Strength evaluation of the steam distribution device in case of fuel channel rupture

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1. Introduction

The nuclear reactors of the Ignalina NPP are RBMK-1500 type reactors. Ignalina NPP has a pressure suppression type confinement, which is referred to as the Accident Localization System (ALS). The ALS prevents the release of the radioactive material from the NPP to the environment during a loss-of-coolant accident. The ALS of the Ignalina NPP with RBMK-1500 reactors consists of a number of interconnected compartments. The schematic view of the Ignalina NPP ALS and the location of main components of the main circulation circuit (MCC) are presented in Fig. 1. Ten water pools are located in the two ALS towers (5 pools in each tower) which separate the dry well from the wet well. These pools condense the accident-generated steam and prevent high overpressures in the compartments. The steam distribution devices (SDD) with the vertical vent pipes, which are inserted under the water of condensing pools, connect the dry well and the wet well. A more detailed description of the Ignalina NPP and the Accident Localization System is presented in [1].

SDD should be capable to withstand the dynamic loads for successful pressure suppression function in case of loss-of-coolant (LOCA) accident. The Lithuanian nuclear regulator, VATESI, recommended performing this analysis in order to verify that the design and strength of the SDD and their connections to the vertical steam corridors are sufficient to withstand the thermal and dynamic pressure loading in case of LOCA.

The structural integrity analysis of the steam distribution device in case of fuel channel rupture is presented in this paper. In case of single fuel channel rupture the steam/gas mixture enters the piping of reactor cavity venting system and is directed to SDDs located in the 5st condensing pool of the left ALS tower. These SDDs are designed for treating releases from reactor cavity and are not loaded during other kind of accidents. Thus, the SDD in 5st condensing pool of the left ALS tower is an object of the analysis of this paper.

The thermal-hydraulic analysis was performed by employing state-of-the art computer code COCOSYS [2] in order to determine pressure and temperature loading.
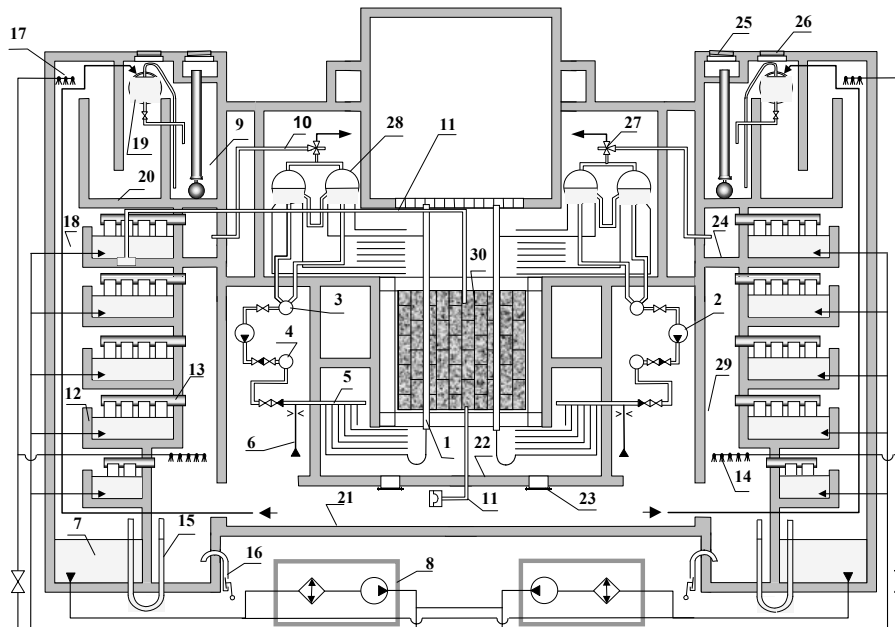

Fig. 1 Scheme of Ignalina NPP ALS and location of the main components of MCC: *1* – fuel channel; *2* – main circulation pumps; *3*– suction header; *4* – pressure header; *5* – GDH; *6* – ECCS headers; *7* – hot condensate chamber; *8* – CTCS pumps and heat; *9* – discharge pipes section; *10* – pipes from MSV and BRU-B; *11* – pipes from reactor cavity; *12* – condensing pools; *13* –steam distribution headers; *14* – BSRC sprays; *15* – S/traps between HCC and BSRC; *16* – BSRC vacuum breakers; *17* – air removal corridor sprays; *18* – air venting channel; *19* – gas delay chamber tank; *20* – gas delay chamber; *21* – reinforced compartments; *22* – down hatches; *27* – MSV and BRU-B; *28* – drum separators; *29* – BSRC; *30* – reactor

The computer code NEPTUNE [3] was used for strength analysis. The NEPTUNE code is based upon the central difference explicit integrator. Thus, the code does not employ stiffness or flexibility matrices but is based upon a nonlinear internal nodal force vector. This approach is ideal for transient, nonlinear analyses in which metals are deforming in an elastoplastic mode, concrete is cracking/crushing and contact impact is taking place. When individual elements failed, their contributions to the internal nodal force vector is reduced to zero and there is no change required to the solution algorithm. Validation of the NEPTUNE computer code for pipe whip analysis was presented in reference [4].

2. Data for the SDH strength evaluation

2.1 Geometrical data and modelling by FE

The SDD consist from 2, 3 or 4 (pertains to length) of prefabricated elements. The construction of one prefabricated element and cross-sections of SDD is presented in Fig. 2.

