Investigation of the hydrogen production by the FeCrAl nuclear fuel cladding using MELCOR 2.2

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Abstract—This paper deals with hydrogen production in nuclear power reactors by cladding of the fuel. The description of accident tolerant fuel, especially FeCrAl cladding material and its oxidation is presented. Model is based on Phebus facility, that was build for better understanding of phenomena occurring during severe accidents in light water reactors. Conventional used zirconium cladding was replaced by FeCrAl alloy and simulated by MELCOR code. This software is plant risk assessment tool for simulating light water reactors and its accidents. Results shows significantly decrease of hydrogen production.

Keywords—accident tolerant fuel, MELCOR, FeCrAl, hydrogen production

1. INTRODUCTION

After disaster in Fukushima there has been an increase in development of accident tolerant fuel (ATF), which should be more tolerant to extreme conditions. To enhance safety of current fleet of light water reactors, number of international working groups are intensive focusing on ATF. The main goals are to retain radionuclides within the fuel and to improve material for cladding, to significantly slowing down the exothermic oxidation of Zr-based material in steam environment.

Two ways of development ATF are: firstly, improvement of the material of fuel pallet and secondly, improvement of cladding material. Cladding material can be improved by coating on the commercially used cladding based on zirconium or replaced the whole cladding by another suitable material. The emphasis is on material which have significantly higher oxidation resistance. A typical example is the iron-chromium-aluminium (FeCrAl) alloys, which possesses desired properties.

2. FECRAL

The iron-chromium-aluminium alloys are typically used within a range of industrial applications, especially where high temperature oxidation resistance is needed [1]. Over past half of century FeCrAl was considering as cladding material for fuel elements in the nuclear power plants. But from early days of nuclear power reactors, Zr-based alloys were chosen for light water reactors fuel cladding, because of their low neutron absorption, good thermal conductivity, high melting point and adequate corrosion resistance. After 2011 Fukushima accident interest in nuclear power applications of FeCrAl alloys has extremely risen. The objective of the studies is to delay severe core degradation by reducing heat generated by exothermic reaction of Zr-based cladding with steam. Also to reduce hydrogen production, because of the ignition risks.

FeCrAl alloys has excellent resistance against oxidation up to 1560 °C, which is close to its melting point [2]. FeCrAl has two different mechanisms of oxidation. If the water temperature is around 300 °C, that corresponds to normal conditions in light water reactors, the alumina layer on the surface of cladding will dissolve and protective chromium oxide will form in this place. After that, if accident conditions will appear, the chromium oxide layer will evaporate and an alumina layer will form to protect the tube. It leads to a conclusion that chromium is protecting the cladding during normal operation conditions and aluminium is protecting the alloy at temperatures higher than 1100 °C. The visualisation of these processes can be seen in Fig. 1 [3].

One of the drawbacks of FeCrAl alloys are higher parasitic neutron absorption. For the similar neutron absorption has to be cladding made from FeCrAl half thickness compare to conventionally used Zr-based cladding. There are also challenges about brittle after neutron irradiation and problems with releasing tritium to the coolant, too [4].

DOI: 10.13164/eeict.2022.220
Figure 1: Schematic representation of the oxide processes on FeCrAl alloys under normal and accident conditions in light water reactors [3].

3. METHODOLOGY

If cooling of the nuclear reactor core is absent for a longer period of time, decay heat and exothermic chemical reactions heats up the fuel, that can eventually resulting in melting. The impact of various cladding materials from a thermodynamic point of view have been conducted [5]. One of the severe accidents analysis tools is MELCOR code, developed by Sandia National Laboratories for U.S. Nuclear Regulatory Commission. It is a second generation plant risk assessment tool. MELCOR code is fully integrated, engineering level computer code focused on progression of severe accident phenomena in light water reactors. These include thermal-hydraulic response of the reactor system, cavity and the containment, loss of coolant phenomena like fuel heat up, cladding oxidation, degradation and melting of the fuel, hydrogen production, fission products release and transport etc [6, 7].

In this work as a reference experiment was used model of experimental facility Phebus. This facility was operated in France between 1988 and 2010. Main purpose was study phenomena occurring during light water reactor severe accidents. The core is a scaled down version of 900 MWe pressurized water reactor by ratio of 1/5000. Test train contains coolant inlet, test bundle, experimental circuit and containment vessel.

This work is focused on test bundle, which contains 20 fuel rods with 12.6 mm pitch and 1 meter height. In Fig. 2, there can be seen the radial cross section of the fuel bundle with its description and in the right side of the picture, there is post-test radiography of the bundle but in axial direction [8]. During experiment, bundle power was increasing to 36.5 kW and the steam mass flow rate was varying from 0.5 to 2.2 g/s, to simulate the accident conditions. The core is divided into 2 radial rings and 14 axial levels. The inner ring has the radius of 21.33 mm and contains the first row of fuel rods and control rod made from silver-indium-cadmium. The outer ring has the radius of 36.5 mm and contains the outer fuel rods. The main events of the experiment happened in degradation phase, that lasted 20 000 seconds. The calculation was initiated 5000 seconds before start of the transient, to obtain steady state.

