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PHYSICS OF COOLABILITY OF TOP FLOODED MOLTEN CORIUM

P.P. Kulkarni, R. K. Singh, A. K. Nayak, P. K. Vijayan, D. Saha and R. K. Sinha
Reactor Design and Development Group,
Bhabha Atomic Research Centre,
Trombay, Mumbai, India

Abstract

During a postulated severe accident in a nuclear reactor in case of ex-vessel scenario the molten corium can be relocated in the containment cavity forming a melt pool. In order to arrest further progression of severe accident, complete quenching of the molten corium pool is necessary. Most common way to deal with ex-vessel scenario is to flood the melt pool with large quantity of water. However, the mechanism of coolability is much more complex involving multi-component, multiphase heat, mass and momentum transfer.

In this paper, a mechanistic model has been presented for the corium coolability under top flooding conditions. The model has been validated with the experimental data of COMECO test facility available in literature. Simulations have been carried out using the model to explore the physics behind the corium coolability with MCCI under top flooding condition. Variations in the thermo-physical properties as a result of MCCI have been considered and its effect on coolability has been studied.

Introduction

During a postulated severe accident, the core can melt, and the melt can fail the reactor vessel. Subsequently, the molten corium can be relocated to the containment cavity forming a melt pool. During the accident progression, the properties of corium such as the viscosity, the melt temperature and thermal conductivity can change drastically due to its interactions with the in-vessel and ex-vessel structures and also with the concrete basement. Similarly, the Modulus of Elasticity, tensile strength and linear thermal expansion coefficient which are some of the key parameters that determine the crack formation during melt quenching, can change depending on the amount of structural and concrete materials mixing with corium. Ex-vessel melt coolability is one of the most critical issues for the safety of current and future light water reactors with respect to stabilization and termination of a postulated severe accident. The most convenient accident management strategy is to cool the melt pool by flooding it from the top. However, the question that arises is to what extent the water ingresses in the corium can melt pool to quench and cool it? When the cavity is flooded with water from top, immediately a crust is formed on the upper surface of the melt pool, which is found to limit the access of the water over-layer to the melt pool below the crust. Initially, due to the intense stirring because of gases liberating during MCCI, the crust will not be stable and bulk cooling will take place. But after some time, as the gas flow rate decreases, a stable crust will prevail. After the stable crust is formed there may be anchoring of crust to the sidewalls of the vessel which may result in a considerable drop in the heat transfer rate due to induced gap in between the crust and the melt pool lying below. Although, the crust limits the water inflow, cooling may occur by different mechanisms like mechanical breach of crust due to its own weight, volcanic eruptions in the crust and water ingression. Water ingresses through the gaps and fissures of the crust enhancing the coolability. Very little information is available at present on the knowledge of mechanism of water ingression or why the water ingression stops after certain depth is reached.

A literature review suggests that there are very little efforts on modeling of water ingression phenomena, both from top and bottom flooding. Originally, the motivation behind modeling of water ingression phenomenon did not aim to study the quenching of molten corium pool during a postulated severe accident condition in a LWR. In fact, models were developed for simulation of cracking behaviour of hot rocks in geological reservoirs. In this context, Lister [1] has done pioneering work in modeling the penetration of water into hot rocks by considering the simplest possible one dimensional model based on the concept of crack front propagation. While Lister's model considered penetration of water into hot but initially solid rock under high pressure condition, Epstein [2] used models of bulk permeability of cracked rock and developed a model for water penetration into initially molten, heat generating rock like material at low pressure which resembles the water ingression phenomena into molten corium pool. In ANL, an integrated model for quenching behaviour (CORQUENCH) [3] which allows 1-D or simplified 2-D ablation calculations with detail sources and sink terms has been developed. Widmann et al [4] have attempted theoretical modeling of the COMET concept by considering porosity formation based on pressure rise due to steam formation below the crust in bottom flooding scenario. However, these models incorporate lot of empirical correlations for describing various phenomena instead of solving phasic equations. There are almost no attempts have been made to derive a complete mechanistic model for explaining these phenomena. The purpose of this work is to investigate and clarify the water ingression and melt coolability behaviour when the melt pool is flooded from the top in an ex-vessel situation. Towards this purpose, mechanistic models were developed to simulate quenching of top and bottom flooded molten pool.

1. Model description

The model considers the heat transfer behaviour in axial and radial directions from the molten pool to the overlaying water, crust generation and growth, thermal stresses built-in the crust, disintegration of crust into debris by brittle fracture, natural convection heat transfer in debris and water ingression into the debris bed. To validate the model, we conducted experiments in a facility named as COMECO [5]. The model was used to simulate the quenching behaviour of the COMECO tests.