The main parts SDD are steam distribution header (SDH) and vertical steam nozzles (Fig. 2). SDH is a horizontal cylinder with outside diameter is 806 mm, wall thickness is 3 mm, and the length is 7500 mm. The vertical steam nozzles are parallelepiped boxes. The cross-section of this box is presented in Fig. 3, section 2-2: length is 1000 mm, width is 50 mm, wall thickness is 3 mm, height is 2100 mm for condensation pool 5. The hood is around the vertical steam nozzle for air cushion. The dimensions of cross-section of the hood are 1026x82 mm. The nozzles are installed by pairs. The distance between of these nozzles is 600 mm across longitudinal axis (Fig. 2, section 1-1). The connection of SDH and vertical steam nozzle are presented in Fig. 3, section 3-3. The vertical steam nozzle is separated in 5 channels. The thickness of dividing walls is 3 mm.

The SDD 7500x2100 model was used for structural integrity analysis. The pipelines of the SDD, the connectors of vertical vent pipes wall of the steam distribution header are included in the FE model. This model was prepared by the ALGOR preprocessor [5].
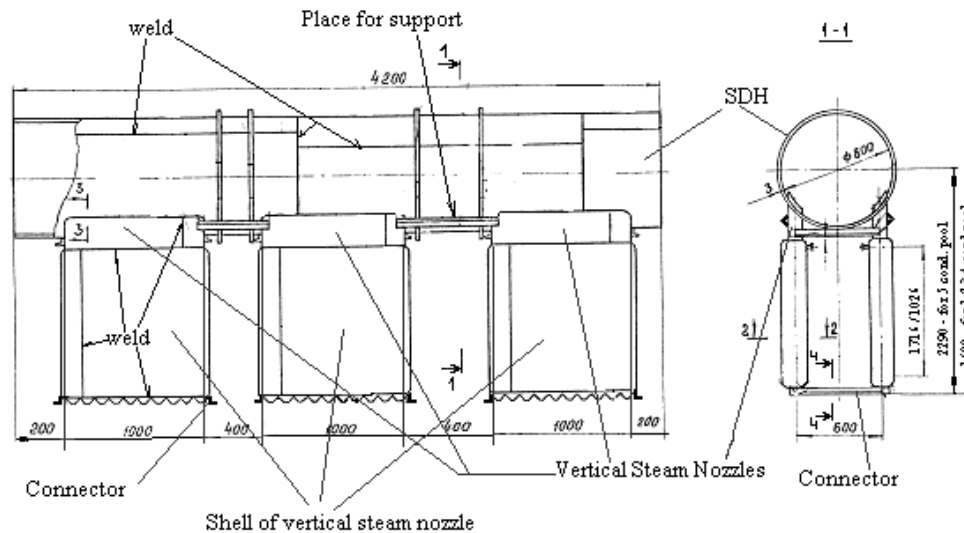

Fig. 2 Construction of one part of SDD, general view of SDD
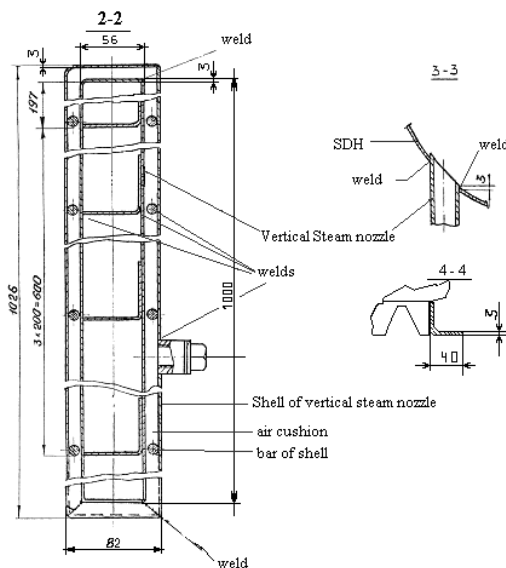

Fig. 3 Construction of one part of SDD, cross-section of vertical steam nozzle and joining of the SDH with nozzles

The ALGOR/NEPTUNE interface program was made to transform all input variables (nodal coordinates as well as element properties) from ALGOR input to NEPTUNE input. The SDD were modelled using four-node quadrilateral plate elements developed by Belytschko, et al. [3, 6]. The formulation of this element is based upon the Mindlin theory of plates and uses the velocity strain formulation. The material model can treat elastoplastic behaviour. An element thickness was the thickness of the pipe wall.

The connectors of the vertical steam nozzles were modeled using 3D beam elements developed by Belytschko, et al. [7]. Beam elements are two-node members allowed arbitrary orientation in the 3D (three-dimensional) X, Y, Z space. An additional node (K-node) is required to define the element orientation. It is a general six degree of freedom element (i.e., three global translation and rotational components at each end of the member). The beam element provides moment, torque and force information. The 3D beam element is a three-dimensional uniform cross-section element capable of performing large deformations and elasto-plastic analysis of general beam-frame

problems. The shape change of cross-section is not accounted in any analysis. Externally, the beam has six degrees of freedom - three displacements and three rotations. It supports full 3D translation and rotation motions. The 3D beam element is often used in analyses when bending, torsion and stretching behavior occurs with large deformations and/or material nonlinear effects.

