中國機械工程學刊第四十一卷第三期第289~295頁(民國一百零九年)
Journal of the Chinese Society of Mechanical Engineers, Vol.41, No.3, pp 289~295 (2020)

Study on Ex-vessel Debris Cooling

Te-Chuan Wang*and Min Lee**

Keywords: Debris coolability, Critical Heat transfer, Kutateladze number

ABSTRACT

Uncertainty analyses are important to evaluate the response of severe accident phenomena associated with using computer codes. MAAP Users' Group (MUG) has been divided the accident phenomena into three categories, i.e. dominant, significant, and minor based on their importance to the accident sequence and progression. Ex-vessel debris cooling has been categorized as a dominant uncertainty with respect to severe accident phenomena. MAAP5 analyses have been performed to investigate the phenomena uncertainties of ex-vessel debris cooling.

Lungmen nuclear power plant (NPP), an advanced boiling water reactor (ABWR), and a station blackout accident, SRBC-PF-R-N sequence based on Final Safety Analysis Report (FSAR) of Lungmen NPP, are selected as a reference plant and a based case to investigate the uncertainties of ex-vessel debris cooling. This paper presented key parameters associated with ex-vessel debris cooling in MAAP5. For the MAAP5 uncertainty studies on ex-vessel debris cooling, heat transfer coefficients and critical heat flux Kutateladze number (FCHF) are investigated. Increase heat transfer coefficient will increase erosion distances. Maximizing the heat transfer coefficients can increase erosion distances in downward directions (about 0.3 m). But the erosion distances are less than the depth of lower drywell concrete floor (1.6 m). No sideward erosions predict for the different heat transfer coefficients. But corium can be cooled down after passive flooder opens. For FCHF is greater than 0.036, water can ingress into the debris, thus cool down the debris. Little erosions (below 0.6 m) happen in downward directions. No sideward erosions predict for FCHF greater than 0.036. However, corium can't be cool down for the small value of FCHF. Small value of FCHF represents impermeable debris. When FCHF is smaller than 0.01, that results in higher corium temperature and continuous erosion on the lower drywell floor and pedestal. At the end time of calculation (250,000 s), erosion distances in both downward and sideward directions exceed the thickness of lower drywell floor and pedestal when FCHF is equal to 0.0036. Therefore, FCHF is a very important parameter to affect ex-vessel debris cooling. This paper successfully demonstrates the key parameters that effect ex-vessel debris cooling, and analysis results can provide useful information for the MAAP5 users, Level-2 probability risk assessment (PRA), and accident management.

Paper Received December, 2019. Revised March, 2020. Accepted April, 2020. Author for Correspondence: Te-Chuan Wang

** Graduate Student, Department of Engineering and System Science, National Tsing Hua University, Hsinchu, 30013, Taiwan, R.O.C.*

*** Professor, Department of Engineering and System Science, National Tsing Hua University, Hsinchu, 30013, Taiwan, R.O.C.*

INTRODUCTION

The conditions leading to a severe accident are those with inadequate cooling of the nuclear fuel even after the reactor was shut down. It is important to cool the debris to stop the accident. If the severe accidents occur and the core debris could not be cooling within the vessel, the reactor vessel would fail and core debris would be released to the containment.

Under these conditions, the objectives of accident management are to cool the core debris by submerging it in water. Therefore, the ex-vessel debris cooling rate has significant uncertainties under these conditions. To address the importance of severe accident phenomena, uncertainty working group of MAAP Users' Group (MUG) has been divided the severe phenomena into three categories (Table I)[1], i.e. dominant, significant, and minor based on their importance to the accident progression. Ex-vessel debris cooling is also a dominant phenomenon. This paper presents the application of uncertainty methodology to ex-vessel debris cooling.

