EXPERT SYSTEM FOR EVALUATION OF THE STRESS-STRAIN STATE OF CONTAINMENT AT NUCLEAR POWER PLANTS WITH VVER-1000

Arutyunyan, R.V.[1)], Ulianov, A.N.[1)], Kiselev, Alexander S.[2)], Kiselev, Alexey S.[2)] and Medvedev, V.N.[1)]

1) Nuclear Safety Institute (IBRAE) of the Russian Academy of Sciences, Moscow, Russia

2) Russian Research Center “Kurchatov Institute”, Moscow, Russia

ABSTRACT

An expert system of evaluation of the Stress-Strain State (SSS) of VVER-1000 Nuclear Power Plant (NPP) containment has been developed at the Nuclear Safety Institute (IBRAE) of the Russian Academy of Sciences. Its prototype – specially adapted to the second power unit of Kalinin NPP – has been installed at the NPP.

The developed procedure of evaluating the containment SSS based on elements of the control equipment and the control system of tendon efforts embedded into the construction together with the CONT Code allows conducting expert evaluations of containment’s SSS and drawing statements on its operational capability at any moment of its operation as well as during Control & Preventive Works (CPW) at the containment pre-stress system.

Using the proposed expert system SSS evaluations of two types are conducted.

The first-type evaluation consists in estimating the current SSS of the containment. Calculations of operational stress state of the containment with consideration for both current temperature conditions inside and outside the containment and efforts in tendons according to CPW data are conducted.

The second type is the evaluation of sufficiency of the level of tendon tension to ensure strength in a case of accident. The following calculations are performed: SSS due to pre-stress, proper weight, the worst weather conditions (winter period: temperature difference along the wall width up to 60^{o}C) and emergency inner pressure. Based on the achieved values of efforts in sections of the containment the relevant statement on operability of the construction is issued.

The use of calculated-experimental SSS evaluations of the above two types makes it possible to reduce CPW costs since it allows revealing the weakest areas of the construction and performing purposeful tightening of tendons of the pre-stress system to establish necessary compressive stresses in these areas.

INTRODUCTION

To control the Stress-Strain State (SSS) of containments during the construction period, special Control-and-Measurement Equipment (CME) is installed within the construction body. In total arrangement of about 300 CME sensors in containment is provided for including: String Reinforcing Force Converters (SRFC, or ‘PSAS’ - Russian-spelled abbreviation) designed to measure stresses in bar reinforcement; String Converters of Linear Deformations (SCLD or ‘PLDS’- Russian-spelled abbreviation) to measure deformations in concrete; and String Temperature Converters (STC or ‘PTS’ - Russian-spelled abbreviation) to measure temperature of concrete.

In the course of the last decade ‘HB005’-type force sensors have been arranged at anchors of tendons of the containment pre-stress system to perform control over efforts in tendons.

In compliance with References [1 and 2], Control and Preventive Works (CPW) are performed at the containment pre-stress system at regular intervals. During CPW acting efforts at some tendons are determined using the screw-nut-separation method.

The application of powerful computer facilities has enabled development of appropriate software to perform detailed calculations of the stress-strain state of containments at Nuclear Power Plants (NPPs).

The above factors have allowed developing an expert system for evaluation of the stress-strain state of NPP containments comprising the CONT Code that in automatic mode obtains, as input data, information from ‘HB005’ force sensors and CME sensors.

WORK WITH THE DATABASE ON READINGS OF CME SENSORS

In the course of the expert system development a database on readings of CME sensors is being generated for which graphic representation appropriate algorithms and program modules have been developed. Such modules provide a temporary-scale format enabling analysis of readings of CME sensors both during a specific period of containment operation and in the course of its long-term running. By way of example, Fig. 1 illustrates increments of bar reinforcement stresses during preoperational tests of the containment at Volgodonsk NPP Unit 1 from 7.09.2000 to 17.09.2000; Fig. 2 demonstrates readings of CME sensors under long-term running of the construction. Lettering of both figures are corresponding to position and direction ff the sensors in reinforcement: h_in – hoop inner; h_out – hoop outer; m_in – meridian inner; m_out - meridian outer; rad – radial;

Such potentialities of representing information allow not only evaluating the containment SSS at a specific period of time but also determining rheological characteristics of the reinforced-concrete construction. The possibility of determining the operational ability of the sensors is also provided for. For instance, in the course of the first two years the sensor PSAS-1143 h_out operated in a stable way, but then its readings became scattered evidencing the sensor failure.

