DEVELOPMENT OF CONCRETE ABLATION MODELS FOR GAMMA ASSESSMENT OF TOTAL RCCS FAILURE WITH AN AIR-INGRESS ACCIDENT IN HTGRS

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ABSTRACT

We considered total reactor cavity cooling system (RCCS) failure with an air-ingress accident due to unthinkable natural disasters as the worst safety issue in a high temperature gas-cooled reactor(HTGR). For this worst accident scenario, we analyzed the integrity of a 600 MWth gas turbine-modular helium reactor (GT-MHR) using the GAs Multicomponent Mixture transient Analysis code (GAMMA). The concrete ablation models, which consist of the endothermic reactions, were developed and implemented into the GAMMA. Through the system assessment we predicted the maximum core temperature, the maximum reactor pressure vessel (RPV) temperature, the ablation thickness of the concrete containment, and the cavity pressure. The maximum fuel temperature was still lower than 1600°C during the 500-hour transient simulation. The concrete absorbed some fraction of decay heat below 40%.The thermally-driven chemical reactions of the concrete produced a considerable amount of gases which can be released through the confinement venting valve. The RPV temperature exceeded its safety limit at 30 hour from the beginning of the accident.

1. Introduction

A high temperature gas-cooled reactor (HTGR) was adopted as one of the generation-IV reactors for its high thermal efficiency by Rankine cycle, diverse industrial utility by waste heat, and inherent safety features by passive heat removal systems such as the reactor cavity cooling system(RCCS). However, it is undeniable issue that passive safety systems could breakdown due to unexpected natural disasters. Several studies were investigated to evaluate the integrities of fuel and reactor pressure vessel (RPV) for the passive system breakdown scenario, such as the RCCS failure[1,2,3] and an air-ingress accident by guillotine break on main coaxial pipe[4]. Among them, only one research [3] considered the effect of the concrete ablation, which makes the concrete containment absorb the decay heat and provide the role for safety as ultimate heat sink in nuclear power plants.

Concrete ablation consists of three main endothermic reactions, which are evaporation of water, dehydration of calcium hydroxide, and decomposition of calcium carbonate, shown as below [5].

$$\mathrm{H_2O(l) + 2258kJ/kg \rightarrow H_2O(g)} \quad (1)$$

$$\mathrm{Ca(OH)_2 + 1340kJ/kg \rightarrow CaO + H_2O(g)} \quad (2)$$

$$\mathrm{CaCO_3 + 1637kJ/kg \rightarrow CaO + CO_2(g)} \quad (3)$$

For the application of the concrete ablation during accident transient, there has been two approaches: one is surface approach by Caldecott tunnel fire simulation[6], and the other is volumetric approach based on kinetics[7].

In this paper, with the system code called GAMMA [8], we will assess the worst accident scenario which the RCCS failure and the air-ingress accident happen simultaneously in a 600 MWth gas turbine-modular helium reactor (GT-MHR), regarding the effect of concrete ablation. We will also evaluate the contributions of the concrete ablation for the cases of without consideration, with surface approach, and with volumetric approach. To analyze the integrity of the reactor, the maximum core temperature, the maximum RPV temperature, the ablated thickness of the containment wall, and the cavity pressure will be calculated with the system code.

2. Concrete ablation model

2.1 Surface approach

The concrete ablation model using surface approach was suggested by K.B. McGrattan to simulate the Caldecott tunnel fire accident occurred in 1982[6]. He calculated the absorbed heat flux by concrete as the multiplication for the ablation rate on the surface and the heat of ablation:

$$q''_{ab} = \dot{m}''\Delta H_{ab} \tag{4}$$

The ablation rate means the mass loss rate of the concrete by the chemical reactions. The heat of ablation is defined as the amount of heat dissipated per unit mass[6]. To simplify the model, he assumed that the ablation rate could be expressed as an Arrhenius form of the surface temperature as follows.