In the MELCOR code input, which was created for simulating FPT1 test at Phebus, the material for the cladding of the fuel was changed to FeCrAl. The FeCrAl alloy was defined as a user specified core material and for application in the generic oxidation model as well. Changes were done in the material package and core package of the code, namely material definition, populating core components with the user defined material and the oxidation parameters of the material. For the fuel cladding and its oxide wide range of properties have to be input into MELCOR code, for example heat capacity, thermal conductivity, emissivity, melting point and others. These material properties was input for FeCrAl with ratio 74% / 21% / 5% and are in [6], too. The changes in fuel geometry, like thickness of cladding or pitch, were not considered. In the further investigation, there should be keep in mind other technical specifications of FeCrAl, for example neutron absorption, melting point and mechanical strength.
4. RESULTS AND DISCUSSION

The simulation was done on the personal computer with Microsoft Windows operating system. When the computing server with Linux operating system was used, results were slightly different. This is the challenge for future focus on these differences.

The main results can be seen in Fig. 3 with the hydrogen production, where in the left side is comparison between cladding composed by Zirconium and FeCrAl. The blue line and blue crosses correspond to Zirconium cladding. The line is results of simulation and crosses are data from measurements at Phebus facility during FPT1 experiment. The difference in hydrogen production is significant. For conventional zirconium cladding in FPT1 test, the mass of produced hydrogen was 96 g, by simulation it is slightly over-predicted around 13 grams. To compare, produced hydrogen when FeCrAl is used for cladding is 21 grams, what is remarkable decrease. The hydrogen produced by FeCrAl is very low, because in figure there is summary of the hydrogen produced by spacer grids, stiffeners and support plate as well. The red line in figure is prediction, when FeCrAl cladding is not melting and survive at its position till the end of the experiment. This condition was redefined in input to investigate the whole time span.

In the right side of figure, there is detailed view just on FeCrAl cladding till time of melting almost whole
cladding material. The total hydrogen production till 13 200 seconds is 13 respectively 12.5 grams in comparison with 98 grams produced by zirconium in simulation and 71 grams in experiment. In this graph the focus is on the different approach to oxidation reactions. The red line with label FeCrAl (FeO) corresponds to prefer oxidation reaction

$$\text{Fe} + \text{H}_2\text{O} \rightarrow \text{FeO} + \text{H}_2$$

(1)

and the production of hydrogen is gentle greater if the reaction

$$3\text{Fe} + 4\text{H}_2\text{O} \rightarrow \text{Fe}_3\text{O}_4 + 4\text{H}_2$$

(2)

is used. The green line with label FeCrAl (Fe3O4) is conducted with preference of oxidation reaction 2. The difference in amount of hydrogen is very small and just in the last hundreds of seconds. This can be caused by different sensitivity to higher temperatures and also different collapsing of cladding material during oxidation.

The visualisation of the simulated fuel bundle is in Fig. 4. The visualisation was done by Symbolic Nuclear Analysis Package (SNAP) software, which can be used as for the creating input for MELCOR, computing it and for making more readable outputs as well [9]. In the left side of figure, there is the mass distribution of UO$_2$ fuel pellets, FeCrAl as cladding and the mass of oxidized FeCrAl before test and in the right side there are the same columns with mass distribution after the test. In the distribution of UO$_2$ and FeCrAl can be seen that in the central ring of the bundle occurred melting and collapsing of whole fuel rods with its content. In comparison with the post-test radiography in Fig. 2, the good match can be considered. In the columns that corresponds to FeCrAl oxide can be seen where the oxidation occurs the most. It is within the nodes in the center of the bundle with highest temperatures and in the molten bulk, too.

![Figure 4: Mass distribution of UO$_2$, FeCrAl and FeCrAl oxide a) before test and b) after test.](image-url)
5. CONCLUSION

To summarize, FeCrAl alloys as ATF cladding material produce less hydrogen as the conventional cladding based on zirconium. The reduction is around 80% compare to the simulation and the experiment. Also, there are small differences if alternative oxidation reactions are preferred by MELCOR. The melting of the fuel rods occurs, and mass distribution is similar to the post-test radiography of the fuel bundle, too.

In the simulation there are still components made from zirconium. To decrease hydrogen production more, these components should be replaced as well. In order to optimize FeCrAl as an alternative cladding material, engineering design improvements could be made. There are challenges as neutron absorption, mechanical strength and melting point.

ACKNOWLEDGMENT

This research work has been carried out in the Centre for Research and Utilization of Renewable Energy (CVVOZE). Author gratefully acknowledge financial support from the Technology Agency of the Czech Republic (project No. TM02000039). I would like to also acknowledge my supervisor, Karel Katovský, for his mentoring and help.

REFERENCES