2.2 Material properties

Regarding material properties, the model to be analyzed has two basic parts: SDH pipelines and vertical steam nozzles made from steel 12Ch18N10T. Standard yield strength, ultimate strength, ultimate strain, area reduction and modulus of elasticity of steel 12Ch18N10T are presented in Table.

Table

Yield Strength, Ultimate Strength, Ultimate Strain and Area Reduction of Steel 12X18H10T [8,9]

Characteristic	Temperature, $^\circ$C			
	20	100	200	300
R^T_m (σ_u), MPa	510	461	421	412
$R^T_{p0.2}$ ($\sigma_{0.2}$), MPa	216	206	187	177
A (δ), %	35	30	27	26
Z (ψ), %	55	55	54	52
E, GPa	205	200	190	180

2.3 Boundary conditions

The model is built in a Cartesian coordinate system, the nodes completely restrained are designated by symbol Δ, translations are designated by T and rotations by R. Certain nodes of the model have translation and rotation restrains that accounts for the effect of surrounding structures.

The SDD 7500x2100 have movable fastening from supply pipe in the concrete floor (this floor is not presented). This supply pipe of SDD can move and rotate in z direction. The nodes on this supply pipe of the SDD have translation and rotation constraints in the x and y directions.
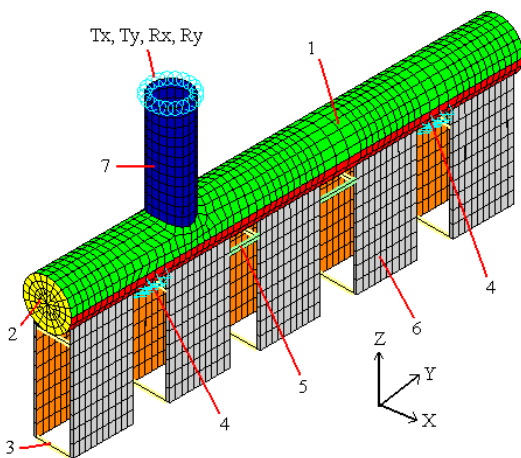

Fig. 4 Combined model for finite element analysis of the SDD 7500x2100: *1* – SDD pipe; *2* – SDD pipe end; *3* – cross connectors; *4* – SDD support constrains; *5* – longitudinal connectors; *6* – vertical vent pipes; *7* – SDD supply pipe

Also the SDD are supported by two supports between the ends of the pipe (Fig. 4, 4 - SDD support constrains – the nodes completely restrained).

2.4 Loads for SDD strength analysis

The state-of-the-art COCOSYS code was used for thermo-hydraulic analysis of the SDD. The results of the thermal-hydraulic analysis of fuel channel (FC) rupture are time histories of pressure in SDD header and vertical vent pipes, temperature and mass flow rate behaviour, as well as dynamic loading on the vertical vent pipes of the SDD subject to this accident. The loads used for SDD strength analysis according to the place of an effect can be divided in internal and external loads.Internal SDD loads are time histories of pressure in SDH and vertical vent pipes, thermal loadings of SDD.

SDD Pressure loads. For thermal-hydraulic calculations SDD headers were divided into three parts. The pressure-time histories in each of the three parts of SDD header and vent pipes are presented in Figs. 5 and 6. The differences between the pressure histories in each of the three parts of SDD headers and in the vertical vent pipes were small. Because of this small difference, the pressure history for Coll2_2 (Fig. 5) was chosen to be the pressure in the entire length of SDD header and pressure history for Pipe2_2 (Fig. 6) was chosen to be the pressure in all SDD vertical vent pipes.
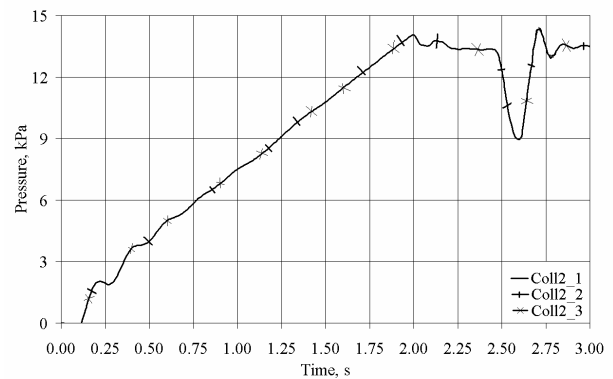

Fig. 5 Resultant pressure in SDD header in case of fuel channel rupture
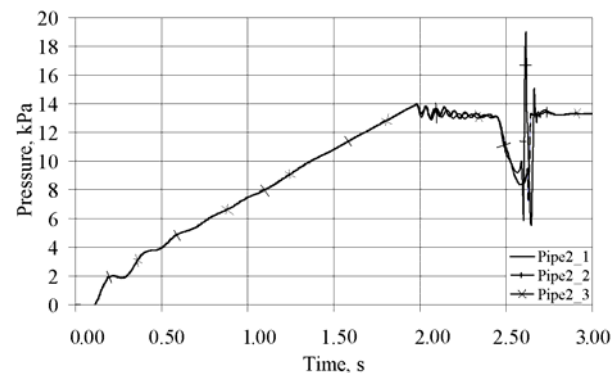

Fig. 6 Resultant pressure in the vertical vent pipes in case of fuel channel rupture

