostov NPP Unit 1, Kalinin NPP Unit 3, Khmelnitsky NPP Unit 2 and Rovno NPP Unit 4), SACOR-428 (Tianwan NPP Units 1 and 2), SACOR-446 (Bushehr NPP), that can be referred to Generation I systems.

At present a new generation SACOR-320 system is in trial operation at Rostov NPP Unit 2. Detailed designed of SACOR-392M and SACOR-491 are being developed for AES-2006 Project and SACOR-466B is being developed for the Belene NPP. System elaboration in its 6 constituent components is covered below.

3 ELABORATION OF THE LIST OF NODES AND REFERENCE POINTS

At the first stage of SACOR development the list of key components and nodes for the main primary-side equipment and pipelines is drawn up on the basis of their design fatigue cyclic damage and points are chosen that are subjected to monitoring within the framework of determining residual life. Initially the critical units and reference points are selected on the basis of a review of the results of checking calculational analyses. The given set of reference points is applied in Generation I SACOR-M.

In the new generation SACOR designs the reference points comprise the nodes where coolant flows of different temperature mix up and the issue of the number of reference points at the PRZ injection nozzle, feedwater nozzle collector-to-SG vessel nozzle and PRZ surge line nozzle that are characterized by stratification onset, was solved separately.

The reference points in pipeline welds with discontinuity flaws detected in the course of preservice and in-service inspection are subjected to fatigue flaw growth check. The areas to be controlled involve the welded joints of RP pipelines if the in-service meeting of the LBB criterion is to monitored.

The areas that can be affected, judged by the operating experience, are also included into the list of reference points which shall also incorporate the area of radius transition in the pocket area, welded joints with the poor structural weld penetration in the jackets at CPS nozzles, SG heat-exchange tubes etc.

4 SENSORS USED IN SACOR

4.1 Standard temperature and pressure monitoring by sensors provided for RP design

VVER-1000 power units are equipped with a sufficient amount of standard devices for pressure and temperature monitoring in different areas of RP as well as temperature monitoring in all the primary side auxiliary systems. The list of standard sensors for pressure and temperature monitoring of the power unit status required for SACOR-M operation, is drawn up on the basis of design documentation using the process diagrams. The main drawback of the standard temperature monitoring equipment is its location far from coolant mixing areas. For the power units in operation it is expedient to use the transmitted-action sensors (location of gate valves and check valves, pressure head and flow rate sensors), which makes the system cheaper and competitive.

4.2 Temperature monitoring in nodes where coolant flows of different temperature mix up.

Additional surface and submerged-type resistance thermometers are introduced into new designs and are given the status of standard sensors. To optimize the number and locations of temperature monitoring sensors it is necessary to consider that submerged thermocouples are efficient when envisaged at the stage of RP equipment design development. The installation diagram for submerged resistance thermometers and displacement sensors assigning them the status of standard sensors is developed at the stage of technical design and the system of sensor-to-SACOR server information transmission is also envisaged there.

For the earlier developed designs (V-320) surface resistance thermometers are used that are installed in the course of commissioning test measurements in line with the standard process. When using the measurement data from the surface thermocouples in SACOR-320 a solution of inverse heat transfer problem will be required to define the boundary conditions over the inside surface of the node. Resistance thermometer is installed at the straight section of the tube at some distance from the nozzle and therefore, pipeline section is annular which makes it possible to simplify the diagram of inverse problem solution and improve its accuracy.

In case a submerged resistance thermometer is installed, the temperature of coolant supplied into RP equipment nozzles is measured directly.

4.3 Temperature monitoring to consider stresses caused by stratification

If the temperatures at the top and bottom of the pipeline differ, additional stratification phenomenon arises. For reference points in the area of mixing coolant flows at different temperatures related to thermal pulse onset and stratification the design envisages submerged thermocouples over the pipeline section. To monitor coolant injection with partial coverage of the pipeline section two submerged thermocouples are installed in steam generator feedwater pipelines and PRZ coolant injection line at the distance of 200-300 mm from the nozzle-to- pipeline junction in the top and bottom of the section of each pipeline. In the MCP the issue of stratification monitoring that can arise under emergency conditions when cold boron solution is supplied and RCP sets are tripped, is solved using the available standard thermocouples and resistance thermometers.

