Accident Tolerant Fuel simulation loaded in advanced nuclear power reactor during severe accident conditions

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***Abstract*—This paper introduces accident tolerant fuels with respect to their current state of development, while the leading causes are briefly mentioned. The main reasons for the development of other cladding materials are presented. Selected types of accident tolerant fuel cladding materials are described in short and then are used for a simulation in a model of advanced power reactor undergoing a severe accident scenario in the MELCOR code.**

***Index Terms*—nuclear fuel, accident tolerant fuel, safety analysis, severe accident, MELCOR**

I. INTRODUCTION

Nowadays, advanced reactor designs have a much higher level of safety with improved safety margins. However, the possibility of an accident is a concern, although the risk is low. There are still ways to improve safety margins; an exceptional way is by introducing accident tolerant fuels (ATF). These materials exhibit enhanced protection against severe accident conditions, reducing the potential for core damage and the release of radioactive materials. ATF considers the use of advanced materials that show superior properties under accident conditions, such as high thermal stability and enhanced oxidation kinetics. There are three main categories under the ATF concept: high thermal conductivity fuels, advanced cladding materials, and zirconium alloys coated with a protective layer. The main events that helped promote and accelerate development are those that occurred at the Three Mile Island and Fukushima-Daichi plants [1].

II. ACCIDENT TOLERANT FUELS

Fuel is protected by cladding tubes from contact with water and steam. Oxidation of the cladding by air and steam occurs under conditions that lead to severe accidents, during which hydrogen is produced. The accumulation of hydrogen produced in the reactor coolant system (RCS) and containment could lead to detonation when ignited at certain concentrations with a containment atmosphere. Combustion could damage the RCS and containment and radioactive release could occur.

Nowadays, in commercial pressurised water reactors (PWRs), zirconium-based cladding is used. Although these alloys have advantages such as high thermal stability and low thermal neutron cross section, the main issue of Zr is still present. Zr alloys are subjected to steam oxidation, which produces a substantial amount of hydrogen and heat, and the process is greatly accelerated by increasing the temperature [3] [4].

The ATFs are based on the principle of Do No Harm, which means that under all operating conditions the ATF fuel system must perform at least as well as or better than the current fuel system. In addition, the new fuel concepts must be compatible with previously used fuel systems in all areas such as storage, proliferation prevention, etc.

III. CLADDING MATERIALS

The two most viable options that could be used as cladding materials are advanced steels, FeCrAl alloys, and refractory ceramic, silicon carbide. An extensive amount of data in non-irradiated state for both materials is available from laboratory testing or other industries of use and are compatible with light-water reactor (LWR) chemistry.

A. FeCrAl alloys

These alloys based on iron, chromium and aluminium are representatives of advanced steels that have greatly improved oxidation resistance. Nuclear-grade alloys have optimised chemistry and microstructure. They have a lower content of chromium (10-13 wt%) and aluminium (4-6 wt %), with minor additions of niobium and molybdenum to improve overall strength. Strength allows for a reduction in the thickness of the cladding tube, compensating for the higher neutronic penalties. In a steam environment, the protective layer of Al_2O_3 is formed on the surface of the material, reducing the further oxidation of the base material by steam, also the Cr_2O_3 layer is formed, improving the overall stability of the protective layers.

B. Silicon Carbide

Has an established use in environments of highly corrosive nature and where parts must withstand high temperatures. Compared with Zr alloys, SiC is chemically inert, has a lower neutron absorption cross section, and is able to cope with higher temperatures. As it is a ceramic material, it is brittle; therefore, the proposed designs are in the form of duplex and triplex structures to improve mechanical strength. The structure may be based only on SiC or may be assisted by metal. The SiC matrix is subject to dissolution phenomena under LWR conditions, the environmental protection barrier is required; if the barrier is not present, the environment in the long term would affect the structure as it would be degraded [5] [6].

IV. METHODOLOGY

The most severe scenario has been chosen to be unmitigated Large Break Loss Of Coolant Accident (LB LOCA), it is a DBA which the plant is designed to cope with; however, if is not mitigated by engineered safety features, it progresses to severe accident.

A. MELCOR code

The MELCOR code allows for advanced modelling of the progression of such a scenario in LWR technology plants. Materials are defined using available data on FeCrAl - C35M from ORNL [2] and on SiC from [7]. Because the materials produce oxides as they are subjected to the steam environment, the oxides and the conditions under which they form have to be addressed in the code by the use of generic oxidation modelling (GOM). The thermophysical properties of the forming oxides were defined using available data from the NIST JANAF database.