SDD thermal loads. For structural integrity assessment of the SDD it is important to know thermal loading on the pipe of the SDH, vertical vent pipes and supply pipe during FC rupture. The temperature-time histories in each of the three parts of the SDD header (as well as in the internal pressure analysis) are presented in Fig. 7. The

temperature history for Coll2-2 (Fig. 7) was chosen to be the temperature in the entire length of SDD header for conservatism. The temperature-time histories in the vertical vent pipes and supply pipe of the SDD also were evaluated.
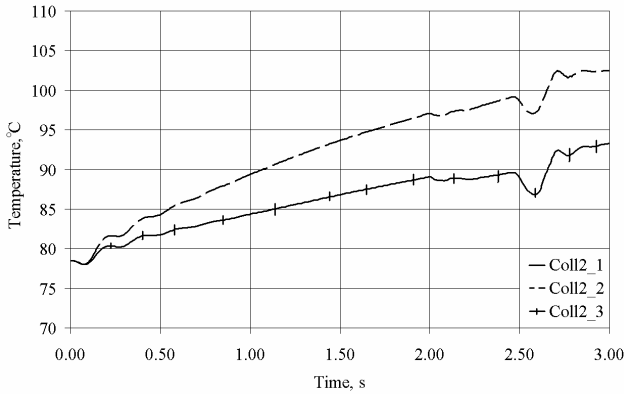

Fig. 7 Temperature in SDD header in case of fuel channel rupture

External SDD loads are dynamic forces.

Dynamic forces. For the SDD loading analysis there are four forces that act on different parts of the SDD. All these forces are schematically presented in Fig. 8. It should be noted that these are the forces of fluid impact on SDD structures and should not be confused with the pressure loading, which is described in previous section (Internal Loads). The calculated loading is presented in Pascals (force per unit area) in order to avoid the dependency on the number of SDD simulated by single node in the thermal-hydraulic model. Pressure loading (Pa) maybe converted to force (Newtons) by multiplying pressure loading by affected area.
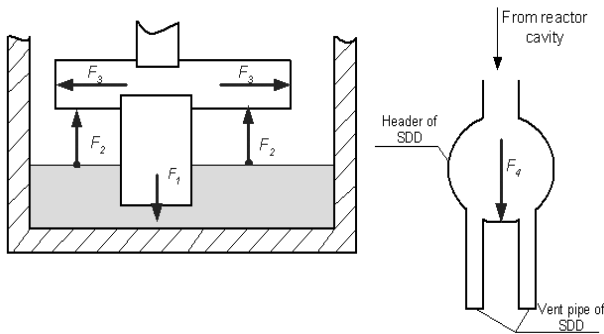

Fig. 8 Forces forming the loading of the SDD

The force F_1 [Pa] (force per unit area of flow) represents the loading of the vent pipe due to steam/gas mixture flow. The loading to the vent pipe wall is calculated from equation.

$$F_1 = \frac{m^2}{\rho_p A^2} \qquad (1)$$

where m is mass flow through the pipe (kg/s), ρ_p is atmosphere density inside the pipe (kg/m^3) and A is area of the flow (m^2).

The equation for F_1 (Eq. 1) is derived from the formula, provided in [10] assuming $\Delta p \rightarrow 0$. Such an as-

sumption is reasonable because the steam/gas mixture is discharged under the water and the water column compensates the pressure difference in the vent pipe and the gas space above the water layer in the pool. The results of the dynamic loading, force F_1, of the vertical vent pipes due to steam/gas mixture flow are presented in Fig. 9.
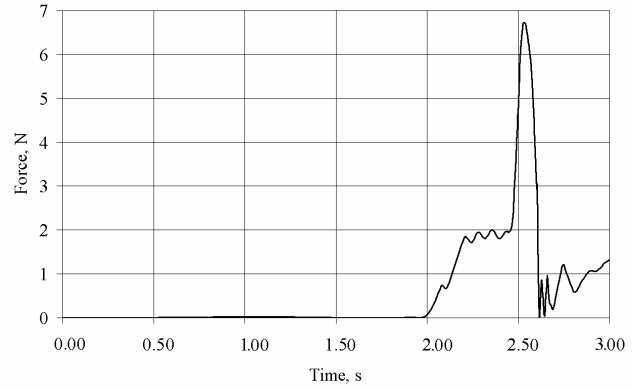

Fig. 9 Dynamic loading on the end vertical vent pipes of the SDD due to single FC rupture (force F_1)

The loading to SDDs due to pool swell is defined as force F_2. It represents the specific force (force per unit area) of water impact on SDD header. This loading appears only in the case if the pool swell phenomenon occurs and water surface level reaches the SDD headers. In accordance with the thermal-hydraulic analysis results water level in this condensing pool increases only 1 cm. This is reasonable, because the steam flow is very low. Therefore, there will be no loading due to the pool swell.
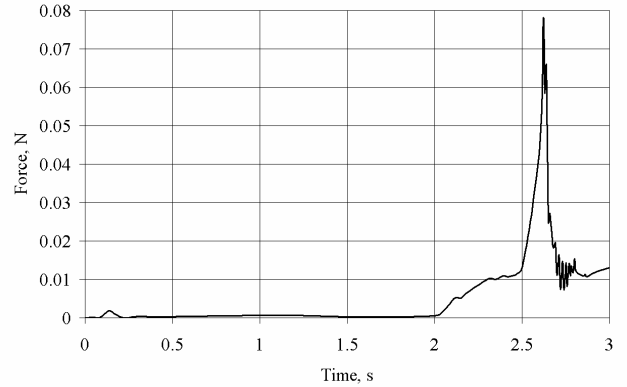

