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Tolerant fuel for VVER reactors

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Abstract. The main factor of destruction of fuel rods in accidents with loss of coolant is associated with the vapor-zirconium reaction occurring between the fuel rod shell and the coolant (water). Improving the reliability of fuel cells can be obtained by modifying or replacing the fuel shell, materials that do not interact with the coolant during normal operation and in emergencies. The loss of coolant accident is a design-basis accident in light water reactors. The postulated accident requires an analysis of the double guillotine break in a main primary coolant pipe, which allows the coolant to freely discharge out of the primary system into the containment of the building. In the present work, the heat stored in the active zone of the reactor, the heat capacity of the fuel and the shell temperatures are determined for ATF materials U-10Mo and U_3Si_2 . The calculated values are compared with the usually used fuel UO_2 . The results showed beneficial effect of using ATF materials. The above quantities are decreased dramatically for ATF, promising to replace UO_2 with ATF fuels. This reduces the probabilities of accidents and oxidation in the nuclear reactors. The calculations are done for nuclear power plant, type VVER-1200.

1. Introduction

After the accident at the Fukushima nuclear power plant in Japan, Russia began the development of new nuclear fuel, called Accident Tolerant Fuel (ATF). The Tolerant Fuel includes the development of new shells and the fuel itself. The shells can be made of various steels, containing different materials such as chromium, aluminium, molybdenum and some ceramics like (SiC). In addition to the Zr alloys and other possible protective coatings.

One of the most important factors in the design of nuclear power plants is the calculation of power production and the removal of heat from the core that allows energy production during operation. The thermal design of a fuel element is constrained by various limits, such as the necessity to stay below the fuel and the cladding melting temperatures at all times. It is also desirable to increase as much as possible the coolant outlet temperature from the core to maximize thermal efficiency [1].

The ATF materials such as high density fuels with uranium, like uranium molybdenum alloy U-10Mo and uranium silicide U_3Si_2 are desirable. Thus, in this work the heat stored in the reactor will be calculated for the above mentioned alloys, in the case of accident with loss of cooling associated with the vapor-zirconium reaction. This work will also consider the materials for cladding. The calculations are carried out using MATHCAD program [4].

ATF includes increasing the thermal conductivity of the fuel and retaining the fission products in the matrix. High-density fuel with uranium, such as uranium-molybdenum alloys (U-10Mo) and uranium silicide (U_3Si_2), is also desirable. This paper will show and calculate the heat stored in reactor when



using Tolerant Fuel in accidents with loss of coolant associated with the vapor-zirconium reaction and consider the materials for fuel and shells. The calculations are carried out using MATHCAD program [2,3].

2. Fuel materials U-10Mo and U₃Si₂

Tolerant fuel is a new generation of safety nuclear fuel with increased resistance to accidents at nuclear power plants with the loss of coolant in the reactor. Alloying elements are specially added to uranium that has a significant impact on its structures, properties, and characters of phase transformations [3,5].

2.1 Uranium and Molybdenum alloys (U-10Mo)

Uranium-molybdenum fuel has a high thermal conductivity, gives off heat more easily and operates at a lower temperature. It also has less energy stored in the reactor core. Therefore, it allows reducing energy release in case of violation of normal operating conditions of a nuclear reactor and increase in its safety and stability in emergency situations. In the event of a violation of heat removal in the core, the Tolerant Fuel must maintain its integrity for a long time without the occurrence of a vapor-zirconium reaction and the release of hydrogen for cladding containing zirconium). This fuel is distinguished by its high thermal conductivity, high density and high melting temperature. For example at 500 °C they were 23 W/m·K and 17.2 g/cm³, respectively, whereas the melting temperature was 1408 °C [6,7].

2.2 The uranium Silicide U₃Si₂

The lower melting point of U₃Si₂ compared with UO₂ is compensated by its higher thermal conductivity, which dramatically reduces the expected average temperature in the fuel rod compared with UO₂ [8].

These properties can have a positive effect on the performance of fuel rods in various emergency conditions of the reactors. The high thermal conductivity of U₃Si₂ with its lower operating temperatures makes it more attractive than UO₂ fuel [9,10,11]. Alhmoud and Kruglov [6] have calculated the thermal conductivity and the density and the melting temperature for U₃Si₂ using MATHCAD program. At 500 °C they were 9.34 W/m·K, 12.2 g/cm³ and 1665 °C respectively. These values will be used at 500 °C will be used for calculations in the present work.