1.1 Governing equations

The conservation equations of mass, momentum and energy from the molten pool to the overlaying water (Fig. 1) as described below:

Molten pool region: In molten pool region, equations are solved for natural convection in the melt pool

$$\frac{\partial \mathrm{T}}{\partial t} + V \cdot \nabla T = \alpha \nabla^2 T + \frac{q'''}{\rho C_p} \tag{1}$$

$$\nabla . V = 0 \tag{2}$$

$$\frac{\partial \mathrm{V}}{\partial t} + (V \cdot \nabla) V = -\frac{\nabla p}{\rho} + \frac{\mu}{\rho} \nabla^2 V + f \tag{3}$$

Solid crust region: Heat transfer in solid crust is due to conduction only. The energy equation can be written as

$$\rho C_p \frac{\partial \mathrm{T}}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r}\left(r \cdot k \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z} \right) + q''' \tag{4}$$

Debris region: Single phase mass, momentum and energy equation in debris

$$\nabla \cdot V = 0 \tag{5}$$

$$V = \frac{\kappa}{\mu}(-\nabla \cdot p + \rho g) \tag{6}$$

$$\gamma_1 \frac{\partial \mathrm{T}}{\partial t} + V \cdot \nabla T = \alpha \nabla^2 T + \frac{q'''}{(\rho C_p)_f} \tag{7}$$

Here q''' is heat generation term in debris region and

$$\gamma_1 = \varepsilon + (1 - \varepsilon) \frac{\left(\rho C_p\right)_s}{\left(\rho C_p\right)_f} \tag{8}$$

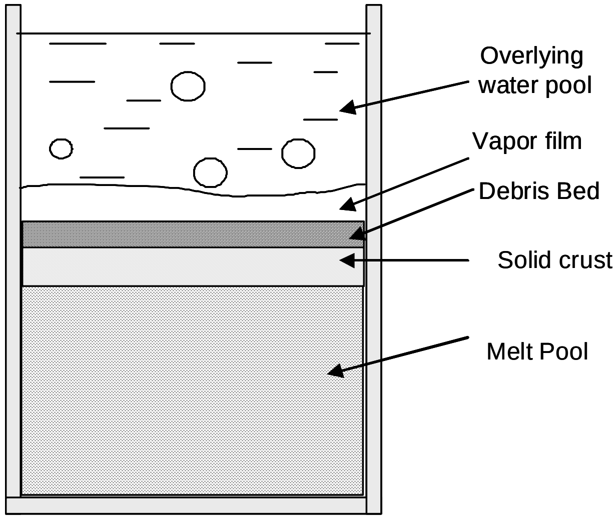

Figure 1 Schematic of the melt pool with water overlayer considered in the analysis

The stream function ψ is related to the velocity as

$$V_r = \frac{1}{r}\frac{\partial \psi}{\partial z};\ V_z = \frac{1}{r}\frac{\partial \psi}{\partial r} \qquad (9)$$

Equation (9) was substituted in equations (5) to (7) to replace the v_r and v_z with ψ . Equations (6) and (7) were then solved for ψ and T.
The boundary conditions for all the above regions are given in Figure 2.

<u>Calculation of surface heat transfer coefficient</u>**:** For calculation of heat transfer from top of the debris to the pool of water, appropriate heat transfer correlations are used as described below. If surface heat flux is greater then the debris bed dry out flux, combination of radiation and film boiling heat transfer is used, i.e. for

$$q''_{surface} > q''_d \qquad h = h_{fb} + h_{rad} \qquad (10)$$

$$h_{fb} = 0.425\left(\frac{h_{fg}\cdot\rho_v\cdot g\cdot(\rho_l-\rho_v)\cdot k_v^3}{\mu_v\cdot\sqrt{\dfrac{\sigma_{ST}}{g\cdot(\rho_l-\rho_v)}}\cdot\Delta T}\right)^{1/4} \qquad (11)$$

The radiation heat transfer coefficient correlations is calculated as

$$h_{rad} = \sigma_{stefan}\cdot\varepsilon_s\cdot(T^2+T_{sat}^2)(T+T_{sat}) \qquad (12)$$

When the surface heat flux is below the dry out flux, i.e.