Fig. 10 Dynamic loading on the SDD sealed header pipe end due to single FC rupture (force F_3)
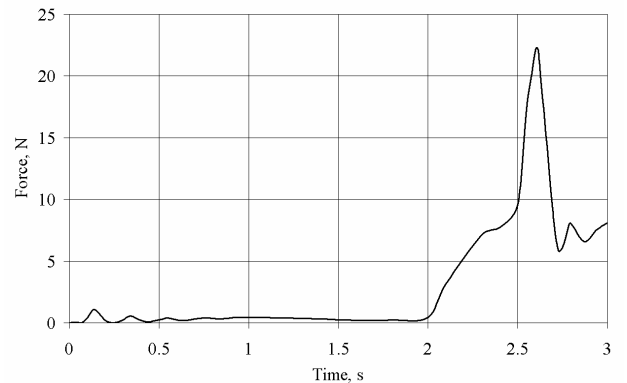

Fig. 11 Dynamic loading at the bottom of the SDD header due to single FC rupture (force F_4)

The loading due to fluid impact to the sealed end of SDH is defined as forces F_3 and F_4. These forces are calculated by Eq. 2, and analysis results of the force F_3 and F_4 are presented in Fig 10 and Fig. 11.

$$F_3 = \rho_h v_h^2 \qquad (2)$$

where ρ_h is atmosphere density inside the SDD header [kg/m^3], and v_h is velocity of the gas flow [m/s].

3. Results of structural analysis

The aim of the structural integrity analysis of the SDD subjected to loading in case FC rupture was to evaluate the following.

1. Structural integrity of the SDD header.
2. Structural integrity of the connection between the SDD header and the supply pipes.
3. Structural integrity of the connection between the SDD header and the vertical vent pipes.

Stress analysis results are presented as stress snapshots at the time step of maximum stress. The Von Misses stresses in the SDD header near the connection of the SDD support are presented in Figs. 12 - 14. The stresses had a maximum value of 126 MPa.

The displacement distribution in SDD pipes resulting from a FC rupture loading is presented in Fig. 15.

The maximum displacement was located in the vertical vent pipe with a maximum value of 3.7 mm.

For a more detailed presentation of the transient stress analysis results, the stress analysis results are presented as stress-time curves in the adjacent elements to the SDD header supports constrains, connection of the SDD header and vertical vent pipe, connection of the SDD header and supply pipe.
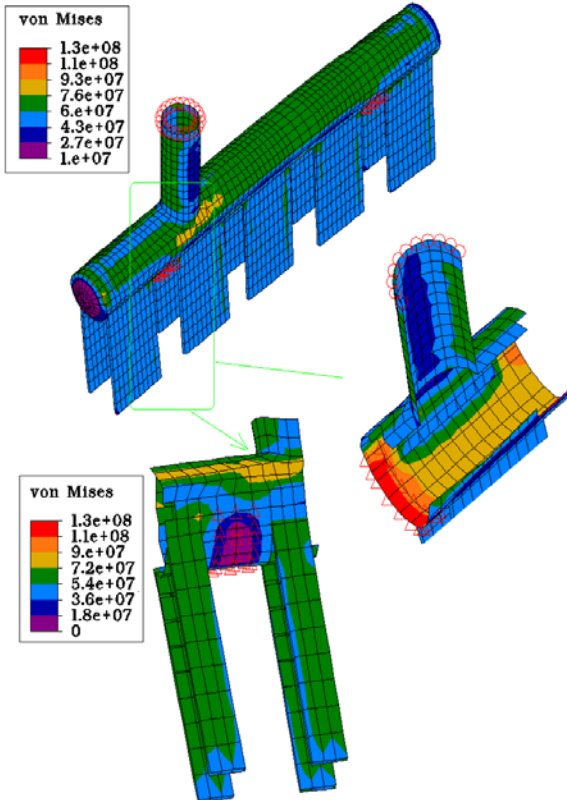

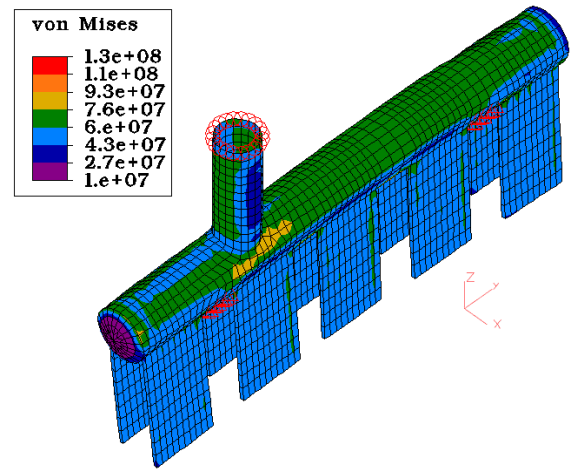Fig. 12 Von Misses stress (Pa) distribution in the SDD near the header supports