The main area of interest in the simulation is the produced hydrogen and heat produced by the oxidation of the cladding. It is a must to note that only the material of the cladding was changed and its properties; no changes to the fuel rod geometry and neutron kinetics models were introduced.

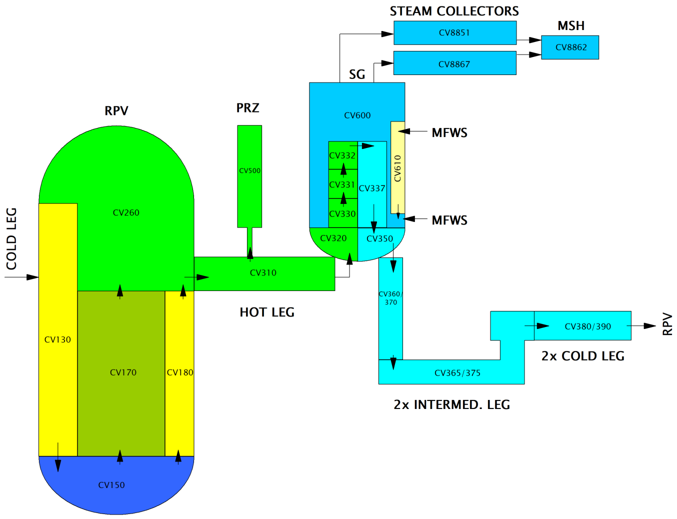

Fig. 1. Control volumes and flow path nodalization of the model (for simplification only one loop with pressuriser and single cold leg are presented) [8].

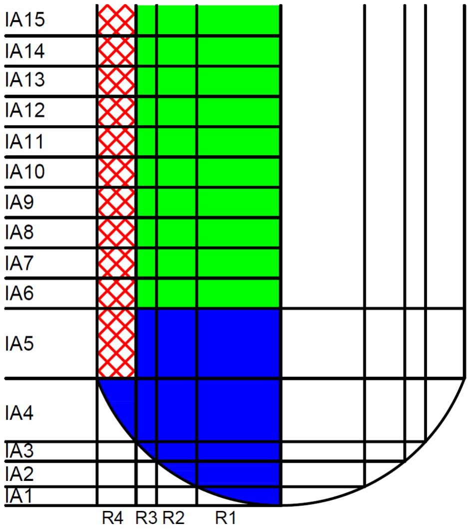

Fig. 2. Core nodalization of core package [9].

B. Advanced power reactor model

For investigation of ATF complex impact, an APR1400 model is used. The RCS configuration of the used model has two reactor coolant loops. Each loop consists of a hot leg, a steam generator, two cold legs, and reactor coolant pumps at each of the cold legs. The nuclear steam supply system is designed to operate at a rated thermal output of 4000 MW. The RCS model includes all the most important systems – detailed primary circuit (reactor pressure vessel with internals, two loops, pressuriser), the most important components of the secondary circuit (steam generators, steam lines, main steam safety and isolating valves) and safety systems (Safety Injection Tanks, Safety Injection Pumps, Safety Depressurisation System).

In Fig. 1 a schematic view of the control volumes of RCS and the secondary system and its layout is shown. The RCS consists of 32 control volumes; the secondary system consists of 11 control volumes. The boundary volumes are the turbine connected to the main steam hub and the main feedwater system.

The reactor core is modelled in detail using one control volume and the COR package. The COR package covers modelling schemes not only for the core, but also for the lower plenum. In total, 15 axial levels and 4 radial rings are used. The nodalization of the COR package is illustrated in Fig. 2, where the green colour represents the active fuel and the blue represents the lower plenum. From that, active fuel is present in 10 axial levels and 3 radial rings.

C. Accident scenario

The initiating event for the scenario analysed is a cold leg guillotine break. Break size is of 200 % cold leg cross-section area and is located between the cold leg volume CV480 of the loop without pressuriser and the RPV downcomer volume CV130. In terms of engineered safety features and accident mitigation, all safety injection pumps are assumed to be unavailable, and only passive Safety Injection Tanks are available.

