THE UNIVERSITY OF TENNESSEE KNOXVILLE

International Journal of Nuclear Security

Volume 9
Number 2 *ICEP 2022 Conference Papers*

Article 3

5-2024

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Mohammed Sarim Salman Karim
Bangladesh Atomic Energy Regulatory Authority

Dr. Debashis Datta
Military Institute of Science and Technology, Bangladesh

Altab Hossain
Bangladesh Military Academy

Recommended Citation

Karim, Mohammed Sarim Salman; Datta, Dr. Debashis; and Hossain, Altab (2024) "Safety and Security Analysis of VVER-1200 Reactor Pressure Vessel Under Pressurized Thermal Shock," *International Journal of Nuclear Security*: Vol. 9: No. 2, Article 3.
http://doi.10.7290/ijns09445599
Available at: https://trace.tennessee.edu/ijns/vol9/iss2/3

International Journal of Nuclear Security, Vol. 9, No. 2, 2024—ICEP 2022 Conference Papers

Safety and Security Analysis of VVER-1200 Reactor Pressure Vessel Under Pressurized Thermal Shock

Mohammed Sarim Salman Karim,[1, 2] Debashis Datta,[1] and Altab Hossain[3]
[1]Nuclear Safety, Security and Safeguard Division, Bangladesh Atomic Energy Regulatory Authority, Dhaka-1207, Bangladesh
[2]Department of Nuclear Science and Engineering, Military Institute of Science and Technology, Dhaka-1216, Bangladesh
[3]Department of Mechanical Engineering, Engineering Faculty, Bangladesh Military Academy, Chattogram-4315, Bangladesh

Abstract
The reactor pressure vessel (RPV) is an important component of a nuclear power plant and of great concern to safety and security globally. Thus, the thermal system of an RPV should be ensured properly through an evaluation system that closely monitors and considers its integrity. This article describes the thermomechanical analyses for a pressurized thermal shock (PTS) scenario of a VVER-1200 RPV owing to a loss of coolant accident (LOCA) and activation of the emergency core cooling system (ECCS). The LOCA transient and activation of ECCS are modeled using ANSYS simulation software. From the analyses of the emergency core cooling injection owing to a LOCA in a PTS scenario, the transient flow distribution and the temperature profile evolution in the RPV wall are evaluated. Subsequently, the stress history in different situations for this transient was computed using thermal loads to show the safety of the VVER-1200.

Keywords: pressurized thermal shock, VVER-1200, reactor pressure vessel

1. Introduction
The reactor pressure vessel (RPV) is the most important component of a nuclear power plant, playing a crucial role in ensuring the safety and security of the entire facility throughout its operational lifespan. As such, the vessel's structural integrity must be

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maintained at the highest level of quality to prevent any accidents or incidents [1,2]. The VVER-1200 reactor is Russian in origin and employs a symmetrical, closed, four-loop configuration, relying on water for both moderation and cooling. To ensure the integrity of the VVER-1200 reactor, the reactor must be capable of withstanding abnormal operational conditions or nuclear transients, creating sharp defects in the RPV's internal surface as well as a high fast neutron fluence, all of which can work together to create a significant thermal shock, lowering the RPV's fracture toughness (K_{IC}). Under transient conditions, the RPV may experience severe thermal stress resulting from extreme temperature gradients caused by rapid cooling owing to emergency core cooling injection to the inner vessel [3,4]. One potential cause of a major thermal shock is known as pressurized thermal shock (PTS), which occurs when the RPV experiences instant cooling from the sudden influx of cold water. PTS can occur during a loss of coolant accident (LOCA), where cold water triggered from the emergency core cooling system (ECCS) is injected via the cold leg into the downcomer while the reactor remains pressurized [5]. This cold water exacerbates the severe thermal shock and increases the risk of integrity loss in the RPV [6].

A study done for the WWER-1000 on its RPV PTS analysis examines the possible defects during anticipated transient events that could occur during PTS events to determine the brittle fracture initiation in plant design life [7]. The structural integrity of the RPV throughout the long-term operation of the nuclear power plants may be significantly threatened by PTS occurrences [8]. The International Atomic Energy Agency published a different technical series to assess the integrity of the RPV of a nuclear power plant called the *Master Curve Approach Demonstration* [9,10]. A deterministic and probabilistic analysis has been done and found that the Master Curve is more realistic than the Favor model [11,12].