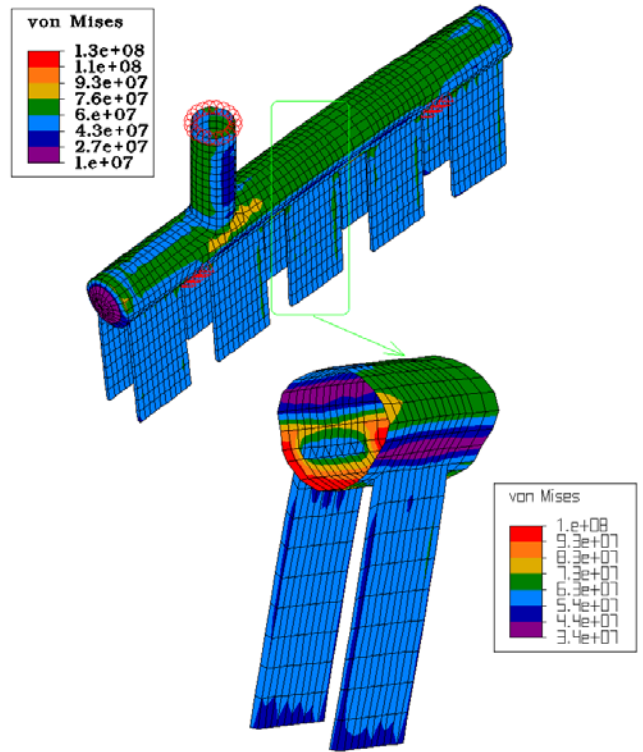Fig. 13 Von Misses stress (Pa) distribution in the SDD

Fig. 14 Von Misses stress (Pa) distribution in the SDD near the connection header and vertical vent pipe

The temporal variation of normal stresses in the element adjacent to SDD header support is presented in Fig. 16. The results show that differences between the normal stress, σ_{xx}, and the normal stress, σ_{yy} are small. The maximum value of stresses is 64 MPa. NEPTUNE calculates stresses at the center of an element for five integration points through the thickness (layers) for the quadrilateral plate element. The normal stress, σ_{xx}, results were presented at two integration points. It was determined that the normal stress, σ_{xx}, in the first integration point (layer 1) is larger than in the second integration point (layer 2), Fig. 17. Accordingly, more detailed analysis results are presented for the first integration point (layer 1).

Temporal variation of normal and shear stresses in the SDD header element adjacent to the connection of SDD header and SDD supply pipe is presented in Fig. 18. It is seen that normal stress, σ_{xx}, is biggest and has a maximum value of 48 MPa. Other stresses are smaller.
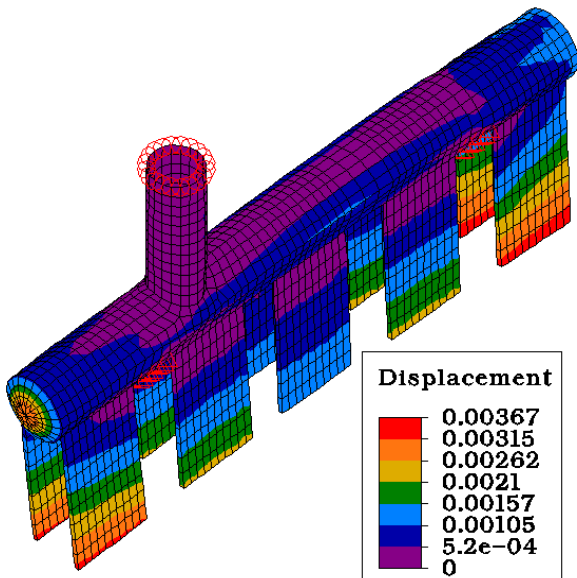
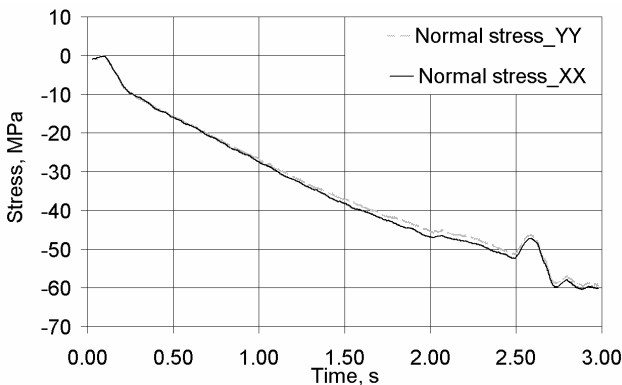Fig. 15 Displacement (m) of SDD pipes

Fig. 16 Normal stress in the adjacent element to SDD header supports constrains

The variation of normal stresses in the SDD supply pipe element adjacent to the connection of the SDD header and SDD supply pipe are presented in Fig. 19. It is seen that the normal stress, σ_{xx}, is biggest and has a maximum value of 48 MPa. The other stresses are smaller.

