Crust Formation and Growth in Analysis of Molten Corium and Concrete Interaction

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CONTENTS

1. Introduction

Research Scope

COCCA

(Code Of Corium Coolability Analysis)

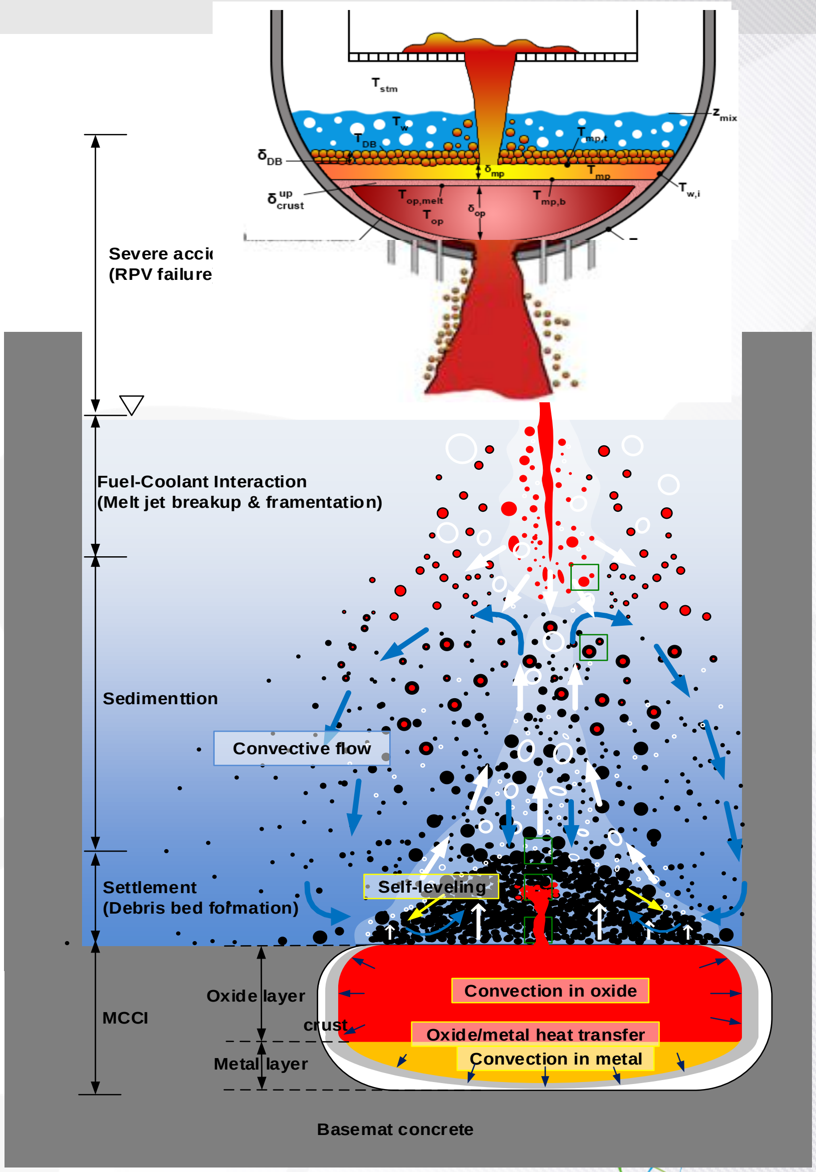
+

COCCI

(Code Of Corium-Concrete Interaction)

= **CASTLE**

(**CA**vity **S**evere acciden**T** rea**L**istic **E**valuation)