$$q''_{surface} < q''_d \qquad h = h_{nb} \qquad (13)$$

Nucleate boiling correlation [7] is used

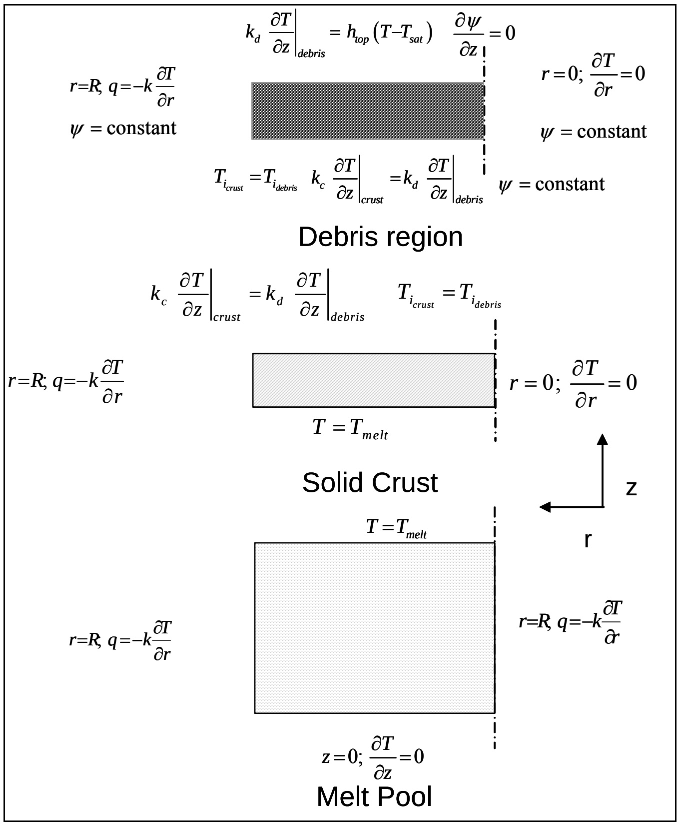

Figure 2 Boundary conditions for the governing equations

The film boiling heat transfer coefficient is calculated using the film boiling model [6] as

$$h_{nb} = \frac{1.25 \times 10^5 \mu_l h_{lv} \left[\frac{C_{Pl}}{h_{lv}}\right]^3 (\Delta T_{\sup})^2}{\left[\frac{C_{Pl} \times \mu_l}{K_l}\right]^{5.1} \sqrt{\frac{\sigma_{ST}}{g(\rho_l - \rho_v)}}} \tag{14}$$

The dryout heat flux was calculated using the following relationship based on counter current flooding limitations (CCFL) as given [8].

$$q_d = 0.539 h_{lv} \frac{\left[(\rho_l - \rho_v)\rho_v g d \varepsilon^3 / (1-\varepsilon)\right]^{1/2}}{\left[1 + \left(\rho_v / \rho_l\right)^{1/4}\right]^2} \tag{15}$$

Crust generation rate is calculated from energy balance as given by

$$\iint \left(-k_m \left.\frac{\partial T}{\partial z}\right|_{pool} + k_c \left.\frac{\partial T}{\partial z}\right|_{crust} \right) dA \cdot \Delta t = A \cdot \Delta z_{crust} \cdot \rho_s \cdot C_{p_s} \cdot \Delta T + A \cdot \Delta z_{crust} \cdot \rho_s \cdot h_{fus} + q''' \cdot A \cdot \Delta z_{crust} \tag{16}$$

There need not be heat flux continuity at liquid solid interface, when crust formation is taking place. In fact, this heat flux discontinuity is only responsible for crust growth. The left hand side of the above equation may be negative also, which implies that crust is dissolving in molten pool. This will occur due to high heat generation rate in pool which leads to increase in pool temperature and top flooding is unable to take the heat away.

Stresses in solid crust: As cooling initiates, there will be a temperature distribution in the crust. Initially, the crust will be formed only at the melting temperature of the material. Once the crust is cooled below its solidus temperature, material tends to shrink. However, depending on thermal gradient in the crust and the boundary conditions, material may not shrink; which will develop stresses in the crust region.The 2-D axi-symmetric equations for stress developed in solid crust are:

$$\frac{\partial}{\partial r}\left(r\cdot\tau_{rz}\right)+\frac{\partial\sigma_z}{\partial z}=0 \tag{17}$$

$$\frac{\partial}{\partial r}\left(r\cdot\sigma_r\right)+r\frac{\partial\tau_{rz}}{\partial z}=\sigma_\theta \tag{18}$$

These equations come from force balance in differential element. The boundary conditions are given in Figure 3, where u is radial and w is the axial displacement.

