Modeling of Accident Tolerant Fuels for APR1400 using MAAP5.05

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1. Introduction

Accident Tolerant Fuels (ATF) are a set of new technologies that have the potential to enhance safety at nuclear power plants by offering better performance during normal operation, transient conditions, and accident scenarios. In the event of a severe accident, a lot of heat and hydrogen are generated by the core cladding oxidation, and the integrity of containment can be threatened. Therefore, if ATF can be applied to suppress or delay the generation of heat or hydrogen due to the cladding oxidation, it will be advantageous in terms of severe accident mitigation. In MAAP5.05, in addition to the core behavior analysis capabilities of the existing UO_2 core and Zircaloy cladding, it is possible to simulate new materials such as ATF. In this study, it will be confirmed that the effect of applying hypothetical ATF to APR1400 using MAAP5.05.

2. ATF Modeling Methods

In order to model ATF material property and reaction phenomena in MAAP5.05, the following properties can be specified by the user: 1) Fuel, clad and clad oxide material properties, 2) Clad oxidation and volatilization reactions with H_2O, 3) Fuel and fuel cladding failure criteria, 4) Fission product release rate from fuel materials. In this study for the ATF application to APR1400, silicon carbide (SiC) is assumed to be the clad material along with uranium oxide (UO_2) as fuel material since the information on these materials is widely available.

2.1 Material Properties

For a given ATF material, the following user-input material properties are needed for cladding, fuel, and cladding oxide materials: Density, specific heat, specific internal energy and thermal conductivity as a function of temperature; as well as melting temperature, latent heat of fusion, viscosity, surface tension, emissivity and molecular weight.

Thermo-physical properties of SiC and SiO_2, from SiC oxidation, are available in open literatures [1] [2] [3] [4] [5]. The material properties for UO_2 used in MAAP5.05 are provided as the fuel properties of APR1400.

2.2 Oxidation model

The general oxidation equation of ATF cladding is:

$$N_1\ clad + N_2\ H_2O = N_3\ clad\ oxide + N_4\ CO + N_5\ H_2 + N_6\ CO_2 + N_1 Q_R \qquad (1)$$

ATF cladding oxidation reaction kinetic equation has a parabolic form, and the reaction rate constant has an Arrhenius form [6]:

$$\frac{dx}{dt} = \frac{Af(P_{ps})}{2\,\rho_{ox}^2 x} e^{-\frac{B}{RT}} \qquad (2)$$

Where x is the oxide layer thickness, and ρ_{ox}^2 is the oxide density.

2.3 Volatilization of oxide material

Some oxide materials such as silica, which is the selected material as the fuel cladding in this study, undergoes volatilization in the presence of steam. The input-driven general volatilization reaction equation is:

$$N_1\ clad\ oxide + N_2\ H_2O = products(not\ tracked) + N_1 Q_V \qquad (3)$$

The following general form of the cladding volatilization reaction kinetic equation to calculate the rate of oxide layer depletion (or thinning) is assumed:

$$\frac{dx}{dt} = -\frac{Af(P_{ps})^C v^{1/2}}{\rho_{ox}} e^{-\frac{B}{RT}} \qquad (4)$$

Where the pressure dependency is introduced by: $f(P_{ps}) = D\ P_{ps}/10^6$ Pa, and A, B, C and D are user-input coefficients, and v is the velocity of the steam.

2.4 Modeling for Application of ATF to APR1400

The ATF features incorporated into the MAAP 5.05 code are illustrated by a number of case studies for LLOCA and SBO in APR1400 reactors to show the impact on core heat-up and disassembly as well as flammable gas generation. The ATF materials used in this analysis are SiC cladding and UO2-like fuel. It is assumed that no material interaction and eutectic formation for SiC cladding and fuel because there is not enough information for this relocated core materials. Thus, the severe accident simulations for each scenario were limited to only until the core relocation to the lower head of reactor vessel.

Oxidation and volatilization data for silicon carbide are available from the paper [6]. Other thermo-physical properties are available in open literature for both SiC and SiO_2.

3. Result for ATF Application in APR1400

To illustrate the potential benefits derived from using accident tolerant fuel materials, LLOCA and SBO scenarios for APR1400 are analyzed using MAAP5.05. Table I shows the summary of key timings for a case with Zircaloy cladding and UO_2 fuel, with SiC cladding and UO_2 fuel. For the SiC cladding cases with LLOCA and SBO scenarios, it can be seen that there is about 25 to 45 minutes of spare time in terms of when the hottest core node is reached 2500 K or when the core material is relocated.

Table I Key timings for APR1400 sequences

Sequence	Core uncovery, seconds	Core exit temp. > 650 K, seconds	Hottest core node temp. > 2500 K, seconds	Time of core material relocation to lower plenum, seconds	Mass of H_2 produced at the time of core material relocation to lower plenum, kg
LLOCA with Zircaloy cladding	147	3,883	4,802	7,915	443
LLOCA with SiC cladding	147	3,953	6,303	9,532	195
SBO with Zircaloy cladding	7,292	8,293	24,003	28,616	603
SBO with SiC cladding	7,366	8,441	26,404	31,273	212

Core heat-up for Zircaloy and silicon carbide claddings of the APR1400 LLOCA scenario are compared in Fig. 1. The LOCA is initiated at time zero and Safety Injection Tank is available but terminated when it runs out of water at around 2140 seconds. The core starts heating up when sufficient primary system inventory is lost at around 3000 seconds. For the Zircaloy cladding case of LLOCA, the hottest core node temperature rises rapidly after around 4000 seconds. For the SiC cladding case of LLOCA, the hottest core node temperature rises gradually mostly due to the decay heat.

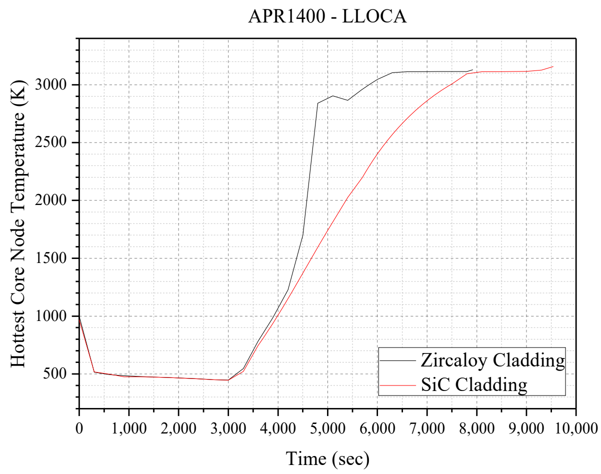

Fig. 1 Hottest core node temperature for LLOCA in APR1400

Fig. 2 shows the total in-core mass of hydrogen and carbon monoxide produced. Significantly less hydrogen is produced for the SiC cladding compared to the Zircaloy cladding. The run is terminated when there is 1000 kg of core material in the lower plenum.

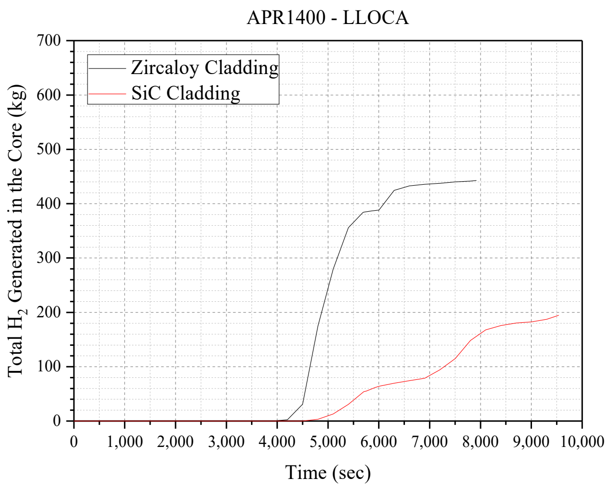

Fig. 2 Total hydrogen generated for LLOCA in APR1400

Core heat-up for Zircaloy and silicon carbide for the APR1400 station blackout scenario are compared in Fig. 3. After core uncovery at approximately 7300 seconds, the temperature of the hottest node increases until SIT injection starts according to the opening of POSRVs which can be operated using battery powers. After the depletion of SIT at around 23000 seconds, the temperature of the hottest node increases steadily, and there is a much more rapid increase for the Zircaloy cladding case of SBO.