$$\dot{m}'' = A\rho_s e^{-E/T_s(0)} \tag{5}$$

The pre-exponential factor A and activation energy E were chosen as 0.05 kg/(m^{2}s) at the surface temperature of 1000°C, which were based on the accident observation[9]. To reflect the significant mass loss rate around 700°C due to the decomposition of calcium carbonate, the parameter A was set for 0.1 m/s. The density was assumed as 2100 kg/m^3 and other parameters were calculated automatically. The heat of ablation was assumed as 2400 kJ/kg from the reference result [9]. Finally, we developed a temperature-dependent function for the ablation:

$$q''_{ab} = 8\times10^{-21}T^{8.3731} \tag{6}$$

This simple empirical model by the surface approach was implemented into the system code. However, it has several limitations to represent the real phenomena:

1. The heat is absorbed permanently by the concrete ablation even if there would be no remaining reactants for the reactions.
2. It is difficult to select which surface to absorb heat in the solid for the case of two-dimensional system code.
3. The exponential form of heat flux only matched with the limestone-type concrete.

For these reasons, we also considered volumetric approach to develop the concrete ablation models based on kinetics in the concrete.

2.2 Volumetric approach

The chemical composition in the concrete could be determined by the rules for manufacture such as American Society for Testing and Materials (ASTM) or American Concrete Institute(ACTI). Through the thermal gravimetric analysis(TGA), and derivative thermogravimetric analysis(DTGA), D. A. Powers et al. provided the pre-exponential factor A and the activation energy E of the three main reactions for various concretes as shown Tab 1 [11].

Reaction	**Basaltic Concrete**	**Limestone-Common Sand Concrete**
Free water evaporation	$A = 4.4\times10^{6}$ $E = 11.6$	$A = 1.29\times10^{6}$ $E = 11.0$
Bound water dehydration	$A = 2.8\times10^{12}$ $E = 41.9$	$A = 1.96\times10^{12}$ $E = 40.8$
Decarboxylation	$A = 3.6\times10^{9}$ $E = 42.6$	$A = 1.98\times10^{7}$ $E = 38.5$

Tab 1: Parameters for chemical reactions in the concrete (A: min^{-1}, E : Kcal/mole)

These parameters were obtained from different heating rate for the concretes based on the fractional loss function[8] described as

$$f(\alpha) = (1 - \alpha)^{n} \tag{7}$$

where α is weight loss fraction of one component in the concrete and n indicates the reaction order.

The form of Eq. (7) indicates the physical limitations on reaction rate due to weight loss. The author of the model guessed the parameter n as 1. Therefore, the overall chemical reaction rate could be expressed as

$$\frac{d\alpha}{dt} = k(T)f(\alpha) = Ae^{-E/RT}(1 - \alpha) \tag{8}$$

where R is gas constant and T is the absolute temperature.

However, it is not supported by the accurate kinetic analysis in terms of the water evaporation. When we calculate the derivative for the weight loss over the time, it estimates relatively higher values and narrower reaction range on the evaporation region than those of real phenomena in the concretes, as shown in Fig. 1 and Fig. 2. Changing the reaction order could be the one of the solutions for this. With increasing number of the reaction order, Fig. 3 showed the peak value of the weight loss rate decreases with an increase in its temperature range. If we treat the reaction order as 3 for the evaporation, we could follow the real trend for the kinetics of the concretes, as shown in Fig. 4. Therefore, we derived the following expression of the weight loss rate for the water evaporation:

$$\frac{d\alpha}{dt} = Ae^{-E/RT}(1 - \alpha)^{3} \tag{9}$$

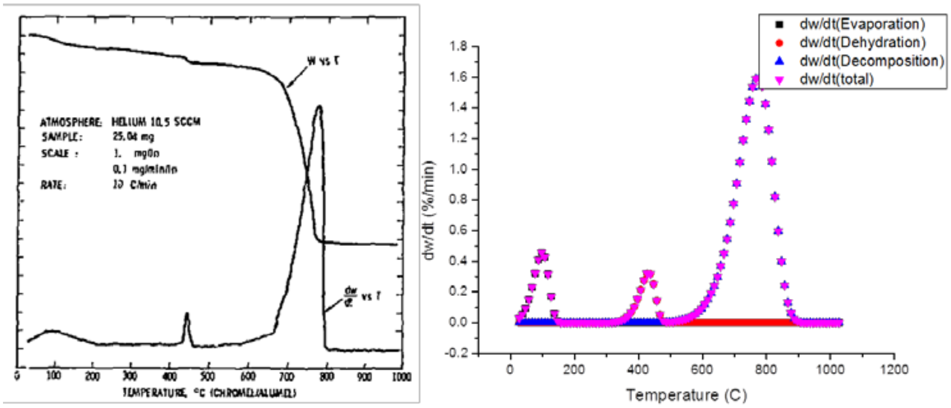


Fig 1. Kinetics for limestone/common sand concrete

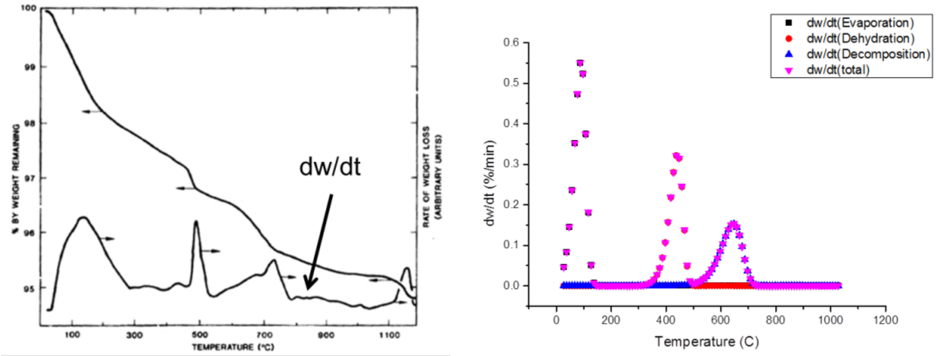


Fig 2. Kinetics for basaltic concrete

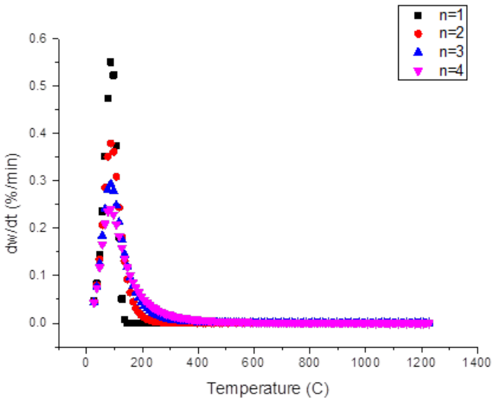


Fig 3. Weight loss rate with different reaction order

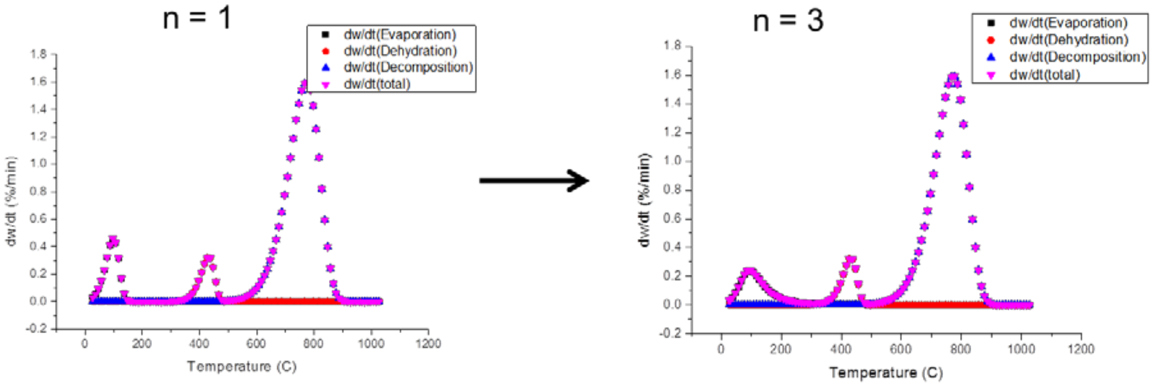


Fig 4. Weight loss rates of limestone/common sand concrete with different reaction orders

Eventually, the volumetric heat by the concrete ablation is calculated as the sum of the multiplications of the weight change and endothermic heat over the concrete volume for the three main reactions:

$$q'''_{ab} = \frac{W_1 d\alpha_1 \Delta H_1 + W_2 d\alpha_2 \Delta H_2 + W_3 d\alpha_3 \Delta H_3}{V} \qquad (10)$$

where W_1, W_2, and W_3 are initial weights of H_2O, $Ca(OH)_2$, and CO_2 in the concrete, and ΔH_1, ΔH_2, and ΔH_3 are endothermic heat for each chemical reactions in the concrete, respectively.

Model verification and validation processes were done with the GAMMA code for the heating rate of 10 °C/min. We selected the three experimental results with the samples of limestone concrete, which have the same engineering standard and composition [12][13][14]: NUREG-CR2282 performed at the heating rate of 10 °C/min, SURC-1 and SURC-3 which have unclear heating rate. As shown in Fig. 5, the GAMMA code was verified with the results calculated by an Excel sheet with the volumetric model. Then, the GAMMA code was validated with the experimental results obtained in 3 different experiments.

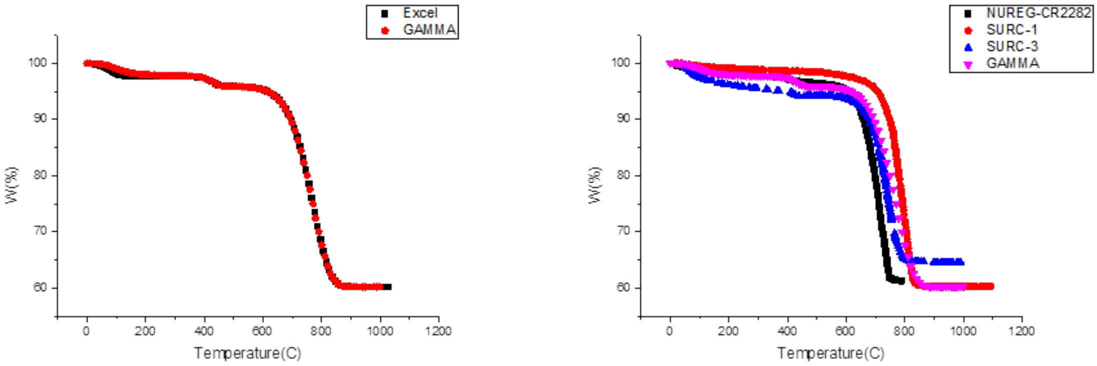


Fig 5. Verification and validation of GAMMA with the volumetric model

3. Assessment for the accident scenario

3.1 GT-MHR

GT-MHR, developed by General Atomics (GA), was chosen for the safety analysis. This reactor system consists of prismatic graphite core, TRISO particles, helium coolant, RCCS, and other specifications. All the detail geometric information of channels, fuel element, reflectors, and other systems were obtained from the materials presented by GA [15][16]. Fig. 6 showed the entire diagram of GT-MHR. Table 2 described the slightly modified operating conditions for GT-MHR.

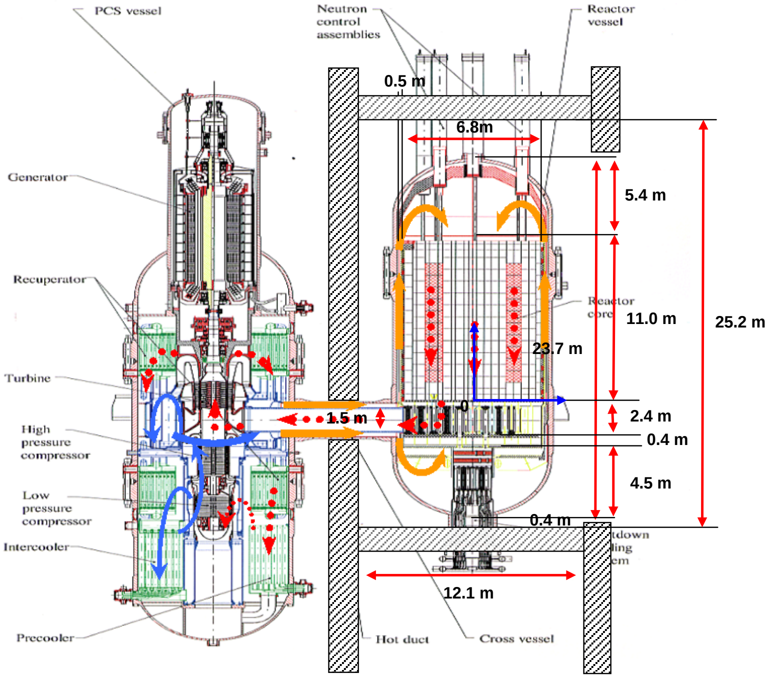


Fig 6. Description for GT-MHR

Parameter	Value
Reactor power	600 MWth
Mass flow rate	320 kg/s
Operating pressure	7 MPa
Inlet/outlet temperature	490/850°C