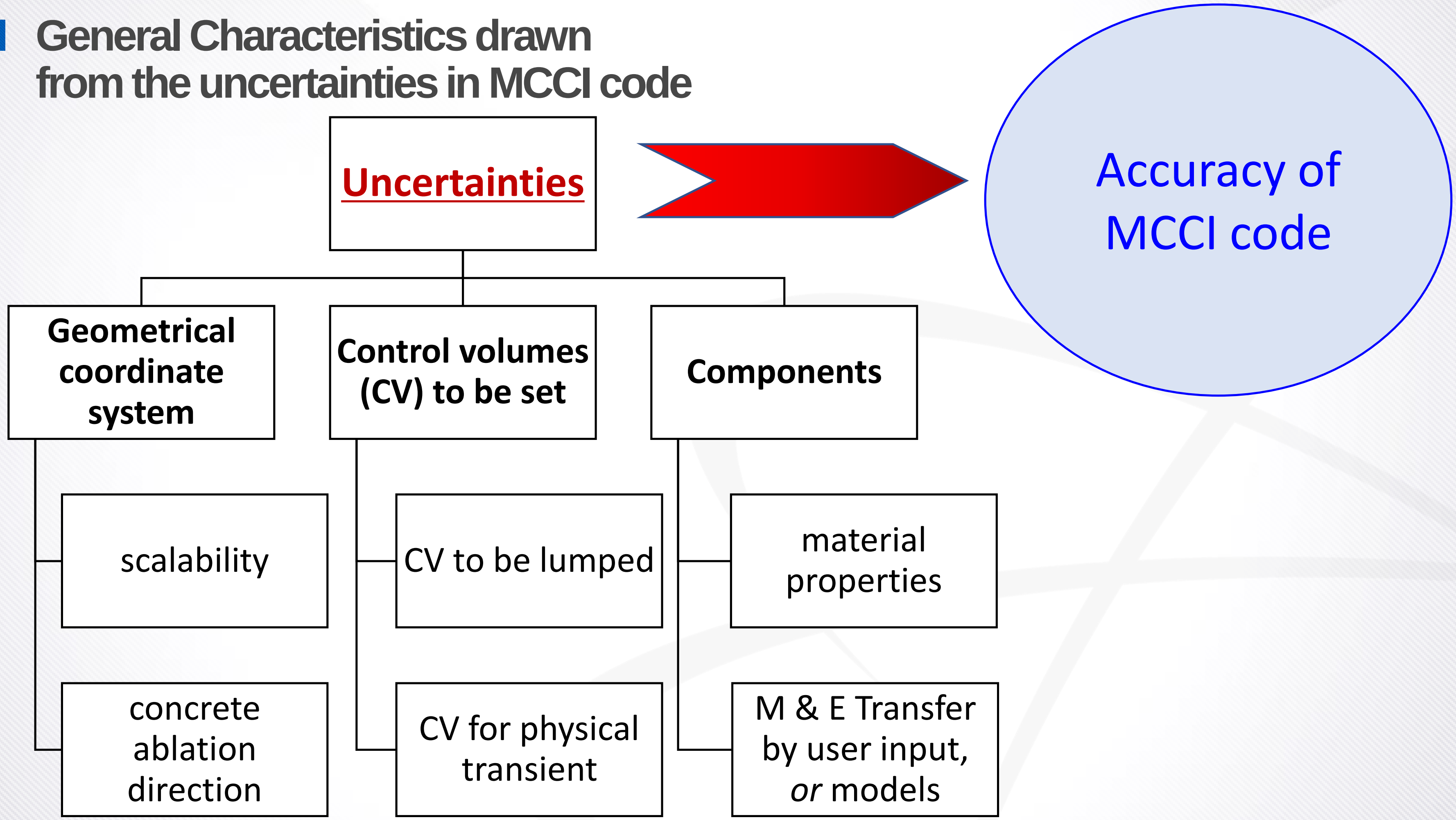


Purpose of this Paper

- To develop the analysis system and general characteristics of COCCI

1. Introduction

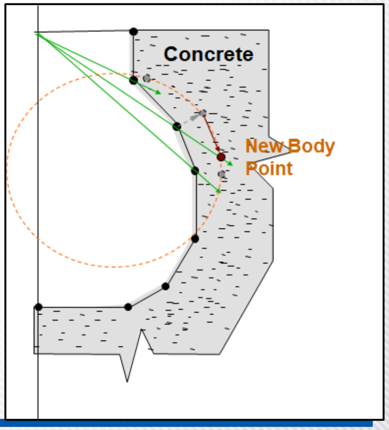
- **General Characteristics drawn from the uncertainties in MCCI code**



2. Review of MCCI Codes

1) MELCOR

- The modeling for the MCCI in MELCOR code is based on the CORCON-Mod3 code [1]. In the MELCOR version 1.8.5, the conservative assumption that water cannot penetrate crust was applied. It was revised by promoting quenching by increasing the thermal conductivities.
- The current version includes the model on water ingression.
- The approach for the crust formation is to construct a steady-state solution to the heat-transfer equations in a right circular cylinder whose average temperature, boundary temperatures, thickness, and volume all match those of the actual layer [2].
- The steady-state conduction leads to quadratic temperature profiles inside the crust.
- Newton's iteration is utilized for calculating the thickness and temperature of the sub-layer.
- And then, the heat fluxes are calculated and used for the heat transfer to the corresponding boundaries.



