



# CORIUM BEHAVIOUR RELOCATED ON CORE-CATCHER

Michel GRADECK

Nicolas RIMBERT, Frédéric PAYOT, Alexandre LECOANET

Université de Lorraine – LEMTA, FRANCE



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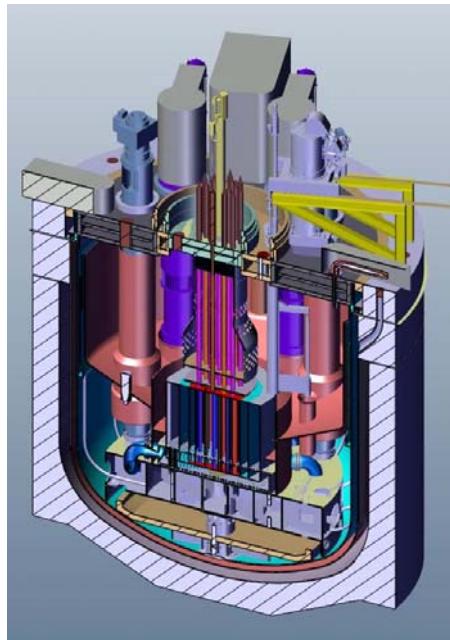
# Content

- Short introduction
- Physical problems
- Steps of the relocation
- Conclusions

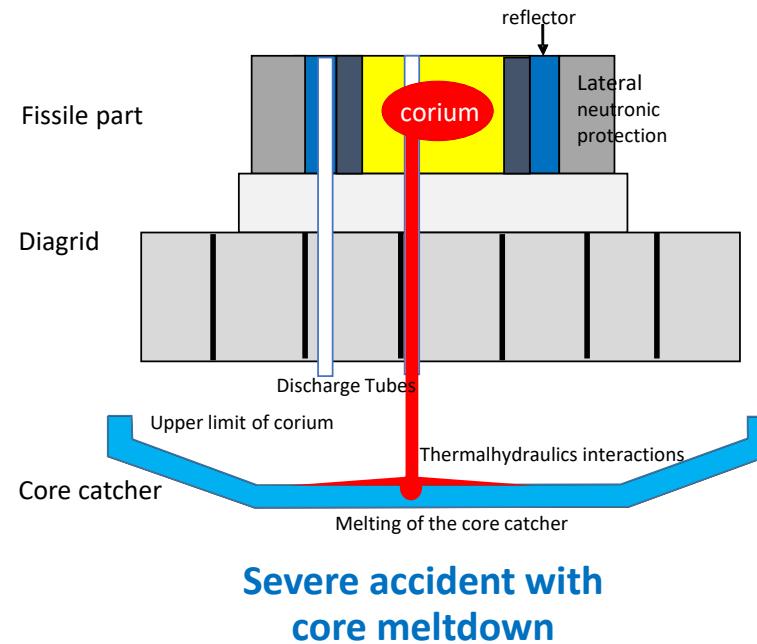


# Introduction (1/2)

- new power plant designs must take into account possible core meltdown
- corium retention must be ensured
- In vessel retention with a core catcher in the lower part of the vessel



Cut of a future SFR



Discharge tubes DT:

- Relocation toward Core-catcher as fast as possible

Core-catcher:

- Corium stabilization

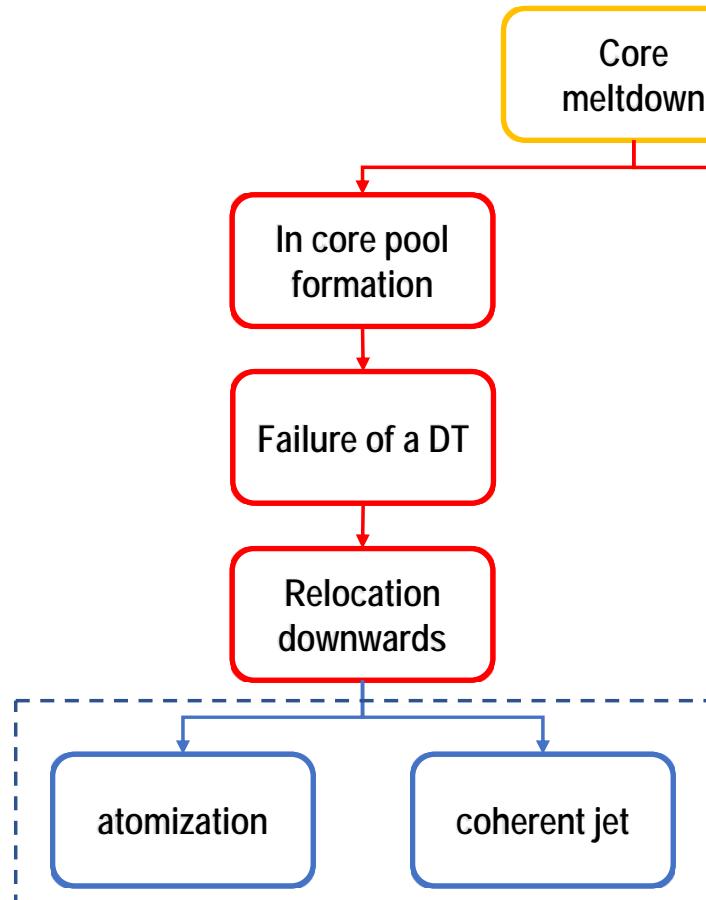


In-vessel retention  
**Advantages**

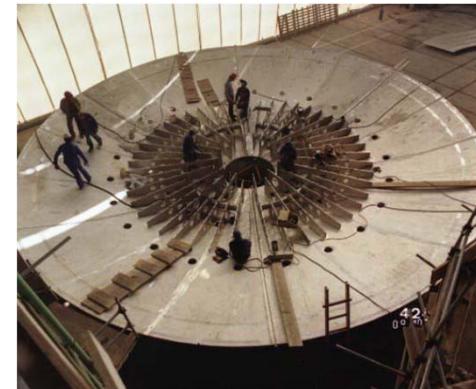
- Reduce corium mass avoid criticality
- Control and know corium path



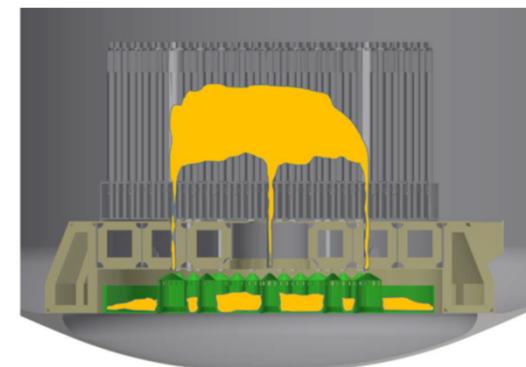
# Introduction (2/2)