Importantly, the risks associated with PTS must be addressed and mitigated to ensure the safety and reliability of the reactor. The ECCS injection during a LOCA involves a complex, 3D mixing phenomenon in the downcomer, which results in highly anisotropic flow patterns. However, traditional safety analysis methods that rely on 1D-system thermal-hydraulic codes such as TRACE, CATHARE, and COBRA are insufficient for predicting the intricate details of these flow features and subsequent thermal shock effects on the RPV [13]. Computational fluid dynamics (CFD) has demonstrated its capability to accurately capture and model the temperature evolution and low pattern for predicting complex, 3D phenomena of PTS events in the coolant during transients with high fidelity [14], providing valuable insights for safety analyses and design optimization.

Notably, CFD modeling requires significant computational resources and expertise, and its accuracy is dependent on the quality of the input data and assumptions used in simulations. Previous researchers modeled a PTS scenario involving the VVER-440 and the VVER-1000 using unsteady Reynolds-averaged Navier–Stokes (URANS) in FLUENT and compared the results with those obtained from TRACE Thermal Hydraulic (TH) calculations by RELAP5. In general, the difference in results was found to be comparatively very low [15]. Another group of researchers carried out URANS CFD simulations to find the numerical prediction analyses of a single-phase PTS situation for

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crack analysis in an RPV wall. The fracture mechanics analysis utilized the extended finite element method and TH code to assess PTS in a pressurized water reactor (PWR) subjected to a large break loss of coolant accident (LBLOCA). [16]. This study provides the calculation of the stress intensity factor along several hypothesized flaws to evaluate the potential crack propagation initiation of the defects [17]. Another study showed nonuniform temperature distributions resulting from separate cold-water injection into the RPV during PTS events when performing a probability analysis for the fracture of a three-loop PWR RPV. The study provides a comprehensive approach to evaluate the structural integrity, uniting 3D CFD simulations with probabilistic fracture mechanics analyses of the vessel for imaginary PTS scenarios [18]. The effect of an asymmetric reactor cooling event for PTS analysis of an RPV was assessed for optimizing the maintenance strategy. According to the findings of this study, unbalanced coolant injections result in around 30% more major states than balanced injections. A risk-based approach was also predicted, with the indications being the probabilities of the occurrence rate for the RPV to represent the risk. [19]. An ECCS nozzle was analyzed for LBLOCA and medium break LOCA with a PTS event using SYSTUS code considering postulated defects within the RPV model [20]. The scenarios that are most important to the overall PTS risk can be determined with the aid of probabilistic risk analysis [21]. A numerical fracture analysis was conducted on an RPV constructed using the Abaqus-FRANC3D cosimulation method, in which the direct thermomechanical finite element method assessed the PTS temperature and internal pressure loads simultaneously for the PTS scenario, confirming the exactness of the projected cosimulation method [22].

The present study combines CFD and thermomechanical analysis of a VVER-1200 reactor during a LOCA-based PTS scenario to evaluate the complex mixing phenomena of ECCS water into the primary coolant in the downcomer through a coupled analysis of ANSYS FLUENT and ANSYS Mechanical. This transient scenario for a LOCA will initiate the ECCS injection of cold water into the inner vessel, mixing with the hot primary coolant at high operating pressure to create a thermal shock. In the worst case, the increase of vessel pressure in this situation can create a massive PTS, which leads to vessel flaws or cracks, increasing the probability of a fracture in the vessel. This paper follows a solid–fluid interaction analysis during the event to provide the temperature profile and stress development of an RPV structure during multiple situations. The goal of this study is to help provide assurance of vessel safety for the PTS possibility. Outcomes from this study can also be used to indicate the strength of the RPV material required to withstand abnormal conditions during the transient event.

2. Materials and Methods

a. RPV Model and Thermomechanical Properties

The simplified geometrical vessel model was developed in ANSYS FLUENT [23] using a four-loop VVER-1200 with ECCS piping for the computational domain. A quarter of the full domain was taken for the computational analysis, making use of symmetrical boundary conditions. As ECCS water injected in the cold leg and primary coolant in the loop was prevented from mixing with hot-leg coolant in the downcomer, the domain

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could be simplified by considering the ECCS part, cold-leg section, and downcomer out of the model. The downcomer was considered to be the outlet of the domain. Without the cold-leg section and downcomer, the model was incomplete, so the boundary condition was applied to the outlet part.

