Transactions of the 15th International Conference on
Structural Mechanics in Reactor Technology (SMiRT-15)
Seoul, Korea, August 15-20, 1999

Analysis of Potential Waterhammer at the Ignalina NPP Using Thermal-Hydraulic and Structural Analysis Codes

Eugenijus Uspuras, Algirdas Kalistka and Gintautas Dundulis

Lithuanian Energy Institute, Lithuania

ABSTRACT: The RBMK-1500 reactors at Ignalina nuclear power plant have a series of check valves in the Group Distribution Headers that serves the coolant distribution to the fuel channels. In the case of a hypothetical guillotine break of the Pressure Header or other pipelines upstream of Group Distribution Headers, the integrity of the check valves and adjusted pipelines is a key issue for the reactor safety during rapid closure. A demonstration is needed that the valves and associated pipelines remain intact following such accidents. This paper describes the analysis of the effect of waterhammer, i.e. the pressure pulse generated by the valves slamming closed. Results of the thermal-hydraulic and structural analysis demonstrate that the risk of failure of the check valves or associated pipelines following either the guillotine break upstream of the Group Distribution Header or guillotine rupture of the Pressure Header is very low.

1. INTRODUCTION

The Ignalina nuclear power plant (NPP) is a twin-unit of RBMK-1500, graphite moderated, boiling water, channeled reactors. The circulation circuit of the RBMK-1500 reactor has a series of check valves in the group distribution headers that serves the coolant distribution of the fuel channels. Within an RBMK-1500, protection of the reactor core following a pipeline or header rupture is provided by the emergency core cooling system (ECCS). This provides water to the core via the group distribution headers (GDH). However to prevent the emergency coolant water leaking through the break, check valves in the GDH have to be closed. In the case of the hypothetical guillotine break of pipelines upstream of GDH, the check valves and adjusted pipelines integrity is a key issue for the reactor safety during rapid closure. A demonstration is needed that the valves and associated pipelines remain intact following such accidents. This include a structural integrity analysis of the effect of waterhammer, i.e. the pressure pulse generated by the valves slamming closed. The thermal-hydraulic analysis was conducted using the RELAP5 code with inertial valve model, and the structural analysis was conducted using the PipePlus code in the present study.

2. THERMAL-HYDRAULIC ANALYSIS

2.1 Thermal-hydraulic Model

The RELAP5/MOD3.2 model of the Ignalina NPP was used for analyses of thermal-hydraulic response of plant to various transients. The RELAP5 computer code has been developed by Idaho National Engineering Laboratory [1]. This is one-dimensional non-equilibrium two-phase thermal-hydraulic system code. The RELAP5 code has been successfully applied to PWR and BWR reactors. Because of the unique RBMK the thermal-hydraulic system design, the assessment study is required to adapt the RELAP5 code to RBMK reactors. A brief description of the main circulation circuit and plant safety systems, as well as general description of the RELAP5 model of Ignalina NPP, are given in [2]. Key features of the RELAP5/MOD3.2 model of the Ignalina plant are as follows:

- Both loops of the main circulation circuit are represented. Flow paths within a loop are modeled by one or more passes. In turn, a core pass model uses one or more equivalent fuel channels. The equivalent fuel channels model the heat generation in a group of real channels, as well as hydraulic properties of this group. The equivalent fuel channels are modeled by multiple axial and radial control volumes.
- Heat transfer among the equivalent fuel channels is approximated by means of heat exchange through the graphite moderator gaps to the reactor cavity gas circuit.
- Steam paths that remove the vapor from steam separators are represented explicitly, including steam lines, steam relief valves, etc.
- Feed water system and ECCS are represented explicitly.

In order to provide confidence in the ability of the models to correctly represent the plant response to upset conditions, the models have been benchmarked for several operational events, such as trip of all the main circulation pumps and spurious opening of three main safety valves, inadvertent actuation of ECCS, etc. The calculation results obtained using the RELAP5 model agree well with the plant data when similar boundary conditions are imposed [2-5].

Two different scenarios were employed for the analysis of the pressure pulses generated by the check valve closure:

- Either the guillotine break upstream of the GDH, or
- The guillotine rupture of the pressure header.

The basic Ignalina NPP RELAP5 model was modified. A GDH check valve instead of standard RELAP5 "check valve" model has been represented by "inertial valve" model. This valve models the motion of the valve flapper assembly in an inertial-type check valve. The abrupt area change model is used to calculate kinetic form losses, assuming that the area between the flapper and the valve seat behaves as an orifice whose area changes in time as a function of the inertial valve geometry.

2.2 Results Of The Thermal-hydraulic Calculations

The following two specific accidents, which lead to waterhammer effects in the RBMK-1500 circulation circuit, have been simulated using the Ignalina NPP RELAP5 model - guillotine rupture of pressure header and guillotine break upstream of the GDH. In last second the pressure pulses generated by the check valve closure following initial break appears to be higher as in the case of the guillotine rupture of pressure header. Therefore, only the investigation results of the waterhammer effects in case of guillotine break upstream of the GDH are presented in this paper. Furthermore, because the waterhammer generated pressure pulse develops rapidly, subsequent analysis was conducted only for initial period of the accident up to 100 seconds.

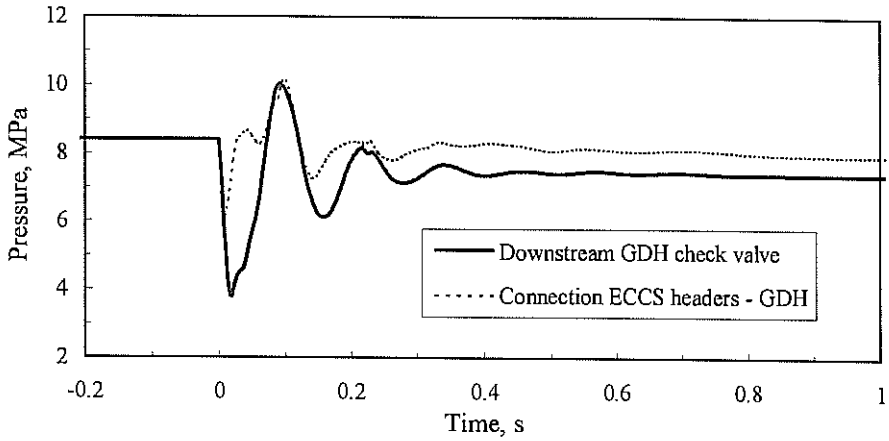

Fig. 1 Pressure pulses in the GDH and GDH-ECCS connecting pipeline

Maximum discharge flow rate through the break is observed during the initial phase of the accident and is equal to about 1400 kg/s. Later discharge flow rate slightly decrease and stabilized at the value of about 1200 kg/s for investigated period. Pressure in the ruptured GDH from the MCP pressure header side drops rapidly up to atmospheric pressure, while the pressure in the circulation circuit decreases slowly following reactor power decrease. It is necessary to note, that in case of guillotine rupture accident reactor will be automatically shutdown by signal of pressure rise in the leaktigth compartments which appears in about 1.0 s after initial rupture of GDH. A GDH check valve closes practically instantaneously after initial rupture because of backflow. Coolant flow through the this check valve stops in about 0.04 s after initial rupture. Closure of GDH check valves prevents a loss of flow from the MCC. Rapid closure of these valves leads to coolant flow and pressure pulses in the GDH and connected lower water communication pipelines (LWCP), Fig. 1 and 2. Pressure pulses in the GDH appears immediately after initial break. Pressure pulses oscillate with decreasing period and cease in about 0.5 s. Maximum pressure in the GDH is about 10.2 MPa and has been observed within about 0.1 s after initial rupture. Maximum pressure pulses reached in case of GDH break are about 15% higher as pressure pulses in case of MCP pressure header rupture accident. Pressure pulses in the adjusted GDH-ECCS pipelines (up to GDH check valves) follows pressure pulses in the GDH. Pressure pulses from the GDH are also transmitted to the LWCP. However, maximum pressure pulses generated following either the guillotine break upstream of the group distribution header, or guillotine rupture of the pressure header, remain far below the value of the hydrotest pressure which is equal 12.4 MPa. Therefore, the risk of failure of the check valves or associated pipelines is very low. Calculated dynamic forces generated by pressure pulses in case of the GDH rupture accident are presented at Fig. 3. These forces would be used in the followup structural analysis of the waterhammer effects on the GDH and adjusted pipelines. However, the maximum pressure forces reached in case of GDH break are about three times higher as dynamic forces in case of MCP pressure header rupture accident.

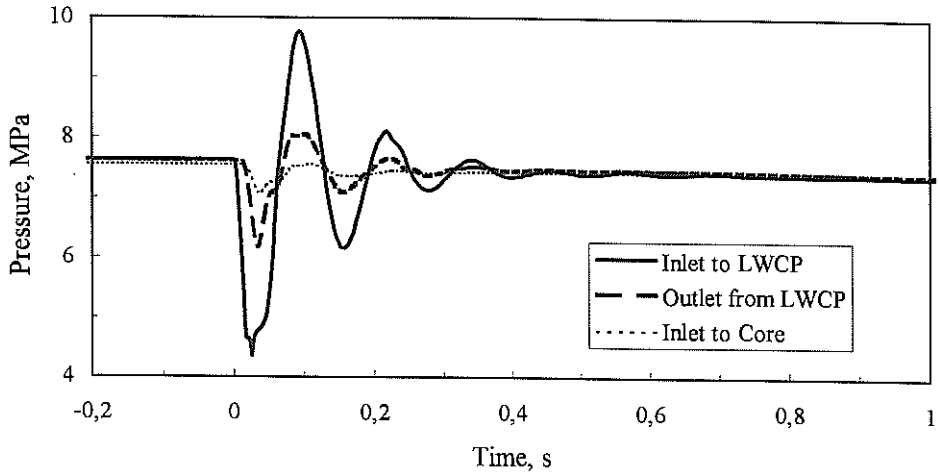

Fig. 2 Pressure pulses in the water communication pipelines and at the core inlet

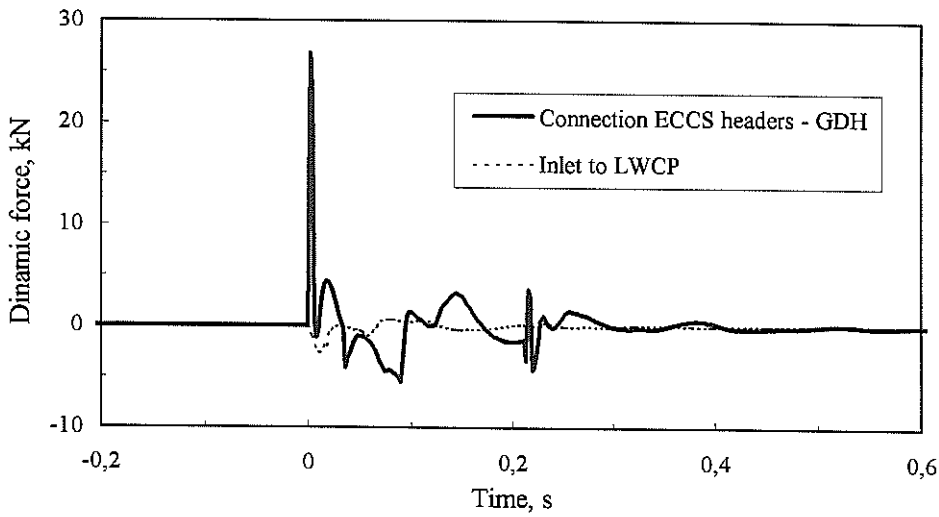

Fig. 3 Dynamic forces generated by the coolant pressure pulses

3. STRUCTURAL ANALYSIS

3.1 Structural Model

The structural behavior of the GDH check valve and associated pipelines was calculated with the PipePlus code [6], developed by ALGOR, Inc. This code is three-dimensional, finite element program for static and dynamic analysis of piping systems. The different structural

elements such as straight and curved pipe elements, anchors and supports and expansion joint elements are prepared from the code library.

For structural analysis of the GDH check valve and associated pipelines in case of the water hammer two models were used. Structural model of GDH connection with ECCS pipelines shown in Fig. 4 and structural model of GDH connection with LWCP shown in Fig. 5. Such separation to two models is possible because GDH pipeline is hardly fasten in all directions in the wall. Structural model of GDH connection with ECCS pipelines include pipelines connecting pressure header with GDH and ECCS pipelines from connection with GDH until ECCS headers. The GDH and ECCS check valves as well as mixer are also included in this model. This model contains anchors and supports of pressure header, GDH and ECCS pipelines. For constraint of boundary elements, i.e. the ends of pressure pipelines, the GDH pipeline gangway through the wall and the ends of ECCS pipelines, anchor elements were used. Structural model of GDH connection with LWCP includes four water communication lines and the GDH pipeline. For constraint of LWCP and the end of the GDH pipeline support elements, which allows pipelines movement only in axial direction, were used (guide element).