4.4 Linear position indicators

When stresses are calculated, it is necessary to use the actual equipment displacement that can differ from the design value due to friction forces that have not been considered and due to the effect of attached pipelines. For NPPs with V-320 VVER linear position indicators are installed on the shock absorbers that monitor the work of the given shock absorbers. These indicators are offered to be used for SG displacement monitoring. Figure 1 presents the position of the given shock absorbers in V-320 Loop 1 SG, providing their signal identifier.

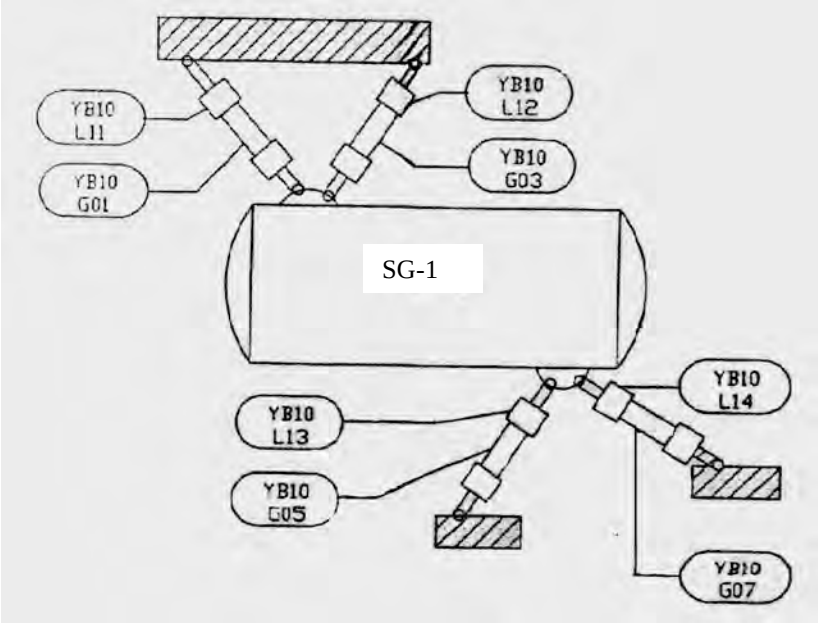

Fig. 1. Position indicator identifiers for SG-1 shock absorbers

5 CALCULATION OF LOADING FACTORS ACCORDING TO STANDARD SENSOR READINGS

5.1 Standard temperature monitoring

Some thermal-hydraulic suppositions are required to define the temperature of coolant that immediately washes the boundary of a number of nodes. It is impossible to measure the temperature field directly in the node and therefore the methods is applied where the temperature field is assumed that gives an admittedly conservative stress value. Such nodes first of all, comprise the nozzles of colder coolant supply into RP equipment. For generation I SACOR-M on the onset of coolant injection a conservative assumption was made that the temperature in the nozzle area instantly becomes equal to supplied water temperature. Without temperature monitoring close to the node approaches are applied that are connected with defining temperature in the distance. At this, it is determined whether the gate valves are open in the injection line and whether pressure differential is realized.

5.2 Solution of inverse task for surface thermocouples

The inverse task of heat conductivity is an incorrectly-stated problem which is demonstrated by its large sensitivity to measurement errors. Obtaining the maximum amount of information at numeric solution implies using small time steps between discretely determined values of temperature, which leads to solution instability. Meanwhile, solution of a direct boundary-value problem of heat conductivity with time step decrement as a rule brings to increase in stability and solution accuracy.

A non-stationary temperature change in a certain point of external thermally insulated surface, where the temperature is measured, differs from temperature changes on internal heated surface. Temperature deviations on external surface are far less than on the heated surface. Besides, a significant time lag in temperature change is observed on external surface. It is also worth mentioning that there are a lot of different laws of temperature change on the heated surface that differ from each other in high-frequency constituents and provide actually the same temperature on the external surface. This is the consequence of the fact that the inverse heat conductivity problem is incorrectly stated and has no single solution, which leads to instability.

5.3 Consideration of actual SG displacements

The methods of determining the displacements of MCP hot and cold leg nozzles is based on a number of suppositions. The resulting transformation comprises three elementary transformations. The first transformation is dimension change at a fixed position of the center, connected with SG temperature change. The second transformation is a special shift of the entire section. The third transformation is section rotation around the centerline. Such a rotation will be assigned by slew matrix M. Each point with coordinates (x, y) that belongs to equipment after the motion will have coordinates (xn, yn). Having assumed that the SG angular displacement is small as the displacements are small in comparison with linear dimensions of equipment, the assumption of sin = , and cos = 1 can be made.