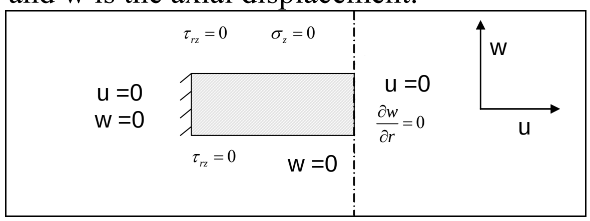

Figure 3 Boundary conditions for stresses in solids

Stress strain relationship is given as

$$\begin{pmatrix}\sigma_r\\ \sigma_\theta\\ \sigma_z\\ \tau_{rz}\end{pmatrix}=\frac{E}{(1+\nu)(1-2\nu)}\begin{pmatrix}1-\nu & \nu & \nu & 0\\ \nu & 1-\nu & \nu & 0\\ \nu & \nu & 1-\nu & 0\\ 0 & 0 & 0 & \frac{1-2\nu}{2}\end{pmatrix}\begin{pmatrix}\frac{\partial u}{\partial r}-\alpha\Delta T\\ \frac{u}{r}-\alpha\Delta T\\ \frac{\partial w}{\partial z}-\alpha\Delta T\\ \frac{\partial u}{\partial r}+\frac{\partial w}{\partial z}\end{pmatrix} \tag{19}$$

Now using equation (19) in stress equations (17) and (18), two equations in u and w are obtained. At the top of the crust there will be no shear stress and the axial stress due to weight of debris and water is negligible. Both equations were discretized in implicit manner and solved with boundary conditions as shown in figure above, to obtain stress distribution in crust.

Criteria for fracture of the solid crust: The solid crust was considered to fracture like brittle materials. For fracture initiation, the Ritchie's model [9] was used. In this model, fracture initiation occurs only when stress exceeds the critical stress in the region. This region is taken generally order of eight-grain sizes. So fracture initiation occurs only when stresses are above critical limits in more than eight-grain size area.

1.2 Solution strategy

The governing equations in melt pool and solid crust region are discretized using finite difference method and solved implicitly using Gauss elimination method to obtain temperature distribution in the melt pool. After evaluating the temperatures, the crust growth rate is calculated and subsequently the thickness of the solid crust region is updated. In debris region, pressure term is eliminated in the momentum equation with the help of stream function approach. Then applying Boussinesq approximation we get momentum equation and energy equation in ψ and T. Then both the equations are solved implicitly. After the temperature distribution has been obtained, the stress equations are solved implicitly by finite difference technique. With the stresses, the fracture conditions are evaluated. If criteria for fracture is satisfied, the fractured grids are merged into debris region. The calculation procedure for debris surface heat transfer coefficient has already been discussed in equations 11-15. When the surface heat flux falls below the dry out flux, water is considered to ingress into debris.

1.3 Model validation

The model was used to predict the COMECO tests. Fig. 4 shows transient temperature history of the molten pool during quenching, as predicted by the model. Theoretical results also show that temperature of top layer falls suddenly in 500 seconds which is closer to measured value. The transient temperature history due to quenching is similar as measured in the experiments (Fig. 5). Model predicts water ingression of 0.11 m. It is very close to experimental result which was around 0.1 m.

