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THERMAL HYDRAULIC AND MECHANICAL PERFORMANCE OF VVER1200 FUEL DURING LOSS OF COOLANT ACCIDENT

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ABSTRACT
The fuel cladding is an important safety barrier against fission gas release for safe operation of nuclear power plant during normal and transient conditions. Thermal stresses generated in fuel pellet and clad may enable crack propagation in clad. New Zr-based alloys are continuously developed.E110 alloy has been designed successfully in Russiafor VVER and RBMK reactors successively. In this work mechanical behavior of VVER1200 clad made of E110 alloy in transient condition (Loss of Coolant Accident) is analyzed. Thermal structural analysis of a VVER1200 central fuel pellet (10 mm long at the center of the fuel rod) after 500 cm^2 break accidentin one circulation loop in cold leg has been studied. A central hot fuel pellet has been simulated using finite element package ANSYS. The thermal stresses, equivalent elastic strain, and deformation have been calculated. The results indicate that no clad failure occur over the analyzed timeperiod(1800 second).

Keywords:
Structural Analysis, Finite Element, ANSYS, Cladding

INTRODUCTION

VVER 'Water Water Energy Reactor' is a pressurized type thermal nuclear reactor with water used both as moderator and coolant. The gap between fuel and clad is filled with helium to an initial pressure of 1 to 3 MPa for common pressurized water reactor (PWR) fuel[1].
Pellet-to-cladding mechanical interaction (PCMI) refers to the stress on the cladding from an expanding pellet, especially during a transient[2]. Pellet expansion results mainly from thermal expansion, and if the stress is large enough it can lead to cladding failure. Evaluating the stresses in the clad is very important during both steady state and transient conditions such as Loss of Coolant Accident (LOCA). In LOCA thermal and pressure shocks may lead to cracking in clad structuredue to difference in thermal expansion coefficient[3].
FRAPCON codehas been used by David Carpenter to predict the behavior of a UO_2 fuel rod with either Zircaloy or silicon carbide cladding[1]. FRAPCON tracks the thermo-mechanical behavior of a single fuel rod up to high burnup. It models the fuel using a series of axisymmetric radial rings at specified axial nodes, and uses a single-ring model for the cladding. It has also detailed correlations for calculating fission gas accumulation and release, fuel and cladding properties as a function of time, temperature, fluence, and corrosion due to hydration and oxidation.
Coupled analysis is carried out by K.M.Pandey and A. Sarkar [4] to find thermal stress, strain and thermal expansion of a nuclear fuel element due to thermal differentiation and pressure difference between gap and coolant.A BWR fuel element is considered, which is made of uranium oxide (UO_2) and surrounded by a zircaloy cladding. They found out that the pellet and cladding expansion due to thermal effect are within safe limit. The stresses developed are permissible.
Failure of nuclear rod cladding material under accident conditions is studied by R.Ruban, et al[5]. They carried out simulations at various heat transfer coefficients to analyze the effect of heat transfer coefficient reduction onthe temperature distribution and the developed thermal strains.

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Loss of coolant accident analysis without emergency core cooling system on in-vessel core melt progression under a severe accident scenario in Bushehr VVER-1000 reactoris evaluated by M. Salehi and G. JahanFarnia[6]. They conducted simulation event of a 25 mm Small Break Loss of Coolant Accident (SBLOCA)using the RELAP5/SCDAP mod3.4 computer code.

NashiyatFyza et al [7]studied LOCA with 500 cm^2 ~~of~~ break in one circulation loop in hot leg and cold leg of the VVER1200 reactor coolant circuit separately. The simulation was performed using PCTRAN VVER1200, Nuclear Transient Accident Simulator developed by Micro Simulation Technology for VVER-1200 reactors. They analyzed thermal hydraulic parameters. The data found from the simulation was in good agreement with IAEA Safety Report Series.

New Zr-based alloys are continuously developed and then are recommended to be candidates for the advanced nuclear power plant, some of Zr-based alloys composition are shown in table 1 [8].

E110 alloy has been designed successfully in Russia [9]for VVER and RBMK (ReaktoryBolshoyMoshchnostiKanalniy)reactors successively. It was observed that E110 has high strength, creep resistance, and resistance to radiation growth.E110 opt. and E110M are modified alloys created for VVER-1200.