2. Review of MCCI Codes

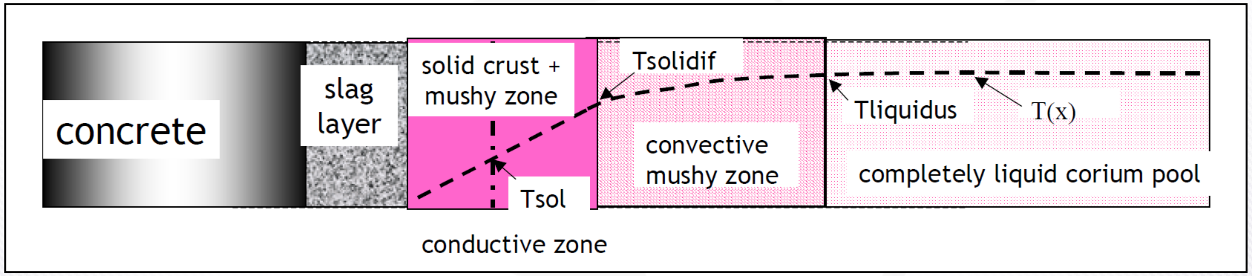
2) MAAP5

- MAAP is a modular accident analysis program that simulates various severe accident sequences [3].
- In the MAAP5 code, the interface of the molten debris and its crust is at the debris melting point.
- Due to the internal heating, three independent crusts, the lower, side, and upper crust, are assumed to have parabolic temperature profiles.
- Based on the temperature profiles, the interface temperatures between the crust and the concrete are calculated.
- The temperature profile in concrete is one-dimensional in the direction of ablation.
- In the case of the upper crust, the heat transfer is calculated based on the convection and radiation to the surroundings.

2. Review of MCCI Codes

3) ASTEC-V2

- In an ASTEC code, the crust that can grow up at the corium-atmosphere interface can be simulated by two different methods [4].
- First, the crust is regarded as a fictive layer. It is calculated under the assumption of the heat flux continuity at the interface. Second, the crust is regarded as an independent layer with a liquid or mushy corium layer.
- The solidification or melting of the crust is determined by the difference between the convection heat flux and conduction heat flux. The mass flow rate from or to the crust also comes from the heat flux difference.
- Based on the two estimated heat fluxes, the interface temperature is calculated.



Layer Build-up in ASTEC code [4]

2. Review of MCCI Codes

4) CORQUENCH-4.1

- In a CORQUENCH code, when the top interface temperature of a corium layer is smaller than the freezing temperature, the potential exists for crust formation to occur at the melt-atmosphere interface depending upon the thermal-hydraulic conditions [5].
- The crust growth depends on whether the incipient crust is stable in the presence of the sparging concrete decomposition gases.
- During the incipient growth phase, the crust will remain thin and decay heat within the crust is negligible. Under the condition, the crust growth rate is calculated by the heat flux difference between the convection and conduction.
- The force balance about the buoyancy force of a rising bubble to the load is calculated to determine whether the crust segment is in a stable state.

2. Review of MCCI Codes

5) WECHSL

- In The WECHSL-Mod3 code is a mechanistic computer code developed by FZK in Germany for the analysis of the thermal and chemical interaction of initially molten reactor materials with concrete in a cavity [6].
- In the WECHSL code, the crust formation is governed by the following mechanisms:

  ✓ The temperature at the crust internal side is freezing temperature. And heat is transferred by the temperature difference with the bulk temperature of melt pool.

  ✓ Heat is transferred by the heat conduction through the crust.

  ✓ Heat is transferred at the crust external side by the temperature difference between interface and surroundings.

- In case that the crust is thin, the steady state heat conduction is solved. Otherwise, the transient heat conduction is applied.