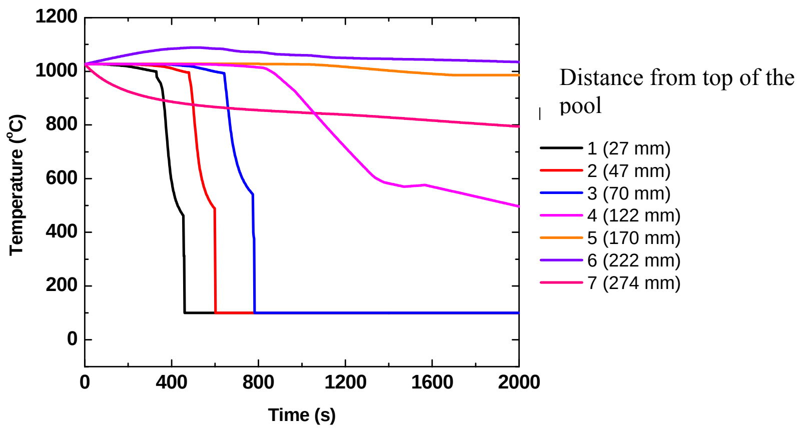

Figure 4 Predicted temperature history during initial period of quenching

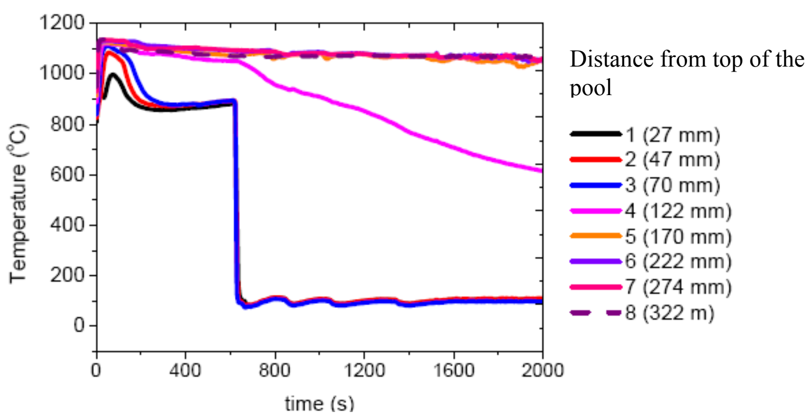

Figure 5 Measured temperature history during initial period of quenching

2. Effect of Molten core concrete interaction (MCCI) on coolability of Corium:

The model was used to predict the coolability of corium in an envisioned scenario following a severe accident. A parametric analysis was carried out to study the influence of change in thermo-physical properties of corium concrete mixture during molten core-concrete interaction. Corium mechanical properties vary with concrete as given in [10]. The effect of change in thermal expansion coefficient on coolability is given in Fig 6a and 6b. Figure 6a shows the water ingression predicted during corium quenching. It can be seen that water is able to ingress up to a large depth into the corium crust. Figure 6b shows that, because of concrete addition, the thermal expansion coefficient is reduced which no longer causes water ingression and coolability is limited as shown in Fig 7a and b. this can be attributed to the fact that, because of decreased thermal expansion coefficient, there are less thermal stresses generated in the corium, which prevents it from fracturing thus limiting water ingression.