Table 1 lists the main parameters of the VVER-1200 considered for computation. The diameter of the RPV, wall thickness, and cold-leg diameter are 4.5 m, 198 mm, and 950 mm, respectively, for the computational domain. The RPV material and its properties were considered to be steel 15H2NMFA for the VVER-1200 in this study. Table 2 lists the main thermomechanical parameters.

Table 1. Main parameters of VVER-1200 [24].

Parameters (unit)	Value
Reactor type	VVER-1200
Normal operating pressure (MPa)	16.2
Normal operational inlet temperature (°C)	298.2
Normal operational outlet temperature (°C)	328.9
Coolant	Light water

Table 2. Thermomechanical properties considered in the computational domain for VVER-1200 vessel base material [25].

Property (unit)	Value
Density (kg/m^3)	7750
Heat capacity (J/[kg·K])	562
Thermal conductivity (W/[K·m])	36.2
Young's modulus (10^3 MPa)	183
Coefficient of linear thermal expansion (10^{-6} K^{-1})	12.6
Poisson's ratio	0.3
Yield strength (MPa)	490

b. Computational Setup

The computational model and simulation were developed and performed in ANSYS software. FLUENT was used for CFD assessment and solid–liquid heat transfer analysis to demonstrate the vessel wall temperature and stress development. Using URANS CFD simulation with a time step of 0.05 s resulted in an average Courant–Friedrichs–Lewy, CFL number of <0.5 in the base mesh. The relevant initial and boundary conditions were applied in the model for realistic results. Dimensions of the computational domain are listed in Table 3.

Table 3. Boundary conditions and dimensions of computational domain.

Parameter	Value (unit)
Transient pressure	6 MPa
Viscosity	0.2 Pa·s
Coolant density	1000 kg/m^3
Inlet velocity of ECCS	0.102 m/s
Inlet temperature of ECCS	10 °C
Inlet mass flow rate of ECCS	80 kg/s
Transient primary coolant temperature	280 °C

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A complete domain was considered when the RPV was filled with stationary water at the operating temperature and pressure during a LOCA scenario. For the purpose of our calculations, the ECCS injection water flow and temperature were assumed to be constant. The flow was assumed to be turbulent and chaotic. The inlet terminal was the cold-leg flow, and the ECCS injection path and the outlet terminal were considered to be the downcomer of the RPV. The inlet terminal was considered to be the Dirichlet boundary condition with constant velocity. The outlet terminal was assumed to be the pressure outlet boundary. The solid–fluid interface was considered to be the wall boundary condition.

After starting the simulation, the whole hot fluid domain started to decrease in temperature because of the insertion of cold fluid by ECCS. After a long period, the total domain reached the equivalent temperature for the transient event. Figure 1 shows the 3D model developed in ANSYS Workbench for computation. The geometrical specification of the vessel is listed in Table 4.