A more accurate estimate of the operational ability of the sensors is performed on the basis of comparisons of the data achieved in-situ with the relevant calculated information (e.g., on stresses in reinforcement) within sensor location areas obtained via the expert system. Fig. 3 illustrates the type of temperature distribution in the containment wall at Kalinin NPP Unit 2 depending on ambient temperature variations inside and outside the containment during 13.09 – 29.12.1999. According to the results achieved, the values of readings of PTS sensors are quite close to calculated curves virtually at all measuring cross-sections. After completing the calculations with consideration for both temperature variations during the period indicated and their comparison with the data of measurements using PTS sensors, stresses in the containment body were calculated and compared with readings of PSAS sensors for the relevant period.

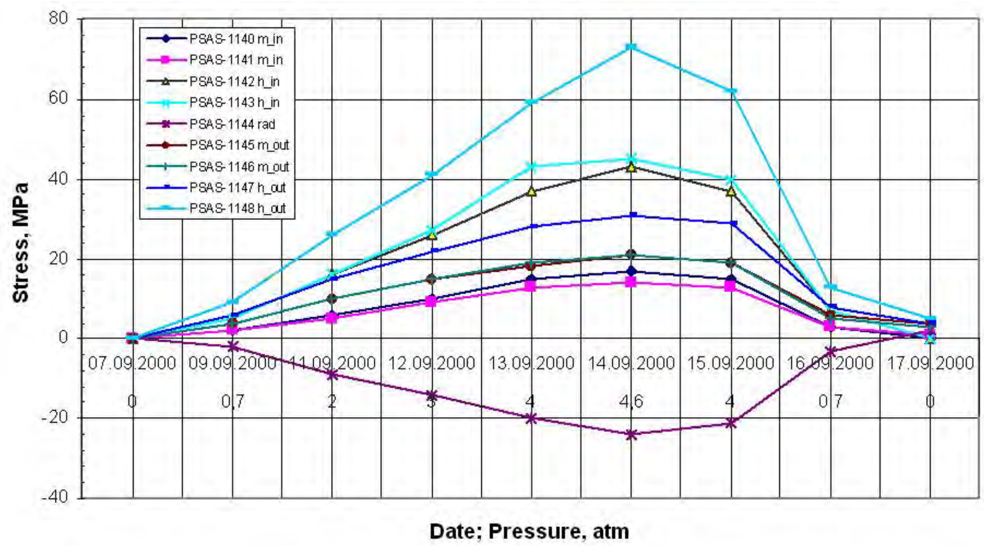

Fig. 1 Increment of reinforcement stresses under impact of test load (07.09.2000 - 17.09.2000), Volgodonsk NPP Unit 1, cross-section #1, level mark 32 m