D. Oxidation modelling

The generic oxidation model in MELCOR uses the Arrhenius correlation for the calculation of oxidation. It is assumed that the material would undergo oxidation by parabolic rate characteristics. The modelling of the SiC oxidation reaction is as follows, with consideration of oxidation of both the Si and C components under high-temperature steam.

$$SiC + 3H_2O \rightarrow SiO_2 + 3H_2 + CO \tag{1}$$

For the C35M, two approaches are determined, while the oxidation parabolic kinetics rate remains unchanged. The first approach considers oxidation of Fe to Fe_3O_4 oxidation, while being accompanied by Cr to Cr_2O_3 and Al to Al_2O_3 oxidations, the oxidation rate of each component is weighted by the percentage of weight of the components in the alloy. The reactions are as follows:

$$Fe + H_2O \rightarrow FeO + H_2 \tag{2}$$

$$2Cr + 3H_2O \rightarrow Cr_2O_3 + 3H_2 \tag{3}$$

$$2Al + 3H_2O \rightarrow Al_2O_3 + 3H_2 \tag{4}$$

The second approach considers only a formation of Al_2O_3 protective layer based on the research [10], which shows that the formed layer of oxides is primarily of Al_2O_3. MELCOR is capable of calculating only three simultaneous oxidation processes, only the elements with the highest weight fraction are considered for oxidation for the C35M alloy. Formed oxides are not treated separately in the code, and one generic oxide is formed. Thus, the thermal properties of each oxide were weighted by their respective molar weights to the total molar weight of the generic oxide formed and by the percentage of element weight in the alloy to determine an estimate on the thermal properties of the generic oxide.

V. RESULTS AND DISCUSSION

As the simulated materials are not in the MELCOR library, for use in scenario, further optimisation and debugging was required, with some estimates imposed. The results of the simulation are shown in the graphs below.

In Fig. 3, the graph of heat produced by cladding oxidation is shown. The lower the heat production by the oxidation, the better, because the heat produced in this way could significantly accelerate the fuel melting in combination with the decay heat from the fuel. As mentioned above, zirconium alloy oxidation produces an excessive amount of heat. In the graph legend, FeCrAl is marked with the FCA shortcut.

Both proposed materials, the SiC and FeCrAl alloy, have shown significantly lower heat production because the reaction heat of the base material is lower. Lower heat production should extend the coping time before the lower head of the RPV fails due to the stresses posed by the melted core; also, the cladding mass plays its role. In case of FeCrAl, differences could be observed between the approaches taken; the weighted approach shows a lower heat production, as the generic oxide would be primarily of Fe_3O_4, that has by orders of magnitude lower values of heat of reaction than Al_2O_3.

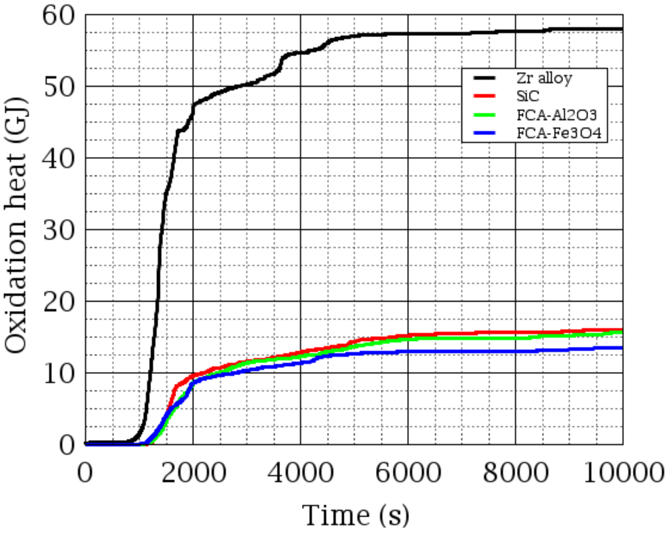

Fig. 3. Total oxidation heat produced due to oxidation of in-vessel components.

Fig. 4 shows the amount of hydrogen produced due to in-vessel oxidation of components. Similarly as in the case of heat production; the hydrogen produced from the oxidation of SiC and FeCrAl is lower, about half that of the Zr alloy. Hydrogen production by SiC oxidation is comparable to that of FeCrAl using the only Al_2O_3 approach. There are certain differences between FeCrAl approaches; the lowest total amount of hydrogen is in case of weighted Fe_3O_4 approach, where by an amount of the reacting base metal a lower amount of hydrogen is produced.