The previous experiments and research about ex-vessel debris cooling have been investigated. In order ro realistically adjust the FCHF value, the Core Concrete Interaction (CCI) series of tests (Farmer et al., 2006)[2] conducted at Argonne National

Laboratories (ANL) are the most modern experiments applicable to debris coolability. The experiments observed two major phenomena related to debris cooling: 1. a solid crust formed on the top of the molten debris after water flooding, i.e. debris uncoolability. 2.water ingression breaks the molten debris into particulated debris, i.e. debris coolability. The experimental data support a minimum long term heat flux of 250 to 300 kW/m^2, and typical values near 500 kW/m^2. In summary, a long-term heat flux between 250 and 500 kW/m^2 will be used in the current evaluation. Benchmarking results (Nagashima et al., 2012)[3] stated that the value of FCHF should varied from 0.0036 (40,000 W/m^2) to 0.1 (1,000,000 W/m^2).

With the survey of the debris bed behaviors, the major uncertainties of cooling of core debris are mainly dependent on debris configuration, debris bed permeability, heat transfer between debris and concrete. The particulated debris is easily cool down than crust formulate molten debris. Debris quenching requires by the overlying water pool and water ingression. Larger heat transfer results in lower debris temperature. Such uncertainties are easily performed using the MAAP5 code with related parameters representing the combined behavior for particulated debris, water ingression, and heat transfer.

This study uses the SRBC-PF-R-N sequence, based on the Lungmen Final Safety Analysis Report (FSAR)[4], as a based case to investigate ex-vessel debris cooling and integrity of lower drywell floor and pedestal.

TABLE I.
Preliminary Assessment Characterization of Severe Accident Physical Phenomena

Phenomena	**Dominant**	**Significant**	**Minor**
1. Clad oxidation		√	
2. Core melt relocation		√	
3. Molten pool in core		√	
4. Crust formation and failure		√	
5. RCS failure modes	√		
6. In-vessel steam explosion			√
7. In-vessel steam generation			√
8. In-vessel debris formation			√
9. RPV failure modes		√	
10. In-vessel cooling mechanism	√		
11. RPV external cooling	√		
12. Ex-vessel steam explosion			√
13. Direct containment heating		√	
14. Mark I liner attack		√	
15. Ex-vessel debris cooling	√		
16. Steam inerting of the containment	√		
17. Hydrogen burning in containment		√	

TABLE II.
Summary of Event Sequence Calculated by MAAP5 for the SBRC-PF-R-N Sequence

Events	Sec	hr	Note
Loss of all AC power MSIV closure Feedwater pump trips	0.0		
Reactor scram	4.2		High Vessel Pressure
RCIC on (suction from CST)	130		Low RPV Water Level
RCIC suction from suppression pool	3,955	1.09	Suppression Pool Level > 7.4 m
RCIC suction from CST	12,787	3.55	Suppression Pool Temperature > 350 K
Battery power unavailable RCIC off	28,800	8	
Core uncover	34,073	9.46	RPV Water Level < 9.15 m
Open 1 SRV	35,531	9.87	Core Water Level < 7.74 m
Core support plate fails	50,592	14.05	Core Support Plate Temperature > 1,650 K
RPV fails	70,469	19.57	

Passive flooder opens	74,833	20.78	Lower Drywell Temperature > 533 K

COPS opens	78,312	21.75	Wetwell pressure> 0.72 MPa
Program ends	250000	69.4	

DESCRIPTION OF LUNGMEN NUCLEAR POWR PLANT

Lungmen NPP is an ABWR plant[4] with thermal power of 3926 MWt. The reactor coolant system (RCS) utilizes 10 reactor internal pumps that eliminate the external recirculation loops and large pipe nozzles. The Emergency Core Cooling System (ECCS) and the Residual Heat Removal System (RHR) both incorporate three redundant and independent divisions. The ECCS network has each of the three divisions containing one high pressure and one low pressure inventory makeup system. The high pressure configuration consists of two motor driven High Pressure Core Flooders (HPCF) and the turbine driven Reactor Core Isolation Cooling System (RCIC). The low pressure configuration utilizes Low Pressure Flooder (LPFL) mode of RHR. Reactor Pressure Vessel (RPV) can be manually depressurized through the Safety Relief Valves (SRVs). Automatic Depressurization System (ADS) needs at least 7 SRVs to open for Lungmen NPP.