Temporal variation of normal and shear stresses in the SDD header element adjacent to the connection of SDD header and vertical vent pipes is presented in Fig. 20. It is seen that normal stress, σ_{xx}, is biggest and has a maximum value of 98 MPa. Other stresses are smaller.
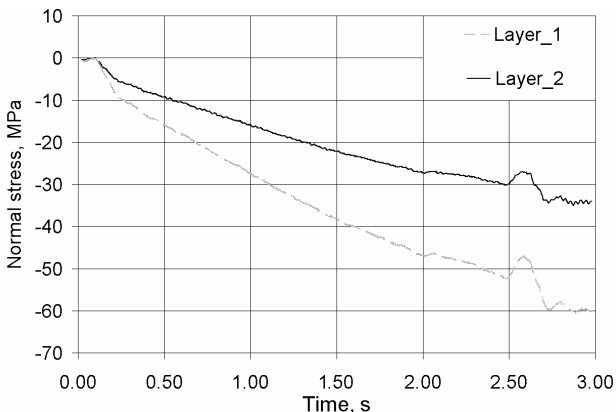
Fig. 17 Normal stress in the adjacent element to the SDD header supports constrains
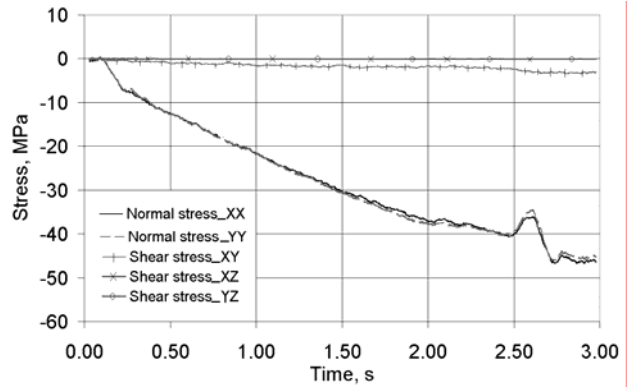
Fig. 18 Normal and shear stress in the SDD header element adjacent to the connection of SDD header and SDD supply pipe
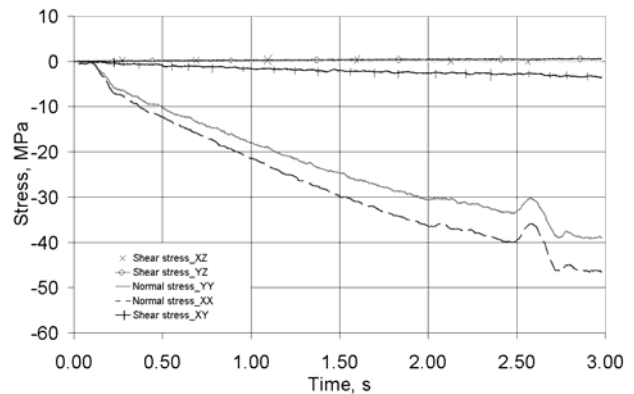
Fig. 19 Normal and shear stress in the SDD supply pipe element adjacent to the connection of SDD header
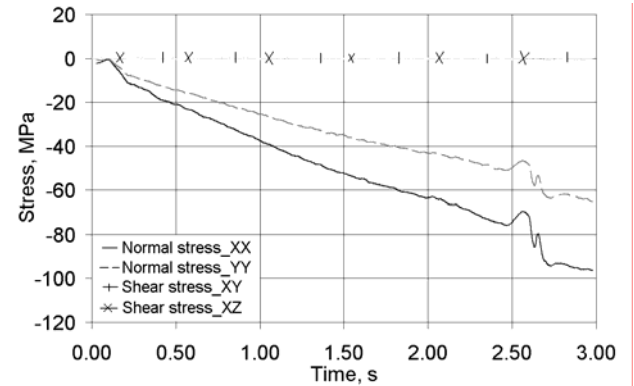
Fig. 20 Normal and shear stress in the SDD header element adjacent to the connection of SDD header and vertical vent pipes

The variation of normal stresses and shear stresses in the vertical vent pipe element adjacent to the connection of SDD header and vertical vent pipes are presented in Fig. 21. The results show that differences between the normal stress, σ_{xx}, and the normal stress, σ_{yy} are small. The maximum value of stresses is 71 MPa at 2.62 s. Other stresses are smaller.

The variation of normal stresses in the SDD header element adjacent to the connection of SDD header and the SDD pipe end are presented in Fig. 22. It is seen that normal stress, σ_{xx}, is biggest and has a maximum value of 135 MPa at 2.73 s. Normal stress, σ_{yy} is smaller.
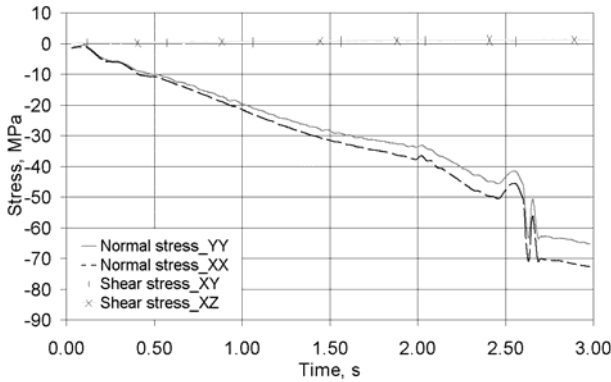
Fig. 21 Normal and shear stress in the vertical vent pipe element adjacent to the connection of SDD header and vertical vent pipes
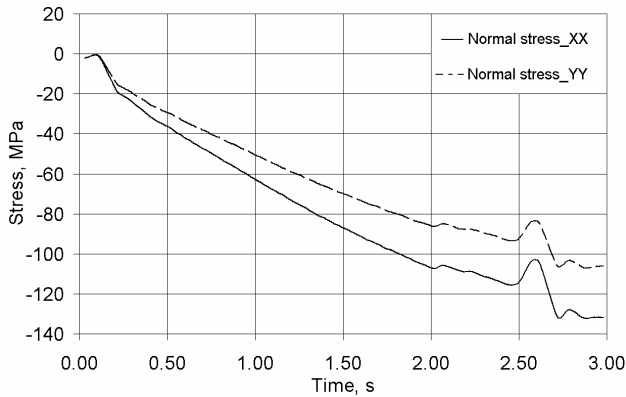