Table 1: Zr-based alloys composition [9]

Alloys	Sn	Fe	Cr	Nb	Others	Remarks
Zry-2	1.5	0.12	0.1	-	0.12 O,0.05 Ni	BWR
Zry-4	1.5	0.2	0.1	-	0.09–0.13 O	PWR
E110	-	-	-	0.95-1.05	≤ 0.10 O	PWR/RBMK/VVER
E110M	-	0.07–0.15	-	0.95-1.05	0.10–0.15 O	PWR/RBMK/VVER
E110opt.		0.025–0.07	-	-	0.06-0.099 O	

In this work, thermal structural analysis of a VVER1200 central fuel pellet (10 mm long at the center of the fuel rod) after 500 cm^2 break in one circulation loop in cold leg has been studied. Three dimension Finite Element (FE) model of nuclear fuel pellethas been analyzed using a structural analysis module.Stresses, strain and deformation have been obtained to simulate the mechanical performance of fuel pellet in case of loss of coolant accident in VVER-1200 reactor. E110M alloy has been used.

VVER1200 Description

The VVER-1200 is a pressurized water reactor that produces 3200 MW thermal power. The major characteristics of VVER1200 are presented in table 2.The fuel rod consists of the following parts: upper plug, cladding, lower plug, UO_2fuel pellets and a lock. The material of the cladding and plugs is Zr E110 alloy[10]. Fig.1 represents fuel rod design [11].

For VVER reactors, the safety criteria are defined in a similar way as follows:

cladding stress always needs to be less than the standard yield strength (for anticipated transient events);no strain limit is defined, however, the failure level for fast transients experimentally verified forWWER reactors is 0.5% plastic deformation[10].

Table 2: Some characteristics of VVER- 1200 reactor [10].

Nominal heat power of the reactor (MW)	3200
Inlet coolant flow rate (m^3/h)	86,000
Coolant temperature at the reactor inlet (^oC)	298.6
Fuel assembly form	Hexagonal
Arrangement of fuel rod	Triangle
Fuel pellet diameter (mm)	7.8
Cladding outside diameter (mm)	9.1
Cladding inner diameter (mm)	7.93
Cladding material	E110M Zr Alloy
Fuel pellet material	UO_2

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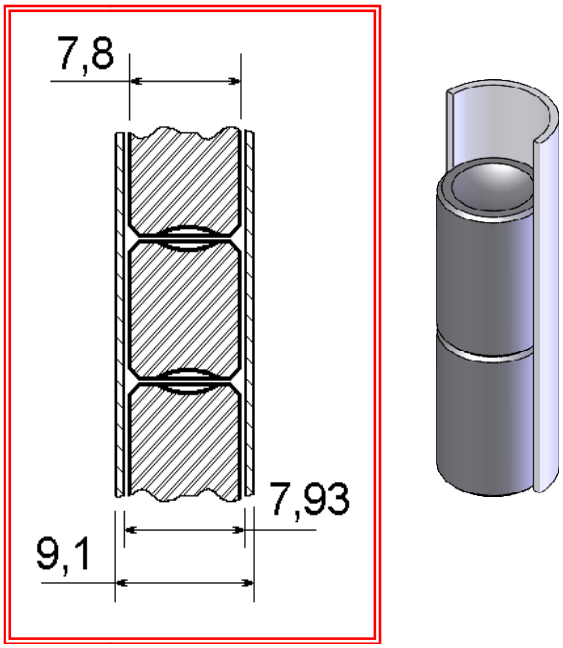

Fig. 1: VVER1200 Fuel Design (Dimensions in mm)[11].

Finite Element Method

The VVER-1200 has been taken as a model for Finite Element analysis. The study deal with the clad mechanical behavior after 500 cm^2 break in one circulation loop in cold leg (LOCA) of the reactor coolant circuit.

Properties for clad [9];[11](with 600 ^oK average temperature) are given in Tables 3.

Table 3: Clad properties used in FE model

Thermal conductivity (W/m.K)	14.4
Specific heat (J/Kg.K)	380
Density (kg/m^3)	5500
Coefficient of thermal expansion (K^{-1})	1.08e-5
Modulus of elasticity (GPa)	90.5
Poisson ratio	0.37

The equation recommended for the thermal conductivity of Zircaloy is [12]:

$$\lambda = 12.767 - 5.4348 * 10^{-4}\, T + 8.9818 * 10^{-6} T^2 \qquad (1)$$

; where$\lambda$is the thermal conductivity in W/ m. Kand T is the temperature in degree Kelvin (^oK). This equation is valid for the temperature range 300 to 1800 K.