3. Shells materials, Zr - chromium alloys and ceramic composite, (SiC)/(SiC)

Zirconium, being a chemically active element, begins to interact with water vapor, in the temperatures 500-600 °C. However, above 900 °C, an exothermic reaction occurs with the release of energy and the formation of a large amount of hydrogen. As a result, the shell absorbs oxygen and hydrogen which weakens it, and due to the intense chemical interaction, so active oxidation occurs that the fuel element shell can completely collapse. Therefore, the development of fuel element shells that are resistant to high-temperature oxidation is of fundamental importance for the safety of nuclear power plant [12].

3.1 Zirconium alloy with Chromium

To meet the above conditions, it is necessary to select the elements that form the strongest oxide film. According to thermodynamic characteristics, Zr is the most sustainable in heat, and (consequently the stronger) which form Zr oxide, but it experiences phase transformations with increasing temperature; which weakens the chromium oxide. However, chromium oxide is a good barrier to oxygen diffusion. Therefore, almost all countries have started using chrome coatings. The advantages of chrome coatings are high melting point, high corrosion resistance in superheated water - up to 1000 °C and high thermal conductivity [12].

3.2 Silicon Carbide composite, (SiC) / (SiC)

This material has recently attracted attention for its possible use in an ATF shell due to its excellent chemical resistance and strength at unexpectedly high temperatures. The use of silicon carbide as the main material for the fuel shell eliminates the possibility of formation of an explosive mixture, since this material has fairly low oxidation kinetics and a high melting point. (SiC) / (SiC) composite has a

melting point of 2800 °C, a thermal conductivity of 25 W/m·K at temperature of 50 °C and resistance in water vapor up to 1200 °C [12].

4. Accident with loss of coolant LOCA

4.1 Amount of heat stored in UO₂, U-10Mo and in U₃Si₂ fuels

Heat is generated in the radius R of the fuel rod and passes radially through the fuel, the gap in the tablet shell δ_{bc} , and the shell itself, δ_{sh} to reach the coolant, T_w [13,14], as can be seen in figure 1. At the same time heat is removed from the heat generating element in the radial direction, through a series of thermal resistances, by conduction and convection.

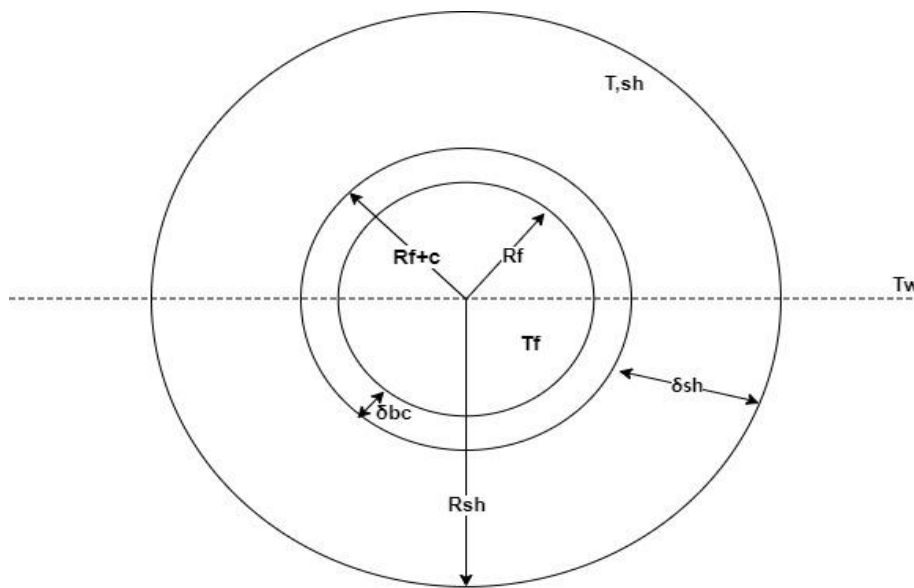


Figure1. Cross section of the fuel assembly for VVER-1200 reactor.

The next table shows the geometric characteristics of the fuel assemblies for VVER-1200 reactors.

Table 1 shows the geometric characteristics of fuel assemblies for VVER-1200 reactors.

Measurements in, mm	The quantity
Fuel rod diameter, d_f	9.1
Cladding thickness, δ_{sh}	0.65
Radius of fuel rod, R_f	3.8
Radius shell, R_{sh}	4.55
Gap thickness, δ_c	0.1

The temperature difference between fuel center and fuel surface for the fuels, UO₂, U-10Mo and U₃Si₂ are obtained by equation 1, derived by D. Olander and A. Motta (1):

$$T_{f,c} - T_f = q1/4\pi K_f \tag{1}$$

Where $T_{f,c}$ is the temperature of fuel in center, T_f is temperature of fuel on the surface of fuel rod, $q1$ is the linear load in the fuel rod in W/m and K_f is the thermal conductivity of the fuel.