3. Methodology in the Developing MCCI Code

General descriptions of the COCCI code

- A domestic computer code for the analysis of MCCI named Code of Corium-Concrete Interaction (COCCI) is under development.
- The analysis system and general characteristics of COCCI were presented in the previous paper [7].
- In the COCCI, independent mass and energy transfer rates and terms are calculated in every time step.
- Based on the values, each mass or energy equation is solved.
- Independent control volumes were basically defined in the code.
- In the definition of the control volume, the meaning of the relative position and representative material properties is indicated.

3. Methodology in the Developing MCCI Code

» Lumped control volumes in the COCCI code

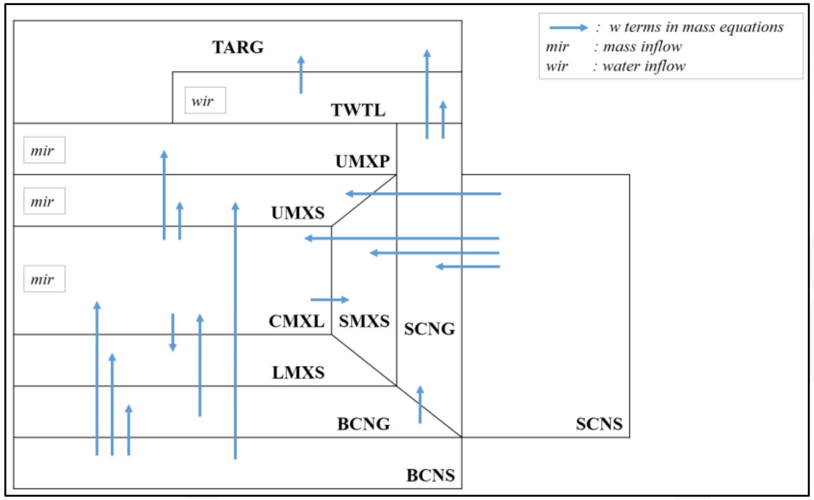
- **Mass and energy flow between the control volumes**

❖ Layer Notation: 'abbc'

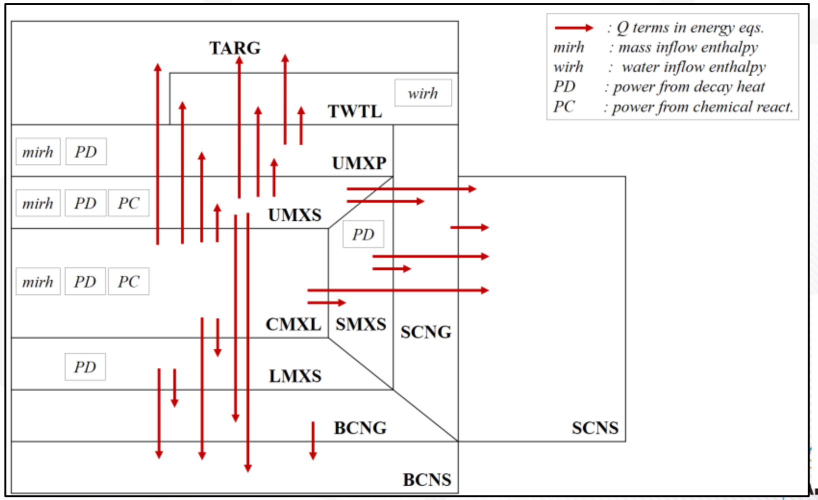
- 'a': location
- 'bb': material composition
- 'c': dominant phase

❖ Example layers

- 중심 혼합물 액체층 (Central MiXture Liquid, CMXL)
- 상부 혼합물 고체층 (Upper MiXture Solid, UMXS)
- 측면 혼합물 고체층 (Side MiXture Solid, SMXS)
- 하부 혼합물 고체층 (Lower MiXture Solid, LMXS)
- 상부 혼합물 입자층 (Upper MiXture Particle-bed, UMXP)
- 측면 콘크리트 기체층 (Side CoNcrete Gas, SCNG)
- 측면 콘크리트 고체층 (Side CoNcrete Solid, SCNS)
- 하부경계 콘크리트 기체층 (Bottom CoNcrete Gas, BCNG)
- 하부경계 콘크리트 고체층 (Bottom CoNcrete Solid, BCNS)
- 상부경계 냉각수 액체층 (Top WaTer Liquid, TWTL)
- 상부경계 공기 기체층 (Top AiR Gas, TARG),