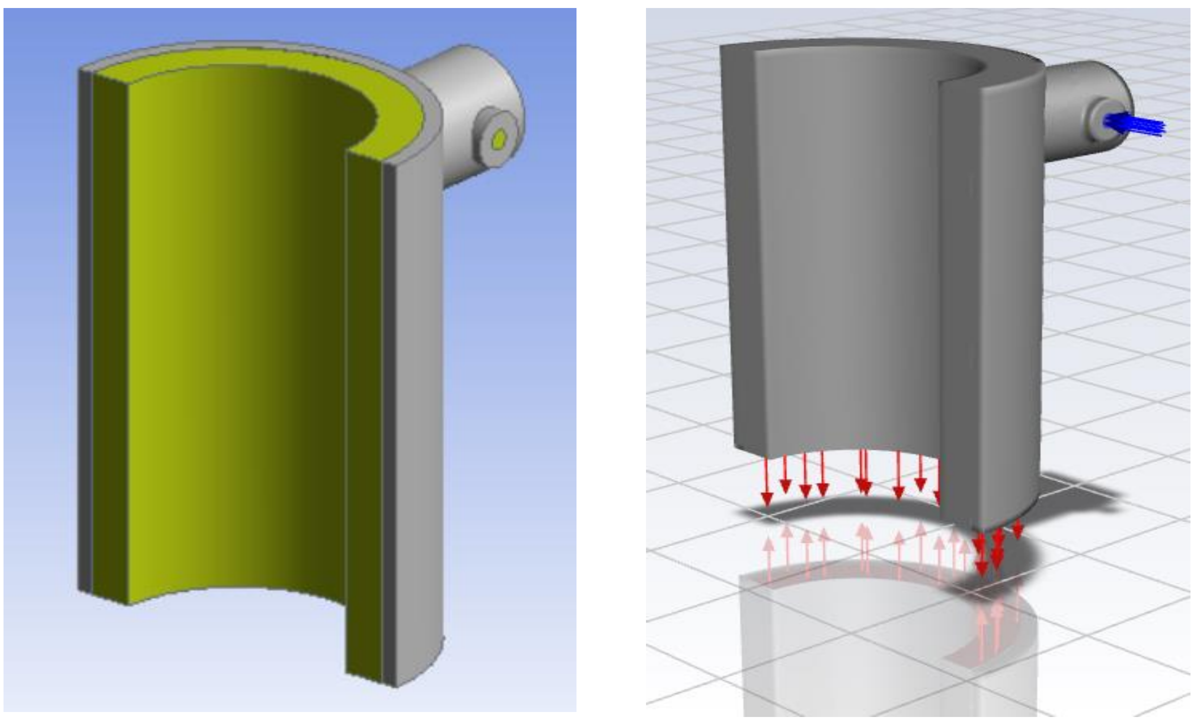

Figure 1. 3D model of simplified VVER-1200 RPV.

Table 4. Geometrical specification of VVER-1200 for computational use.

Parameter	Value (unit)
Vessel diameter	4.5 m
Vessel height (belt line region)	6000 mm
Thickness	198 mm
Cold-leg diameter	950 mm
ECCS inlet diameter	225 mm

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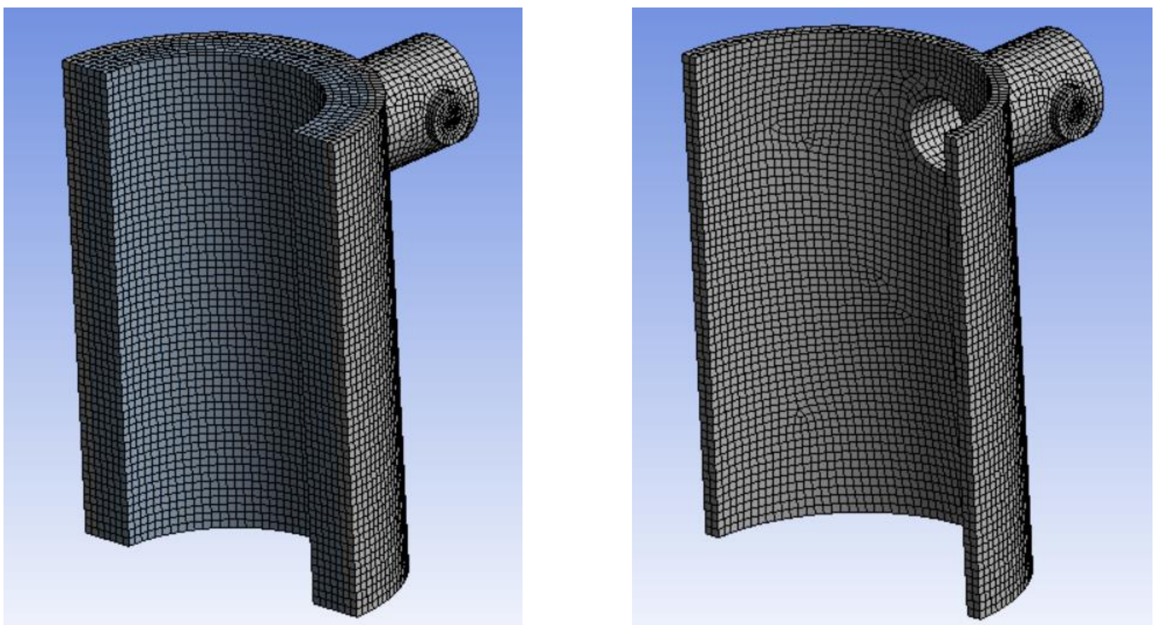
For stress analysis of the RPV structure, a couple analyses were applied to the tetrahedron meshed 3D model and symmetric part. The simulation result from ANSYS FLUENT was coupled with ANSYS Mechanical for static structure analysis. Different initial and boundary conditions were applied for analysis. The mesh configuration of the CFD computational model used for VVER-1200 is shown in Table 5.

