High temperature oxidation of the feeder pipe and its potential risk as the hydrogen gas management during SB-LOCA of CANDU reactor

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1. Introduction

CANDU (Canadian Deuterium Uranium) reactor has 380 horizontal fuel channels (FC) as the reactor core and each FC is connected the inlet and outlet feeder pipes to the reactor header. Depending on the FCs location, the power and flow rate have the distribution of the cosine profile and the diameter of the feeder pipe as well as its length are strongly varied. The longest length of the feeder pipe is about 18 meters [1], which is three times longer than the axial length of the pressure tube (6 meters).

Feeder pipe is the carbon steel (ASTM A106 Grade B) and its high content of the carbon (C) facilitates higher mechanical strength than the general stainless steel (SUS) [2,3]. On the other hands, the carbon steel has relatively lower oxidation resistance than the SUS and the feeder pipe oxidation of the high temperature steam environment has been arisen as one of the pending issues of the CANDU reactor safety under severe accident [4,5,15].

Present study deals with (i) the investigation of the oxidation model for the carbon steel under steam environment and (ii) the evaluation of the hydrogen (H_2) gas generation from the feeder pipe, by using the M-CAISER (MARS-CAISER) code developed by the KAERI.

2. Methods and Results

2.1 Feeder pipe characteristics

The number of the feeder pipe including the inlet and outlet is 720, which is twice as large as the number of the FCs, and its geometry is quite complex connecting to the reactor headers (four inlet headers and four outlet headers). According to the design manual of the Wolsong Unit-II, the holdup volume of the D_2O in the feeder pipes is 8.67 m^3 (inlet) and 18.97 m^3 (outlet), which is almost 23% of the total fluid volume of the PHTS (120.18 m^3); the reactor core is 7.82 m^3 [5].

Based on the design values (volume and diameter) of the feeder pipe, we estimated surface area (As) of the feeder pipe reacting with the steam for the oxidation compared to the 380 FCs consisting of the fuel and sheath: 2500 m^2 for the fuel sheath, 700 m^2 for the inlet feeder and 1200 m2 for the outlet feeder, respectively. The difference in the surface area between the inlet and outlet feeders is due to the different diameter and the surface area of the feeder pipes is large enough to react actively the superheated steam.

Table xx. Feeder pipe characteristics of the CANDU reactor (Wolsong Unit-II)

Material	ASTM A106 Grade B Seamless carbon steel pipe for high temperature service	
Constituent	Fe (Bal), C (0.30), Mn (0.29-1.06), P (0.035), S (0.035), Si (0.1), Cr (0.40), Cu (0.40), Mo (0.15) Ni (0.40), V (0.08)	
Dimension	Size#1	3-1/2" Sch 80 (3.36" inside diameter)
	Size#2	3" Sch 80 (2.90" inside diameter)
	Size#3	2-1/2" Sch 80 (2.32" inside diameter)
	Size#4	2" Sch 80 (1.94" inside diameter)
	Size#5	1-1/2" Sch 80 (1.5" inside diameter)
Design fluid Volume	Inlet feeder	8.67 m3
	Outlet feeder	18.97 m3
Design temperature	Inlet feeder	279 C
	Outlet feeder	316 C
Design pressure	Inlet feeder	12.90 MPa(g)
	Outlet feeder	10.69 MPa(g)
Code classification	ASME Section III Class 1	
Seismic classification	DBE category A	
Velocity limitation	Single phase, two phase (homogeneous) : U < 50 feet/s	
Inlet feeder power limitation	3-1/2" = All 3" = All 2-1/2" = All 2" = All 1-1/2" = below 4.01 MW	
Outlet feeder power limitation	3-1/2" = All 3" = All 2-1/2" = below 5.87 MW 2" = below 4.09 MW 1-1/2" = below 2.44 MW	

2.2 High temperature Fe-steam oxidation model for the feeder pipe

Oxidation kinetic is described by the parabolic rate constant (Kp), which is also strongly influenced by the gas environment (Fig. 1). Literature survey with respect to the pure iron and carbon steel oxidation indicates that steam environment provides the highest Kp compared to that of oxygen, hydrogen and carbon dioxide [6].

Parabolic rate constant shows a significant difference depending on the containing element (such as Cr, Ni and C), although the major element of the carbon steel and the SUS is the same ferrite (Fe). Therefore, the models of the SUS oxidation of the pressurized water reactor (PWR) applied to the several severe accident codes (COMPASS, MAAP, MELCOR) are hard to use for the analysis of the PHWR feeder pipe case (Fig. 2) [7-9].

As researches with respect to the feeder pipe oxidation have been reported with very limited cases, literature survey has been conducted for several substitute materials such as zircaloy, stainless steel, carbon steel and pure iron. Interesting point is that the carbon steel, pure iron and zircaloy show similar oxidation kinetics in the temperature range from 1000 to 1500 kelvin. So, reference model to analyze the feeder pipe steam oxidation is selected to be the same model of the zircaloy using the sheath material; Baker-Just [10] and Cathcart-pawel model [11]. If experimental research about the oxidation kinetics at the feeder pipe material (ASTM A106 grade B) under high temperature can be made, this will be useful to supplement the lack of the model uncertainty in the present study.

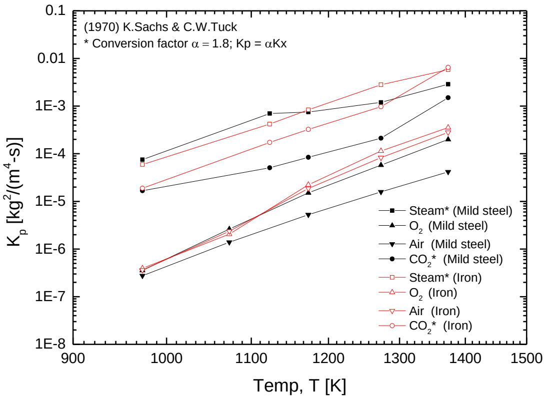

Fig. 1. Parabolic rate constant (Kp) versus time with pure iron and low carbon steel (so called mild steel)

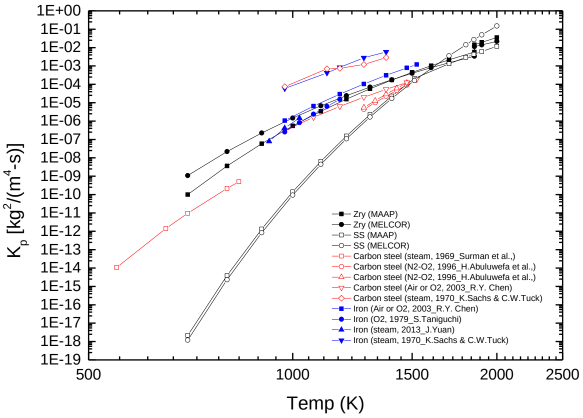

Fig. 2. Parabolic rate constant (Kp) versus time with different materials.

2.3 Hydrogen gas generation during SBLOCA with moderator cooling system

Previous study reported the SB-LOCA (RIH 2.5% break) with successful moderator cooling system (MCS) by using M-CAISER code, which showed detailed analysis and methodology during the severe accident [5]. Oxidation model in the M-CAISER code is based on weight gain (dM/dt) of the metal substrate similar to the case of COMPASS, MELCOR and MAAP code. Accumulated mass of the hydrogen gas is calculated by the fraction of the molar mass between the reactant (Fe or Zr) and the product (H2) (Eq. 1-2), in which molar mass of the Zr, Fe and H2O is 91.2, 55.8 and 2.0 [g/mol], respectively,

$$Zr + 2H_2O \rightarrow 2H_2 + ZrO_2 + Qox \qquad (Eq.1)$$

$$Fe + H_2O \rightarrow H_2 + FeO + Qox \qquad (Eq.2)$$

where Q_{ox} is the heat of the reaction.

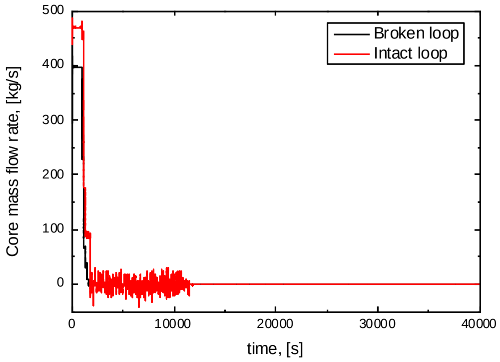

Fig. 3. PHTS mass flow rate, [I][J] = [1][2] for the broken loop and [2][2] for the intact loop

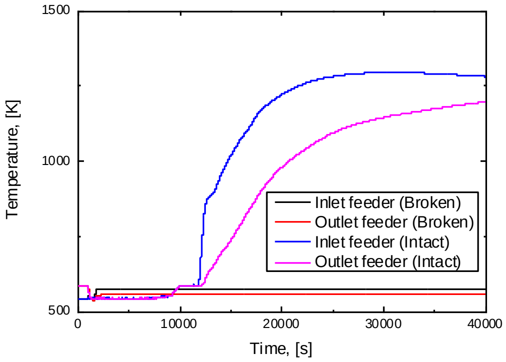

Fig. 4. Feeder pipe temperature, [I][J] = [1][2] for the broken loop and [2][2] for the intact loop

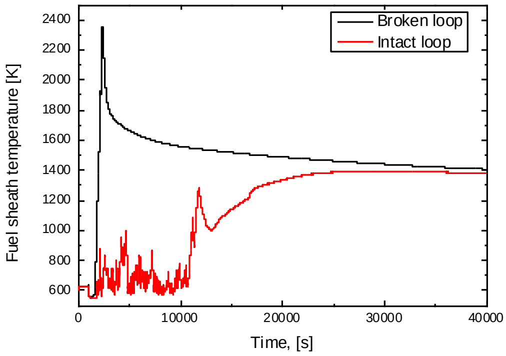

Fig. 5. Fuel clad temperature, [I][J] = [1][2] for the broken loop and [2][2] for the intact loop

Under the SB-LOCA with MCS, two types of PHTS (the intact and broken loop) show different behavior of the thermal-hydraulics. In case of the intact loop, fuel channel maintains its integrity without failure because MCS keeps constant moderator temperature enough to cool the calandria tube. This is explained by the formation of the natural convection in the PHTS, in which steam superheated from the reactor core is able to transfer the heat to the feeder pipe by the convective heat transfer. Maximum temperature of the inlet and outlet feeder pipes at the intact loop is about 1295 and 1248 K, respectively.

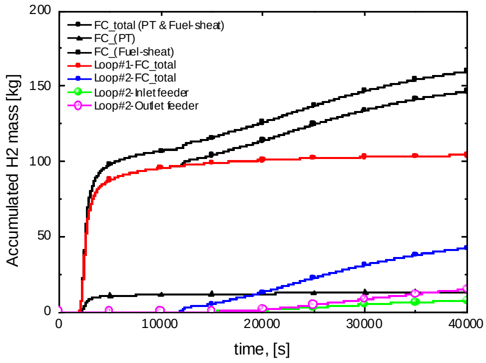

Fig. 6. Accumulated hydrogen gas generation by the Fe-H2O reaction

Due to the loop isolation in the LOCA progress, the Zr-H_2O reaction of the reactor core causing H_2 generation also depends on the loop condition. Broken loop already reaches high temperature enough to occur the zircaloy oxidation at the fuel channel, while the intact loop maintains relatively low temperature because of the natural convection in the PHTS. This phenomena was already demonstrated in the FSAR of the Wolsong Unit-II [12].

During 40,000 seconds, oxidation of the feeder pipe leads to the increase of the accumulated H_2 mass (12.5 %): about 20 kg and 160 kg for the feeder pipe (including inlet and outlet) and fuel channels (including cladding and pressure tube), respectively. Oxidation of the carbon steel is exothermic reaction like zircaloy. Fe-steam reaction is divided by three cases depending on the reaction temperature and oxygen concentration: FeO (Wustite), Magnetite (Fe3O4) and Hematite (Fe2O3). Assumed to the reaction under high temperature (beyond 1000K) like severe accident, the oxide formation is governed by the Wustite [13.14]. By considering the standard formation of the enthalpy, we can calculate exothermic heat by the formation of the FeO. Compared to the Zr-steam reaction (Qox,zr = 6.76 MJ/kg(Zr)), the Fe-Steam reaction shows relatively small reaction heat, 0.56 MJ/kg(Fe), which is nearly identical to the heat of reaction for the FeO in MAAP and MELCOR [7,8]. It seems to be negligible corresponding to about 10% of the Zr-steam reaction, but it is obvious that the feeder pipe temperature is able to increase more from the exothermic reaction. Present study does not consider the exothermic heat (Qox) during Fe-steam oxidation and, the result of the present study is more conservative.

3. Conclusions

We evaluated an additional generation of the H_2 gas by the carbon steel oxidation under steam environment during SB-LOCA induced severe accident with the M-CAISER code. Even though the oxidation models depend on the type of materials, the parabolic rate constant (Kp) of the feeder pipe material is similar to that of the fuel-sheath material, zircaloy. It is revealed that, under the accident scenario such as SBLOCA, the hydrogen generation from feeder pipes is not negligible, which amounts more than 10% of the total hydrogen mass in a core.

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