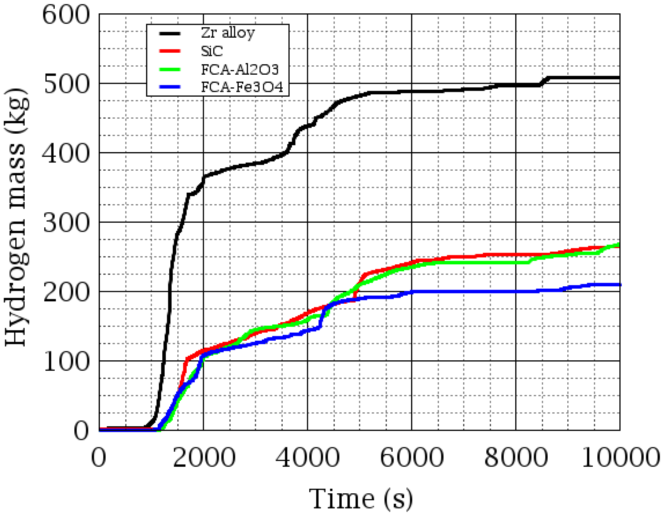

Fig. 4. Total hydrogen mass produced due to in-vessel oxidation of components.

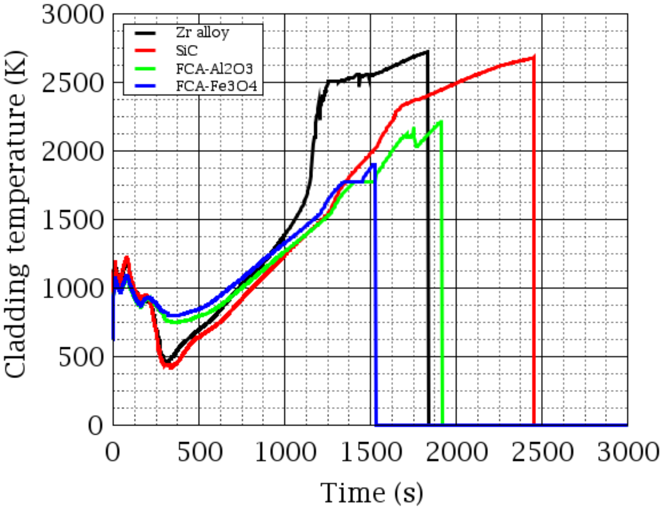

Fig. 5. Cladding temperature in core axial node 12, radial ring 2 - the first node that melts and collapses.

Fig. 5 shows the surface temperature of the cladding tube in the radial ring 2 and the axial node 12. This node is the first to collapse due to melting of the cladding in the case of the Zr alloy and FeCrAl. Because of the high melting point of SiC, the fuel inside the rod is melted first, resulting in the collapse of the cladding tube by the damage function.

The oxidation heat of the Zr alloy has effects on temperature, and, as can be seen, the rate of increase in temperature is higher than that of other materials, also the ZrO_2 thermal conductivity is lower, reducing the amount of heat transferred. The FeCrAl alloy melts at lower temperatures as a result of its lower melting point. SiC shows the latest collapse time because it has a higher thermal conductivity and melting point compared to other materials.

In Table I, times of RPV lower head and the first cladding failures are listed. In all cases of the use of ATF cladding, lower head failures occurred later compared to Zr alloy cladding. As mentioned above, both FeCrAl and SiC materials exhibit lower cumulative hydrogen production, reducing the risk of structural damage posed by possible hydrogen ignition.

The report [11] examines the influence of the ATF cladding on the TMI-2 accident scenario and shows that the amount of oxidation heat and hydrogen oxidation produced has been significantly reduced. Compared to the production rates, considering that the oxidation in this study progresses at higher temperatures, where the oxidation is faster, it is possible to state that the results are correlating in trends.

VI. CONCLUSION

In this study, the ATF cladding was simulated using the MELCOR code in a severe accident scenario. Two different materials, advanced nuclear grade stainless steel C35M and ceramic SiC, were defined and simulated in the advanced power reactor model. The results have shown a significant decrease in the production of oxidation heat and total hydrogen mass, however, in the case of FeCrAl, with a trade-off of a lower melting point, which may result in a sooner breakdown of the cladding. Research is needed on how oxides are formed by oxidation of FeCrAl alloys as there are still many estimates, primarily regarding their thermal properties and composition. Furthermore, the generic oxidation model would require further optimisation and verification, especially when modelling the heat released from the material by oxidation and its kinetics.

TABLE I
TIMES OF RPV AND FIRST CLADDING FAILURES AND CUMULATIVE HYDROGEN PRODUCTION

	RPV failure (s)	First clad failure (s)	H_2 mass (kg)
Zr alloy	8435	1835	509,1
SiC	10215	2450	265,3
FCA-Al_2O_3	9555	1915	267,9
FCA-Fe_3O_4	9960	1525	210,8

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