Analysis of Hydrogen Generation during TMI-2 Severe Accident using CINEMA

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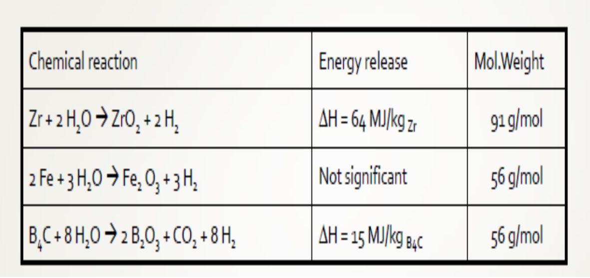
1. Introduction

Hydrogen generation in the core during severe accidents is very important, because hydrogen production mass affects hydrogen bahavior in containment. Main hydrogen is generated due to core material oxidation by steam, as shown in Table I. Many models on the core material oxidation have been developed for an exact estimation of hydrogen generation mass during the severe accidents, which are explained section 3. For this reason, a numerical model development for core material oxidation, in particular, Zircaloy oxidation of the fuel cladding in a computer code development of severe accident sequence analysis.

Table I: Hydrogen generation from chemical reaction of oxidation for core material.



Chemical reaction	Energy release	Mol.Weight
$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$	$\Delta H = 64\ MJ/kg_{Zr}$	91 g/mol
$2Fe + 3H_2O \rightarrow Fe_2O_3 + 3H_2$	Not significant	56 g/mol
$B_4C + 8H_2O \rightarrow 2B_2O_3 + CO_2 + 8H_2$	$\Delta H = 15\ MJ/kg_{B_4C}$	56 g/mol

As an integrated severe accident computer code development in Korea, CINEMA (Code for INtegrated severe accidEnt Management Analysis) has been developing for a stand-alone severe accident analysis. The basic goal of this code development is to design a severe accident analysis code package by exploiting the existing domestic DBA (Design Basis Analysis) code system for the severe accident analysis. The CINEMA computer code is composed of CSPACE (COMPASS Safety and Performance Analysis CodE for nuclear power plants), SACAP (Severe Accident Containment Analysis Package), and SIRIUS (SImulation of Radioactive nuclide Interaction Under Severe accident), which are capable of core melt progression with thermal hydraulic analysis of the RCS (Reactor Coolant System), severe accident analysis of the containment, and fission product analysis, respectively, as shown in Fig. 1. The CINEMA code integrates the modules using MPI (Message Passing Interface). The MPI protocol enables the independent analysis modules to perform calculation through the communication of coupled information with other analysis modules. CSPACE, SACAP, and SIRIUS were developed and configured by different bodies and thus designed to run independently. Therefore, the CINEMA code was designed to integrate the analysis modules by facilitating seamless communication among the modules while assuring the independence of each module.

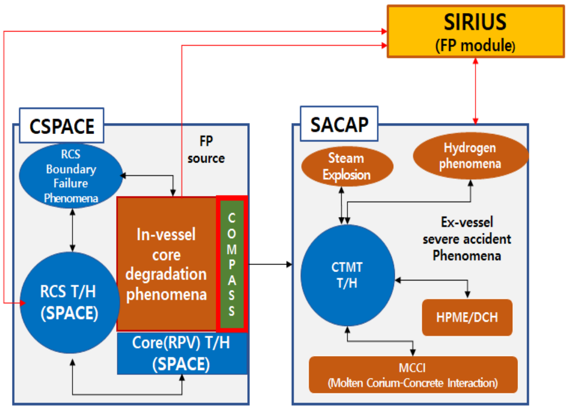


Fig. 1 CINEMA computer code structure.

Numerical model on the hydrogen generation for the CINEMA computer code was estimated using TMI-2 severe accident data in this study.

2. TMI-2 Severe Accident

On March 28, 1979, the TMI-2 pressurized water reactor underwent a prolonged, a total loss of feed water with a SBLOCA (Small Break Loss Of Coolant Accident) that resulted in a partial melting of the core, significant cladding oxidation, and a significant release of fission products from the fuel [1]. The progression of the TMI-2 accident was mitigated by an injection of the emergency cooling water. Fig. 2 shows the end state of TMI-2 severe accident. During the TMI-2 severe accident, approximately 62 tons of core material was melted and 19 tons was relocated to the lower plenum of the reactor vessel. However, the reactor vessel did not fail. During the TMI-2 severe accident, approximately 460kg of hydrogen was generated in the core.

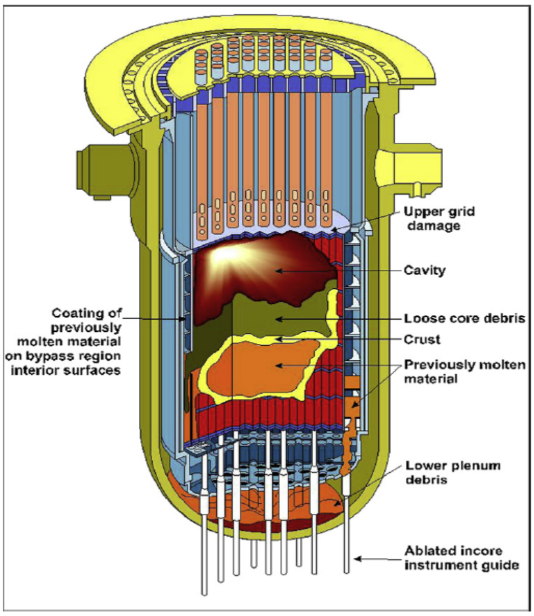


Fig. 2. End state of TMI-2 severe accident.

3. CINEMA Model for Hydrogen Generation

In general, a fuel cladding oxidation starts at approximately 1,000 K of temperature and highly oxidation is generated when the temperature is higher than approximately 1,500 K, which results in a formation of ZrO_2 and α-Zr layers on the fuel cladding. Two phenomena are likely to limit the local oxidation kinetics or even stop the oxidation reaction. The first one is that low partial pressure of steam (accumulation of hydrogen near the cladding) leads to a reduction of steam diffusion toward fuel claddings. The second one is that local fuel cladding failure and Zircaloy relocation leads to stop of oxidation locally.

Fig. 3 shows Zircaloy oxidation rate as a function of the cladding temperature in general oxidation model of the fuel cladding. The heated metal Zircaloy bonds with steam to cause oxidation which has exothermic reaction heat. For oxidation of metal Zircaloy in the CINEMA computer code, the Cathcart model and Baker-Just model are used according to the fuel cladding temperature. It uses the Cathcart model at a low temperature and the Baker-Just at a high temperature. The oxidation start temperature of each model is given as user input. The initial oxidation temperature of the Cathcart model has a default value of 1173.15 K while the oxidation start temperature of the Baker-Just model has a default value of 1850.15 K. The mass of metal Zircaloy changes over time by the oxidation reaction. The mass of the oxidized zircaloy can be obtained from the mass of zircaloy involved in oxidation.

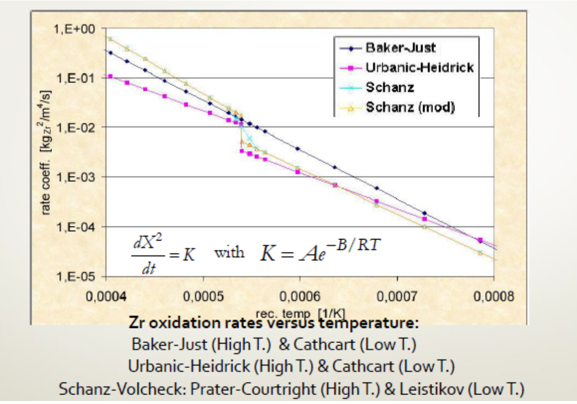


Fig. 3. Zircaloy oxidation rate as a function of fuel cladding temperature in oxidation model.

Moreover, the hydrogen (H_2) is generated by oxidation of Zircaloy (Zr) with steam (H_2O) as follows;

$$Zr + 2H_2O = ZrO2 + 2H_2 \tag{1}$$

For this reason, the hydrogen generation mass (m) by Zircaloy oxidation with steam can be expressed based on the number of moles in the element as shown below.

$$\frac{dm^{H_2}}{dt} = (4.03188/91.22)\frac{dm^{Zr,ox}}{dt} \tag{2}$$

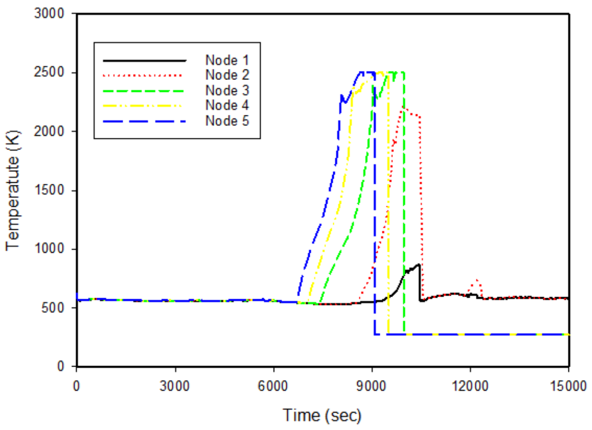
4. CINEMA Input Model

TMI-2 core contains 177 fuel assemblies. The reactor coolant system (RCS) consisted of the reactor vessel, two vertical one-through steam generators, four reactor coolant pumps, an electrically heated pressurizer, and interconnecting piping. The system was arranged with two heat transport loops, each with two RCPs and one steam generator.

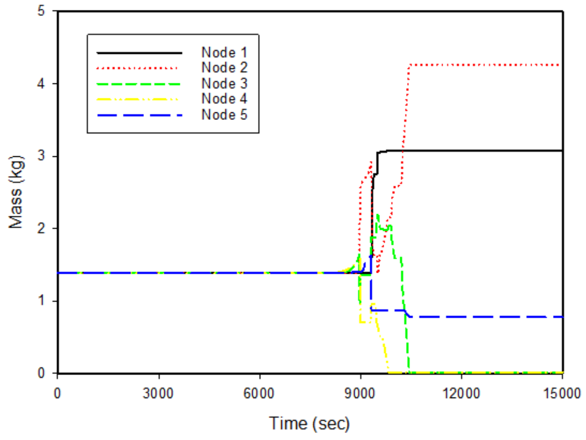
All primary and main secondary systems are modeled including the pressurizer, PORV (Pilot-Operated Relief Valve), and safety injections for CINEMA calculation. In core input model, 3 radial and 5 axial nodes are used. Fuel and control rod are connected to the fluid volumes in the core. A steady state calculation was performed to verify the input nodalization of CINEMA for TMI-2 severe accident. The steady state results of the CINEMA calculation for a selected set of parameters were in very good agreement with the TMI-2 operating conditions. The steady state conditions obtained from the simulation were used as initial conditions for the transient calculation.

5. CINEMA Results and Discussion

Fig. 4 shows CINEMA results on the fuel cladding surface temperature and fuel cladding mass for the central channel in the core, respectively. Position of nodes 1, 2, 3, 4, 5 are 0.36 m, 1.09 m, 1.82 m, 2.55 m, 3.28 m from the bottom of the fuel rod, respectively. Fuel cladding mass of only one fuel rod is in this Figure. The fuel cladding surface temperature is rapidly increases by oxidation heat when the temperature reaches at approximately 1,500 K. Top of the fuel cladding (Node 4, 5) is melted and relocated to the lower part of the core. Theses fuel cladding surface temperature and relocation affect the hydrogen generation from the oxidation. The lowest value of the fuel cladding temperature after approximately 9,000 s means that all cladding is melted and relocated to the lower part.



(Fuel Cladding Surface Temperature)



(Fuel Cladding Mass of One Fuel Rod)

Fig. 4 CINEMA results on TMI-2 severe accident

Fig. 5 shows a comparison of CINEMA results with TMI-2 data on the generated hydrogen mass. The calculated hydrogen generation mass is in general agreement with the hydrogen production estimated from post-accident observations and inferences. The measured hydrogen production at the start-up of the RCP (Reactor Coolant Pump) was approximately 300kg. At the startup of the RCP, the CINEMA calculations of cumulative hydrogen production is higher than 300kg. However, the CINEMA results and measured total hydrogen productions are very similar, which were approximately 465 kg and 460 kg, respectively. For this reason, hydrogen generation model for the CINEMA computer code is validated using the TMI-2 data. Hydrogen production was calculated to not occur after 10,500 s because the portions of the core with intact fuel rods and some metallic cladding were too cool to rapidly oxidize.

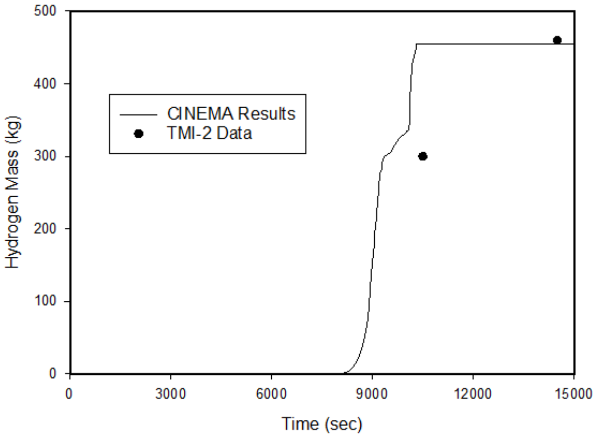


Fig. 5 Comparison of the CINEMA results on hydrogen generation mass with TMI-2 data.

6. Conclusions

Numerical model for hydrogen generation in the CINEMA computer code was estimated using TMI-2 severe accident data. The calculated hydrogen generation mass is in general agreement with the hydrogen production estimated from post-accident observations and inferences. For this reason, hydrogen generation model for the CINEMA computer code is validated using the TMI-2 data.

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REFERENCES

[1] J.M. Broughton, P. Kuan, D.A. Petti, E.L. Tolman, et al., A Scenario of the Three Mile Island Unit 2 Accident, Nuclear Technology, Vol. 87, p. 34, 1989.