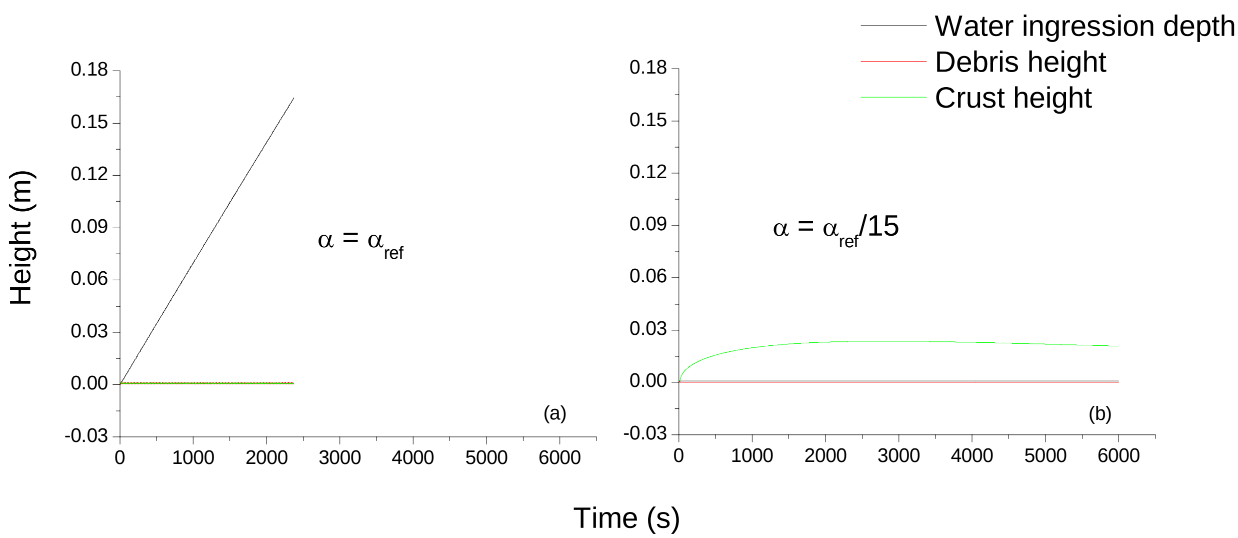

Figure 6. Effect of concrete addition on thermal expansion coefficient of corium

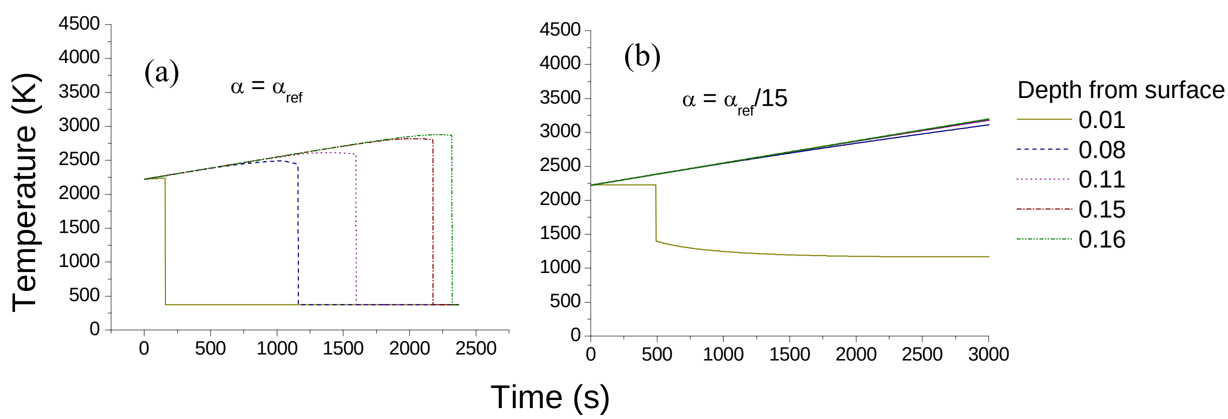

Figure 7. Temperature history of corium before and after changing the thermal expansion coefficient

Similar effect is seen when there is increase in corium strength as shown in Fig 8a and b. as the strength of corium increases, it is difficult to fracture it and it stops the water ingression. The corresponding temperature history is given in Fig 9a and b.

