Upper-Bound Assessment of Corium Droplet Formation and Airborne Transport Potential Following Jet Impingement on the Concrete Floor of a Dry Reactor Cavity

Byung Jo Kim and Hoon Goo Oh
KEPCO Engineering and Construction Company, Inc., Republic of Korea
bjokim@kepco-enc.com, hgo@kepco-enc.com

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1. Introduction

During the progression of a severe accident, core melt may relocate into the lower plenum, where thermal and mechanical loads imposed by the high-temperature melt can lead to failure of the lower head. The released corium then reaches the reactor cavity floor and initiates molten core concrete interaction (MCCI). The initial distribution, average thickness, and spreading area of the melt formed on the cavity floor constitute important initial conditions governing subsequent concrete ablation, heat-transfer area, and melt coolability.

In a pre-flooded reactor cavity, relative motion between the corium jet and the coolant can induce jet breakup. The resulting droplets exchange heat with the surrounding coolant and may subsequently form a widely distributed and extensive debris bed on the cavity floor. In contrast, dry-cavity conditions may occur in reactor designs for which a dry cavity is intended, such as the Czech export reactor design, or during specific accident sequences at some domestic NPPs where cavity pre-flooding is not assured. Under such conditions, because the density of the surrounding gas is much lower than that of the melt, breakup of the jet during its fall is limited, and a substantial fraction of the corium may directly impinge on the concrete floor in the form of a coherent jet.

Two initial phenomena are of particular interest during jet impingement on a dry cavity floor. The first is splattering, whereby surface instabilities in the radial liquid film formed by the impinging jet cause droplets to detach from the film. The second is localized concrete erosion caused by the momentum and heat flux of the high-temperature jet. Large-scale jet-impingement experiments have shown that intense initial splashing decreases after a melt pool forms within the eroded region, a behavior referred to as the pool effect. These observations indicate that the initial bare-floor impingement regime should be distinguished from the subsequent pool-impact regime.

The present study focuses on the initial dry-floor impingement stage before a sufficiently deep local melt pool is established. Representative release conditions obtained from MAAP5 calculations [1] are used to evaluate whether the jet reaches the cavity floor in a coherent form, whether the splattering criterion is satisfied, the size distribution of the generated droplets, and the fraction of droplets that may be transported by natural-convection airflow. Concrete erosion, bubble entrainment and bubble bursting after local pool formation, melt spreading, and wall run-up are being investigated as part of ongoing follow-up studies.

2. Analysis Methodology

2.1. Jet Falling and Floor-Impact Conditions

Under dry-cavity conditions, the breakup length of a corium jet falling through the surrounding gas is estimated using the following Epstein's correlation [2]:

$$L_{br}/D_o = \frac{1}{2E_0}\left(\rho_l/\rho_g\right)^{0.5} \quad (1)$$

where L_{br} is the jet breakup length, D_o is the jet diameter at the vessel failure opening, E_0 is model constant, and ρ_l and ρ_g are the densities of the liquid corium and the surrounding gas, respectively. The jet is assumed to remain substantially coherent until it reaches the cavity floor when

$$L_{br} > H \quad (2)$$

where H is the vertical distance between the reactor pressure failure location and the cavity floor. For the plant-representative corium and cavity-gas conditions considered in this study, the minimum failure-opening radius required to satisfy the coherent-jet criterion is approximately 0.0069 m, corresponding to a minimum source-jet diameter of approximately 0.0138 m. In comparison, the predicted failure-opening radius ranges from approximately 0.10 to 0.40 m. The released corium jet is therefore expected to reach the dry cavity floor predominantly in a coherent form, with only limited breakup occurring during its fall.

2.2. Splattering Onset Criterion and Droplet Conversion Fraction

When a liquid jet impinges on a solid surface, a thin radial liquid film is formed around the impact point. Disturbances in the incident jet and capillary instabilities developing within the spreading film may cause droplets to detach from the liquid film, resulting in splattering.

Bhunia and Lienhard proposed the following empirical criterion for the onset of splattering, defined

as a condition under which at least 5% of the incident liquid flow is converted into splattered droplets [3]:

$$\frac{H}{D_0} > \frac{130}{1+5\times10^{-7}We_0^2} \quad (3)$$

where the Weber number based on the jet at the vessel opening is defined as

$$We_0 = \frac{\rho_l u_0^2 D_0}{\sigma} \quad (4)$$

Here, u_0 denote the jet velocity at the reactor vessel failure opening.