The coordinates of any point of equipment after the displacement can be determined on the basis of the three above transformations and put down in the following form:

$$\begin{pmatrix} xn \\ yn \end{pmatrix} = M \cdot \begin{pmatrix} x \\ y \end{pmatrix} + \begin{pmatrix} x_0 \\ y_0 \end{pmatrix} + \begin{pmatrix} x \cdot \alpha t \cdot (T - T_0) \\ y \cdot \alpha t \cdot (T - T_0) \end{pmatrix} \qquad M = \begin{pmatrix} 1 & -\ddot{o} \\ \ddot{o} & 1 \end{pmatrix} \qquad (2)$$

Suppose that the initial position coordinates of three position indicators in equipment (x_i, y_i) are known. Once we know the parameters of three elementary transformations the post-displacement finite coordinates of the indicator can be determined using ratio (2) and having solved the system of linear equations the parameters of SG as a solid body can be obtained. After that using ratio (2) displacement of any SG point can be obtained. Calculations of SG displacements were performed on the basis of actual readings acquired by SACOR-M at the Kalinin NPP Unit 3 for verification of the methodological part of the calculation of displacement of any SG point based on shock absorber readings and good coincidence of the results was obtained.

5.4 Calculation of integral temperatures and temperature moments in pipelines

The formula can be applied to determine the constants in formula (1) for integral temperature and temperature moment, that allows using one base function TB0 (t) from average temperature across the section to calculate these constants. The temperature field T(M, t) is also assumed to be piecewise-constant for angle φ. Then the general formula for integrated temperature and temperature moment will be written as follows:

$$T^{in}(t) = \left(R^2 - (R-h)^2\right)\left(Tw_i(t) \cdot T0_i^{in} + \int_{t-tmax}^{t} \frac{\partial Tw_i(\tau)}{\partial \hat{o}} TB0_i^{in}(t-\hat{o})d\hat{o}\right);$$

$$MY^T(t) = -\frac{2}{3} \cdot \left(R^3 - (R-h)^3\right)\left(Tw_i(t) \cdot MY0_i + \int_{t-tmax}^{t} \frac{\partial Tw_i(\tau)}{\partial \hat{o}} MYB0_i(t-\hat{o})d\hat{o}\right); \quad . \qquad (3)$$

Where the constants are determined from the formulae

$$T0_i^{in} = (\varphi_{i+1} - \varphi_i) \qquad TB0_i^{in}(t-\tau) = (\varphi_{i+1} - \varphi_i) \cdot TB0^{cp}(t-\tau)$$

$$MY0_i = (\cos\varphi_{i+1} - \cos\varphi_i); \qquad MYB0_i = (\cos\varphi_{i+1} - \cos\varphi_i) \cdot TB0^{cp}(t). \qquad (4)$$

$$t > 0; \quad i = 1...\hat{E}$$

$TB0^{cp}(t)$ is the basic function for the same coolant temperature in the pipeline section, R is the pipeline radius, h is the pipeline thickness. I.e. the calculation of integral temperature and temperature moment at a known position of the sensors over the pipeline section is confined to the calculation of some effective temperature values, that are a linear combination of thermocouple readings. For consideration of non-stationary processes of tube heatup Duamel integral ratio is used and in case of a symmetrical structure a calculation of a basic function of a single temperature jump will be sufficient.

6 CALCUATION OF COEFFICIENTS IN STRESS VERSUS LOADING FACTOR FORMULA

6.1 Reference points in equipment (reactor, SG, PRZ) outside the nozzle area of attached pipelines

For this group approaches are used that are connected with a calculation of decisive coefficients by approximation of design calculation results. In the nodes there are no boundary forces from attached pipelines and respectively formula (1) is significantly simplified.

$$(\sigma_L) = D + A_j \cdot p_j + B4_k \cdot T_k(t) + \int_{t-t\max_k}^{t} \sigma b_k(t-\tau)\frac{\partial T_k(\tau)}{\partial \tau} d\tau \qquad k = 1,...,K \tag{5}$$

For the points positioned on the cladding inside and in case of the same coolant temperature at the inside boundary of the node the basic function becomes very simple and it can be approximated by an analytical dependence. Verification of obtained coefficients is performed by a comparison with a design strength calculations. The operating parameters are assigned as an input deck that models the sequence of design conditions in SACOR formula to calculate stresses and stresses are calculated to them. The sequence of obtained stresses and the values of stresses under design conditions are plotted and the obtained results are compared. Reference /2/ provides an example of comparison of stresses under design conditions and those obtained from SACOR-M formulae for design condition sequence.