The Lungmen containment design involves several safety features to mitigate the consequences of postulated severe accidents. They are passive flooder (PF), drywell spray, and containment overpressure protection system (COPS), etc. The passive flooder opens a connection between the suppression pool and the lower drywell when the gas temperature of the lower drywell is high enough (533 K) to melt the fusible plug. The flow path is opened as a direct result of high temperature in the lower drywell and is designed to cause the lower drywell to be flooded when there is no water overlying core debris in the lower drywell. The floor of the Lungmen NPP lower drywell includes a 1.6 meter layer of concrete above the containment liner. The sidewalls of lower drywell for the Lungmen NPP is the pedestal. The key design of severe accident mitigation for Lungmen NPP is basaltic concrete in the lower drywell floor and pedestal. Basaltic concrete produces less non-condensable gases than limestone-common sand concrete does. This will reduce the impact of containment pressurization because of production of non-condensable gases. However, basaltic concrete is more rapidly eroded during core concrete interaction than limestone-common sand is. Therefore, one would expect the erosion rate would be faster in the Lungmen NPP. The width of the pedestal is 1.7 meter.

The drywell spray is one of the RHR modes. The spray keeps the upper drywell cool during severe accidents, preventing degradation of penetration seals to avoid leakage through the movable penetrations. The COPS consists of two 8 in-diameter overpressure relief rupture disks. To relieve containment pressure, the rupture disk must burst and the escaping fission products are forced through the suppression pool such that any fission product release to the environment is greatly reduced. The rupture disk will burst when the wetwell pressure reaches to 0.72 MPa. The Lungmen containment configuration is shown in Fig. 1.

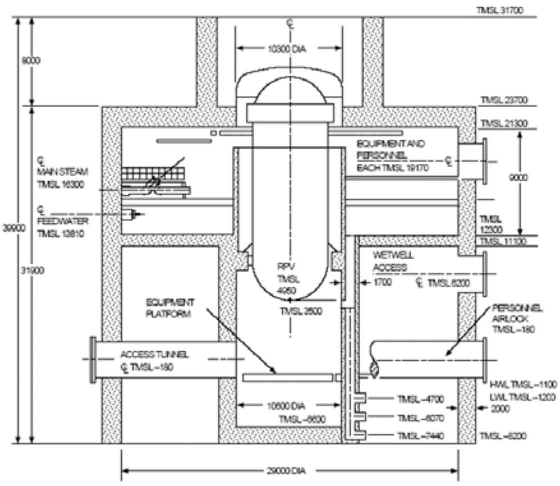

Fig. 1 Lungmen Containment Configuration

BRIEF DESCRIPTION OF MAAP5 CODE

MAAP5[5](Modular Accident Analysis Program Rev. 5.0.0), developed by Fauske & Associates, Inc.'s (FAI) based on the MAAP4 code, is a severe accident analysis code. It is a computer program capable of simulating the response and mitigation actions of light water reactor NPPs including ABWR during severe accidents. It was expanded from MAAP4 to include the necessary models for accident management assessment. MAAP5 provides a flexible, efficient, integrated tool for evaluating the in-plant effects of a wide range of postulated accidents and for examining the impact of operator actions on accident progressions. The entire spectra of severe accident phenomena, including core heatup, degradation and relocation, lower plenum phenomenology, corium-concrete interactions, containment hydraulics, hydrogen combustion, passive flooder opens, COPS activation, and radionuclide release and transport are modeled in MAAP5. Users need to set up the MAAP5 parameter file and input file to run MAAP5 code. In the parameter file, users should specify the plant and system configurations, including reactor core parameters, primary systems and safety systems parameters, containment and auxiliary building parameters, and engineered safeguards safety systems. The values of parameters used for the MAAP5 models governing these phenomena are based on MAAP5 suggestion. In the input file, users should define the sequence and operation interventions. The MAAP5 code is used in this analysis. The MAAP5 reactor and containment nodalizations of Lungmen NPP are shown in Fig. 2 and Fig. 3.

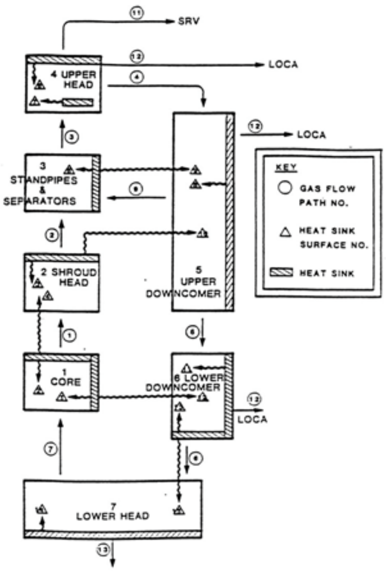

Fig. 2 MAAP5 Reactor Nodalizations

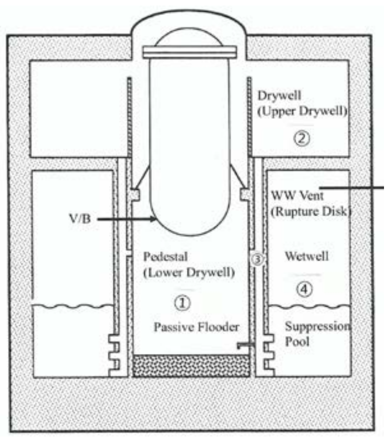

Fig. 3 MAAP5 Containment Nodalizations

SBRC-PF-R-N sequence analysis

The SBRC-PF-R-N accident is initiated by loss of on-site and off-site AC power (SB) with RCIC operating for 8 hours (RC). Passive flooder (PF) is actuated to flood the lower drywell and the fission products are released through the overpressure protection relief rupture disk (R). This accident sequence is denoted as SBRC-PF-R-N. This sequence assumes that RCIC system operates for 8 hours, providing core cooling. After RCIC fails, core water level begins to fall. Then core damage will occur. The operator depressurizes the vessel when water level reaches about two-thirds core height by opening one SRV. Because of loss of all core cooling systems, the fuel melts and finally vessel fails. After vessel failure, the core debris and lower plenum water will fall to the lower drywell floor. The containment continues to pressurize as water boils. When lower drywell dries out, the core debris begins to heat up. The core debris radiates energy to the lower drywell gas. The passive flooder will open after the lower drywell gas temperature reaches 533 K. When the passive flooder opens, water pours from the wetwell into the lower drywell. This quenches the corium and causes the wetwell pressure to increase rapidly to the rupture disk rupture pressure 0.72 MPa. The major sequence of events is demonstrated in Table II.

UNCERTAINTY STUDIES ON EX-VESSEL DEBRIS COOLING

Before the uncertainty studies, the important input parameters for ex-vessel debris cooling in MAAP5 are listed below:

1. HTCMCR: HTCMCR is the nominal downward heat transfer coefficient for convective heat transfer from molten corium to the lower crust for corium-concrete interaction calculations. The default value of HTCMCR is 3500 W/m^{2o}C. The minimum and maximum values of HTCMCR are 500 and 10000 W/m^{2o}C, respectively. HTCMCR is the equivalent heat transfer coefficient for downward heat transfer.
2. HTCMCS: HTCMCS is the nominal sideward heat transfer coefficient for convective heat transfer from molten corium to the side crust for corium-concrete interaction calculations. The default value of HTCMCR is 3000 W/m^{2o}C. The minimum and maximum values of HTCMCS are 500 and 10000 W/m^{2o}C, respectively. HTCMCS is the equivalent heat transfer coefficient for sideward heat transfer.
3. HTCMCU: HTCMCU is the nominal upward heat transfer coefficient for convective heat transfer from molten corium to the upper crust or upper interface (if the crust does not exist) for corium-concrete interaction calculations. The default value of HTCMCU is 3000 W/m^{2o}C. The minimum and maximum values of HTCMCU are 500 and 10000 W/m^{2o}C, respectively. HTCMCS is the equivalent heat transfer coefficient for upward heat transfer.
4. FCHF: FCHF is the critical heat flux (CHF) Kutateladze number. Kutateladze number (Ku) is the ratio of latent heat of phase change to convective heat transfer and defined as :

$$Ku = h_{fg} / C_p \Delta T.$$

Where h_{fg} is latent heat of evaporation, C_p is the specific heat capacity of the fluid and ΔT is the difference between the temperature of the liquid and saturation temperature. This number applies to the case of pool levitation of droplets from a heated surface in contact with an overlying water pool. Large values (on the order of 0.1) represent efficient water ingression, resulting in coolable debris. Small values (on the order of 0.0036) represent impermeable debris. The uncoolable debris transfers energy to concrete, resulting in concrete erosion and subsequent pressurization of the containment. Hence, the value of FCHF has a strong influence on concrete erosion and containment failure.

The HTCMCR, HTCMCS, and HTCMCU are associated with heat transfer from the corium to concrete. Increase these parameters will increase heat transfer and results in more erosion. The FCHF is associated with corium coolability. Small value represents water can't impermeable into the corium. That will also results in more erosion. In order to achieve larger erosion distances, the sensitivity studies can be divided into two categories:

(1). Maximize heat transfer coefficients

Maximizing and minimizing heat transfer coefficients are to understand ex-vessel debris cooling and maximum erosion distances on core concrete interaction. Set the maximum values for HTCMCR, HTCMCS, and HTCMCU. That is HTCMCR=10,000, HTCMCS=10,000, and HTCMCU=10,000. Set the minimum values for HTCMCR, CTCMCS, and HTCMCU. That is HTCMCR=500, HTCMCS=500, and HTCMCU=500. Analysis results are compared with those of suggested values (HTCMCR=3500, HTCMCS=3000, and HTCMCU=3000) and shown in Fig. 4 , Fig. 5 and Fig. 6. As the Figures show, the erosion begins after vessel failure (70,469 s). Maximizing the heat transfer coefficients can increase erosion distances in downward directions (about 0.3 m). But the erosion distances are less than the depth of lower drywell concrete floor (1.6 m). No sideward erosions predict for the different heat transfer coefficients. Corium in lower drywell for both cases can be cooled down after passive flooder opens (74,833 s).

(2). Minimize water ingression

Minimizing water ingression into the debris can cause uncoolable debris. That results in more core concrete interaction on the lower drywell floor and pedestal. Set the FCHF to the maximum value (0.3), reduced to 10% of the suggested value (0.01), increased to 10 times of the minimum value (0.036), and the minimum value (0.0036) to investigate the erosion distances on the lower drywell floor and pedestal. The analysis results are also compared with those of the suggested value (0.1) and shown in Fig. 7, Fig.8 and Fig. 9. For the larger FCHF values (greater than 0.036), water can ingress into the debris and cool down the debris. Little erosions (below 0.6 m) happen in downward directions. No sideward erosions predict for FCHF greater than 0.036. For the smaller FCHF values (smaller than 0.01), they represent impermeable debris. Corium in the lower drywell can't be cool down quickly (Fig. 9) after passive flooder open (74,833 s). That results in larger erosion distances in both downward and sideward directions (Fig. 7 and Fig. 8). Although average temperature of corium in lower drywel drops slowly for FCHF=0.01, corium temperature is still higher than 1000 K (Fig. 9). Erosion in both downward and sideward directions occurs. Erosion in downward direction exceeds the thickness of lower drywell floor (1.6 m) at the end time of calculation (250,000 s). Erosion distances in both downward and sideward directions exceed the thickness of lower drywell floor and pedestal (1.7 m) at 250,000 sec when FCHF is equal to 0.0036.

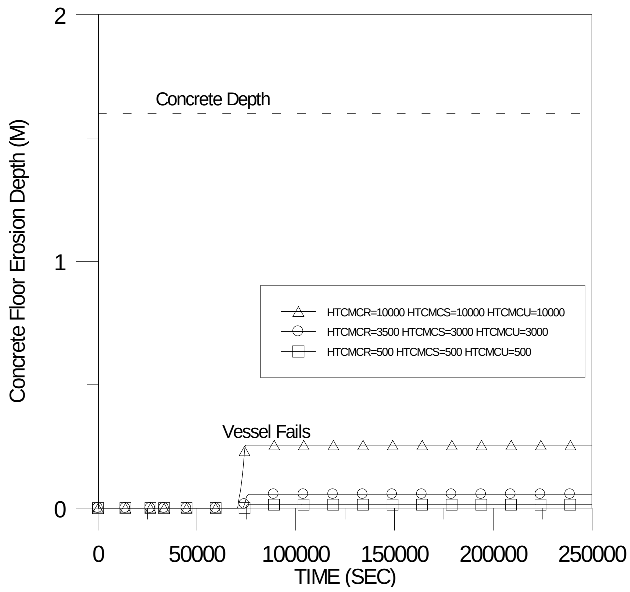

Fig. 4 Downward Erosion Depth for Different Heat Transfer Coefficients in the SBRC-PF-R-N Sequence

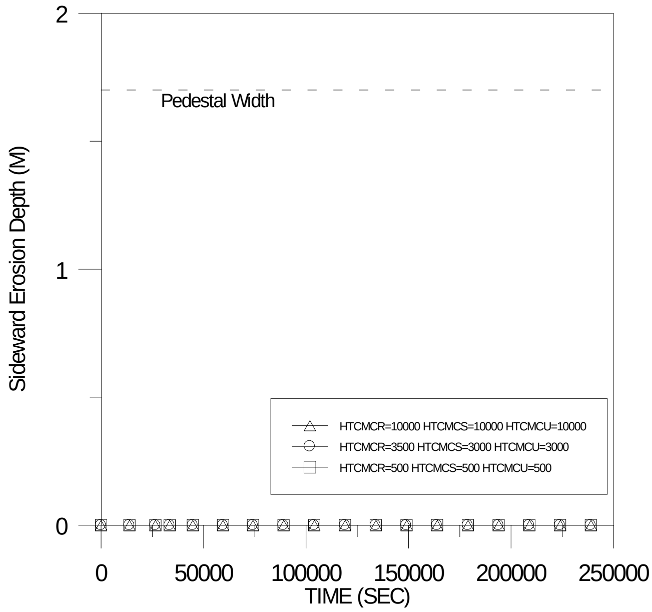

Fig. 5 Sideward Erosion Depth for Different Heat Transfer Coefficients in the SBRC-PF-R-N Sequence.

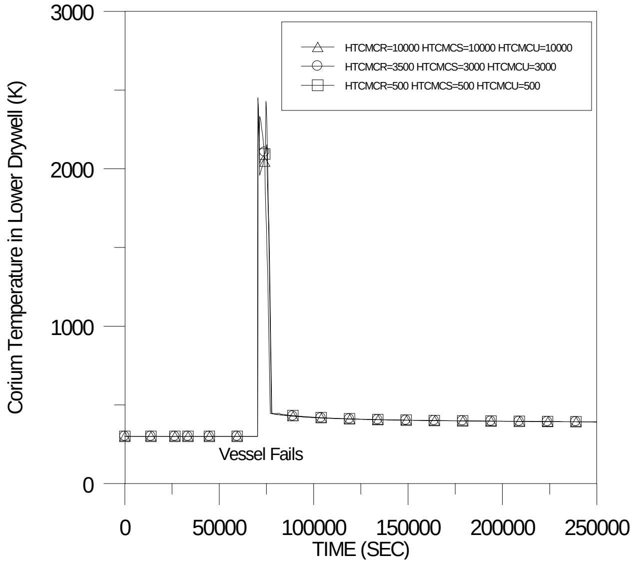

Fig. 6 Average Temperature of Corium in Lower Drywell for Different Heat Transfer Coefficients in the SBRC-PF-R-N Sequence

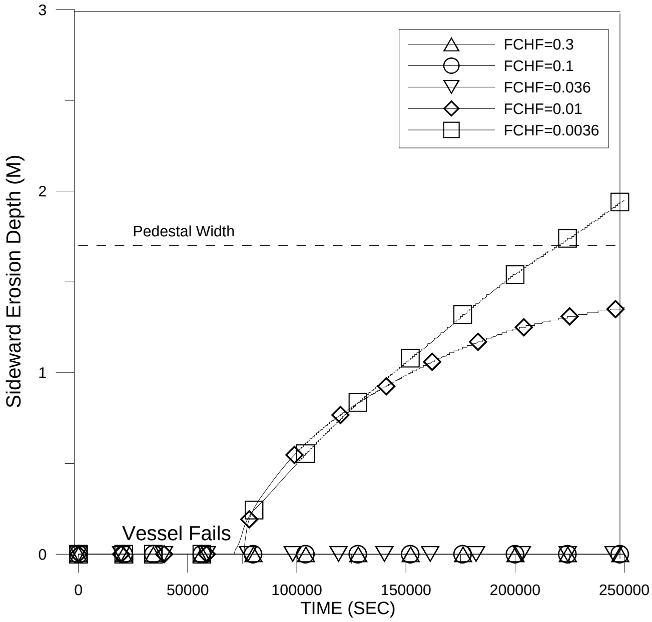

Fig. 8 Sideward Erosion Depth for Different FCHF in the SBRC-PF-R-N Sequence

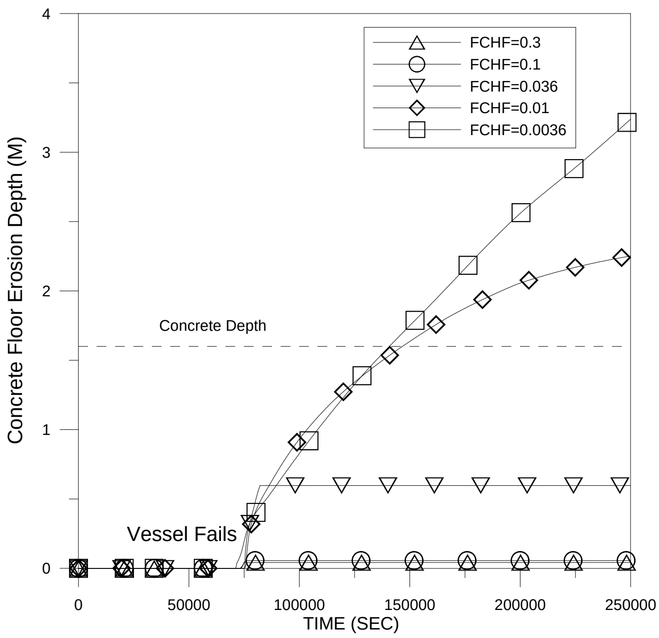

Fig. 7 Downward Erosion Depth for Different FCHF in the SBRC-PF-R-N Sequence

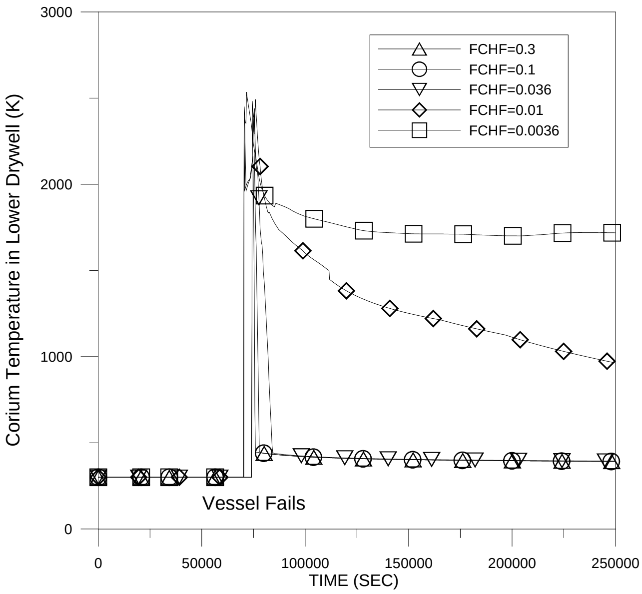

Fig. 9 Average Temperature of Corium in Lower Drywell for Different FCHF in the SBRC-PF-R-N Sequence

CONCLUSION

For the sensitivity studies on ex-vessel debris cooling, increased heat transfer coefficient will increase erosion distances. Maximizing the heat transfer coefficients can increase erosion distances in downward directions (about 0.3 m). But the erosion distances are less than the depth of lower drywell concrete floor (1.6 m). No sideward erosions predict for the different heat transfer coefficients. But corium can be cooled down after passive flooder opens. The erosion distances are within the thickness of lower drywell floor and pedestal. For the larger FCHF values (greater than 0.036), water can ingress into the debris and cool down the debris. Little erosions (below 0.6 m) happen in downward directions. No sideward erosions predict for FCHF greater than 0.036. However, corium can't be cool down for the small value of FCHF. Small value of FCHF represents uncoolable corium. When FCHF is smaller than 0.01, that results in higher corium temperature and continuous erosion on the lower drywell floor and pedestal. At the end time of calculation (250,000 s), erosion distances in both downward and sideward directions exceed the thickness of lower drywell floor and pedestal when FCHF is equal to 0.0036. Therefore, FCHF is a very important parameter to affect ex-vessel debris cooling and core concrete interaction.

ACKNOWLEDGMENTS

The authors would like to thank the Taiwan Power Company (TPC) for supporting this work.

REFERENCES

Farmer, M.T., Lomperski, S., Kilsdonk, K., Aeschlimann, R.K., Basu, S., "OECD MCCI Project 2-D Core Concrete Interaction (CCI) Tests: Final Report," OECD/MCCI-2005-TR05, Feb. (2006).

Henry, R.E., Paik, C.Y., Henry, C.E., "MAAP5-Modular Accident Analysis Program for LWR Power Plants," Fauske & Associates, Inc. (2008).

Nagashima, K., et al., "Application of Uncertainty Analyses with the MAAP4," Uncertainty Working Group of the MAAP User's Group, (1995).

Nagashima, K., et al., " MAAP4 Uncertainty and Sensitivity Analysis," Uncertainty Working Group of MAAP Users's Group, (2012).

Taiwan Power Company., "Final Safety Analysis Report of Lungmen Nuclear Power Station," (2007).

爐外熔渣冷卻研究

王德全 李敏
國立清華大學工程與系統科學系

摘要

爐外熔渣是否可被冷卻是嚴重事故一個重要的物理現象，對事故演進與後果影響很大，本研究使用美國電力研究所(EPRI)所發展的MAAP5程式，進行爐外熔渣是否可被冷卻的工具，MAAP5程式為核能工業界廣泛使用之嚴重事故分析程式，目前台灣廣泛使用在嚴重事故現象的研究。研究方法是對爐外熔渣冷卻有關的參數進行靈敏度分析，結果發現增加熱傳係數會增加向下侵蝕厚度(約0.3 m)，但仍小於下乾井水泥地板的厚度(1.6 m)，但不會造成側向的侵蝕，被動式淹灌器(Flooder)開啟後，熔渣即可被水冷卻。臨界熱通率Kutateladze number (FCHF)對爐外熔渣冷卻有顯著的影響，較大的FCHF(大於0.036)可讓冷卻水可滲入熔渣並進而冷卻熔渣，只會造成向下些許的侵蝕(低於0.6 m)，並不會造成側向侵蝕。較小之FCHF(小於0.01)無法完全讓冷卻水滲入熔渣進行冷卻，當FCHF值等於0.01，被動式淹灌器開啟後，雖然熔渣溫度緩慢下降，但仍高於1000 K，使得水泥地板與基座持續侵蝕，在計算結束時(250,000 秒)，會使得熔渣的溫度上升，並持續侵蝕水泥地板與基座(Pedestal)，計算結束時(250,000 秒)，向下侵蝕會超過地板水泥的厚度。當FCHF值等於0.0036，在250,000秒時，側向與向下侵蝕都超過基座(1.7 m)與地板水泥的厚度。因此FCHF對爐外熔渣冷卻是一個很重要的參數。