Fig. 22 Normal stress in the SDD header element adjacent to the connection of SDD pipe end

The variation of normal stresses in the SDD pipe element adjacent to the connection of SDD header and SDD pipe end are presented in Fig. 23. It is seen that normal stress, σ_{yy}, is the biggest and has a maximum value of 34 MPa. Normal stress, σ_{xx} is smaller.
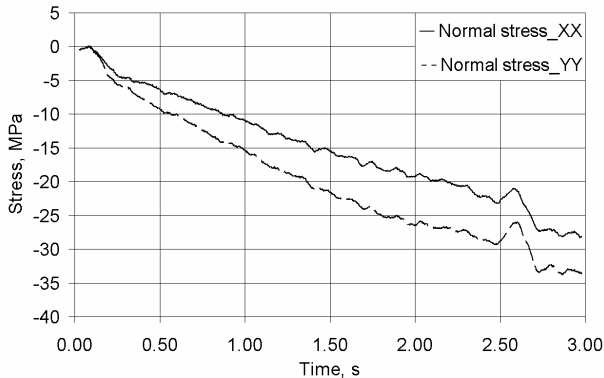

Fig. 23 Normal stress in SDD pipe end

In summary, the maximum calculated stress of 135 MPa in SDD header is below the yield stress value of 177 MPa and the material ultimate strength of 412 MPa. This means that structural integrity of SDD header, SDD vertical vent pipes and SDD supply pipe will be maintained, i.e., no failure will occur from loading during FC rupture.

4. Summary and conclusions

Fuel channel rupture was chosen in order to evaluate the loading on the SDD located in condensing pools 5 of the left ALS tower of the Ignalina NPP. Models for thermal-hydraulic analysis of the reactor cavity venting system and ALS compartments were developed. The state-of-the art computer code COCOSYS was used for such analysis.

Finite element models were prepared for structural analysis of the SDD. The structural integrity analysis was performed for the SDD 7500x2100 using the NEPTUNE code. Pressure, dynamic loading and temperature histories obtained from the thermo-hydraulic analysis were used as loadings for the structural analysis. Structural integrity analysis of the SDD, the connection between SDD header and vertical nozzles, and the SDD supply pipe subjected to FC rupture is presented in this paper.

From the completed analysis were obtained that calculated stress levels in SDD supply pipe, SDD header and SDD vertical vent pipe are below yield strength.

According these results of analysis it is possible to indicate that structural integrity of SDD located in condensing pools 5 of the left ALS tower will be maintained during FC failure.

Acknowledgments

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GARO PASKIRSTYMO ĮRENGINIO STIPRUMO ĮVERTINIMAS TRŪKUS KURO KANALUI

R e z i u m ė

Straipsnyje pateikta pereinamojo proceso, vykstančio garo paskirstymo įrenginiuose veikiant apkrovoms trūkus kuro kanalui, analizė. Termohidraulinių procesų analizė atlikta naudojant kompiuterinę programą COCOSYS. Garo paskirstymo įrenginio, garo paskirstymo įrenginio kolektoriaus sujungimo su tiekimo vamzdžiu, garo paskirstymo įrenginio kolektoriaus sujungimo su vertikaliais garo išmetimo vamzdžiais stiprumui įvertinti panaudota baigtinių elementų kompiuterinė programa NEPTUNE. Analizė parodė, kad trūkus kuro kanalui garo paskirstymo įrenginio struktūrinis vientisumas nebus pažeistas.

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STRENGTH EVALUATION OF THE STEAM DISTRIBUTION DEVICE IN CASE OF FUEL CHANNEL RUPTURE

S u m m a r y

The paper presents transient analysis of the steam distribution device (SDD) subjected to loading in case of fuel channel (FC) rupture. A thermo-hydraulic analysis of the SDD was performed using the state-of-the-art COCOSYS code in order to determine pressure and temperature histories resulting from a FC rupture. The finite element code NEPTUNE was used to evaluate structural integrity of SDD header, of the connection between SDD header and supply pipe and of the connection between SDD header and the vertical vent pipes. Results show that structural integrity of SDD will be maintained during a FC failure.

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ОЦЕНКА ПРОЧНОСТИ ПАРОРАЗДАЮЩЕГО УСТРОЙСТВА В СЛУЧАЕ РАЗРУШЕНИЯ ТЕХНОЛОГИЧЕСКОГО КАНАЛА

Р е з ю м е

В статье представлен анализ переходных процессов в коллекторах парораздающих устройств (ПРУ) при воздействии нагрузок в случае разрушения технологических каналов (ТК). Термогидравлический анализ конструкций ПРУ выполнен используя компьютерный код COCOSYS для определения зависимостей давления и температуры в случае разрыва ТК. Для оценки прочности коллекторов ПРУ, соединения между коллектором ПРУ и подводящей трубы, соединения между коллектором ПРУ и вертикальными соплами использована конечно элементная программа NEPTUNE. Полученные результаты подтверждают, что в случае разрушения ТК структурная целостность коллекторов ПРУ не будет нарушена.