Mass transfer in CAC-2D



Energy transfer in CAC-2D

3. Methodology in the Developing MCCI Code

Crust formation and growth in the COCCI code

- Crusts in the COCCI consists of UMXS, SMXS, and LMXS according to the locations, upper, side, and lower. MXS means a mixture solid.
- The crust is formed when the interface temperature of CMXL (Center Mixture Liquid) is lower than the solidus temperature of the corium mixture.
- According to the location of the crust formation, one of the three control volumes is determined to be formed.
- The solidification of the liquid layer or melting of the solid layer is wholly dependent on the governing energy equation. Based on the calculated temperatures in the configuration of layers, heat fluxes at the interfaces are calculated.
- Surplus of energy in the crust layer causes the melting of the layer, and lack of energy in the liquid layer causes the solidification of the layer.

3. Methodology in the Developing MCCI Code

Crust formation and growth in the COCCI code

- **After the corium lumps are discharged from the reactor vessel to the reactor cavity, they spread and remain static.**
- **In the initial time of being static, the mass of the CMXL increased due to the inflow of the concrete ablated by the heat transfer from CMXL to the concrete layers.**
- **After that, the surface temperature of the CMXL decreased to the solidus temperature of the corium mixture layer. The mass of the crust on each direction gradually increased as the CMXL was cooled.**

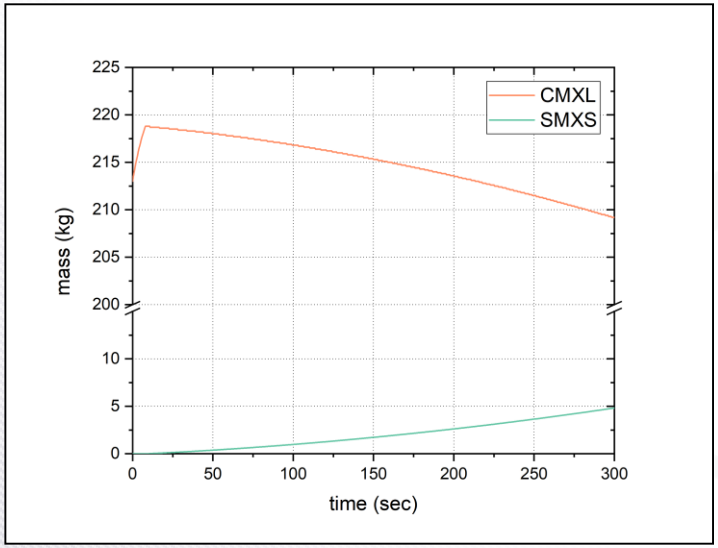


Fig. Mass Variations of Control Volumes in COCCI Code

4. Conclusions

- **The analysis system of the COCCI is established for :**
  - having various geometrical analysis coordinate systems
  - modeling the physical transient phenomena
  - seeking broad extensibility and applicability

- **The analysis methodologies for the crust formation and growth are reviewed in the existing MCCI analysis codes.**

- **The analytic characteristics for the crust formation and growth in the developing COCCI were explained.**

References

[1] USNRC, MELCOR Computer Code Manuals Vol. 1: Primer and Users' Guide, Sandia National Laboratories, SAND2021-0252 O, January 2021.

[2] Sandia National Laboratories, CORCON-MOD3: And Integrated Computer Model for Analysis of Molten Core-Concrete Interactions, NUREG/CR-5843, SAND92-0167, 1993.

[3] FAI, Modular Accident Analysis Program 5, November, 2008.

[4] IRSN, ASTEC V2 MEDICIS MCCI module – Theoretical manual, DPAM/SEMIC, 2008-102, 2008.

[5] Farmer, M.T., 2018. The CORQUENCH Code for Modeling of Ex-Vessel Corium Coolability Under Top Flooding Conditions, Code Manual – Version 4.1b, No. ANL-18/22. Argonne National Lab. (ANL), Argonne, IL (United States).

[6] J.J. Foit et al., The WECHSL-Mod3 Code: A computer program for the interaction of a core melt with concrete including the long term behavior, FZKA 5522, 1995.

[7] S.H. Kim et al., "Development of Computer Code for Analysis of Molten Corium and Concrete Interaction," Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, July 9-10, 2020.

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