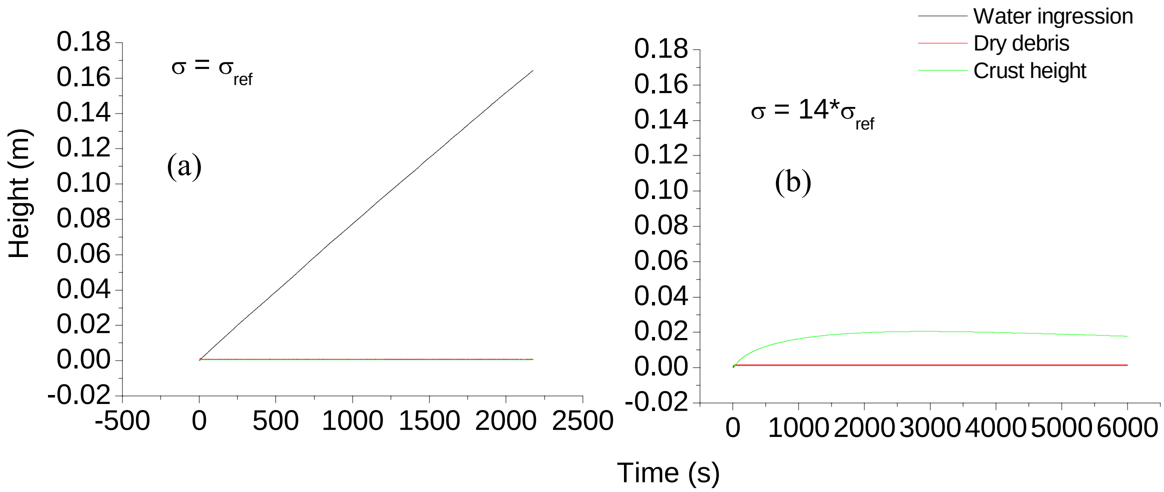

Figure 8. Effect of change in strength of corium on water ingression

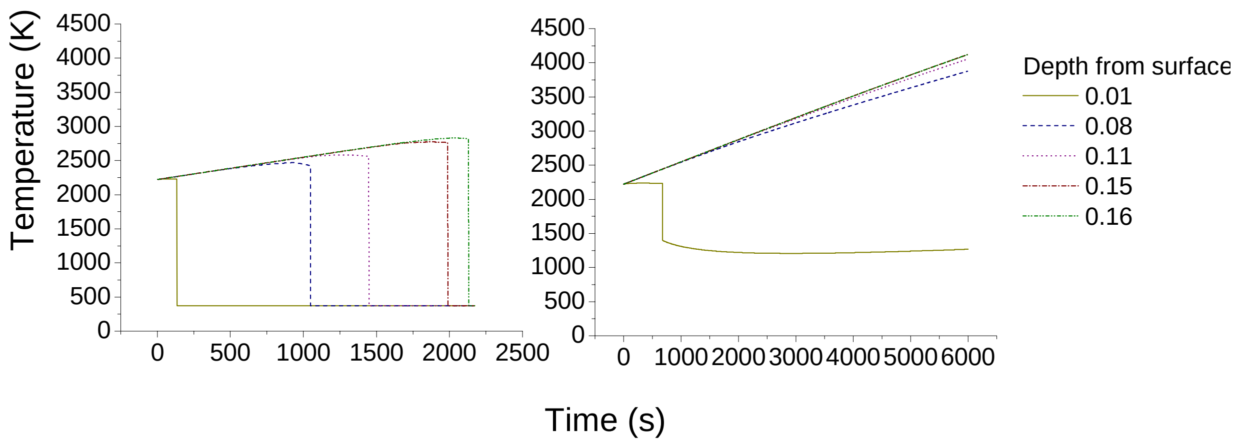

Figure 9. Temperature history of corium before and after changing the corium strength

Since it was observed that, the factors which make the corium difficult to break hinder the coolability. It was conceived that, coolability is influenced by a dimensional parameter consisting of different parameters which can influence the fracture of corium. One such parameter was thought to be $E\alpha/\sigma$ where E is Young's modulus, α is thermal expansion coefficient and σ is strength of corium. Analysis was carried out by varying individual parameters but keeping the dimensionless parameter same. It was found that, resultant coolability was unaffected as shown by Figs 10 and 11.

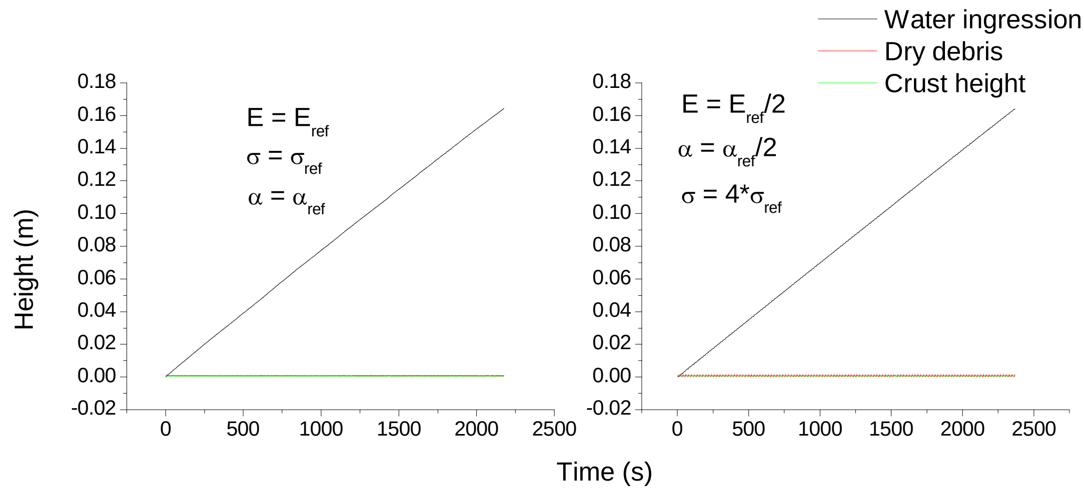

Figure 10. Effect of keeping dimensionless parameter constant on water ingression