Model Description

In the present work, the centerline 10 mm long hot pelletin the center of the fuel rod is simulated. Three dimension structural modelusing ANSYS Finite Element (FE) package is used. The stress distribution, thermal strain, and deformationthrough the clad are simulated under LOCA conditions of500 cm^2 break in one circulation loop in cold leg of the VVER1200 reactor coolant circuit".

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Referring tosimulation of LOCA with 500 cm^2Breakperformed by NashiyatFyza et al [6] using PCTRAN VVER1200, The initial steady state conditions of the plant are as follows:
Reactor Power: 100%
RC Pressure: 155 bar
Coolant Temperature: 306.9 ºC (core average)
Time in Life: BOC (Beginning of Cycle)
In this analysis no intervention of operator during the accident scenario is considered.
In our present work the output results obtained by NashiyatFyza et al for temperature and pressure are utilized as input to the ANSYS structural module.Mesh sensitivity test is conducted to define the optimum number of finite elements in the simulated model. The model has 41575 elements. The mesh element is shown in Fig. (2). Coolant hydrostatic pressure and gap pressure are introduced as structural loads. Gap pressure of 1 MPa is used.

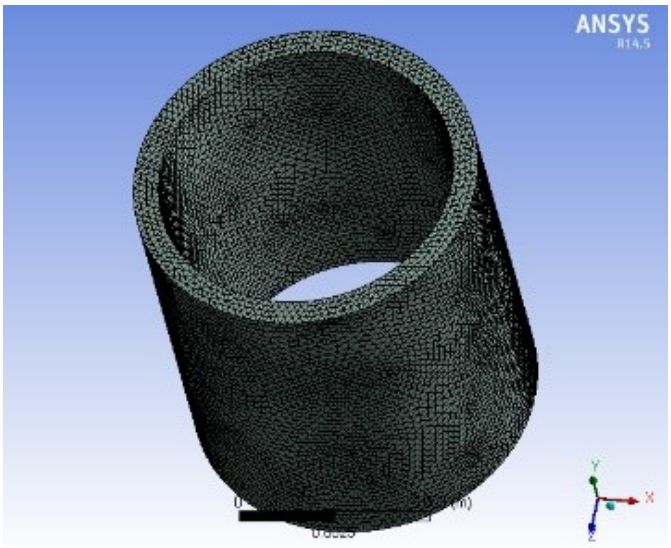

Fig. 2: Mesh element of the structural module

According to elasticity theory [12], an infinitesimal volume of material at an arbitrary point on or inside the solid body can be rotated such that only normal stresses remain and all shear stresses are zero. The three normal stresses that remain are called the principal stresses:
σ1 – maximum, σ2 – middle,and σ3 – minimum. The principal stresses are always ordered such that σ1 > σ2 > σ3.
Equivalent stress is related to the principal stresses by the equation[13]:

$$\sigma_e = \sqrt{\frac{(\sigma1-\sigma2)^2+(\sigma2-\sigma3)^2+(\sigma3-\sigma1)^2}{2}} \qquad (2)$$

Each of the components of thermal strain iscalculated through the equation[13]:

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$\varepsilon^{th} = \alpha^{se} (T - T_{ref})$ (3)

Where:
ε^{th} - thermal strain in one of the directions x, y, or z.
α^{se} - Secant coefficient of thermal expansion defined as a material property in Engineering Data.
T_{ref} - reference temperature or the "strian-free" temperature.

The von Mises or equivalent strain ε_e is calculated through the equation[13]:

$$\varepsilon_e = \frac{1}{1+\nu'}\sqrt{\frac{(\varepsilon_1-\varepsilon_2)^2+(\varepsilon_2-\varepsilon_3)^2+(\varepsilon_3-\varepsilon_1)^2}{2}} \quad (4)$$

, wherev' is the effective Poisson's ratio

RESULTS AND DISCUSSION

The results during analyzed timeperiod of 1800second under LOCA condition reflect the following performance:

- The decrease in system pressure due to LOCA causes a coolant pressure drop. The resulted internal pressure in the inner clad side generates ballooning of the cladding. The maximum deformation occurs at the outer surface of the cladwith value of about17 µm which is well below the maximum permissible deformation of the clad (35 µm)[8]. The clad deformation is presented in Fig. (3).