Table 5. Mesh configuration for computational setup.

Parameters	Value
Number of nodes	96,623
Number of elements	96,689
Growth rate	1.2
Average skewness	0.5

The meshed domain of the solid structure (RPV) and solid–fluid structure for the FLUENT simulation is shown in Figure 2.



(a) (b)

Figure 2. Meshed structure of RPV (a) with fluid and (b) without fluid.

3. Results and Discussion

The complex anisotropic 3D CFD modeling by ANSYS FLUENT showed the resulting temperature profile for a LOCA in which the ECCS injected comparatively cold water into the hot coolant in high-pressure conditions. As documented in Figure 3, the fluid-to-solid interaction results show the contour profiles at different time periods. The temperature near the wall where coolant from the ECCS was impinged quickly decreased in temperature and gradually deceased the near-surface temperature of the nozzle, developing two plumes that expanded with time. Temperature distribution is a very important parameter to assess in the stress analysis because sudden injection of cold water from the ECCS can create a temperature gradient in the wall surface, which

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may generate and accumulate stress. The flow was turbulent in the CFD domain, as shown by the variation of temperature in Figure 3.

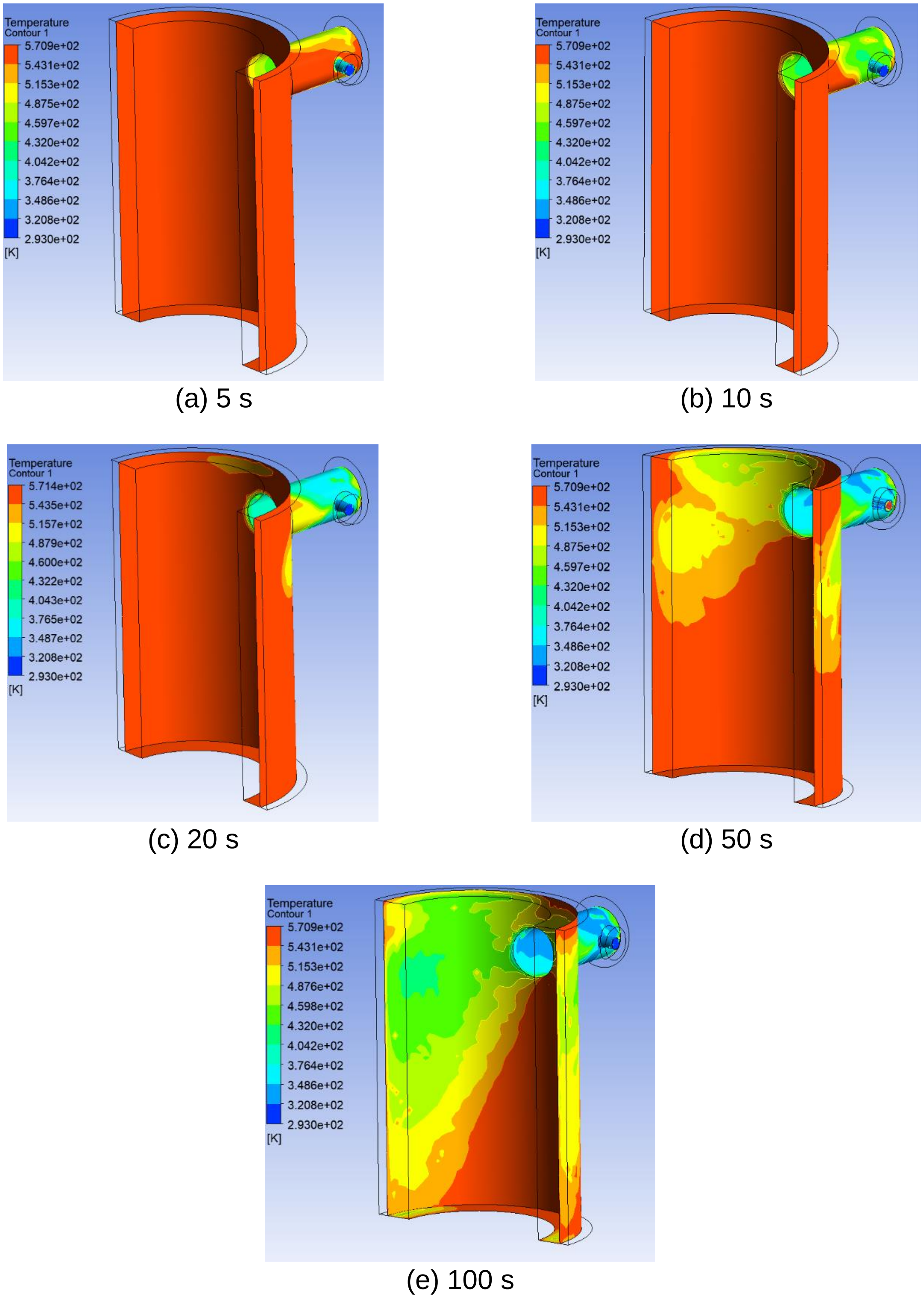

Figure 3. Temperature contour at different transient times, showing the surface temperature profile of the RPV wall.

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Figure 4 depicts the stress contour of the VVER-1200 RPV inlet nozzle and inner wall, demonstrating the maximum intensity of stress that the RPV experiences during the transient at 100 s in a high magnitude of pressure of 7 MPa. The nozzle's corner experienced the highest stress of around 243 MPa, which is below the yield strength (490 MPa), owing to the temperature gradient. Because of this stress, during a PTS, this corner section of the nozzle should be observed closely for defect or complications.

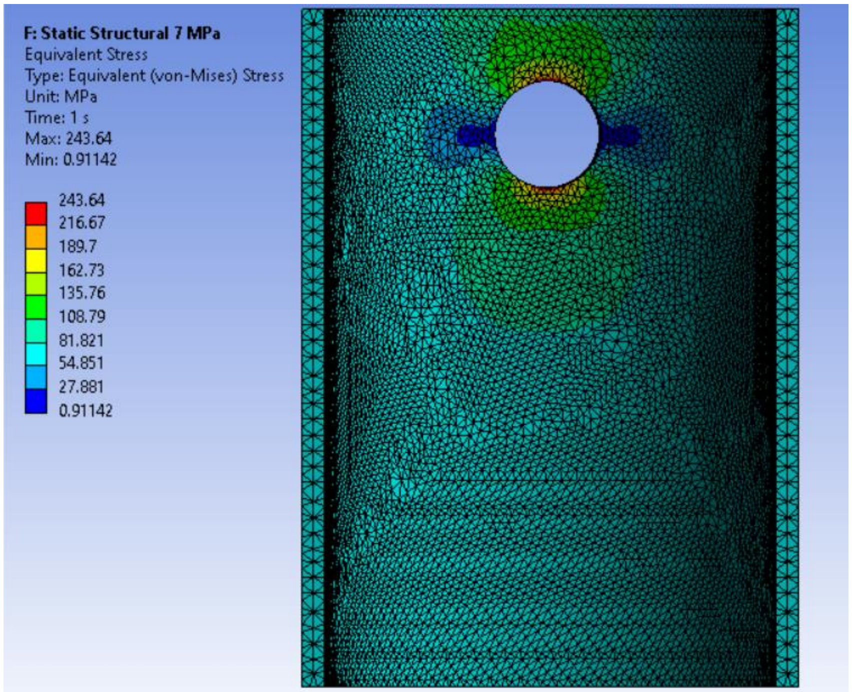

Figure 4. Stress contour (MPa) during the transient at 100 s.

After this simulation, a further study was done by increasing the pressure from 7 MPa to 16 MPa sharply which represents a worst-case PTS during a transient event. The stress was evaluated along the path line of the thickness of the RPV at 100 s transient time under the nozzle area, which is shown in Figure 5. The stress decreased along the path line from the inner part to the outer part as the temperature gradient decreased steadily.