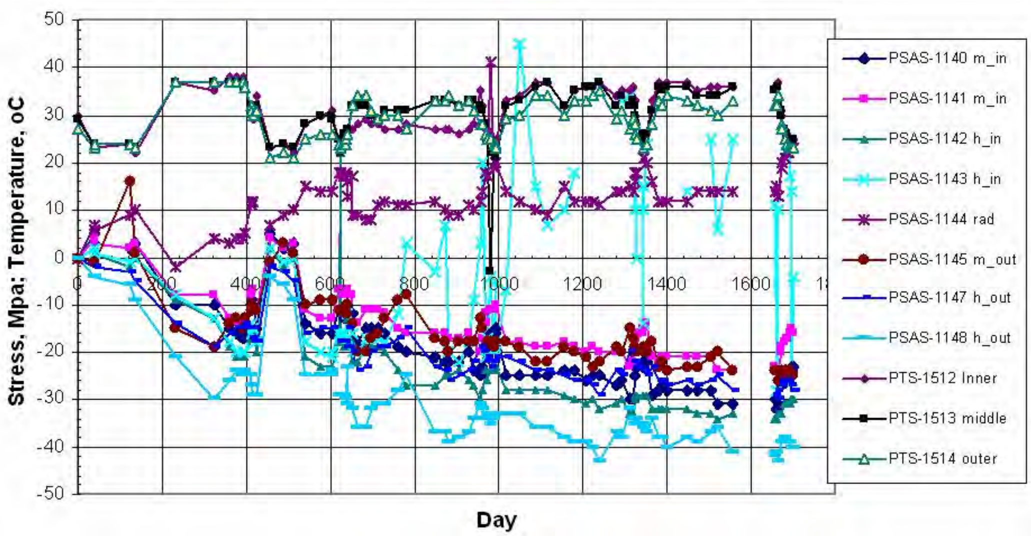

Fig. 2 Increment of bar reinforcement stresses and temperature measurement results from 17.09.2000 (end of the containment tests) to 13.05.2005, Volgodonsk NPP Unit 1, cross-section #1, level mark 32.6 m

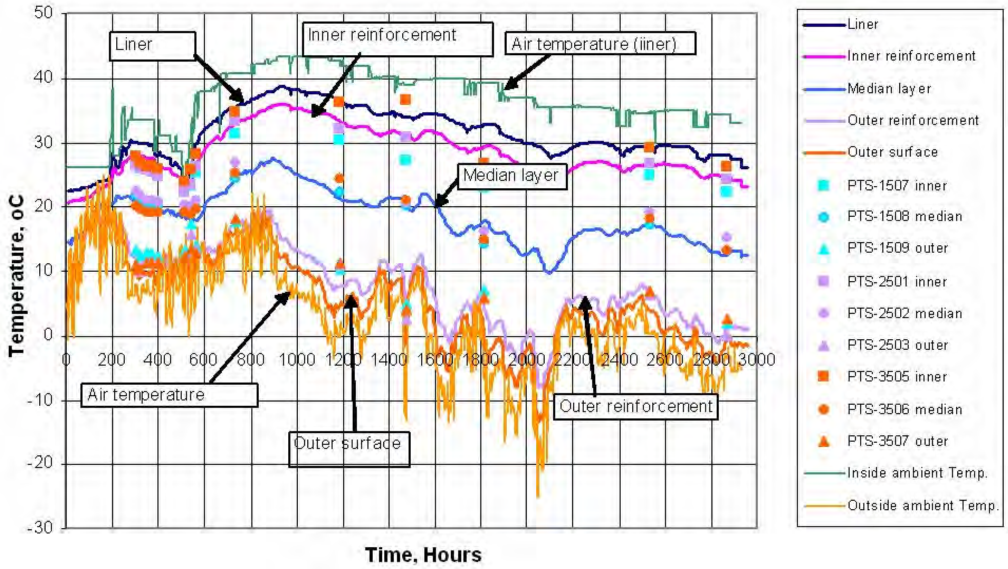

Fig. 3 Temperature variations over time at different points over the containment thick during the period of 13.09.99 - 29.12.99 according to calculations (achieved with consideration for the data on ambient temperature variations inside and outside the containment) and in-situ measurements

Fig. 4 illustrates the character of stress variations over time in the containment body during the same observation period using the results of calculations and in-situ measurements (PSAS – 3122). The results depicted show a rather good agreement between the calculated and the experimental curves evidencing proper operation of the sensor.

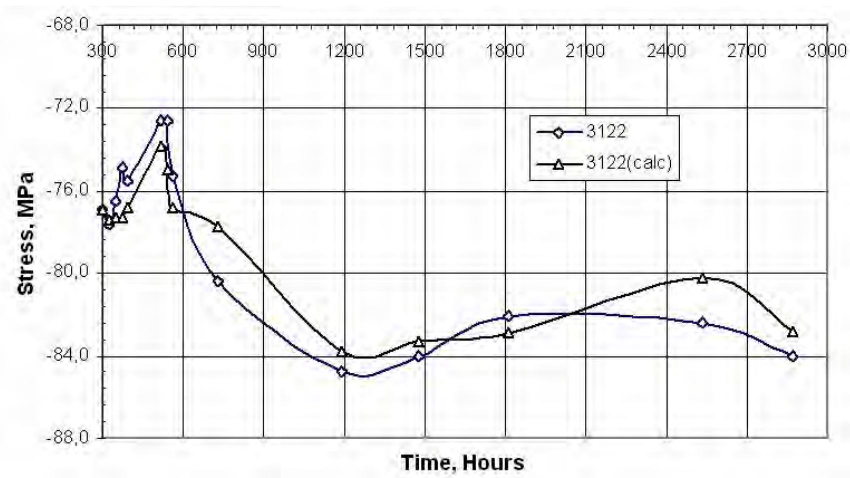

Fig. 4 Stress variations over time in meridian inner reinforcement at the level mark of 59 m during 13.09.99 - 29.12.99 according to the data of calculations and in-situ measurements (PSAS-3122)

WORK WITH THE DATABASE ON READINGS OF '..005' FORCE SENSORS

To evaluate the containment SSS over time, at first one needs to follow the dynamics of variations in tendon efforts using the results of in-situ measurements based on 'HB005' force sensors being presently the most reliable indicator of the status of the pre-stress system.

The results of measurements achieved using 'HB005' force sensors at Unit 1 of Volgodonsk NPP during 05.09.2000 through 16.04.2006 evidence that for the most part the character of variations in readings of these sensors over time appears rather convincing. Seasonal variations in efforts related to temperature variations in sensor installation areas are reflected along with rather stable readings characterizing the type of effort decrease due to relaxation of reinforcement and creepage of concrete (Fig. 5).

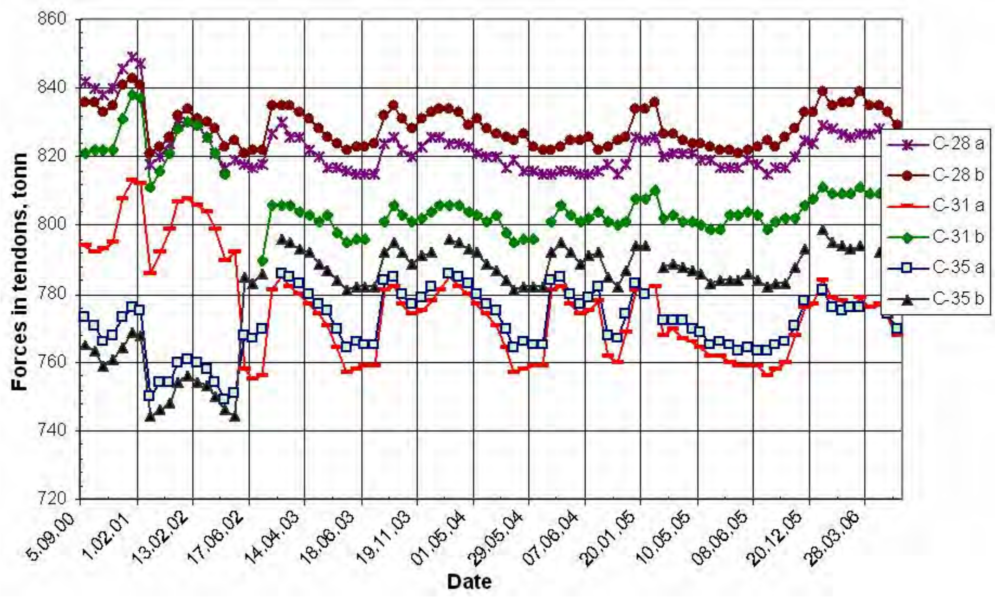

Fig. 5 Variations in efforts at tension anchors of tendons in the cylindrical part of containment at Volgodonsk NPP Unit 1 during 05.09.2000 - 16.04.2006 achieved using 'HB005' force sensors

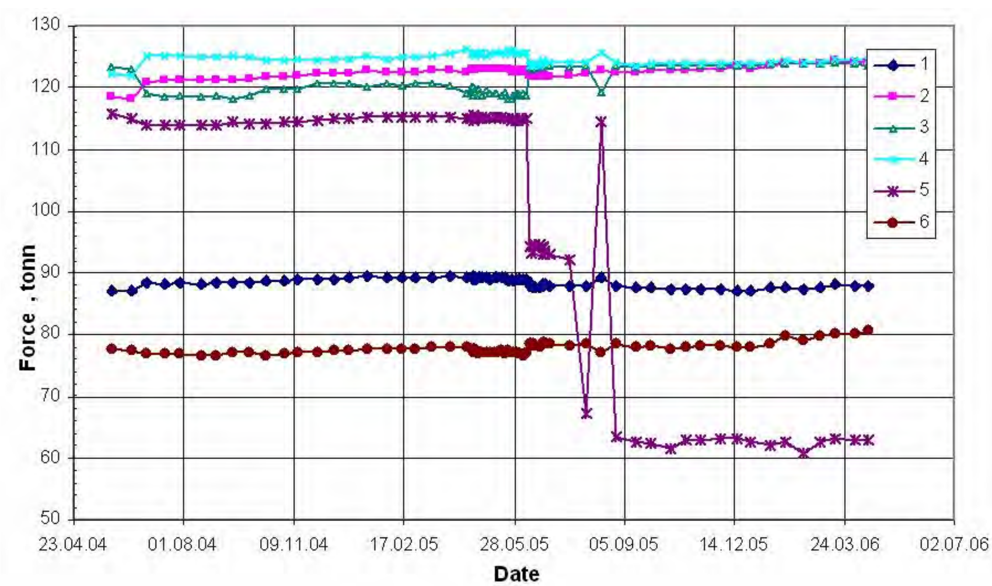

Fig. 6 Effort variations in segments of 'HB005' force sensor installed at the tension anchor of tendon 'C-111' during 28.05.2004 - 14.04.2006 (Kalinin NPP Unit 2)

A minor group of sensors installed in both the cylindrical and the domical parts of the containment is the only exception: their readings vary step-wise in proportion to 1/6th of the effort. This phenomenon is due to specific design of the sensors wherein the acting effort is first measured by six elements and then is summed up. At such design of the sensors failures of one or two elements in the course of operation are quite probable. This phenomenon, however, is easily traced via unreasonable jumps of readings as seen in Fig. 5 (sensor 'C-35 b'). By way of example, Fig. 6

represents variations in efforts in segments of ‘HB005’ force sensor installed at tension anchor of tendon ‘Ts-111’ of the containment at Kalinin NPP Unit 2. Analysis of the readings of efforts in each of the six segments of the sensor has revealed variations in the 5th segment only at the early period of its operation, the remaining segments being operating in a stable way. Thus the efforts in tendon ‘Ts-111’ have been invariable but restoration of the sensor operability is required.

WORK WITH THE DATABASE ON RESULTS OF CPW AT THE CONTAINMENT PRE-STRESS SYSTEM

To maintain the containment pre-stress system of NPPs with VVER-1000 in operable condition, a control over residual effort in tendon tension is performed at regular intervals. The work scope and schedules are regulated by the Rosenergoatom Concern’s Regulations ‘RD EO-0129-98’ and ‘RD EO-0130-98’.

The control over efforts in tendons is performed by means of standard hydro-jacks of ‘DG 650/1200’-type using the method of separation of screw nut of anchor.

Based on the results of CPW at the containment pre-stress system, predicted efforts in tendons by the time of next-in-turn CPW are calculated.

By way of example, several results of CPW at the containment pre-stress system of Volgodonsk NPP Unit 1 (since the end of squeezing up to now) are demonstrated in Table 1.

Table 1. Results of CPW at the pre-stress system of containment cylinder at Voldodonsk NPP Unit 1 since the end of squeezing up to now

Tendon number	Tension 2000		CPW-2002		CPW-2003		CPW-2004		CPW-2005		CPW-2006	
	Jack	HB 005	Jack	HB 005	Jack	HB 005	Jack	HB 005	Jack	HB 005	Jack	HB 005
1	1000	835.5				821.5		817.5		824		819.5
2	990				900						880	
3	1000	811.5	940			784		785		790		793
5	990				900						895	
8	1000	863.5				832		833		834		836.5
9	1000	818.5	955			793		788		791		793
12	990	827	925			775		775.5		777		776

PECULIARITIES OF THE DEVELOPED CONTAINMENT MODEL

To perform the SSS calculations, the finite-element method is applied and a detailed mathematical model of containment is used taking account of: exact tracing of tendons, geometric characteristics of containment, sealing liner and containment reinforcement.