RCCS inlet temperature	43°C

Tab 2: Selected operating conditions for GT-MHR

3.2 Analysis tool

The Gas Multicomponent Mixture transient Analysis (GAMMA) code was used for the assessment. The GAMMA code was developed to predict air-ingress phenomena in HTGRs by implementing various gas and solid properties, numerical heat transfer and fluid flow, molecular diffusion, graphite oxidation reaction, and other natural phenomena [8]. The capability of the GAMMA was demonstrated with various verification and validation tests, including a HTTR-simulated air-ingress experiment, a SANA-1 afterheat removal test (IAEA Benchmark), and a HTTR RCCS mockup experiment [17].

The fundamental governing equations are mass, momentum, energy conservation equations in GAMMA. For fluid, the GAMMA code uses a semi-implicit first-order upwind scheme. For the case of the solid, the Crank-Nicolson method was applied. The ablation heat should be counted during the solid calculation procedure since it affects the source term in the solid. In the GAMMA code, the energy equation in the unfueled solid region was originally described as

$$\left(1-\varphi\right)\varphi_g\left(\rho C_p\right)\frac{\partial T_g}{\partial t}=q'''_{het}-q'''_{sf}+q'''_{gf}+\frac{\partial}{\partial x_i}\left(\lambda_{eff}\frac{\partial T_w}{\partial x_i}\right) \tag{12}$$

where φ, ρC_p, λ_{eff}, x_i are porosity, volumetric heat capacity, effective thermal conductivity, and mesh size, respectively. Subscripts, g and w, mean gas and wall.

This energy equation includes the heat generation and dissipation by the graphite oxidation reaction (q'''_{het}), the heat exchange term between the fluid and solid (q'''_{sf}), and the heat transfer between fueled and unfueled zone (q'''_{gf}). Here we inserted new minus term (q'''_{ab}) for the endothermic reactions in the concrete into the right-hand side of Eq.(12) as follows.

$$\left(1-\varphi\right)\varphi_g\left(\rho C_p\right)\frac{\partial T_g}{\partial t}=q'''_{het}-q'''_{sf}-q'''_{ab}+q'''_{gf}+\frac{\partial}{\partial x_i}\left(\lambda_{eff}\frac{\partial T_w}{\partial x_i}\right) \tag{13}$$

3.2.1 Simulation

The GAMMA nodalization for GT-MHR was described in Fig 7. Green blocks represent fluid regions, blue blocks represent the boundary volume, and others are solid parts. Steady-state for the normal operation was achieved by the boundary volumes connected with inlet and outlet. When it reached the steady-state, the assessment for the accident scenario started with an air-ingress through the connections with the reactor cavity (FB130-FB300, FB100-FB300) and a total RCCS failure through the removal of the inlet and outlet for RCCS (Air in, Air out). The concrete was constructed with 2 m thickness in block 635. The adiabatic condition for the outside of the concrete was applied. No concrete spallation and pressure contribution by gases generated for the concrete ablation were assumed. The venting valve, which has 0.01 m^2 for the area, 2 bar for the pressure criteria of the valve, and 0.1/s for the opening and closing rates, was installed between the cavity and environment to avoid an increase in cavity pressure.

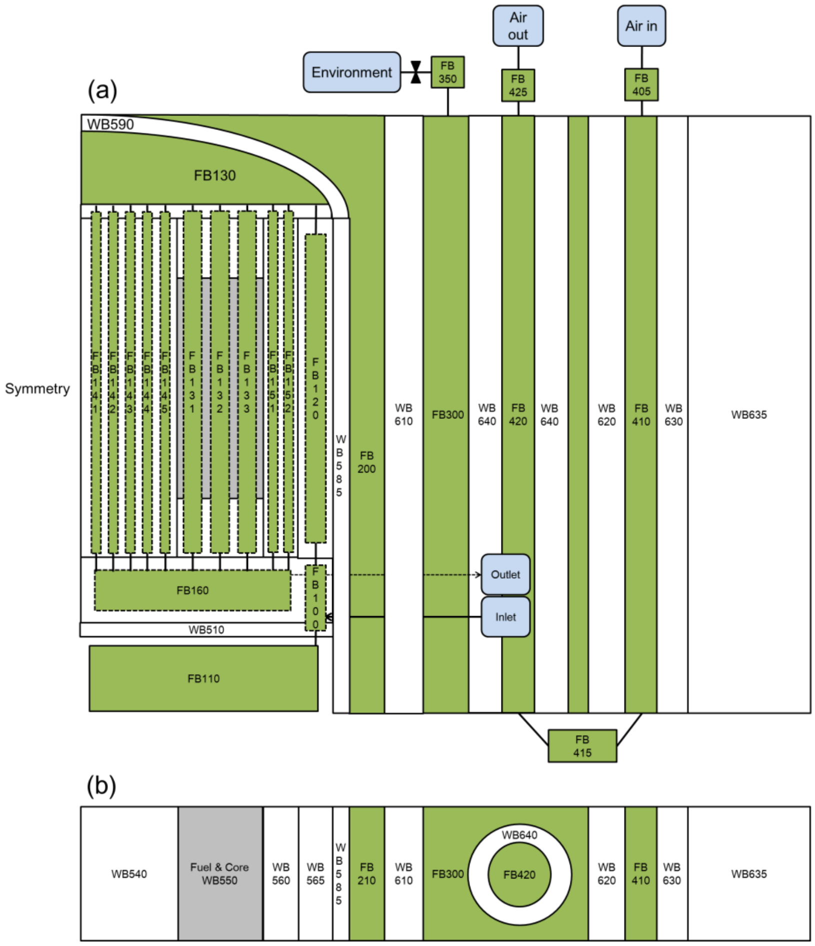
3.2.2 Concrete property

Limestone was selected as the concrete material since it satisfies both of the surface and volumetric approaches. The thermal properties of the concrete such as the specific heat, density, and thermal conductivity were obtained from the experimental results [18].

The initial weight percentage for each reactant was found from the composition of the concrete [15]. For the case of limestone, 2.3% for H_2O, 1.8% for $Ca(OH)_2$, and 35.7% for CO_2 are assigned for each initial weight percent. However, the weight percentage of free water could be diminished during the operation of the plant, since the evaporation reaction also occurred in the room temperature. Using the current fractional weight loss, α_n, we can calculated one for the next time as follows:

$$\alpha_{n+1} = Ae^{-E/RT_n}(1-\alpha_n)^3\Delta t \qquad (11)$$

As a result, Fig. 8 showed the fractional weight loss for the evaporable water was evaluated over the 10-year operation period. We selected the initial weight loss fraction of H_2O as 0.995, assuming that the accident happens after 1 year operation.



Block	Meaning	Mesh
FB100	Inlet plenum	4
FB110	Lower plenum	3
FB120	Inlet riser	16
FB130	Top plenum	3
FB131~133	Core coolant channels	14
FB141~145	Central reflector bypass	14
FB151~152	Side reflector bypass	14
FB160	Outlet plenum	10x10
FB200	Vessel cooling system	3x21
FB300,350	Reactor cavity	3x33, 1
FB405	RCCS inlet header	1
FB410	RCCS downcomer	14
FB415	RCCS lower plenum	1
FB420	RCCS riser	14
FB425	RCCS outlet header	1
WB510	Outlet plenum shield	9x2
WB540	Central reflector	5x14
WB550	Fuel & Core	3x10
WB560	Side reflector	2x14
WB565	Permanent side reflector	1x14
WB585	Core barrel	3x19
WB590	Top plenum shield	4x3
WB610	Reactor pressure vessel	5x23
WB640	RCCS panel	2x23x4
WB620	RCCS downcomer wall	3x23
WB630	Reactor cavity wall	1x23
WB635	Concrete	20x23

Fig 7. GAMMA nodalization for GT-MHR ((a) : side view, (b) : top view)

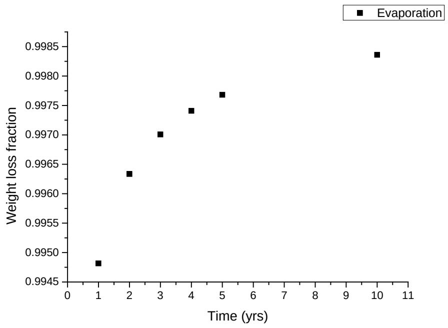


Fig 8. Weight loss fraction vs time for the evaporable water

3.4 Results

Based on the simulation results by volumetric model, the core temperature kept increasing by the graphite oxidation until 130 hours after the accident, as shown in Fig. 9. Between 130 hours and 300 hours from the accident, the maximum fuel temperature slightly decreased due to the heat transfer balance for the decay heat and energy redistribution in core and reflector regions. Eventually, the fuel kept the maximum temperature below 1600°C after 500 hours from the accident. The RPV temperature exceeds the safety limit, 600°C, for all cases. Fig. 11 showed that the thermal effect of concrete ablation was not enough to cover the RCCS operation capability. 40% of the decay heat produced at 500 hours after the accident was absorbed by the concrete wall, as shown in Fig. 12. When we define the ablation thickness of concrete as the position which the concrete temperature reached 100°C, the ablation thickness of the concrete were calculated as Fig. 13.

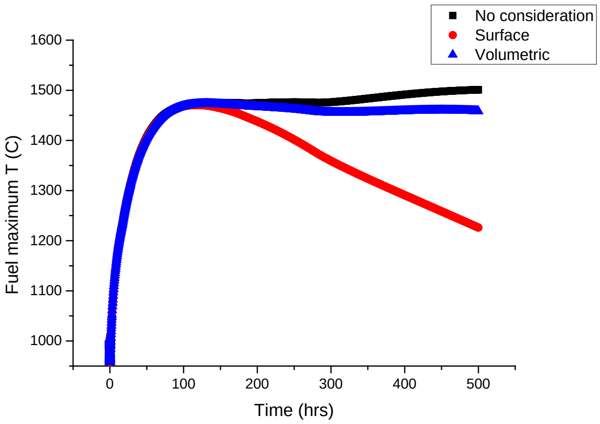


Fig 9. Trends of fuel maximum temperature

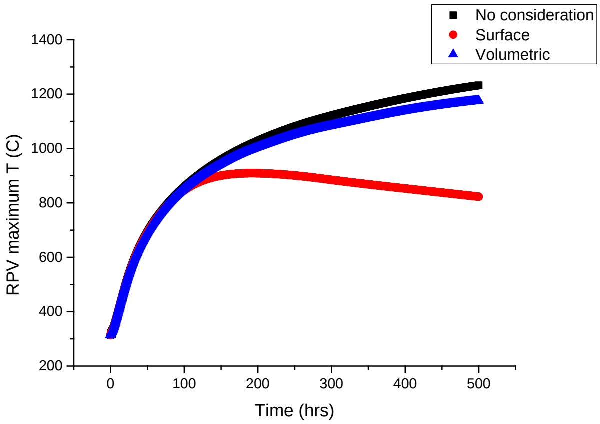


Fig 10. Trends of RPV maximum temperature

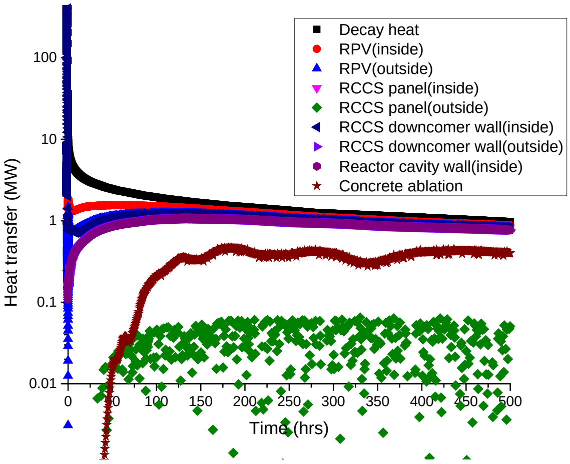


Fig 11. Trends of heat transfer

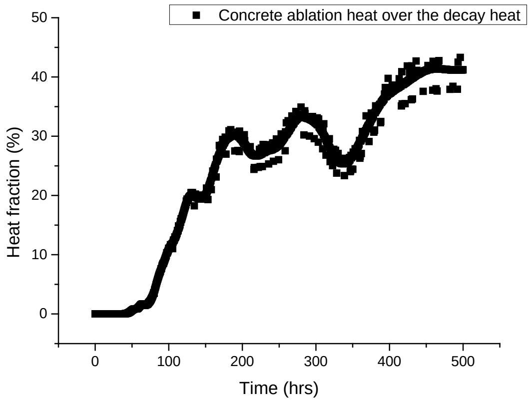


Fig 12. Trends of heat fraction for the concrete ablation heat over the decay heat

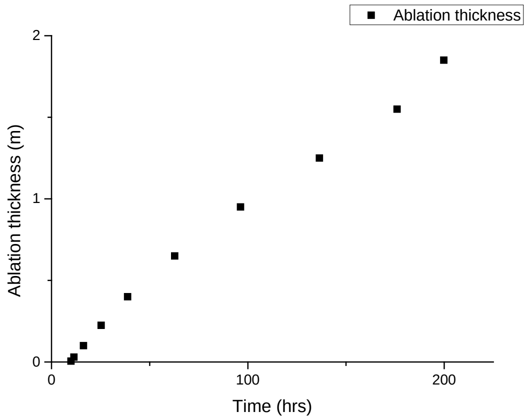


Fig 13. Trends of ablation thickness

As you see, the concrete ablation could give more thermal margins for the nuclear power plant safety. However, the concrete ablation results in an increase in the cavity pressure since the considerable amount of the steam and CO_2 by the chemical reactions are generated. Fig. 14 showed the mass of the gases generated by evaporation, dehydration and decomposition reaction. However, we assumed that these gases were released through the confinement venting valve.

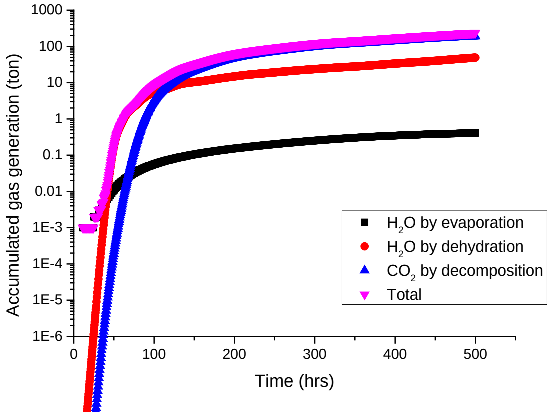


Fig 14. Trends of accumulated gas mass

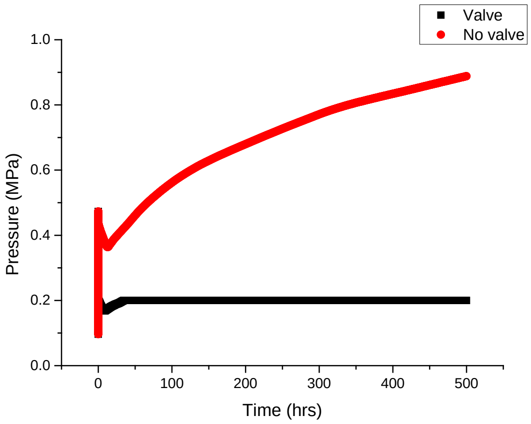


Fig 15. Trends of cavity pressure with and without the venting valve

4. Conclusions

There has been almost no investigation to analyze the safety of the nuclear power plant with the consideration of the concrete ablation effect. Using the system code, GAMMA, we assessed the complex accident scenario including air-ingress and RCCS failure. In this assessment, we found out that the concrete absorbed some fraction of decay heat below 40% and the integrity of the GT-MHR fuel was maintained within the safety limit in this accident scenario during the 500-hr transient simulation. On the other hand, the thermally-driven chemical reaction of the concrete produced a considerable amount of gases which can be released through the confinement venting valve and the RPV temperature exceeded its safety limit at 30 hour after the transient start.

Acknowledgement

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIP) (No. 2009-0083498)

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