For the representative MAAP5 conditions of the 1000 MWe-scale plant considered in this study [1], the jet Weber number is sufficiently large that the splattering-onset criterion in Eq. (3) is satisfied during most of the corium release period. In the experiments reported in Ref. [3], up to approximately 75% of the incoming liquid flow was observed to undergo splattering. However, because the plant-scale conditions considered in the present study substantially exceed the given experimental ranges of [3], the experimental data cannot be used to determine the splattered mass fraction directly. Accordingly, to obtain a conservative upper bound on the amount of corium potentially available for airborne transport, the splattered fraction is specified as 1.0. Thus, the entire impinging corium jet is assumed to be temporarily converted into liquid droplets upon impact. This assumption should not be interpreted as a best-estimate prediction of the actual splattered mass fraction; rather, it represents a conservative bounding condition for evaluating the maximum potentially transportable corium mass.

2.3. Prediction of the Droplet Size Distribution and the Critical Diameter for Airborne Transport

The Sauter mean diameter (SMD) of the droplets generated by splattering of high jet Reynolds number is estimated using the empirical correlation proposed by Ahmed et al. [4]:

$$d_{SMD} = 0.00621 \frac{\mu_l^{0.07} D_j^{0.1}}{u_j^{0.5}} \quad (5)$$

where d_{SMD} is the Sauter mean diameter, D_j and u_j are the jet diameter and velocity at impact with the cavity floor, respectively.

Because a single mean diameter is insufficient to evaluate the fraction of fine droplets that can be transported by the upward gas flow, the droplet-size distribution is represented by a Rosin–Rammler cumulative distribution [5]:

$$F_d(d) = 1 - exp\left[-\left(\frac{d}{X}\right)^q\right] \quad (6)$$

where $F_d(d)$ is the cumulative volume fraction of droplets with diameters smaller than d, q is the distribution-spread parameter, and X is the characteristic droplet diameter. The characteristic diameter is related to the Sauter mean diameter by

$$X = \Gamma\left(1 - \frac{1}{q}\right) d_{SMD} \quad (7)$$

where $\Gamma()$ denotes the gamma function. To represent a relatively broad droplet-size distribution and thereby conservatively increase the predicted fraction of fine droplets, the distribution parameter is specified as q=2.0.

The maximum upward gas velocity induced by natural convection in the reactor cavity is estimated [6] as

$$u_{g,max} = 0.14\left(g \cdot D_{equival}\right)^{0.5} \quad (8)$$

where $D_{equival}$ is the equivalent diameter of a circular cavity having the same horizontal cross-sectional area as the actual reactor cavity. For a sufficiently small spherical corium droplet, the terminal settling velocity can be estimated using Stokes' law:

$$v_{term} = \frac{(\rho_l - \rho_g) g \cdot d^2}{18\mu_g} \quad (9)$$

where d is the droplet diameter and μ_g is the dynamic viscosity of the cavity gas.

The critical droplet diameter for natural-convection transport, d_{crit}, is obtained by equating the maximum upward gas velocity to the droplet terminal settling velocity:

$$d_{crit} = \left(\frac{18\mu_g u_{g,max}}{(\rho_l - \rho_g) g}\right)^{0.5} \quad (10)$$

Droplets with diameters not exceeding d_{crit} ($d < d_{crit}$) are conservatively assumed to be entrained in the upward natural-convection flow and transported out of the lower cavity region.

The instantaneous volume fraction of splattered corium droplets that can be transported by natural convection is therefore expressed as

$$f_{escape}(t) = F_d[d_{crit}; d_{SMD}] \quad (11)$$

Finally, the cumulative fraction of the total released corium volume that can potentially be transported by the upward gas flow is calculated as

$$f_{escape,total} = \frac{\int_0^{t_f} f_{escape}(t)\dot{Q}(t)dt}{Q_{total}} \quad (12)$$

Here, $\dot{Q}(t)$ is the time-dependent corium volumetric release rate [m^3/s], t_f is the total release duration [sec], and Q_{total} is the total volume of corium released into

the reactor cavity [m^3]. These quantities are given from MAAP5 calculation [1].

3. Results and Discussion

3.1 Droplet Size and Potentially Transportable Fraction

The calculation results for the cavity geometry and Large LOCA case of 1000 MWe-scale plant[1] at representative times are summarized in Table I.

Table I. Representative impinging-jet and droplet-generation results at selected times

time (sec)	$\dot{Q}(t)$ (m^3/s)	u_j (m/s)	D_j (m)	d_{SMD} (mm)	Fraction with $d < d_{crit}$
0	0.21	14.7	0.14	0.916	0.418%
5	0.67	15.4	0.24	0.946	0.391%
14	1.5	14.5	0.36	1.02	0.339%
18	0.5	13.2	0.22	1.02	0.340%

Using the 1000 MWe-scale reactor cavity geometry [1] and the thermophysical properties of air at 700 K, the critical droplet diameter, Eq. (10), is calculated as 0.105 mm. For a total released corium volume of 16.47 m^3, the transportable fraction of 0.38% corresponds to 0.063 m^3. Using a corium density of 8,000 kg/m^3, the corresponding mass is about 500 kg, which is relatively small compared with the total mass of corium released into the reactor cavity (~130,000 kg).