A 3D model of the containment of Volgodonsk NPP Unit 1 comprising 188652 linear volume elements and 208716 nods is demonstrated in Fig. 7.

While modeling loads of pre-stressed tendons, the force effect of each individual tendon is accounted for. The tendon tracks are taken similar to those of the full-scale construction.

A peculiarity of effort distribution along the length of tendon consists in a decrease in efforts at a segment of its length close to the tension anchor due to load transfer from jack to anchor. This phenomenon is taken into account in calculations.

Thus to calculate the load due to pre-stress, tendon efforts acting at the tension end of tendon (at jack) are set, which are taken on the basis of predictions by FSUE ‘Atomenergoproekt’ for the period of next-in-turn CPW. Then a decrease in efforts along the length of tendons due to the effect of friction on walls of their housing tubes is accounted for, the friction coefficient being taken equal to ‘$\mu = 0.09$’ with a possibility of its variation. Losses in tendon efforts by anchoring are also taken into consideration. Note that at tension ends of tendons equipped with force sensors ‘HB005’ the efforts are set in accordance with the data of measurements. For tendons provided with no force sensors ‘HB005’ average losses by the considered point of time are taken calculated using the measurement data of ‘HB005’ force sensors installed at other tendons.

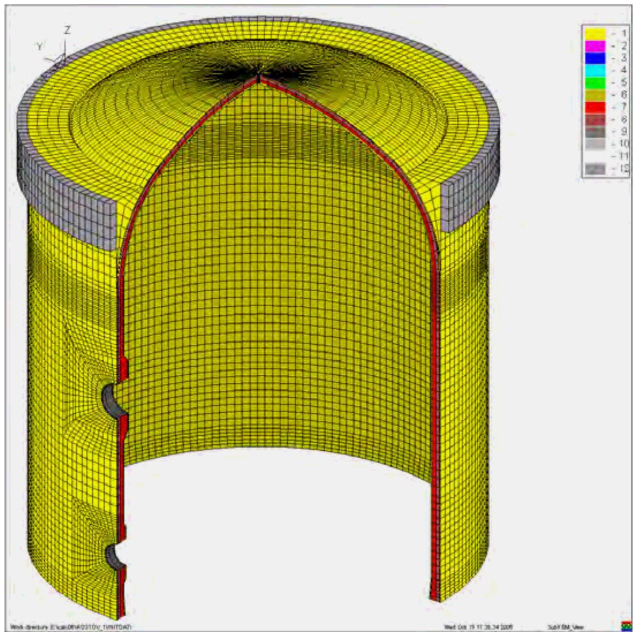

Fig. 7 Finite-element model of the containment of Volgodonsk NPP Unit 1

The character of effort distribution along the tendon length taken while loading the construction with pre-stress loads is demonstrated in Fig. 8.

As inner pressure inside the containment increases (e.g. in case of a design-basis accident), it undergoes deformations and expands in volume. Tendons of the pre-stress system are lengthened concurrently that results in increase in their efforts, i.e. in their self-tension. Accordingly, changes in tendon efforts depending on load variations on inner pressure are taken into account in calculations. The calculated value of the self-tension coefficient equals 1.1 for the emergency pressure of 0.39 MPa.