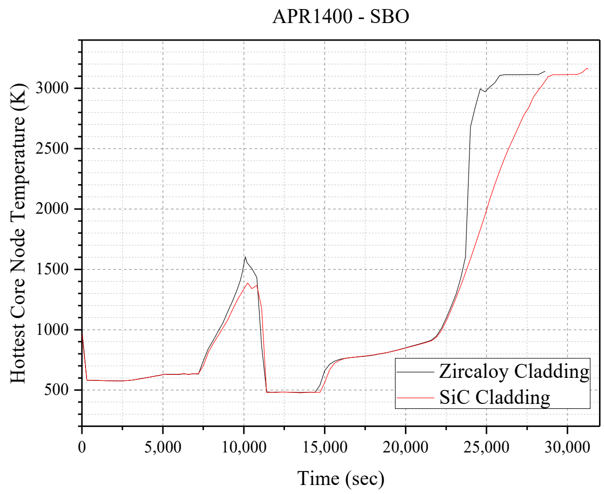

Fig. 3 Hottest core node temperature for SBO in APR1400

Fig. 4 shows also that there is significantly less hydrogen generated for the SiC cladding compared with Zircaloy cladding in SBO scenarios. Heating and H_2 generation progress to the point where core materials relocate to the lower plenum and the run is terminated.

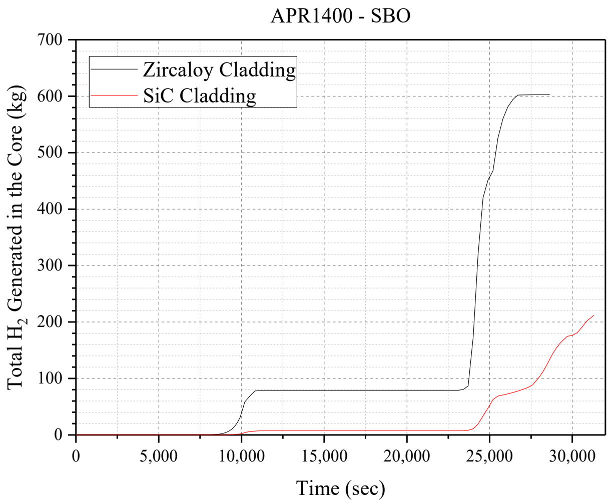

Fig. 4 Total hydrogen generated for SBO in APR1400

4. Conclusions

Four cases are addressed for the ATF application in APR1400: Zircaloy cladding and UO_2 fuel in LLOCA, SiC cladding and UO_2 fuel in LLOCA, Zircaloy cladding and UO_2 fuel in SBO, SiC cladding and UO2 fuel in SBO. Through the case studies, it is confirmed that the silicon carbide oxidation reaction contributes significantly less heat to core heat-up compared to the Zircaloy cladding oxidation reaction.

In addition, it can be expected for the benefits of ATF during severe accidents: 1) Reduction of hydrogen generation during the accident, 2) Increased time for operator actions due to extended fuel heatup time and improved cladding properties, and 3) Potential dose reduction by enhanced retention of fission products.

Since the science for material interaction between the relocated core materials such as SiC with UO_2 is not well enough understood yet, the run period of MAAP5.05 was limited to the stage before analysis of the relocated mixture. However, if ATF for APR1400 is actually developed and the fuel and cladding materials are confirmed in the future, MAAP5.05 can be used to examine the positive effects of ATF in mitigating severe accidents.

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