6.2 Calculation of pipeline stressed state using the beam models

For reference points in comparison with Generation I SACOR-M it is necessary to introduce boundary conditions into the nodalization where beam models are applied for RP pipelines in the form of equipment displacement and assign stratification in the form of temperature moment. The calculation results provide forces and moments that act on the T-joints and nozzles for pipeline-to-equipment welding.

6.3 Calculation of local stresses from boundary forces and basic functions for 3-D nodes.

For assembly incuts into RP equipment a calculation of base functions and calculations to determine stresses from the boundary moments are performed. At this, FEM nodalizations are used that were created at the stage of strength design justification. These nodes shall include T-joints at MCP for all the coolant supply nozzle out of auxiliary systems into RP, feedwater nozzle, collector-to-SG vessel welding joint. Boundary forces are assigned for the nozzles that are defined from attached pipeline calculations and loading these nozzles with pressure and temperature field is also considered.

7 RESTORATION OF INFORMATION FOR THE OPERATING PERIOD

In the course of introducing the SACOR-M system at the operating power units a task was solved on restoration of information on the history of loading for the period of previous operation. The first variant was archive database recovery saved in magnetic carriers at a NPP. The set of application software for SACOR-M comprises a modulus that allows fetching standard sensor readings out of computer system archive database, the sensors being integrated into the SACOR-M system. The developed modulus helped to restore the loading history of equipment and pipelines of Khmelniskaya NPP Unit 2 beginning with May 2004 up to February 2008. The second version of recovery for design conditions and states on the basis of the entries in the operational log which is more time consuming and more conservative. After this, based on design changes of operating parameters a calculation of the sequence of recorded design conditions and their states is performed

using SACOR-M system. A trial comparison of calculations of design conditions and sensor reading data records of a 4-year operation of Rostov NPP Unit 1 has shown double conservatism of design calculations.

8 CONCLUSIONS

A multi-purpose tool has been created that can solve general problems of equipment service life management for a specific design reactor:

- At transition to daily power maneuvering (automatic consideration of cumulative fatigue usage factor in power maneuvering at all the power units with SACOR-M introduced);
- At transition to NPP operation with a longer interval between repairs;
- For optimization of the non-destructive testing program of RP equipment in order to reduce the time of preventive maintenance (work is under way to make the inspection intervals longer at MCP welded joint with weld discontinuity detected in the Kalinin NPP Unit 3;
- For in-service inspection of detected flaws (for example, the area of welded joint 111 at SG of the Rostov NPP unit 2);
- For justification of flaw fatigue growth in introducing the LBB concept (Novovoronezh NPP Unit 3);
- For justification of fatigue service life for RP equipment in reactor service life extension and also a solution of local tasks in the course of operation
- In exceeding the design number of the conditions that is established in the process specification (for example, at scheduled trips of RCP sets);
- In justification of residual life of RP equipment in case of a single designed mode and off-design conditions (for example, using SACOR-M at Unit 1 of the Rostov NPP after a failure of BRU-A to fit);
- For optimization of operating conditions and revealing of unfavourable loading factors (for example, heat pulses in injection pipelines and surge line at incorrect operation of PRZ fine injection controller at Tianwan NPP Unit 1).

REFERNCES

1 Shary N.V., Semishkin V.P., Piminov V.A., Dragunov Yu.G. WWER-type reactor main equipment and pipeline strength. – M.: IzdAT, 2004.

2 Operating experience of system of the automated control of a residual cyclic resource for RP with VVER-1000. Bogachev A.V., Bakirov M.B., Dranchenko B.N., Semishkin V.P. 18th International Conference on Structural Mechanics in Reactor Technology (SMiRT 18). Beijing, China, August 7-12, 2005.