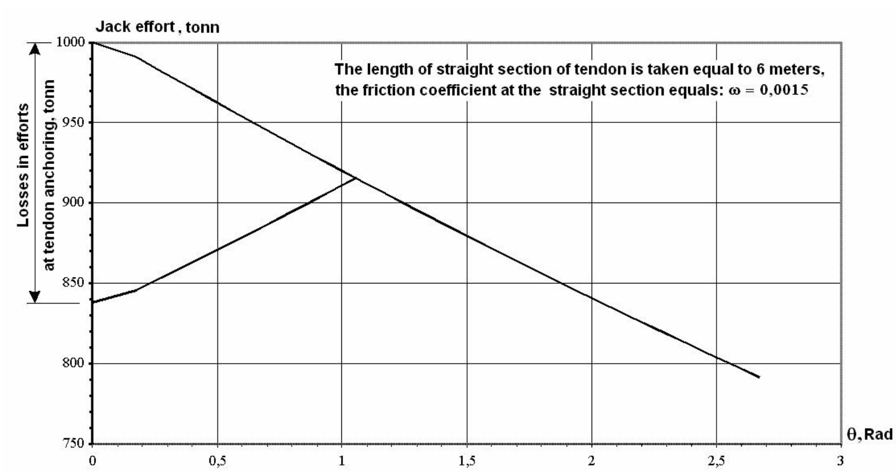

Fig. 8 Variations in efforts along the length of tendon in the cylindrical part of containment from the connection ring to the base depending on the friction force between tendon and its housing tube taking account of the losses by anchoring

OPERATION OF THE EXPERT SYSTEM FOR EVALUATION OF THE STRESS-STRAIN STATE OF CONTAINMENT AT NPP WITH VVER-1000

The CONT Code representing an element of the expert system enables: -calculated estimates of the containment SSS; -analysis of sufficiency of its squeezing; -prediction of both the needed level of efforts in tendons of the pre-stress system and the due scope of work on correction of tendon efforts in the course of CPW at the containment pre-stress system.

To estimate sufficiency of the containment squeezing providing operability of the construction in case of a design-basis accident, one needs to calculate: the containment SSS due to the action of pre-stress, its own weight, the temperature gradient caused by the temperature difference inside and outside the containment by the instant of accident and the emergency inner pressure. Through summation of the contributions of individual loading factors, components of hoop and meridian efforts in containment wall are calculated. Using the achieved values of efforts in sections of the containment one may consider the availability of critical zones in the containment wall requiring both strength analysis and operability analysis.

The input data generated at the phase of the expert system adaptation to calculations at a specific power unit that may not be varied by user include:

- Containment geometry;
- Finite-element decomposition of containment volume;
- Tracing geometry of tendons of containment pre-stress system;
- Physical-chemical properties of containment materials;
- Super-cell representation of basic finite-element model; and
- Description of surfaces of containment model and boundary conditions.

The input data that may be varied by user of the expert system while analyzing the containment operation comprise:

- Efforts in tendons;
- Coordinates of location of CME sensors;
- Azimuthal and axial coordinates of cross-sections for which graphics of stresses and forces in the wall are plotted;
- Pressure inside the containment in case of accident;
- Friction coefficient for tendons of the containment pre-stress system in tendon-housing tubes;
- Losses of tendon forces (%) of the containment pre-stress system while anchoring;
- Squeezing increase coefficient due to deformation of the containment while loading with inner pressure;
- Mechanical properties of containment materials;
- Threshold sensitivity level of CME stress sensors;
- Value of critical level of effort components in containment wall.

By default the last-mentioned parameter equals ‘0’. This means that critical zones in containment wall are determined through the criterion of the absence of positive tensile strains. In case of assigning other criteria of the containment operational ability, this parameter may be changed in either positive compressing-effort direction (tensile strains of a specified level are admissible) or negative one. The calculations are performed in compliance with the CONT Code User Manual (see below).

The calculation allows achieving the following data:

- displacements of the model nodes due to effects of applied loads, deformations and tension in elements of the model;

- effort variations in tendons of the pre-stress system (for pre-stressed containment) in case of containment deformation;

- efforts (M, N) in elements of the model;

- load levels resulting in attainment of various limiting states (cracking of concrete; yielding of liner and reinforcement, plasticity exhaustion in reinforcement or in liner); and

- crack-generation areas in concrete;

No physical constants are embedded into the program text. All physical-mechanical and geometrical characteristics are assigned explicitly in input data.

Supplementary program blocks have been also developed that in automatic mode and with consideration for the aforementioned input data enable: -identification of zones with minimum squeezing efforts by the instant of next-in-turn CPW; -identification of a group of tendons which tightening is first-of-all necessary; -prediction of the level of efforts in the said tendons; and –visualization of the information achieved on location of critical zones.

In a case that maintenance personnel discovers a spontaneous rupture of one or several tendons during the containment running, the expert system determines sufficiency of the squeezing level of the construction necessary for carrying the emergency load. If the needed squeezing level is not provided, the expert system indicates the need for undertaking urgent actions on restoration of the operational ability of the construction, such as: tightening of tendons passing close to ruptured tendons or urgent replacement of ruptured tendons.