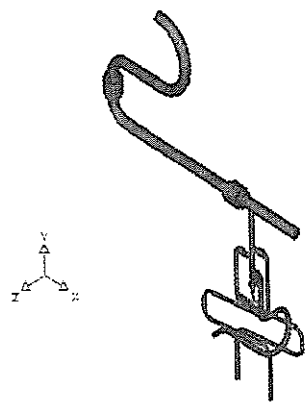

Fig. 4 Structural model of GDH connection with ECCS pipelines

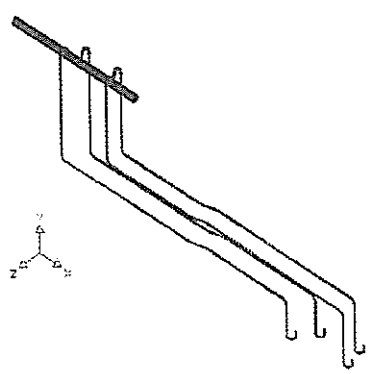

Fig. 5 Structural model of GDH connection with LWCP

3.2 Results Of The Structural Calculations

Several calculations are performed for evaluation of the structural integrity of GDH check valves and associated pipelines in case of the waterhammer event. It was assumed in calculations that the initial coolant temperature in the pipelines was equal to 285 °C, the pressure in the GDH-ECCS connecting pipelines was equal to 0.12 MPa and in the LWCP connected to GDH it was 9.7 MPa. These pressure values are maximum values obtained from the RELAP5 calculation in case of the waterhammer. In the structural analysis the following loading were taken into account: dead weigth, pressure, thermal loading and time history (load from water hammer). Dynamic forces generated by the coolant pressure pulses in case of waterhammer were obtained from the RELAP5 calculations.

PipePlus performs time history analysis using the modal superposition method. In order to investigate the correct value of the cutoff frequency, the following equation of motion was used for a single-degree-of-freedom system [7]:

$$\ddot{u} + 2\omega\zeta\dot{u} + \omega^2 = -a(t) \qquad (1)$$

The relative displacement spectrum S_D and pseudo-acceleration spectrum S_A of the dependence dynamic forces from time (Fig. 3 are shown) present in Fig. 6. The cutoff frequency of 400 Hz was used for dynamic analysis.

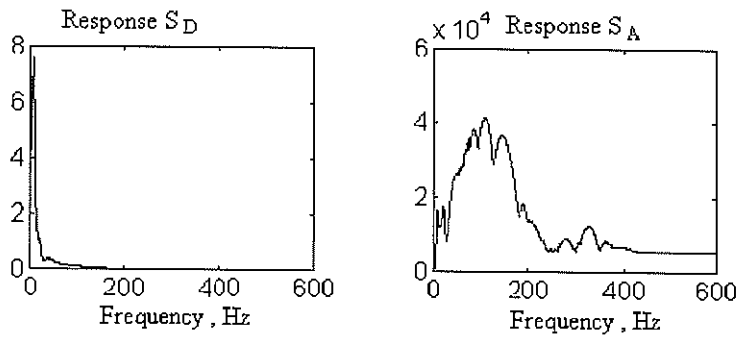

Fig. 6 The response spectra of the dependence dynamic forces from time

Results of the structural calculations shows, that in case of the waterhammer event even in case of worse loading (dead weight + inner pressure + waterhammer load) maximum ratio of load in GDH connection with ECCS pipelines is about 0.751, i.e. less than 1, (Fig. 7). Therefore, structural integrity of the pipelines, following the waterhammer, will not be violated.

Results of the structural analysis of the GDH connection with LWCP are shown in Fig. 8. Maximum calculated stresses in case of worse loading (dead weight + inner pressure + waterhammer load) is about 244 MPa. Pipelines of GDH, ECC and water communication lines are manufactured from the austenitic steel 08X18H10T. Strength limit for this steel is 412 MPa at temperature 300 °C. Thus, strength margin in this case is equal 1.68. While the structural analysis was conducted using the conservative assumption, it could be concluded that integrity of the GDH connection with LWCP in case of waterhammer event will not be violated.