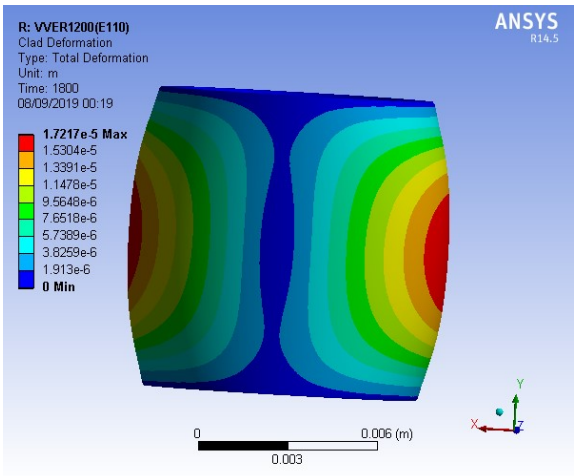

Fig. 3: Clad Deformation

- Average equivalent von-Mises stress is about 207 MPa in the beginning of the analysis and due to sudden change in coolant pressure the equivalent stress decreases gradually over time to about 38 MPa at the end of the analyzed timeperiod.The dominant stress during the analysis time is well below the yield strengthwhich means that the caseis far away from bursting.
- Average equivalent elastic strain is about 0.2 % as shown in Fig. 4.The results agree with TRANSURANUS straindue to irradiation induced swelling for VVER conditions (E110M) [14]. The higher values shown on the top and bottom boundary of the clad are due to boundary conditions effect.

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Deformation, equivalent stress, and equivalent elastic strain values over analyzed time are represented in table 4.

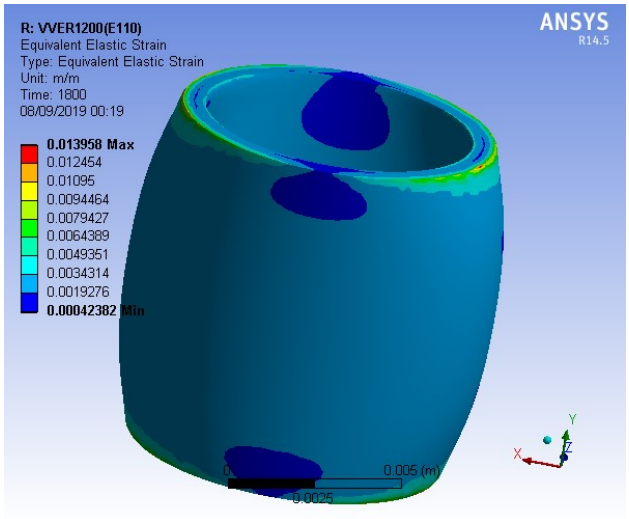

Fig. 4: Clad Equivalent Von-Mises stresses

Table 4: deformation,Von-Misesequivalent stresses and equivalent elastic strain values over analyzed time.

Deformation (Maximum)

Time [s]	Maximum [m]
1.	9.5295e-005
23.5	7.8659e-005
50.	5.9066e-005
90.	2.949e-005
100.	2.2097e-005
250.	1.7217e-005
300.	
500.	
700.	
900.	
1100.	
1200.	
1300.	
1400.	
1500.	
1600.	
1700.	
1800.	

Equivalent Stress (Average)

Time [s]	Average [Pa]
1.	2.077e+008
23.5	1.7154e+008
50.	1.2895e+008
90.	6.4665e+007
100.	4.8594e+007
250.	3.798e+007
300.	
500.	
700.	
900.	
1100.	
1200.	
1300.	
1400.	
1500.	
1600.	
1700.	
1800.	

Equivalent Elastic Strain (Average)

Time [s]	Average [m/m]
1.	2.3183e-003
23.5	1.9147e-003
50.	1.4392e-003
90.	7.2157e-004
100.	5.4217e-004
250.	4.2382e-004
300.	
500.	
700.	
900.	
1100.	
1200.	
1300.	
1400.	
1500.	
1600.	
1700.	
1800.	

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CONCLUSION

- The present work studies the new clad (E110M) behavior under LOCA condition "500 cm^2 break in one circulation loop in cold leg of the VVER1200 reactor coolant circuit". The analysis time is 1800 s
- Structural modelusing ANSYS Finite Element (FE) package is presented. The stress distribution, thermal strain, and deformation through the clad are simulated under LOCA condition.
- Deformation, Von Mises equivalent stress, and equivalent elastic strain values are obtained over analyzed time. all the results are in the permissible limits.
- The resultsindicate that no clad failureoccur.

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