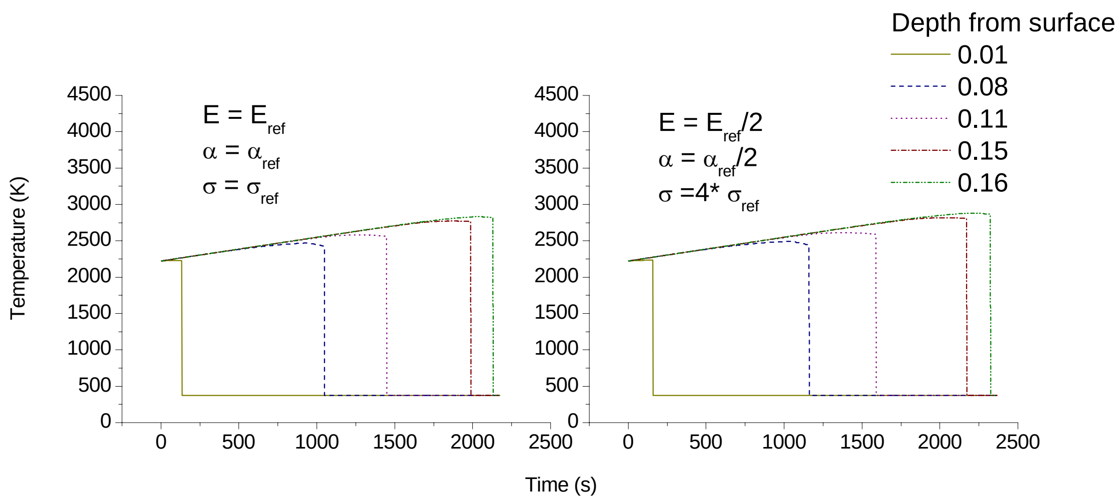

Figure 11. Temperature history of corium with varying individual parameters

3. Conclusions:

In this paper, numerical investigation was carried out to investigate the water ingression phenomena in melt pool coolability under top flooding condition. The model includes the heat transfer behaviour in axial and radial directions from the molten pool to the overlaying water, crust generation and growth, thermal stresses built-in the crust, disintegration of crust into debris, natural convection heat transfer in debris and water ingression into the debris bed. To validate the model, experimental data from test carried out on a facility named as COMECO (COre MElt COolability) was taken. The model was found to simulate the quenching behaviour and depth of water ingression reasonably. Effect of MCCI on the change in properties and subsequently on the coolability of the corium was explored. It has been found that, the coolability is influenced by a dimensionless parameter $E\alpha/\sigma$. Higher is the parameter, better is the coolability.

NOMENCLATURE

d	Particle diameter (m)
g	Gravitational acceleration (m/s^2)
h	Latent heat of vaporization (kJ/kg)
p	Pressure (Pa)
z	Axial direction (m)
Cp	Specific heat capacity at constant pressure (J/kg K)
F	Interfacial drag force (N/m^3)
G	Mass flux (kg/m^2.s)
J	Superficial velocity (m/s)
K	Permeability
Q	Volumetric heat generation (W/m^3)
T	Temperature (K)

Greek letters

α	Void fraction
ε	Bed porosity
μ	Viscosity (Pa.s)
ρ	Density (kg/m^3)
σ	Axial Stress (N/m^2)
σ_{ST}	Surface tension (N/m)
η	Bed passability
τ	Shear stress (N/m^2)
ν	Poisson's ratio

Subscripts

g	Gas
i	Interfacial
l	Liquid
p	particle
r	radial
rel	Relative
sat	Saturated
v	Vapor
z	axial

4. References

[1] C. R. B. Lister, "On the Penetration of Water into Hot Rock", *Geophys. J. R. Astron. Soc*., 39, 1974, pp 465-509.

[2] M. Epstein, "Dryout Heat Flux during Penetration of Water into Solidifying Rock", *J. Heat Transfer*, 128, 2006 , pp 847-850.

[3] M.T. Farmer, J. J. Sienicki and A. Kovtonyuk, "OECD MCCI analytical support (stand alone task) water ingression modelling of the OECD/MCCI SSWICS tests", NRC/MCCI/2003-TR01. 2003.

[4] W. Widmann, M. Buerger, G. Lohnert, H. Alsmeyer and W. Trommb, "Experimental and theoretical investigations on the COMET concept for ex-vessel core melt retention", *Nucl. Eng. Des.*, 236, 2006, 2304-2327.

[5] A. K. Nayak, B. R. Sehgal and R. S. Rao, "Study on Water Ingression Phenomena in Melt Pool Coolability." 11th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-11), Avignon, France, October 2-6, 2005.

[6] P. J. Berenson, "Film Boiling Heat Transfer from a Horizontal Surface." *J. Heat Transfer*, 83, 1961, pp 351-357.

[7] W. H. Rohsenow, "A Method of Correlating Heat Transfer Data for Surface Boiling of Liquids." *Trans. ASME*, 74, 1952, pp 969-976.

[8] R. Sinha, A. K. Nayak and B. R. Sehgal, "Modeling the Natural Convection Heat Transfer and Dryout Heat Flux in a Porous Debris Bed." *ASME J. of Heat Transfer*, 130, 2008,104503.

[9] R. D. Ritchie., J. F. Knott and J. R Rice., "On the Relationship between Critical Tensile Stress and Fracture Toughness in Mild Steel." *J. of Mechanics and Physics of Solids*, 21, 1973, pp 395 – 410.

[10] S. Lomperski and M.T. Farmer, "Corium crust strength measurements", *Nuclear Engineering and Design* 239 2009, 2551–2561,