If containment zones with positive tensile strains in wall are discovered, the following information is displayed in the protocol: -a table indicating the numbers of tendons of the pre-stress system passing close to critical zones; and – a figure (see Fig. 9) visualizing the location of critical zones (red color) and tendons passing through them (colored). By way of example, Fig. 9 demonstrates the layout of tendons, the containment zone with tensile strains being colored red. The expert system determines the numbers of tendons passing through this zone and points out the need for correction of efforts therein.

The expert system allows excluding unjustified tightening of tendons during CPW that produces adverse effects on the state of these tendons as well as on that of concrete and metal liner of the construction.

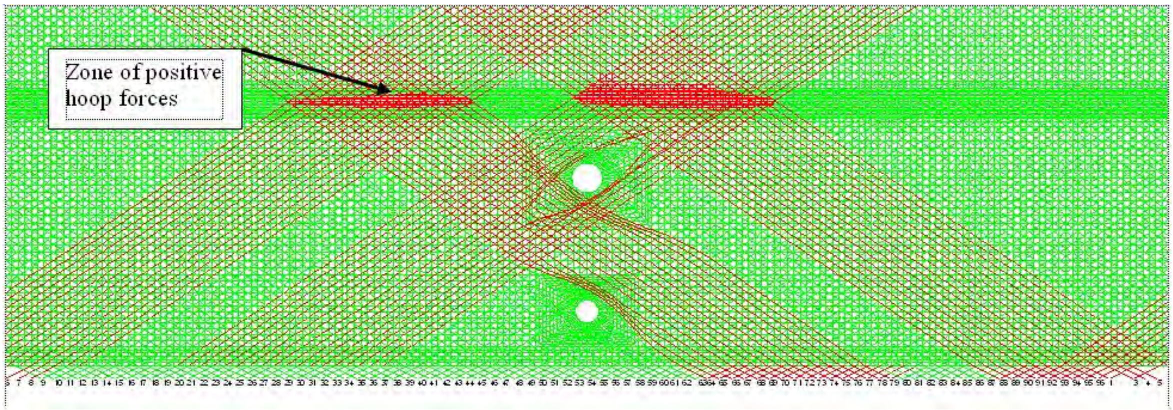

Fig. 9 Visualization of the tensile-strain zone in cylindrical part from calculation protocol

CONCLUSIONS

1. Using readings of CME sensors and ‘HB005’ force sensors the expert system allows generating a database, graphic depiction of the data enabling evaluation of the operational ability of the sensors.
2. In calculations of the containment stress-strain state readings of both CME sensors and ‘HB005’ force sensors are used.
3. The expert system allows excluding unjustified tightening of tendons during CPW that produces adverse effects on the state of these tendons as well as on that of concrete and metal liner of the construction.
4. In a case that maintenance personnel discovers a spontaneous rupture of one or several tendons during the containment running, the expert system determines sufficiency of the squeezing level of the construction necessary for carrying the emergency load or indicates the need for undertaking urgent actions on restoration of its operational ability, such as: tightening of tendons passing close to ruptured tendons or urgent replacement of ruptured tendons.

ABBREVIATIONS

CME	= Control-and-Measurement Equipment
CPW	= Control and Preventive Works
HB005	= Sensors of efforts in tendons
NPP	= Nuclear Power Plant
PLDS (Russian-spelled abbreviation)	= String Converters of Linear Deformations (SCLD)
PSAS (Russian-spelled abbreviation)	= String Reinforcing Force Converters (SRFC)
PTS (Russian-spelled abbreviation)	= String Temperature Converters (STC)
SSS	= Stress-Strain State

REFERENCES

1. Requirements to Servicing and Repair of the Containment Pre-stress System at Nuclear Power Plants with VVER-1000 and Reactor Installations ##302, 338, 187, RD EO-0130-98 (in Russian), 1998.
2. Requirements to Servicing and Repair of the Containment Pre-stress System at Nuclear Power Plants with VVER-1000 and Reactor Installations #320, RD EO-0129-98 (in Russian) , 1998.