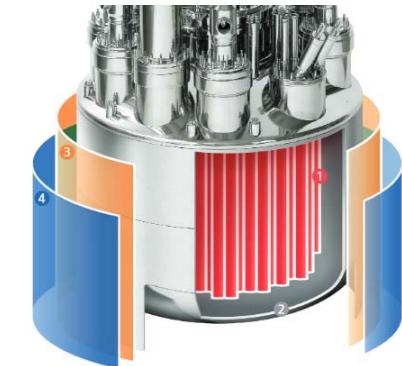
Depends mainly on the core-catcher design



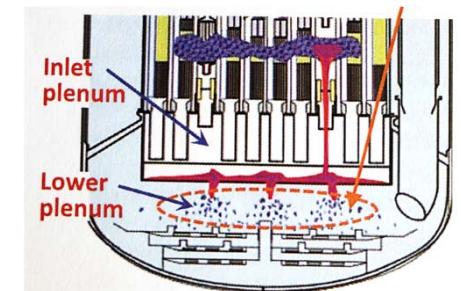
Core-catcher of Super Phenix



Artistic view of corium relocation  
(pictures from Guidez et al. (2021))



Core-catcher of Russian BN800



Relocation of the corium in JSFR  
(from Tohru Suzuki et al. (2014))



# Physical problems to be addressed (1/1)

- First stage of the relocation
  - FCI (interaction of corium jet with surrounding Na)
    - Coherent corium jet (ie no fragmentation)
    - Fragmentation of the corium jet
- Second stage of the relocation
  - Impact of fragmented debris and Formation of a bed
  - Impact of the corium jet on the core-catcher material  
(most critical case)
  - Duration of the jet impact
- Third stage of the relocation
  - Cooling of debris bed
  - Cooling of the corium pool

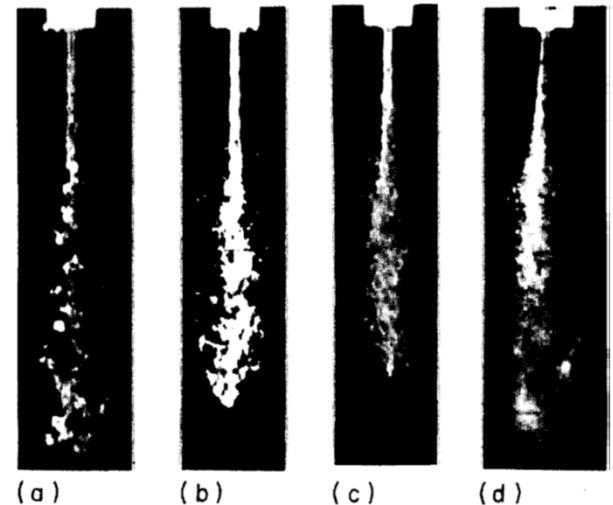
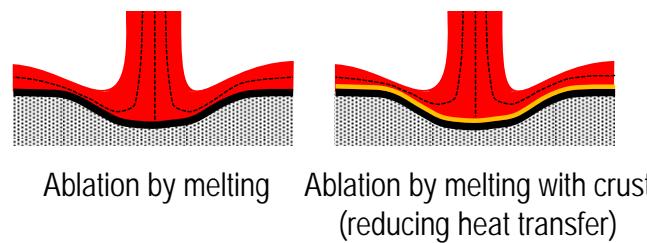


Fig. 1. Appearance of disintegrating jet from IKE experiments (Woods metal into water,  $D = 4$  mm): (a) jet velocity  $2 \text{ m s}^{-1}$ ; (b) jet velocity  $4 \text{ m s}^{-1}$ ; (c) jet velocity  $6 \text{ m s}^{-1}$ ; (d) jet velocity  $15 \text{ m s}^{-1}$ .

Berg et al. (1994)

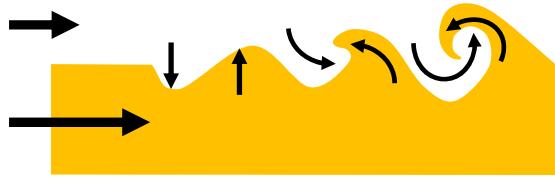




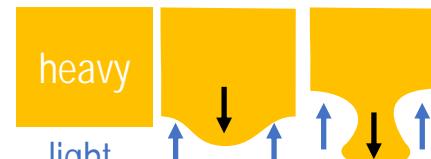
# First step of the relocation (1/8)

Fragmentation? very complex and intricated phenomena

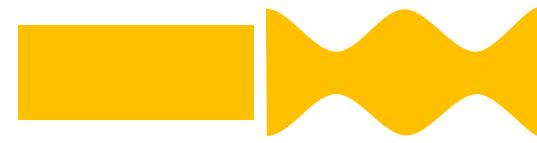
- Fragmentation is initiated by instability mechanisms  
(Kelvin Helmholtz, Rayleigh-Taylor, Rayleigh-Plateau, etc)



KH → Shear stress



RT → gravity

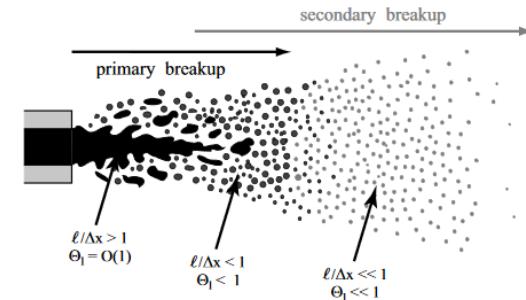


RP → capillarity

- Two steps: primary breakup and secondary breakup

primary breakup

secondary breakup



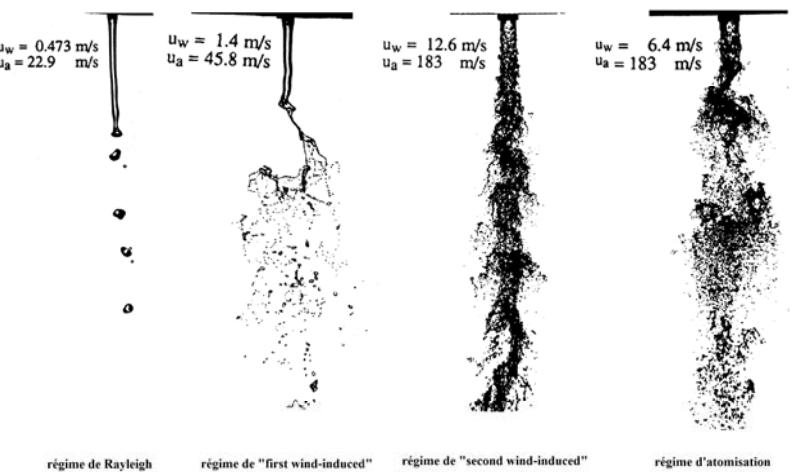


# First step of the relocation (2/8)

## Fragmentation? very complex and intricated phenomena

- These various mechanism of breakup are based mainly on injected velocity and fluid properties.
- Characterizing Non-Dimensional number:

$$We = \frac{\rho_A U^2 D}{\sigma} \quad Oh = \frac{\mu}{\sqrt{\rho D \sigma}} \quad Re = \frac{UD}{v} \quad Fr = \frac{U}{\sqrt{gD}} \quad \frac{\rho_L}{\rho_A} \quad \frac{\mu_L}{\mu_A}$$



Chigier et Farago [1992], gas liquid systems

- Most of the studies have been made with gas-liquid system (liquid jet in a surrounding gas,  $\frac{\rho_L}{\rho_A} \gg 1$ )

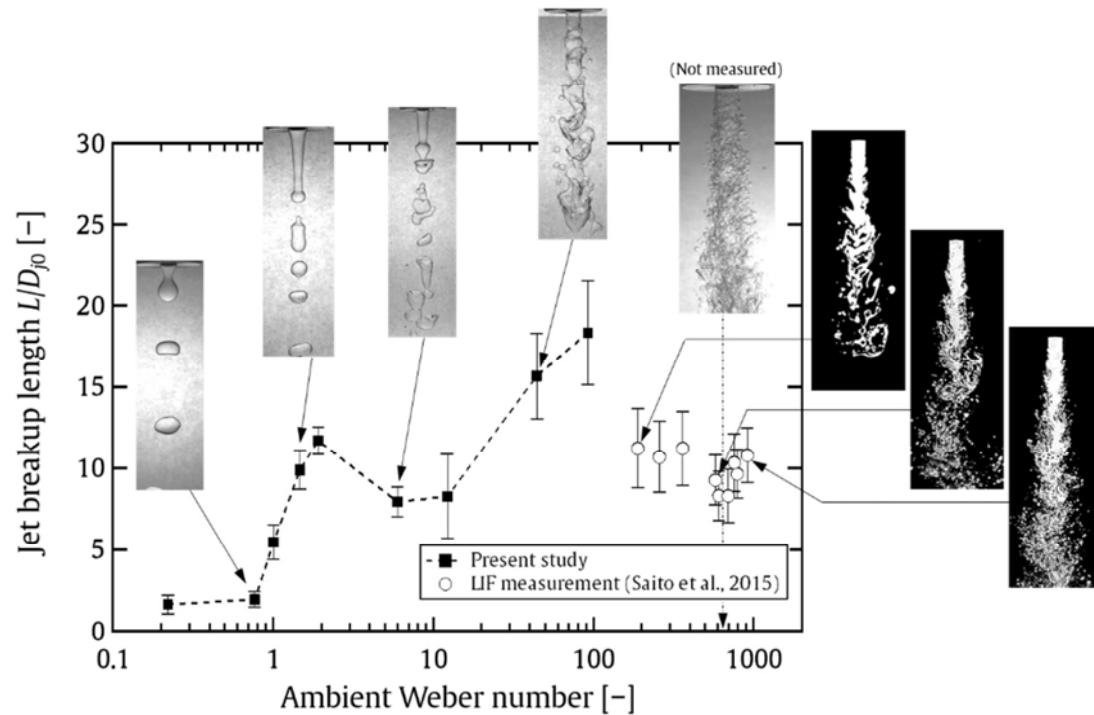
For high velocity jet, turbulence fluctuations are to be taken into account ! So a multiscale physics!!

multiphase also as some vaporization of the coolant is expected as well as solidification of the particle!!!!



# First step of the relocation (3/8)

Consequences of the Fragmentation? Corium interact with the core-catcher as a spray of molten materials (short time interaction) and a debris bed will be formed (size of the debris)



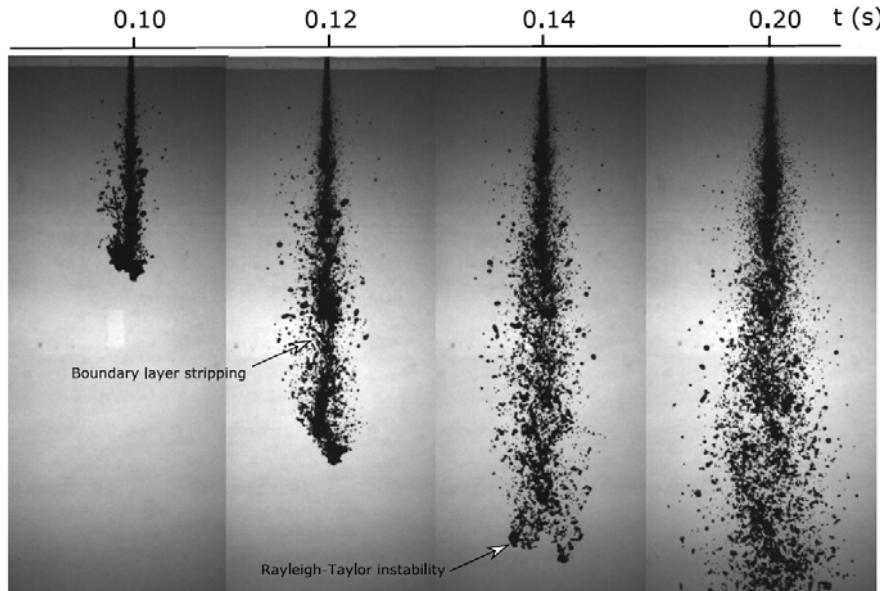
Saito (2015)

Breaking length

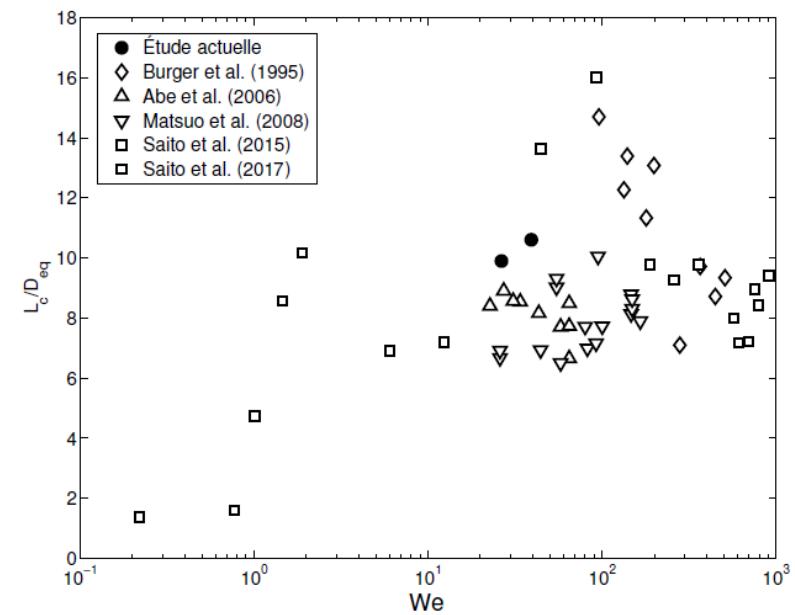


# First step of the relocation (4/8)

Studies at LEMTA with Liquid/liquid system (Fields metal injected in a water pool)



Experiments performed at LEMTA ([M. Hadj Achour, 2017](#))  
(water/liquid metal system, We~26)  
32.5% Bi, 51% In, 16.5% Sn



Breaking length as a function of the Weber number  
(water/liquid metal system)



# First step of the relocation (4/8)

Studies at LEMTA with Liquid/liquid system (Fields metal injected in a water pool)

PhD thesis of Miloud Hadj Achour (2017)

Fields metal ( $T=85^{\circ}\text{C}$ ) injected in a water pool ( $T=40^{\circ}\text{C}$ )  
 $U_j = 2,3 \text{ m/s}$ ,  $D_j = 2\text{mm}$ ,  $We \sim 26$

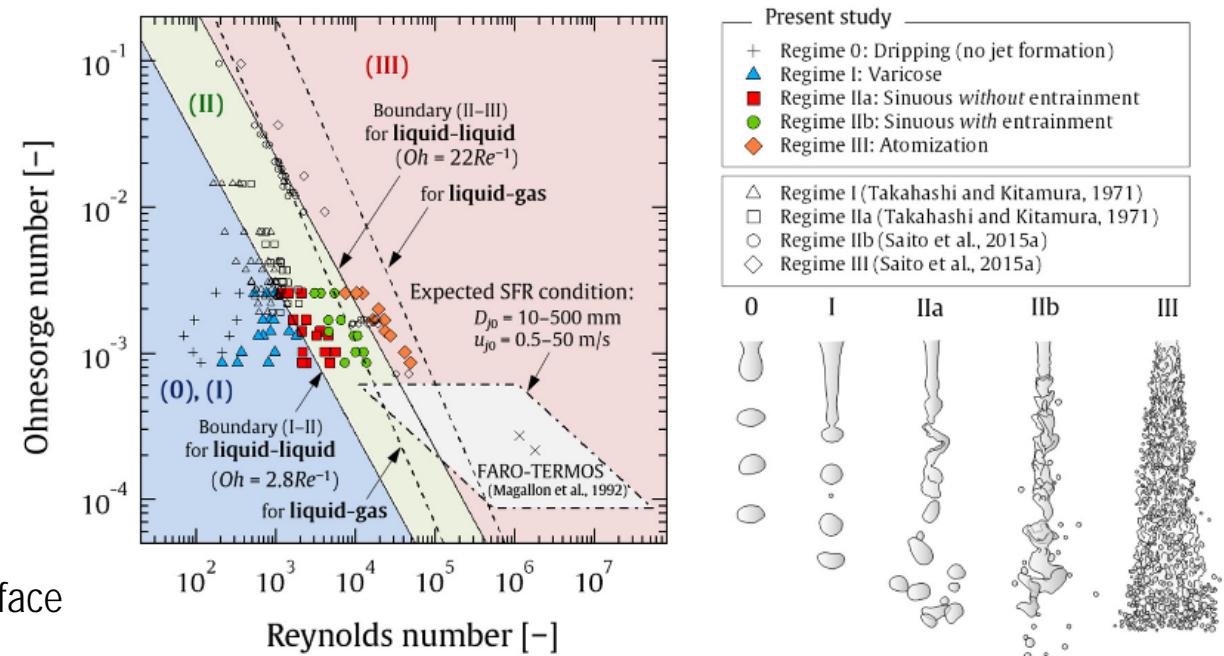




# First step of the relocation (5/8)

Differences between water/corium & sodium/corium  
(ie LWR & SFR): [from Tohru Suzuki & al. \(2014\)](#)

- **water/corium:**
  - Formation of vapor film on the jet surface
  - Low heat transfer due to vapor film
  - Deep penetration
  - High possibility of direct contact with Vessel
- **sodium/corium:**
  - No significant vapor film formation on the jet surface
  - High heat transfer due to liquid/liquid contact
  - Rapid jet breakup
  - Low possibility of direct contact with Vessel

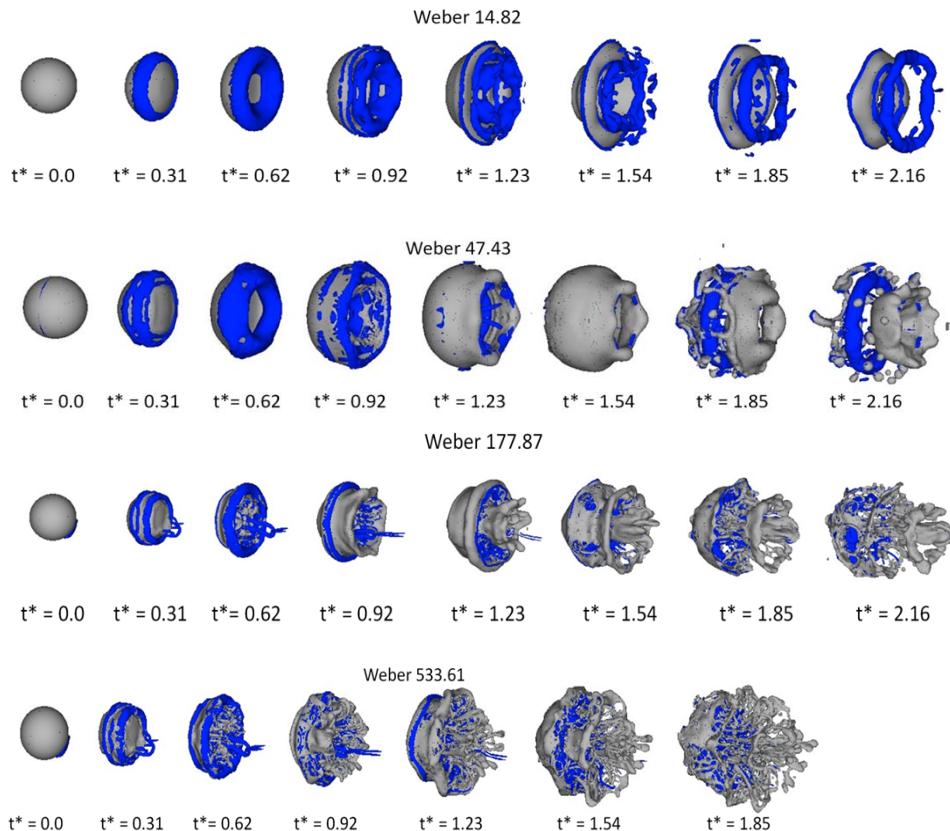


Flow transition criteria, [from Tohru Suzuki & al. \(2014\)](#)

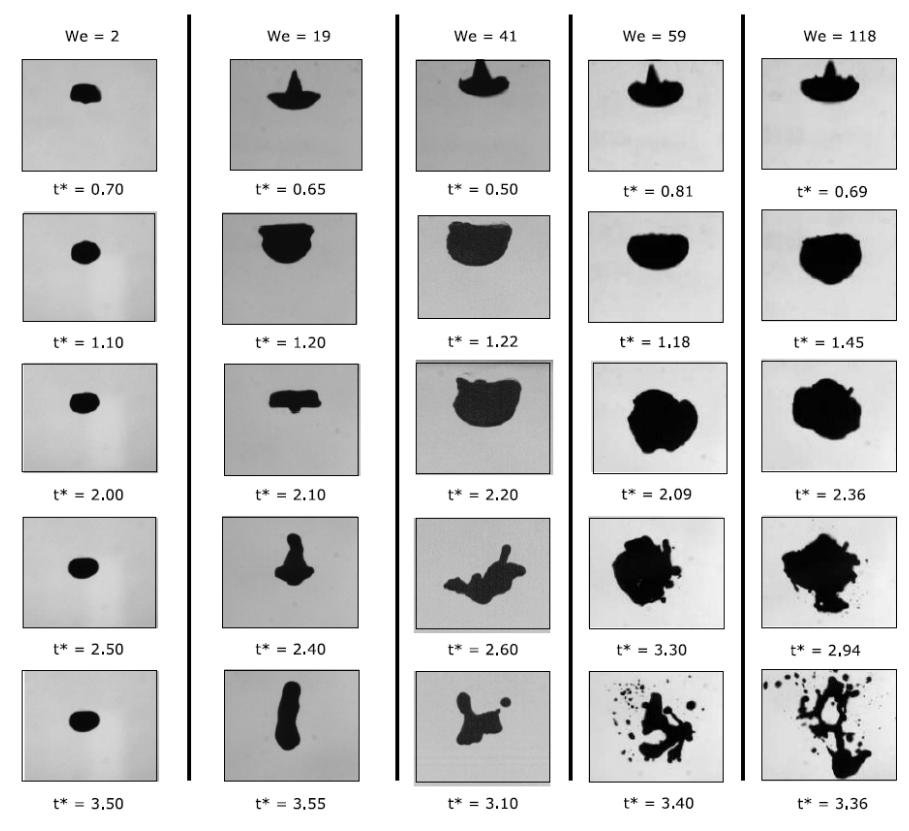


# First step of the relocation (6/8)

DNS simulations performed with Gerris code  
phD thesis of S. Castrillon Escobar (2016)



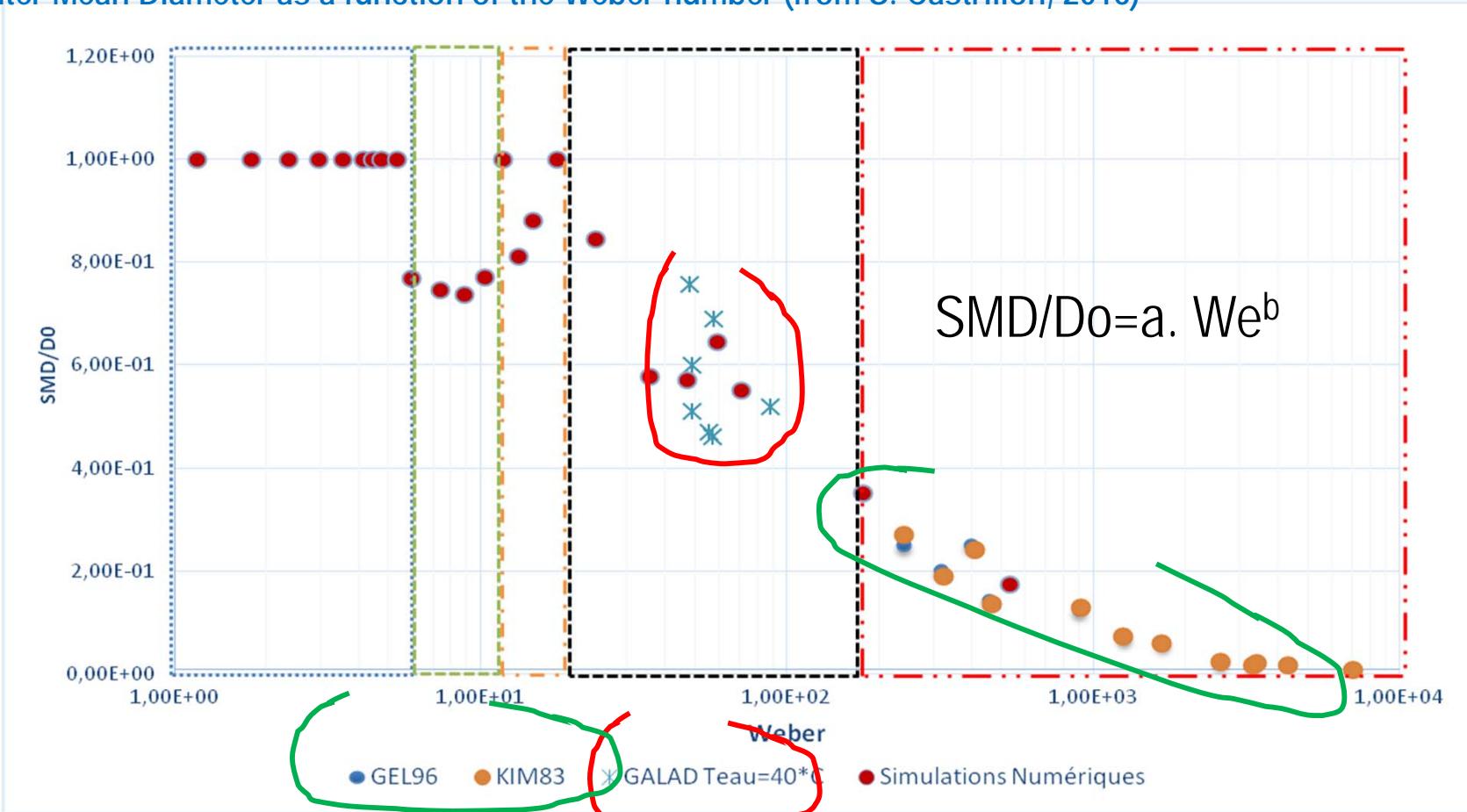
Experiments performed at LEMTA  
PhD thesis of M. Hadj Achour (2017)





# First step of the relocation (7/8)

Sauter Mean Diameter as a function of the Weber number (from S. Castrillon, 2016)





# First step of the relocation (8/8)

## Fragmentation? What could we conclude?

- gas-liquid systems and liquid-liquid-systems are driven by almost the same phenomena
- We could estimate : a breaking length (mainly function of the Weber number or Froude number) and the size distribution of the debris
- real phenomena may be much more complex)

Conditions  
 $V_{jet} \sim 10 \text{ m/s}$   
 $D_{jet} \sim 80 \text{ mm}$   
 $t_{jet} \sim 150\text{s}$

Métal -----Oxyde  
 $1 10^6 < Re < 3 10^6$   
 $0,1 < Pr < 0,5$   
 $We \gg 1000$



# Recent studies at LEMTA



UNIVERSITÉ  
DE LORRAINE

Ecole doctorale Energie Mécanique et Matériaux

Instabilité et dispersion de jets de corium liquides :  
Analyse des processus physiques et modélisation dans le  
logiciel MC3D

## THESE

Soutenue publiquement le  
13 Septembre 2016

Pour obtenir le grade de

Docteur de l'Université de Lorraine

Spécialité : Mécanique et Energétique

Présentée par

Sebastian CASTRILLON ESCOBAR

Préparée au Laboratoire d'études du Physique de Corium  
IRSN (Institut de Radioprotection et de Sureté Nucléaire)

Et

LEMTA (Laboratoire d'énergétique et de mécanique théorique et appliquée)

### Composition du jury

|                |   |   |
|----------------|---|---|
| Rapporteurs :  | M. Stéphane ZALESKI<br>M. Sergei SAZHIN                       | Professeur, Université Pierre et Marie Curie<br>Professeur, Université de Brighton                          |
| Examinateurs : | M. Bruno TOURNIAIRE<br>M. Hervé COMBEAU                       | Docteur-ingénieur, EDF<br>Professeur, Université de Lorraine  |
| Encadrants :   | M. Michel GRADECCK<br>M. Renaud MEIGNEN<br>M. Nicolas RIMBERT | Professeur, Université de Lorraine, LEMTA<br>Docteur-ingénieur, IRSN<br>Maitre de conférences, ESSTIN-LEMTA |
| Invité :       | M. Pascal PILUSO  | Docteur-ingénieur, CEA  |



UNIVERSITÉ  
DE LORRAINE

École Doctorale EMMA Lorraine

Fragmentation de métal liquide dans  
l'eau

## THÈSE

présentée et soutenue publiquement le 6 Décembre 2017

pour l'obtention du

Doctorat de l'Université de Lorraine

(Spécialité: Mécanique et Energétique)

par  
Miloud HADJ ACHOUR

### Composition du jury

|               |   |   |
|---------------|---|---|
| Rapporteur :  | Mme Patricia ERN<br>M. Sergei SAZHIN  | Directrice de Recherches, CNRS, IMFT<br>Professeur, Université de Brighton  |
| Examinateur : | M. Nicolas RIMBERT<br>M. Louïes TADIRST<br>M. Laurent DAVOUST<br>Mme Nathalie MARIE<br>Mme Anne TANIÈRE MIKOŁAJCZAK | Maître de conférences, Univ. Lorraine, LEMTA<br>Professeur, Aix-Marseille Université, IUSTI<br>Professeur, Grenoble-INP, SIMaP<br>Docteur-ingénieur, CEA Cadarache<br>Professeur, Université de Lorraine, LEMTA |
| Encadrant :   | M. Michel GRADECCK  | Professeur, Université de Lorraine, LEMTA   |
| Invité :      | M. Renaud MEIGNEN<br>M. Pascal PILUSO   | Docteur-ingénieur, IRSN Cadarache<br>Docteur-ingénieur, CEA Cadarache   |

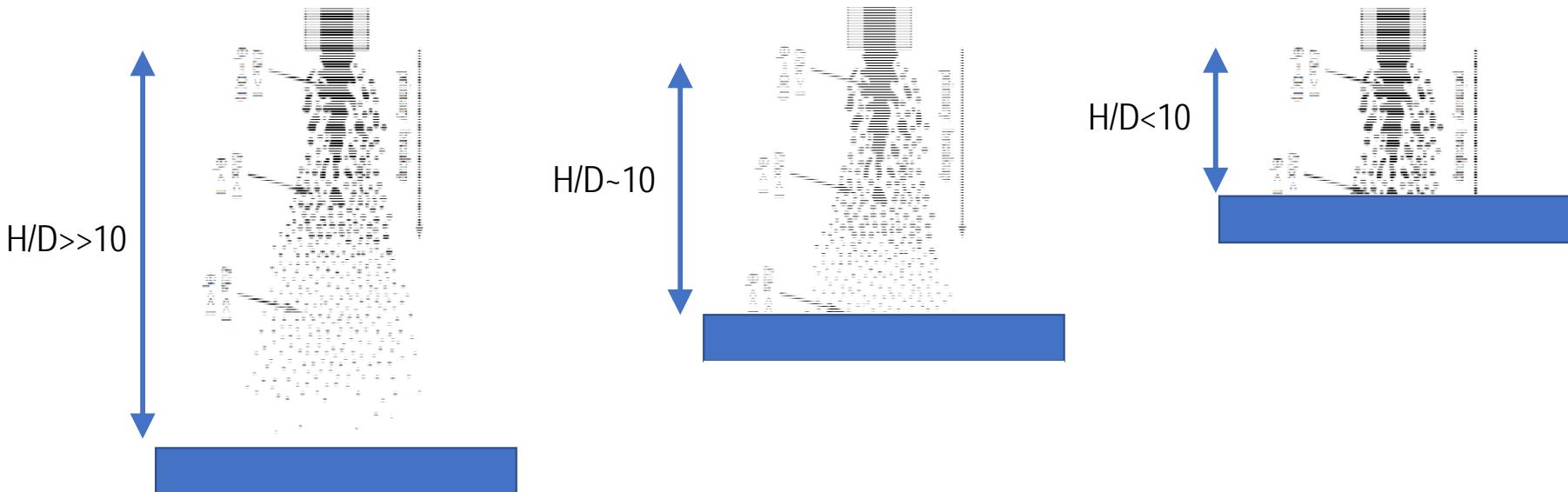
Le Laboratoire d'Energétique et de Mécanique Théorique et Appliquée – LEMTA — UMR 7503



# Second step of the relocation (1/4)

## Thermal interaction with the core-catcher

- Consequences of the Fragmentation?
- Corium will interact with the core-catcher as a spray of molten materials (short time interaction) and a debris bed will be formed (size of the debris)
- Question to be addressed: (i) breaking length of the jet and (ii) size of the debris and formation and coolability of the debris bed

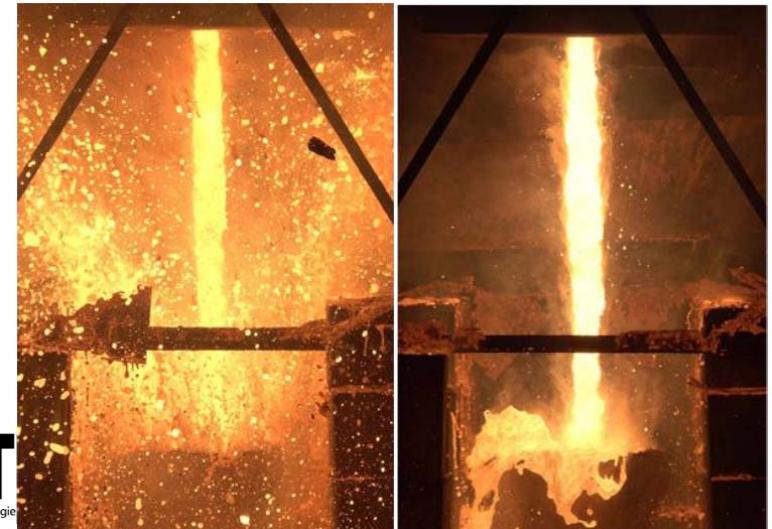
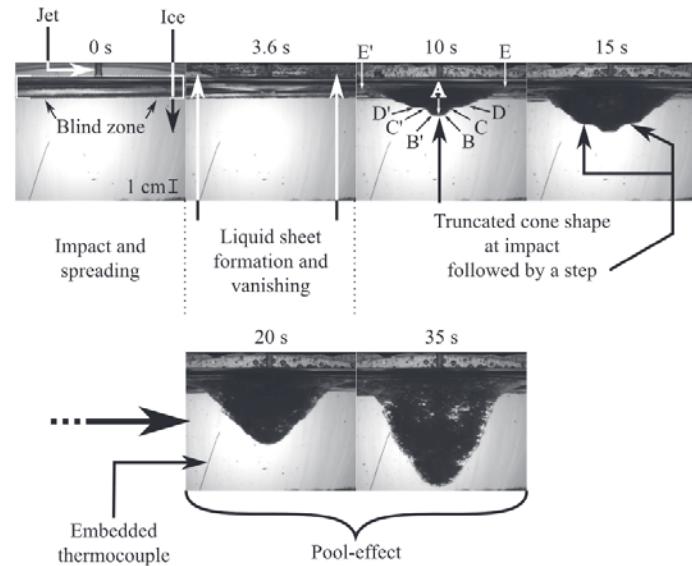




# Second step of the relocation (2/4)

Impact of a coherent corium jet on the core-catcher material  
(probably the most critical case)

→ This issue has been addressed recently (HANSOLO at LEMTA, JIMEC at KIT)



HANSOLO (water/ice) :  $T_j=50^\circ\text{C}$ ,  $Re_j=55000$  ( $D_j \sim 6\text{mm}$ )  
Picture from Lecoanet et al. (2021)

JIMEC (steel/steel) :  $T_j=50^\circ\text{C}$ ,  $V_j=2,5$  (exit) to  $5,1\text{m/s}$  (impact)  
Picture provided by Xiaoyang (KIT)

duration of the metal melt jet flow = 31s

17



## Second step of the relocation (4/4)

**What could we conclude?**

- **Fragmentation: Heat load will be spread on a larger surface and thus will reduce thermal load**
- **No fragmentation: this is the critical situation studied during A. Lecoanet PhD thesis**



# Recent studies at LEMTA & KIT



Étude de l'ablation d'une paroi  
solide par un jet liquide

## THÈSE

présentée et soutenue publiquement le 28 janvier 2021  
en vue de l'obtention du

Doctorat de l'Université de Lorraine  
(Spécialité : Mécanique et Energétique)  
par  
Alexandre Lecoanet

Composition du jury :

|                          |   |  |
|--------------------------|---|--|
| Rapporteurs :            | Mme Cathy CASTELAIN<br>M. Christian BUYER-QUIL                    | Directrice de recherche, CNRS, LTN<br>Professeur, Univ. Savoie-Mont Blanc,<br>LOCIE                                    |
| Examinateurs :           | Mme Nathalie MARIE<br>Mme Xiaoyang GAUS-LIU<br>M. Michael BIRHANU | Ingénieur-chercheur, CRA,<br>DES/IRENE/DTN/SMTA/LMAG<br>Docteur-ingénieur, KIT, ITES<br>Chargé de recherche, CNRS, MSC |
| Directeur de thèse :     | M. Michel GRADECK   | Professeur, Univ. Lorraine, LEMTA  |
| Co-directeurs de thèse : | M. Nicolas RIMBERT<br>M. Frédéric PAYOT                           | Professeur, Univ. Lorraine, LEMTA<br>Chef de projet,<br>CEA, DES/IRENE/DER   |
| Invité :                 | M. Christophe JOURNEAU  | Expert international, CEA,<br>DES/IRENE/DTN/SMTA/LEAG  |



H2020 project n°754501  
workpackage n°WP2.2, T2.2.3

Experimental results and post-test analysis of the  
HAnSoLO and JIMEC tests on interaction  
between corium jet simulant and sacrificial solid  
material

June, 2020



1



## Study of the ablation consecutive to jet impingement on a meltable solid – Application to SFR core-catcher

A. Lecoanet<sup>a,b,\*</sup>, F. Payot<sup>c</sup>, C. Journeau<sup>a</sup>, N. Rimbert<sup>b</sup>, M. Gradeck<sup>b,c\*</sup>

<sup>a</sup> CEA, DES/IRENE, Culombe, DTN, LEMTA, LEAG, F-54290 St Paul de Durance, France

<sup>b</sup> Université de Lorraine, CNRS, LEMTA, F-54000 Nancy, France

<sup>c</sup> CEA, DES/IRENE, Culombe, DER, F-33100 St Paul de Durance, France

### ARTICLE INFO

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Liquid jet  
Core-catcher  
Corium-sacrificial interaction  
Sodium fast reactor  
Fuel effect

### ABSTRACT

In the scope of safety studies for future sodium cooled fast reactors (SFR-Na), the use of discharge tubes and liquid core-catchers are forums for severe accident mitigation. During relocation of corium onto the core-catcher, complex thermal hydraulics phenomena can occur. This work focuses on the ablation of the core-catcher by the corium's jet. For that purpose, as experiments using corium and Na are difficult to achieve, we performed experiments using simulants materials with jet on transparent ice. Transparent ice allows for ablation rate measurements. Two types of simulants were identified in a first phase of the study. We also studied the influence of temperature (30, 50, 70 °C) and velocity (1, 2, 3, 5, 7, 9, 10 m/s) of the jet. Comparison with existing data have been done and finally, a scaling law in the first regime, for which the ablation rate is constant, has been found.

Journal of Nuclear Engineering and Radiation Science

## Ablation of a solid material by high temperature liquid jet impingement: an application to corium jet impingement on a SFR core-catcher

Michel Gradeck<sup>1</sup>

Université de Lorraine, CNRS, LEMTA, F-54000 Nancy, France  
LEMTA 2 avenue de la forêt de Haye BP90961 54505 Vandoeuvre les Nancy Cedex  
michel.gradeck@univ-lorraine.fr

Xiaoyang Gaus-Liu<sup>2</sup>

Karlsruhe Institute of Technology (KIT)  
Hermann-von-Helmholtz-Platz 1, 76344, Eggenstein-Leopoldshafen, Germany  
Xiaoyang.gaus-liu@kit.edu



# Third step of the relocation (1/4)

## Coolability of a debris bed?

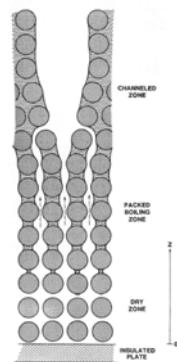
- Debris bed = inconsistent (or consistent) porous media (particles are supposed to be partly solidified or not) and we must also consider a residual heat source

- Thus very complex two-phase flow in inconsistent porous media
- coolability is controlled by the liquid sodium flow within the bed
- a coolability limit is defined estimating the DHF (Dryout Heat Flux)

under this limit, power is being removed from the debris bed under convective or boiling regimes, increasing the average void fraction,

above this limit, part of the heat generation accumulates within the solid, resulting in an overheating of the particles leading to their fusion and later to a pool

- important parameters: Thickness of the bed, porosity or permeability, particle diameters and temperature





# Third step of the relocation (1/4)

## Flow in porous media

- Described using the Darcy-Forcheimer equation (1914)

$$-\frac{dp}{dz} = \rho g + \frac{\mu}{K} J + \frac{\rho}{\eta} |J| \times J$$

$$K = \frac{\varepsilon^3 d^2}{36k_0 \tau^2 (1 - \varepsilon)^2} = \frac{\varepsilon^3 d^2}{A(1 - \varepsilon)^2}$$
$$\eta = \frac{\varepsilon^3 d}{B(1 - \varepsilon)}$$

- Generalization of the previous equation to two-phase flow (Buchlin et al., 1987)

$$-\frac{dp_g}{dz} = \rho_g g + \frac{\mu_g}{K_{rg} \times K} J_g + \frac{\rho_g}{\eta_{rg} \times \eta} |J_g| \times J_g$$

$$\Phi_{DHF} = \frac{h_{lv} \sqrt{\rho_g (\rho_l - \rho_g) g \eta (1 + \frac{\lambda_c}{H})}}{\left(1 + \left(\frac{\rho_g}{\rho_l}\right)^{1/4}\right)^2}$$

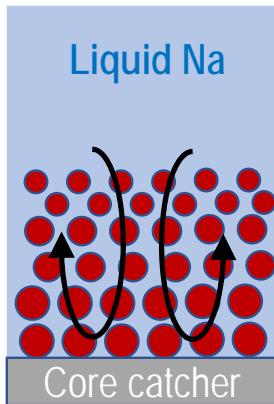
$$-\frac{dp_l}{dz} = \rho_l g + \frac{\mu_l}{K_{rl} \times K} J_l + \frac{\rho_l}{\eta_{rl} \times \eta} |J_l| \times J_l$$

with

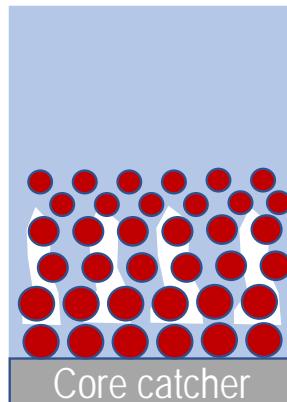
$$\lambda_c = \frac{\sigma \sqrt{\frac{\varepsilon}{K}}}{\sqrt{5}(\rho_l - \rho_g)g}$$



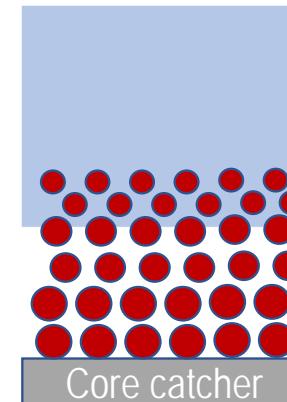
# Third step of the relocation (1/4)



Coolable without boiling



Coolable with boiling



uncoolable (Dryout)

**Simplified 0D model for DHF  
(from Lipinski, 1982)**

$$\Phi_{DHF} = \frac{h_{lv} \sqrt{\rho_g(\rho_l - \rho_g)g\eta(1 + \frac{\lambda_c}{H})}}{\left(1 + \left(\frac{\rho_g}{\rho_l}\right)^{1/4}\right)^2}$$

with

$$\lambda_c = \frac{\sigma \sqrt{\frac{\epsilon}{K}}}{\sqrt{5}(\rho_l - \rho_g)g}$$



# Concluding remarks

- First stage of the relocation
  - FCI (interaction of corium jet with surrounding Na)
    - Coherent corium jet (ie no fragmentation)
    - Fragmentation of the corium jet
- Second stage of the relocation
  - Impact of fragmented debris and Formation of a bed
  - Impact of the corium jet on the core-catcher material (most critical case)
  - Duration of the jet impact
- Third stage of the relocation
  - Cooling of debris bed
  - Cooling of the corium pool

Probably fragmention will occur....

...but the critical case should be the case studied by A. Lecoanet but it can be interesting to invetigate the case of a spray of molten material impinging the core-catcher

I have not talk about the cooling of a corium pool but it should be also addressed and we need also some more precise modelling of the DHF

Should be studied with LIVE tests at KIT



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## **PhD Students of the team:**

Sebastian Castrillon Escobar (2016), Miloud Hadj Achour (2017), Alejandro Villarreal Larrauri (2020), Alexandre Lecoanet (2021),  
[Antoine Avrit, Gagan Kewalramani, Bowen Ji, Linkai Wei](#)

## **Colleagues:**

Prof. Nicolas Rimbert, Technical staff of LEMTA

## **Partners:**

Renaud Meignen (IRSN), [Nathalie Seiler, Frédéric Payot & Christophe Journeau \(CEA\)](#),  
Xiaoyang Gaus Liu (KIT)



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Thank you!