$q1$ obtained the equation:

$$q1 = \frac{q_{fuel\ rod}}{H_0} \times K_z = 2.27 \times 10^4 \frac{W}{m} \tag{2}$$

Where $q_{fuel\ rod}$ is the average heating power of a fuel element and its equal to $6.54 \times 10^4 W$, H_0 is the height of active zone in the reactor and its equal to 3.73 m and K_z is the coefficient of unevenness in height and its equal to 1.465.

It should be mention that the value of q_1 has been taken as constant for the three fuels considered [1].

The heat stored in the active zone of reactor during operation can be obtained by the equation, [1]:

$$Q = \rho \times C_p \times V_f \times \Delta T, Q = \rho \times C_p \times V_{sh} \times \Delta T \quad (3)$$

Where, ρV_f is equal to the fuel Mass in the fuel rod and its equal to 1.7 Kg and the fuel Volume in the fuel rod $V_f=170 \text{ cm}^3$, wharase the volume of the shell for the (zirconium alloy E110) $V_{sh}= 64 \text{ cm}^3$.

Table 2 shows the physical and thermal properties of UO_2 , U-10Mo, U_3Si_2 and shell (E110 zirconium alloy).

Table 2. The physical and thermal properties of UO_2 , U-10Mo, U_3Si_2 and shell (E110 zirconium alloy) after reference [6].

Material	Average density ρ , g/cm^3	Average heat capacity, C_p (J/g·K)	Q in J (heat stored in the active zone of the reactor)
UO_2	10.4	0.330	321480
U-10Mo	17.2	0.175	10500
U_3Si_2	12.2	0.202	24543
zirconium alloy E110	6.5	0.5	15925

The average density of the fuels and their average heat capacities are taken from reference [6], whereas the heat stored of the reactor are calculated in the present work after the mentioned equations.

4.2 Estimation of the shell temperature immediately after stopping the core reactor with LOCA accident when using UO_2 , U-10Mo, and U_3Si_2

One of the consequences of a low fuel thermal conductivity is that large temperature gradients are needed in the fuel pellet to drive the heat flux out from the fuel to the coolant [15]. The large temperature gradient means that there is much stored energy in the fuel, which is one of the reasons why cooling must be provided even in the case of a loss of coolant accident [1].

The results considered in table 3 are obtained by the next equation, [1]:

$$Q = M \times C_p \times \Delta T \quad (4)$$

Where, Q is the heat stored in the fuel rod immediately after the shutdown of the reactor in J, C_p is the average heat capacity in J/g·K for the fuels UO_2 , U-10Mo and U_3Si_2 , whereas M is the mass of fuel in the fuel rod equal to 1.7 Kg and ΔT is the temperature difference in K between fuel center and fuel surface of the fuel rod.

It should be mentioned that the temperature of the fuel surface T_f is usually equal to the shell temperature.

Table 3 shows the results of calculations for Q, C_p , ΔT and shell temperatures.

Table 3. Calculations of the shell temperatures with LOCA accident using Tolerant Fuels in the VVER-1200.

Material	Q (J)	Average heat capacity, C_p (J/g·K)	ΔT (°C)	Shell temperatures, °C
UO ₂	321480	0.330	696	1251
U-10Mo	10500	0.175	84	460
U ₃ Si ₂	24543	0.202	169	572

It is evident from tables 2 and 3, that the heat stored in the active zone of the reactor is decreased from 321480 (J) for UO₂ to 10500 (J) for U-10Mo and 24543 (J) for U₃Si₂. This reductions in heat stored in the fuels are accompanied by decreasing heat capacity of the materials. These reductions in both parameters reduce the temperature of the fuel rod which leads to less probability of accident, which helps the coolant function. Both parameters decrease the shell temperature as well which reduces the possibility of oxidation, namely shell temperature decreases from 1251 °C for UO₂ to 460 °C for U-10Mo and to 572 °C for U₃Si₂. The less thermal expansion accompanying the less heat stored, leads to less thermal variation in the dimensions of the design of the system.

5. Conclusion

Tolerant fuel is a new generation of safety nuclear fuel with increased resistance to accidents at nuclear power plants with loss of coolant in the reactor. The temperatures of the ATF materials including shells are reduced dramatically compared with temperature of UO₂ fuel. This reduces the probability of accidents and oxidation, as its well-known that hydrogen start to be dangerous in the reactor at 1200 °C or higher. The calculated temperature of the shells of the ATF materials being much less than 1200 °C, namely 460 °C and 572 °C for U-10Mo and U₃Si₂ respectively [16].

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