*Transactions of the 17th International Conference on Structural Mechanics in Reactor Technology (***SMiRT 17)**
Prague, Czech Republic, August 17 –22, 2003
Paper # B01-4

Numerical FEM Analyses of Primary Coolant System at NPP Temelín

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ABSTRACT

The main goal of this paper is to inform about beginning and first steps of implementation of aging management system at NPP Temelín. Ageing management system is important not only for achieving the current safety level but also for reaching the operational reliability of a production unit equipment above the life time assumed by original design, eg. above more than 40 years. Method of location of the most degradation regions is described. A global shell model of the primary coolant system including all loops and their components – reactor pressure vessel (RPV), steam generator (SG), main coolant pump (MCP), pressurizer, feed water and steam pipelines system is shown. The results of a stress-strain analysis on the measured service parameters base are presented. Validation of the presented results is very important and the method comparison of service measurement data with numerical results is described. The global/local approach is mentioned and discussed. Effects of the whole global system on individual components under monitoring are transferred to more accurate local spatial models. The local spatial models are used for analysing the gradual lifetime exhaustion of a facility during its service operation. Two spatial local models – feed water nozzle of SG and main coolant piping system T-brunch are presented. Results of analyses of the local spatial models are processed by means of neural network computing method. Neural network method of analysis is described. Based on analyses performed and on results from neural network and with the knowledge of real material characteristics an actual gradual damage of material of components under monitoring can be got. The procedures applied are included in DIALIFE diagnostic system. Gradual damage to material of components under monitoring can be followed just in the power plant when using tools of diagnostic system.

KEY WORDS: finite element method (FEM), stress, strain and thermal analysis, primary coolant system, NPP component, steam generator, reactor, instrumental and control system (I&C), diagnostic system, measurement, service condition.

INTRODUCTION

NPP Temelín has been finished the construction of both units and NPP starts a new period of operation. The Units of NPP Temelín has been successfully tested during commissioning process and trial operation period has been finished too. The first power service operation period is running under monitoring processes. A new period can be started with NPP running - comparison and assessment measured date stored in databases. Measured data by installed Instrumental and Control system (I&C system) as well as monitoring and diagnostic systems are storing during operation of units. Saved data gives us the first useful information about unit components behavior during real service operating condition. We have a first experience with real service operating conditions of NPP and we can do the first comparison of project presumptions with measured parameters. Evaluation of measured data – pressures and temperatures of media, speeds and flowages of media, metal surface temperatures, displacements, vibrations and strain gauges measurement can be used for validation of analyses. Development and implementation of aging management system starts together with NPP service operation. It is advantageous to start with the ageing management system just at very beginning when putting production units of the above-mentioned industrial branches into operation. It will remove all doubts of equipment conditions when such system is to be applied lately.

Ageing management system is important not only for achieving the current safety level but also for reaching the operational reliability of a production unit equipment above the life time assumed by original design, eg. above more than 40 years. It is important for operating organization and for national economy. Profound knowledge of ageing phenomena is consequential for every decision-making considering an extension of unit service life. Time of unit technical availability depends on the life extension of a limited number of equipments with respect to distinction of financial maintenance and replacement costs. Diagnostic system represents the basic tool of ageing management program and it has to be attached to respective data bases of operating organization (owner of equipments) and it will include the third section i.e. program body of ageing management.

LOCATION THE MOST DEGRADATION REGIONS

Different stresses affect material during equipments operation. It makes its gradual damage, but also it can produce a sudden damage of material and even of the whole equipment. Stresses can be considered as load of normal operating conditions, abnormal conditions and extreme load. The ageing management system also includes a section investigating the failure causes, distinguishing between failure cases and their analyses. The goal is to obtain an acceptable trend of a failure (damage – degradation) of equipment material. The trend of material damage and equipment function can be managed under real operating service conditions using the ageing management system of equipment.

Material of components is not uniformly degraded during operation and its service life. Places of components with greatest material degradation have to be located. The highest stress level or the highest thermal shock, most extreme corrosion environment, the greatest erosion exists at these places usually. Three basic sources could be used for determination of the most degraded places:

- ☞ Safety analysis reports of selected components of primary coolant system and secondary circuit;
- ☞ Continual measurement during NPP operation (I&C system, monitoring and diagnostic systems, local measurement);
- ☞ Numerical FEM models of components. Non-destructive examination and testing of material samples can support the detection of critical places too;

SAFETY ANALYSIS REPORTS

Institute of Applied Mechanics Brno,Ltd (IAM Brno) prescribed extent of safety analysis reports of NPP components for NPP Temelín. Reports were done during construction of NPP. They were prepared on project service conditions and their assumed project number. The extent of analyses was prepared in accordance with Czech Standard NTD A.S.I., Section III, (A.M.E. Standard Technical Documentation – Strength Assessment of equipment and Piping of Nuclear Power Plants of VVER Type"[2].). The Standard Technical Documentation of A.M.E. Section III was elaborated by a team of experts on the base of an actual knowledge and practice as a part of row of recommendations for an assessment of strength and reliability, choice of materials and solution of service problems of the Czech nuclear plants. The assessment philosophy of strength and service life in Czech Standard is the same as used in Russian Standard PNAE-G7-002-86 and ASME Code, Section III. The Czech Standard is not conflict with Russian standards and adopted any usefully parts from ASME Code, Section III. Safety analysis reports contain results of analyses (thermal, strain and stress, seismic, dynamics and etc.), assessment of components limit states and assumed cumulative damage due to project service conditions. IAM Brno provided consultation suppliers during elaboration of safety reports and did the third party verifications of all safety analysis reports of components delivered on NPP Temelín. Summary of results show us the critical places of NPP components.

CONTINUAL MEASUREMENT DURING NPP OPERATION

I&C system, Monitoring and Diagnostic Systems (MDS), Special Temporary Measurement (STM) and Chemical and Laboratory Parameters System enable to obtain detailed information about actual service conditions of power plant components. Internal pressures and temperatures of media, speeds and flowages of media, metal surface temperatures, displacements, vibrations and strain gauges measurement can be used for validation of previous analyses. The comparison of project presumptions with measured parameters could be done. In many cases additional local measurements are applied. Thermocouples and strain gauges measurements are used as a local measurement near the assumed critical places of components. The places were detected on experience base and results of safety analyses reports. Measured values can be used for comparison of project and real service operating conditions, detection of unexpected evaluations and mainly for validation of next analyses on numerical FEM models. Local measurements were planned for commissioning process only, but the measurement is running during first NPP operating periods too. Continual measurement during NPP operation enables to confirm sooner detected critical places in safety analyses reports or indicates on new undetected regions.

NUMERICAL MODELS OF PRIMARY COOLANT SYSTEM

The critical areas are usually located in regions with highest stress level or highest thermal shocks, the most extreme corrosion environment, the greatest erosion, and the like exist. Numerical models can help us to detect the critical places. NPP primary coolant system and their components make up very complicated system and the design of numerical models has to be very accurate. Analysis of components influence on each other is very important. Effects of the whole system on individual components under monitoring are transferred to more accurate local spatial models. The local spatial models are usually used for analysing the gradual lifetime exhaustion of a facility during its operation. It was a reason why we decided to create a global model of primary and secondary circuits with all the most important components as it is shown on Fig. 1. We wanted to simulate behavior of all components system. The global shell spatial numerical FEM model makes a base for the simulation of real service conditions during NPP operation. Used numerical FEM model was used for:

1. To analyse and assess service conditions that occurred during NPP operation;
2. To transfer inner effects of individual facilities to local spatial models those are used for detailed tension analysis with the assessment of lifetime exhaustion in accordance with Czech Standard of NPP;
3. Determination of critical places in primary circuit;
4. Comparison of calculated results on the global model (displacements, tensions, etc.) with measurements in operation, which verifies the used model.

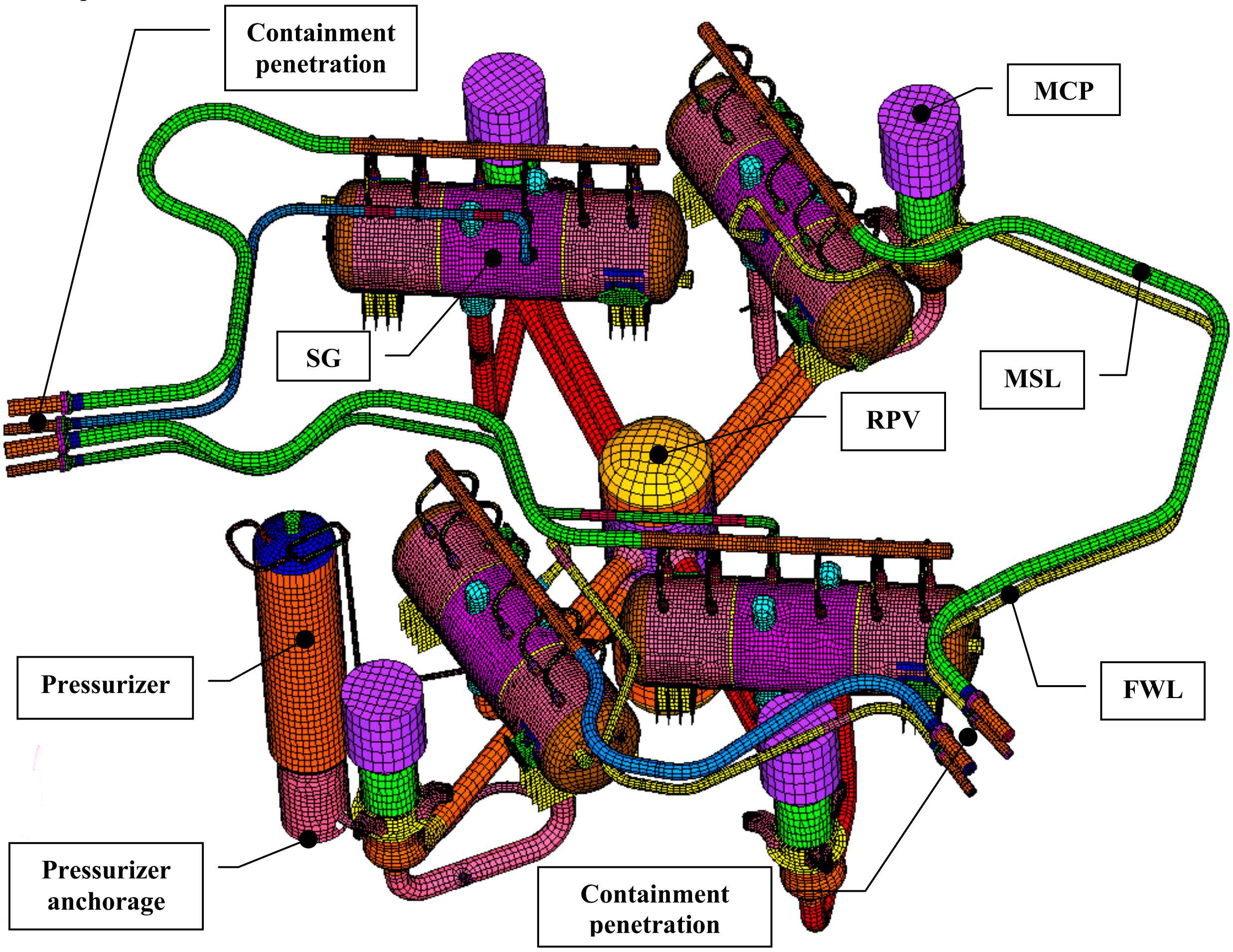


Fig. 1 Global FEM model NPP Temelín primary coolant systems with the most important components

Three fixed regions are on primary and secondary circuit only – reactor pressure vessel (RPV) in the middle part, pressurizer anchorage and hermetical containment penetration. Steam generators (SG), main circulation pumps (MCP) and pipelines can dilate freely. NPP Temelín installed displacement sensors on each SG and MCP and component displacements are measured during service operating conditions as is shown on Figure 2. Presented results of displacement measurement show us the movement of components cannot be neglected. SGs have two different displacements – in primary piping system direction and in axe of SG's body.

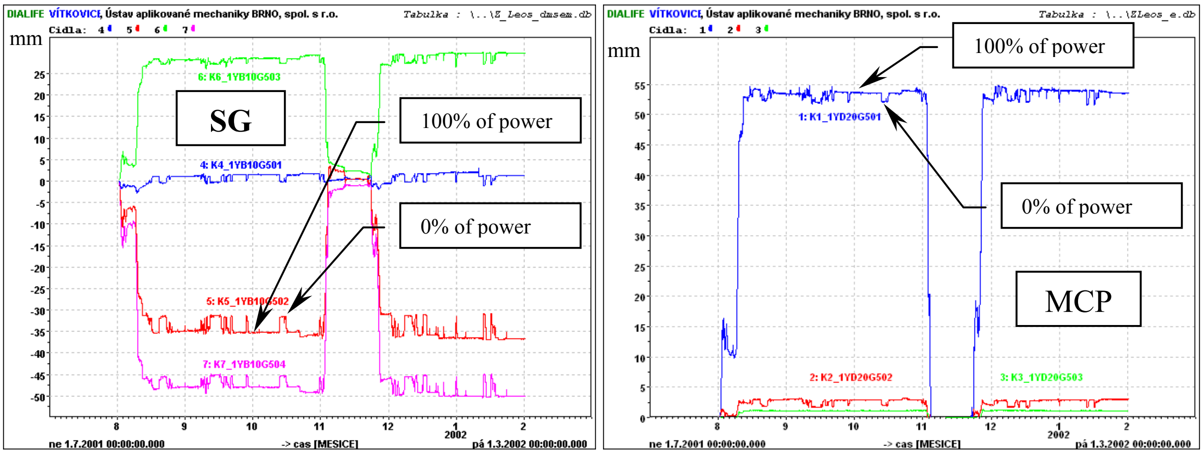
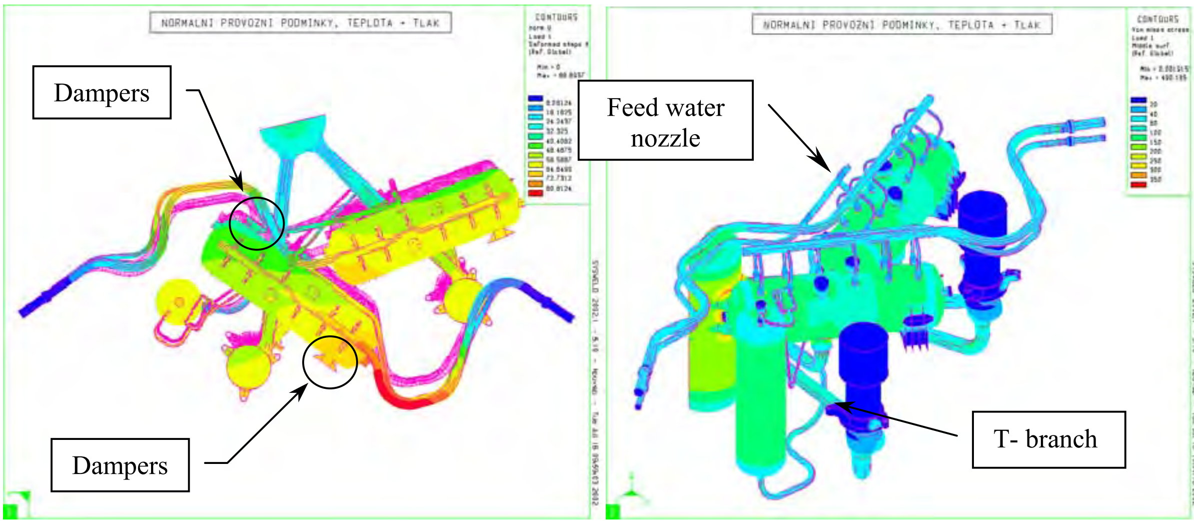


Figure 2 Displacement SG supports and MCP body during service conditions

Displacement measurement of SGs and MCPs is very useful and measurement can be used for validation of FEM global model behavior (Figure 3a). Additional displacement measurement on SGs seismic dampers during test periods was used too. SGs rotation could be verified during heating-up of circuit. Stress distribution during normal operating condition is shown on Figure 3b. Stress level values were used during selection of critical places.



a) Components displacement - FEM model b) Stress distribution - nominal operation of unit

Figure 3 Results of stress analysis on global model – loop 1 and 4

Critical places were selected on a charge of safety analysis reports, continual measurement and FEM analyses on global model. 32 critical areas were selected for aging management program at NPP Temelín. The units of NPP Temelín have four loops and any places have to be calculated four times. It means 97 places were selected fully for aging management program in beginning. The other places can be added during NPP service operation. Of course it will be depend on eventually situations on NPP. Selected areas were classified and separated on two groups. Detail stress analyses will done on places assigned first group, cumulative damage will calculated from safety analysis reports on places assigned second group. SG feed water nozzle (four places – four loops)[5] and T-branch to pressurize from main coolant pipeline No.4[6] for detail stress analysis during first year were chosen.

LOCAL FEM MODELS

Two local 3D models were created during first year of aging management system implementation at NPP Temelín. Feed water SG nozzle is shown on Figure 4 and T-branch is shown on Figure 5. Calculated and validated displacements of analyzed places on global model were used as boundary conditions on local models. It means the same service operating conditions have to be simulated on global and local models.

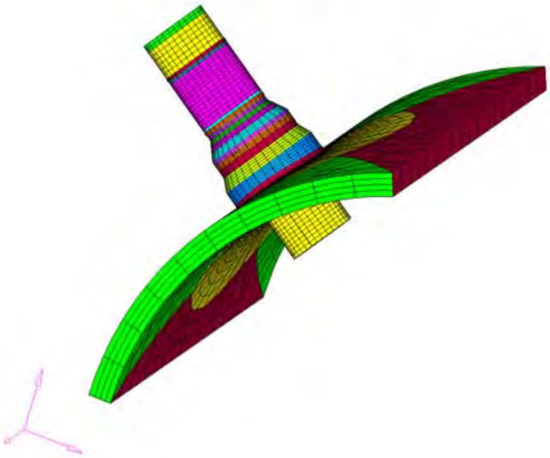


Fig.4 Feed water nozzle of SG[5]

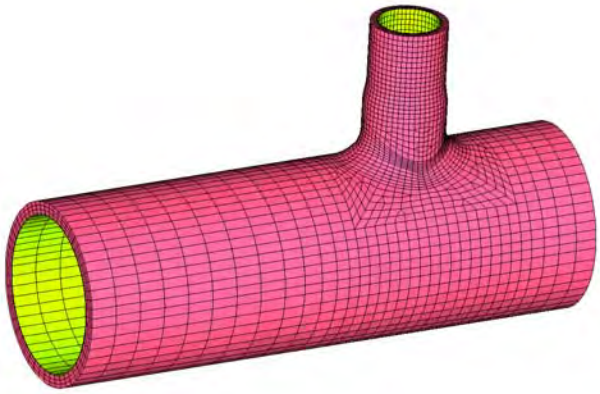


Fig.5 T-branch to pressurize[6]

Sketch of displacement translation from global model on local model is shown on Figure 6. Tips illustrate the position and direction used boundary conditions. Coordinate system was chosen the same as in global model.

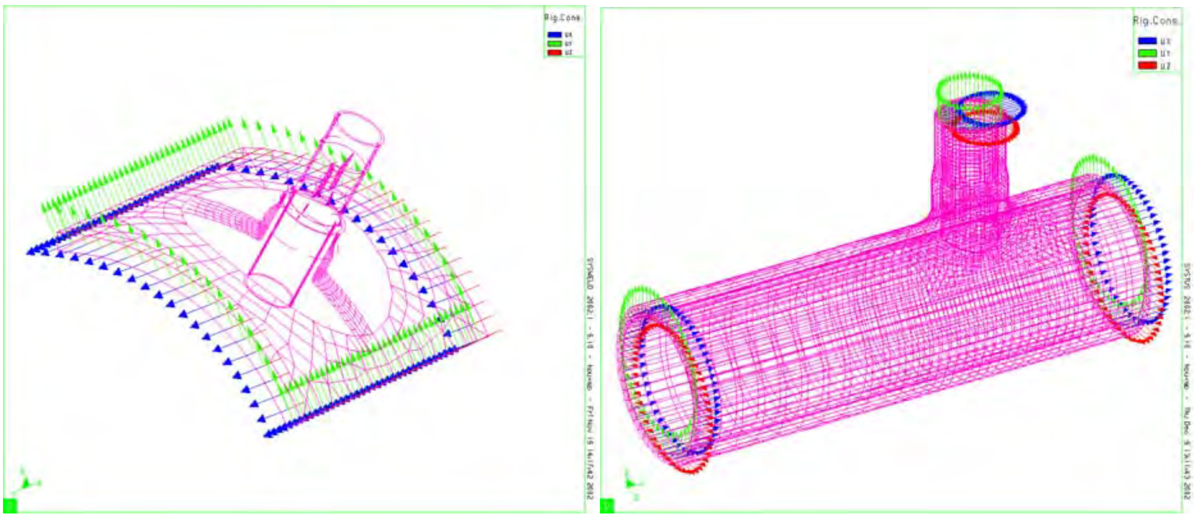


Fig.6 Sketch of boundary conditions on local FEM models

We could obtain the exact effect of complicated global system of primary and secondary circuits on selected areas. Measured evaluations of I&C sensors were applied as loading of analyzed structures – Internal pressures and temperatures of media, speeds and flowages of media. Surface evaluation of thermocouples measurement or local strain gauges measurement was used for validation of FEM thermal or strain analysis. Surface temperature evaluation at SG feed water nozzle during real service operating conditions is shown as an example on Figure 7.

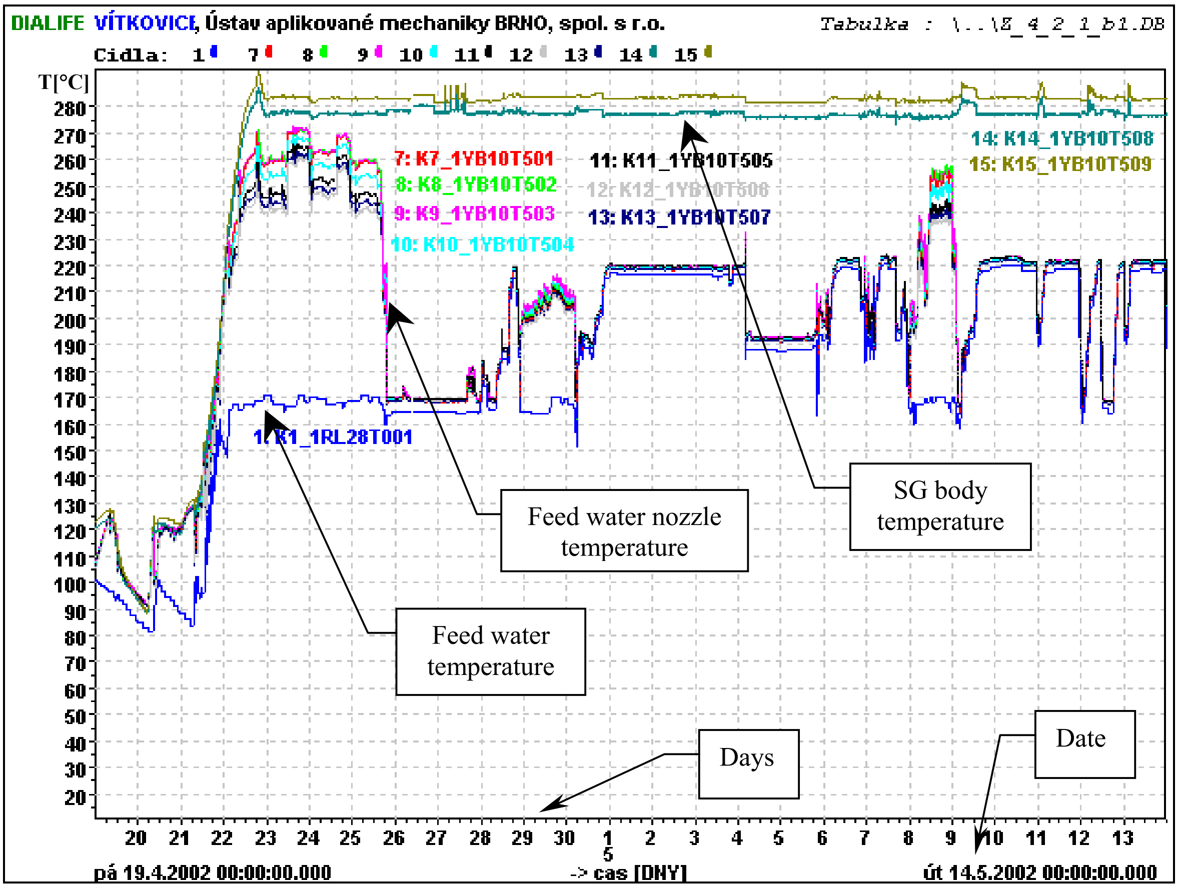


Figure 7 Surface thermocouple measurements at feed water nozzle areas [5]

The results of the thermal and stress-strain analyses were not used for the assessment of calculated places, but they were used for training neural networks (NN). NN are implemented in diagnostic system DIALIFE that represents the basic tool of ageing management program.

NEURAL NETWORK

Neural networks (NN) are one of the methods of artificial intelligence (AI). NN was created on principles and structures similar to human brain. Neural networks consist the layers of basic functional units - neurons and connections among them. These connections provide data transmission. Every unit (neuron) can be connected with any other unit except units in the same layer. The neural network transforms input vector $\mathbf{X}=\{x_1, x_2, \ldots, x_n\}$ to output vector $\mathbf{Y}=\{y_1, y_2, \ldots, y_m\}$ when the input signal is received. In our case selected I&C sensors are input vector and full stress tensor is output vector.

It is necessary to learn NN before their usage. The training pair is formed by input values (signals) and by required output values (signals). The set of internal parameters (weights) is tuned when the neural network is learned by training algorithm. The weighted connections between units (neurons) are tuned to minimize difference answer the network gives and the desired output. Once the weights are set the network is learned and NN is able to extrapolate and interpolate outside training area with the maintain FEM comparable accuracy.

The neural network is used for determination of stress state in selected critical areas. Measured data from I&C and monitoring systems is input vector; stress tensor is output vector form NN. Measured quantities are temperature and pressure of media, volume flow of media. Surface temperatures are used for resolution of service operating conditions in any cases. The goal for usage of neural networks for lifetime assessment is to save calculation time in comparison with classical FEM. Neural network gives the answer by at least two orders faster and with the same accuracy as FEM [4]. The average neural network answer time is about 0.002s [4]. These results qualify this method for usage in on-line systems that work continually for long service time. The above-described procedure allows assessing lifetime with higher accuracy and thus saving the maintenance costs. Example of FEM and NN SIGMA XX comparison is shown on Figure 8.

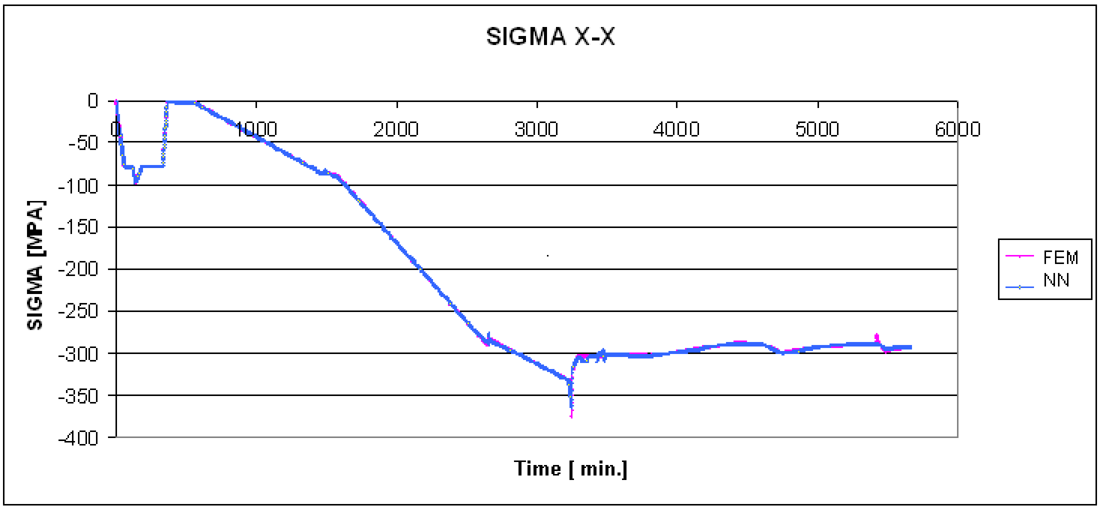


Figure 8 Comparison of SIGMA XX evaluations between FEM and NN – SG feed water nozzle

NN were implemented in diagnostic system DIALIFE and were used for determination of stress tensor due to service operating conditions. Assessment of determinate stresses has been followed. NN are applied on SG feed water nozzle and T-branch at NPP Temelín.

DIAGNOSTIC SYSTEM DIALIFE [2]

Diagnostic system represents the basic tool of ageing management program. Institute of Applied Mechanics Brno, Ltd. develops the diagnostic system DIALIFE in co-operation with Czech NPPs (Dukovany and Temelín). The developing of programming system DIALIFE is nature continuation the long-term service that IAM has provided on both NPPs. Diagnostic system DIALIFE runs on NPP Dukovany for last seven years and is continually actualized. System is implemented at NPP Temelín at the present time and the system is under developing. Basic architecture of diagnostic system DIALIFE implementation on NPPs is shown on Fig. 9.

Instrumentation and Control Systems (I & C), Monitoring and Diagnostic Systems (MDS), Special Temporary Measurement (STM) and Chemical and Laboratory Parameters System enables to obtain detailed information about actual service conditions of power plant components. Thermocouples and strain gauges are used for local measuring, near the critical places of components. The saved data from these systems serves as input data for assessment procedure in system DIALIFE. Recording the changes of temperature, deformation, media pressure, flow, chemical concentration in the media etc. during operation is very important and it is in fact the history of plant operation. Result data can be needed like a base for next decision making about plant in future. Diagnostic system is implemented on NPP net and system is able to communicate with other systems through net as is shown on Figure 9.

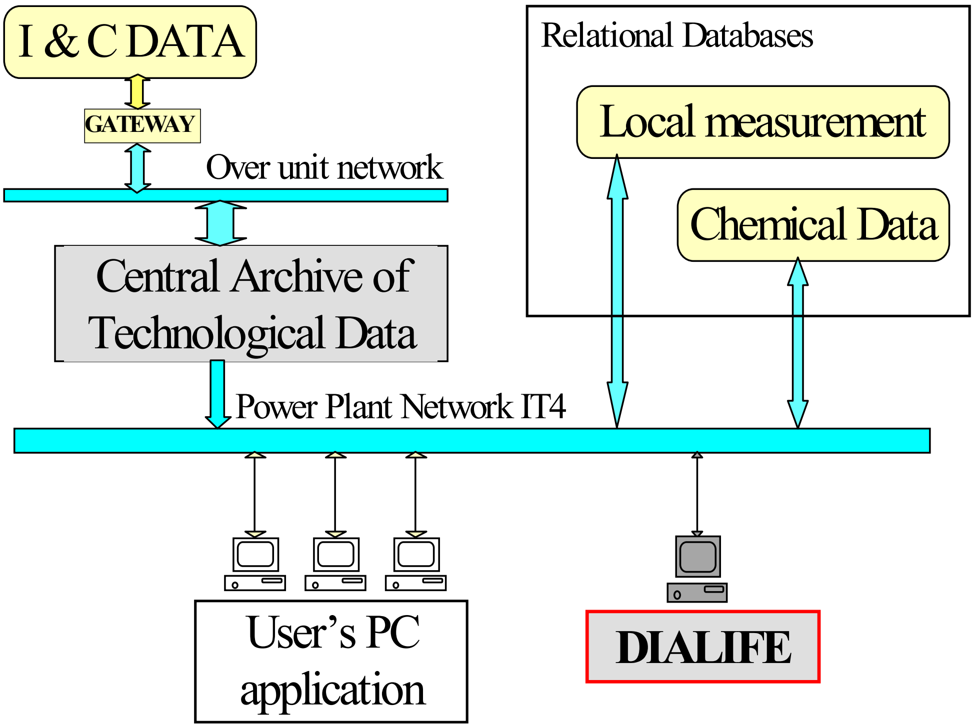


Figure 9 Architecture of DIALIFE software net communications on NPPs

Ageing management system of production unit equipments includes catalogue of mechanisms of material ageing producing its gradual damage under operating conditions. Catalogue of phenomena of material ageing includes data of their initiation and main influences and criteria for identification of critical zones of equipment. Several places (parts) can be defined that affect mostly the equipment safety and reliability. At that each place can have different mechanism of material damage, too, or even they can act simultaneously. At the same time material of the same or similar equipment can be damaged in different ways. Catalogue of mechanisms must be based on experience and knowledge that will be periodically updated keeping abreast with the development. New knowledge of science and research should be applied for tests and repairs. It has to cover all equipments included in the ageing management system. Decisive mechanisms of nuclear power plant components and its material damaging include mainly:

- Fatigue of material due to fluctuating loading;
- Stress corrosion cracking;
- Erosion;
- Thermal and strain ageing of a material;
- Assessment of allowable failure growth to an allowable size, given by fracture mechanics;
- System function

Assessment procedures of mentioned damage mechanism are implemented in diagnostic system DIALIFE [7]. The assessment procedures are common used during service operating periods. Usage of assessment method is depending on damage mechanism of analyzed critical place. All 97 critical places were implemented in diagnostic system DIALIFE in beginning of NPP Temelín production and diagnostic system DIALIFE started to assess a damage of detected places. Stored service operation parameters of NPP are using as input data for assessment. Detected critical places were separated on two groups. Detail thermal, strain and stress analyses are doing on the critical places included in first group. Cumulative damages of critical places included in second group are used from safety analysis reports. Neuron network have been applied on two areas since. The other places are under preparation.

One of the important outputs from diagnostic system DIALIFE is trend of damage of selected critical places. The output has a useful feedback on NPP service because it is possible to detect service period with larger damage, present status of damage and trend on next service period. Trend of fatigue damage of SG feed water nozzle and location of damage is shown on Figure 10.

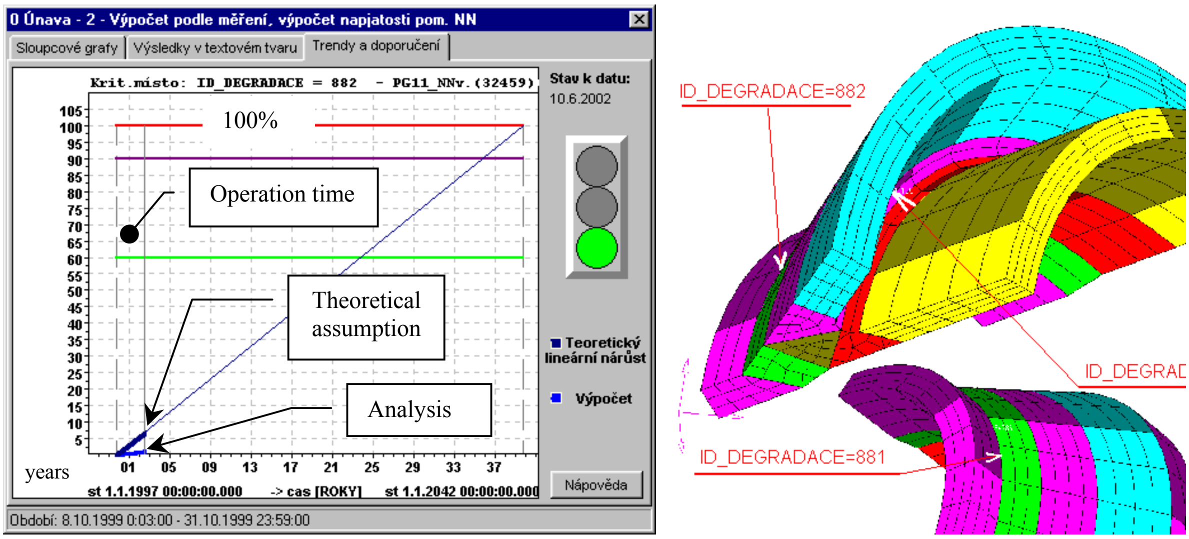


Figure 10 Trend of fatigue damage on SG feed water nozzle during first operation period

CONCLUSION

The goal of an equipment owner is to operate this equipment as long as possible when the maintenance costs are still reasonable. At the same time the equipment operated must be reliable and comply with safety at a general acceptable standard. In order to achieve this goal the operation, maintenance and repairs must be managed. But fair information based on quality theoretical analyses and experimental measurements are needed. Theoretical analyses include calculations of stress, strain, of material damage and of performance functions. Mathematical models of the material damage and equipment performance must follow from experimental tests of material under the service conditions and in an environment very close to real ones. Experimental measurements give parameters representing the environmental effect or material and/or equipment response to a given load. In such case data measured by sensors of I & C systems, diagnostic systems and CHEMIS systems come in effect. Sources of the optimisation of operation management and maintenance management also include the results of non-destructive inspections.

First analyses were done during first year of aging management system implementation at NPP Temelín. Stored service parameters were assessed and compared with design from the beginning of NPP operation. First tests of NPP started on August 1999. Components were separated on two groups. Places with higher loading were assigned to the first group; places with smaller loading were assigned to the second group. Detail stress analyses of service operation conditions are assumed to do on selected places in first group. The content of groups can be exchanged with larger time period. The work on aging management system implementation at NPP Temelín is continuing.

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