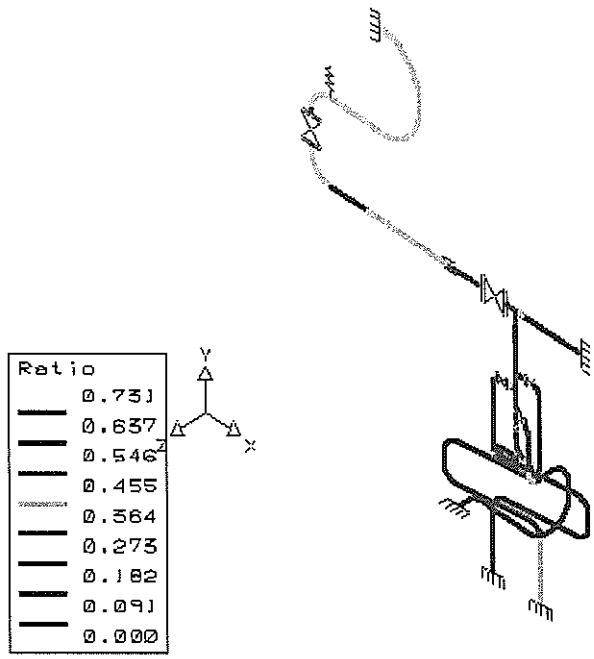

Fig. 7 Load ratio in GDH connection with ECCS pipelines

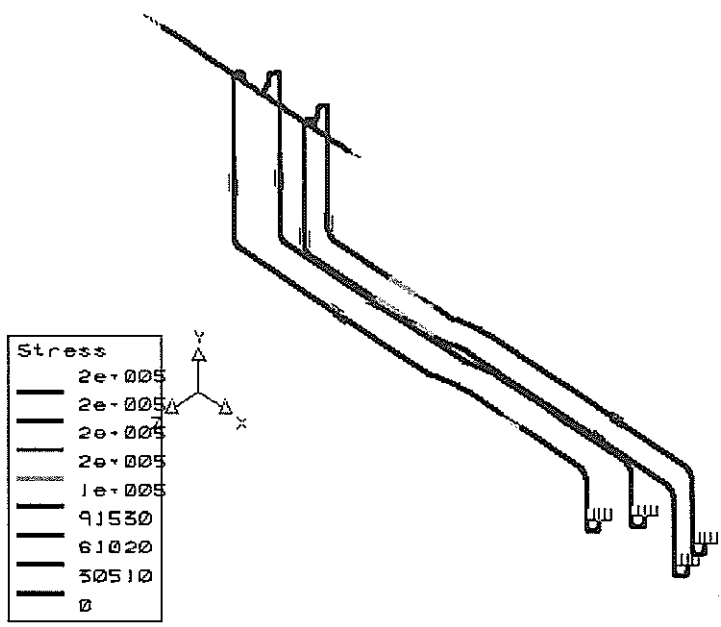

Fig. 8 Calculated stresses in the GDH connection with LWCP

4. CONCLUSIONS

The thermal-hydraulic and structural analysis of waterhammer effects following the guillotine break upstream of the group distribution header, or guillotine rupture of the pressure header at the Ignalina NPP with RBMK-1500 reactors was conducted. Results of analysis demonstrated that the risk of failure of the check valves or associated pipelines is very low.

NOMENCLATURE

BWR	Boiling Water Reactor
ECCS	Emergency Core Cooling System
GDH	Group Distribution Header
LWCP	Low Water Communication Pipelines
MCC	Main Circulation Circuit
MCP	Main Circulation Pump
NPP	Nuclear Power Plant
PWR	Pressure Water Reactor
RBMK	Russian Acronym for "Channeled Large Power Reactor"

REFERENCES

1. Fletcher, C. D., et al., *RELAP5/MOD3 code manual user's guidelines*, Idaho National Engineering Laboratory, NUREG/CR-5535, January 1992.
2. Uspuras, E., "Development of RBMK-1500 models using state-of-the-art codes," *Heat and Mass Transfer in Severe Reactor Accidents*, pp.564-576, Begell House, Inc., New York, Wallington, 1996.
3. Uspuras, E., Kaliatka, A., "RELAP based safety analysis of the Ignalina NPP," *Proc. of the Topical Meeting on Safety of Operating Reactors*, p. 307-313, Seattle USA, September 1995.
4. Uspuras, E., Kaliatka, A., Vileiniskis V., "Benchmark analysis of three main safety valves LOCA event using RELAP5 and ATHLET codes," *Trans. of the Int. Exchange Forum on Analytical Methods and Computational Tools for NPP Safety Assessment*, p. 77-92, Obninsk Russia, September 1997.
5. Vilemas, J., Uspuras, E., Kaliatka, A., "Benchmark analysis of inadvertent ECCS actuation using RELAP5 and ATHLET codes," *Proc. 6th Int. Conf. on Nuclear Engineering*, ICONE - 6355, San Diego USA, May 1998.
6. ALGOR. Pipe Plus. Release notes. Algor, Inc, USA, 1996
7. Gupta A. K. Response Spectrum in Seismic Analysis and Design of Structures, CRC Press, 1993.