3.2 Implications for Plant Safety

The analysis results indicate that, even if substantial hydrodynamic splattering occurs during jet impingement on the solid floor, most of the melt is unlikely to be transported into the upper region of the reactor cavity by buoyancy-driven natural-convection flow because the characteristic diameter of the generated droplets is approximately 1 mm. Instead, most droplets are expected to fall back onto the cavity floor.

Although the corium near the impact point may be temporarily dispersed in the form of liquid droplets, the droplets may recoalesce after re-deposition or form partially solidified debris. Therefore, the total corium inventory participating in MCCI is not expected to decrease substantially as a result of splattering alone.

The fraction of the total released corium that can escape from the designated melt-retention region in the form of fine droplets is expected to be very small. Nevertheless, the effects of droplet deposition on cavity walls and the potential consequences for nearby equipment are currently being evaluated in follow-up studies.

The final wetted area and thickness of the melt layer on the cavity floor are governed not only by splattering, but also by the gravity-current behavior of the radially spreading liquid film, melt solidification, and concrete erosion.

3.3 Major Model Assumptions and Uncertainties

The present study constitutes an upper-bound assessment and therefore involves the following major assumptions and uncertainties.

First, the Bhunia–Lienhard correlation [3] was developed from experiments involving turbulent water and water–alcohol jets with diameters of several millimeters. The Weber numbers under the corium conditions considered in this study substantially exceed the experimental range of the correlation. Nevertheless, the assumption of complete splattering is considered defensible for the present upper-bound assessment. Furthermore, accident scenarios involving reactor vessel breach under high internal pressure were excluded based on the assumption that depressurization actions would be successful. If the vessel failure was to occur at a point where depressurization has not been sufficiently achieved, the present results may not be applicable.

Second, the Ahmed correlation [4] was developed for splash-plate nozzles with diameters ranging from 0.5 to 2.0 mm. Its application to a plant-scale corium jet with a diameter of several tens of centimeters therefore requires substantial extrapolation.

Third, a bare-substrate splattering was assumed to occur throughout the entire corium release period. In reality, as a local melt pool develops, splattering caused by direct jet impingement on the solid surface is expected to decrease, and the flow regime may transition to plunging-jet behavior accompanied by gas entrainment and bubble bursting. Large-scale experiments have shown that intense initial splashing weakens after melt accumulates within a jet-eroded cavity and that the erosion rate also decreases following the onset of the pool effect. These observations suggest that applying the bare-substrate splattering model over the entire release period may overestimate the actual transportable corium fraction.

In last, the natural-convection model evaluates only the sustained upward transport of droplets by the cavity gas flow. Direct droplet deposition on nearby walls due to the initial horizontal momentum generated during jet impact was not considered and is currently being assessed in follow-up work.

4. Summary

An upper-bound assessment of corium droplet formation and potential airborne transport following jet impingement on a dry concrete reactor cavity floor was performed using empirical correlations.

First, under the representative MAAP5 release conditions, the estimated jet breakup length was substantially greater than the distance between the reactor vessel failure location and the cavity floor.

Therefore, most of the released corium jet was predicted to reach the concrete floor in a coherent form.

Second, considering the jet Weber number and the fall distance, the entire impinging jet was conservatively assumed to be temporarily converted into droplets upon impact.

Third, the Sauter mean diameter of the generated droplets was estimated to range from approximately 0.92 to 1.02 mm. Based on the balance between the upward natural-convection velocity and the terminal settling velocity of the droplets, only droplets smaller than approximately 0.105 mm were considered capable of being transported upward.

Fourth, application of the Rosin–Rammler droplet-size distribution indicated that approximately 0.38% of the total released corium could potentially be transported into the upper cavity region by natural convection. Consequently, more than 99.6% of the released corium was predicted to fall back into and remain within the lower reactor cavity region.

Follow-up studies are in progress to extend the present upper-bound assessment to the subsequent stages of dry-cavity melt behavior. These studies address jet-induced concrete erosion and the transition from bare-substrate splattering to plunging-jet behavior involving gas entrainment and bubble bursting as a local melt pool develops. Melt spreading, gravity-current propagation, wall run-up, and droplet deposition are also being evaluated to establish more realistic corium behavior as well as the initial and boundary conditions for subsequent MCCI analyses.

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