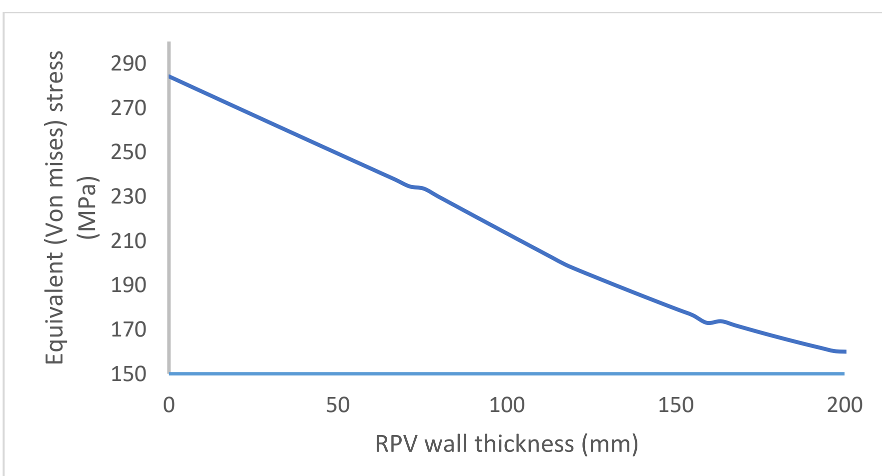

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Figure 5. Stress distribution along the path line of vessel thickness owing to increased pressure (16 MPa) at 100 s transient.

Figure 6 compares simulated axial stress (megapascals) along the RPV wall thickness (millimeters) to another study [26], where the close match was justified. The deviation of the stress value was a result of the transient time difference between these two different LOCA studies. From Figure 6, we can conclude that both curves follow the same trend for the resultant axial stress along the wall at the maximum stress concentration region where the ECCS impinges the coolant.

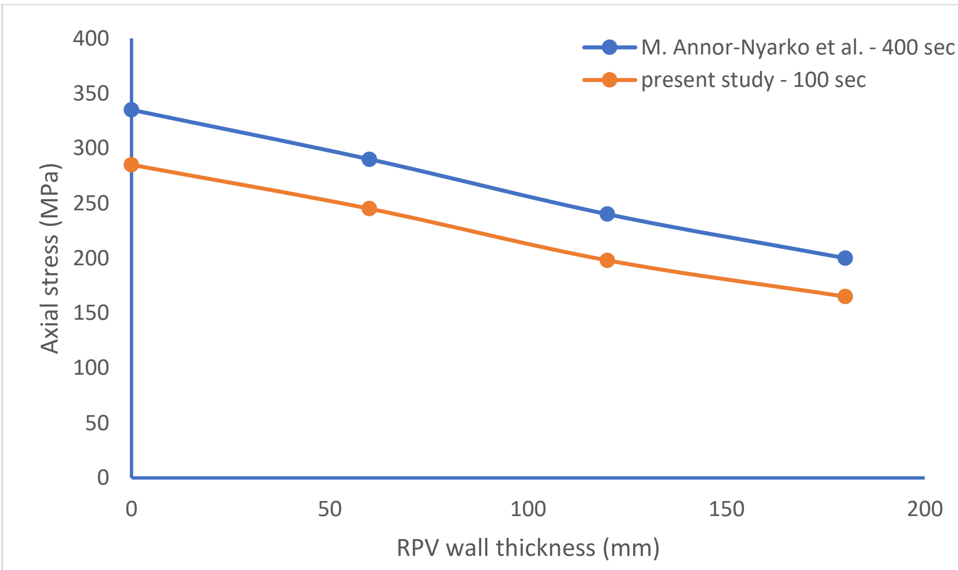

Figure 6. Comparison of simulated axial stress (MPa) in two studies along the RPV wall thickness (mm).

4. Conclusion

A coupled analysis of VVER-1200 during a LOCA event followed by a PTS initiation is one of the critical anticipated operational occurrence (AOO), which can be a significant and impactful scenario influencing the targeted lifetime operation. In this study, the fluid–solid interaction of an RPV was simulated through ECCS injection in the inner vessel, and simulation results were shown for 100 s. Furthermore, the stress profile was assessed in an increased pressure environment. The main conclusions from the analysis can be summarized as follows:

- The fluid–solid interaction of the inner vessel because of the injection of ECCS in a LOCA condition in a stratified primary coolant under high pressure started the cooling of the vessel surface by two cooling plumes. The developed model was a simplified symmetric VVER-1200 considering the material properties.
- The corner region of the inlet nozzle was found to be the most crucial for this transient event and assessed stress found below the yield strength, indicating the strength of the vessel material.
- The sudden increase of operating pressure for this transient at 100 s may initiate PTS. Stress evaluated along a path line of vessel thickness found that around

243 MPa, stress at the inner surface decreased gradually, which is below the yield strength (490 MPa). This result shows a good agreement for the safety of the reactor vessel.

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6. Author Contact Information

Mohammed Sarim Salman Karim: sarim@baera.gov.bd
Debashis Datta: datta@baera.gov.bd
Altab Hossain: altab@nse.mist.ac.bd

DOI: