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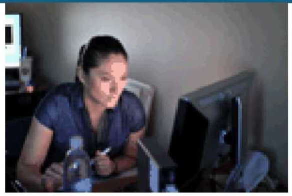
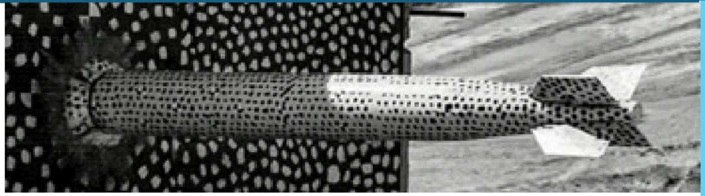
State-of-the-Art Severe Accident Analysis – Evolution of Reactor Safety after Fukushima Daiichi





PRESENTED BY

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Acknowledgements

Co-authors

- Randy Gauntt, Nathan Andrews, Lucas Albright, Patrick Mattie (SNL)

Collaborations

- Michael Salay, Richard Lee, Hossein Esmaili and Don Algama (NRC)

Previous collaborations

- R. Wachowiak, T. Kindred, K. Voelsing and R. Yang (EPRI)
- G. Geiger (formerly of JENSEN HUGHES), M. Griffiths and H. Luo (JENSEN HUGHES)

Summary

- In-Core Damage Progression Insights
- Lower Head Failure Insights
- Ex-Vessel Damage Progression Insights

In-Core Damage Progression

In-Core Damage Progression – Signatures from Unit 2

Three reactor pressure excursions

First reactor pressure excursion steam-limited

- Insufficient injection into reactor vessel to reflood lower part of core/debris

How does core/debris come into contact with water?

- 2 more reactor pressure excursions occur
- Late reactor pressure excursion possible

TMI-2-like crucible debris configurations tend to exhibit coherent melt progression

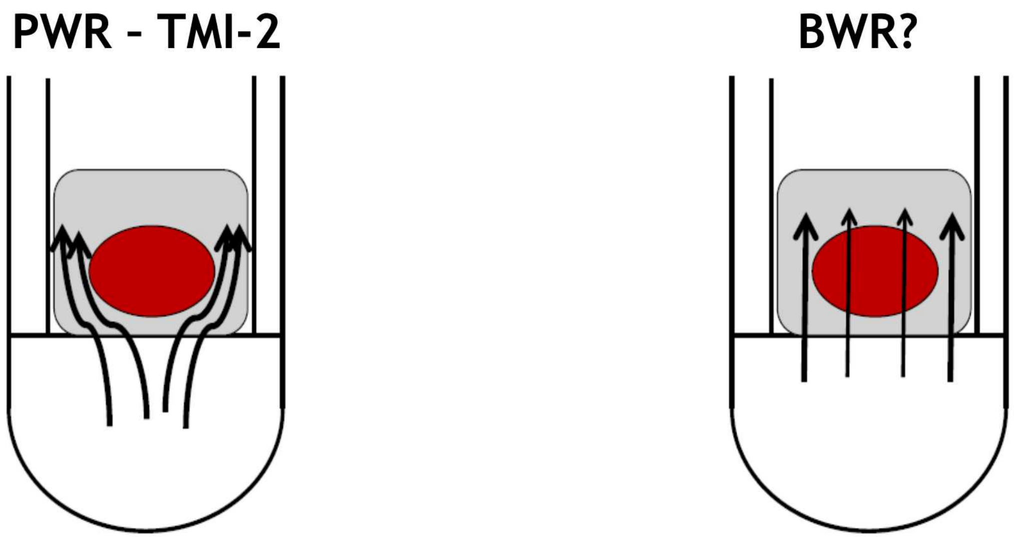
- Rapid slump of large mass of structural and fuel debris upon core plate failure

Unit 2 illustrates potential for more distributed slumping to lower plenum

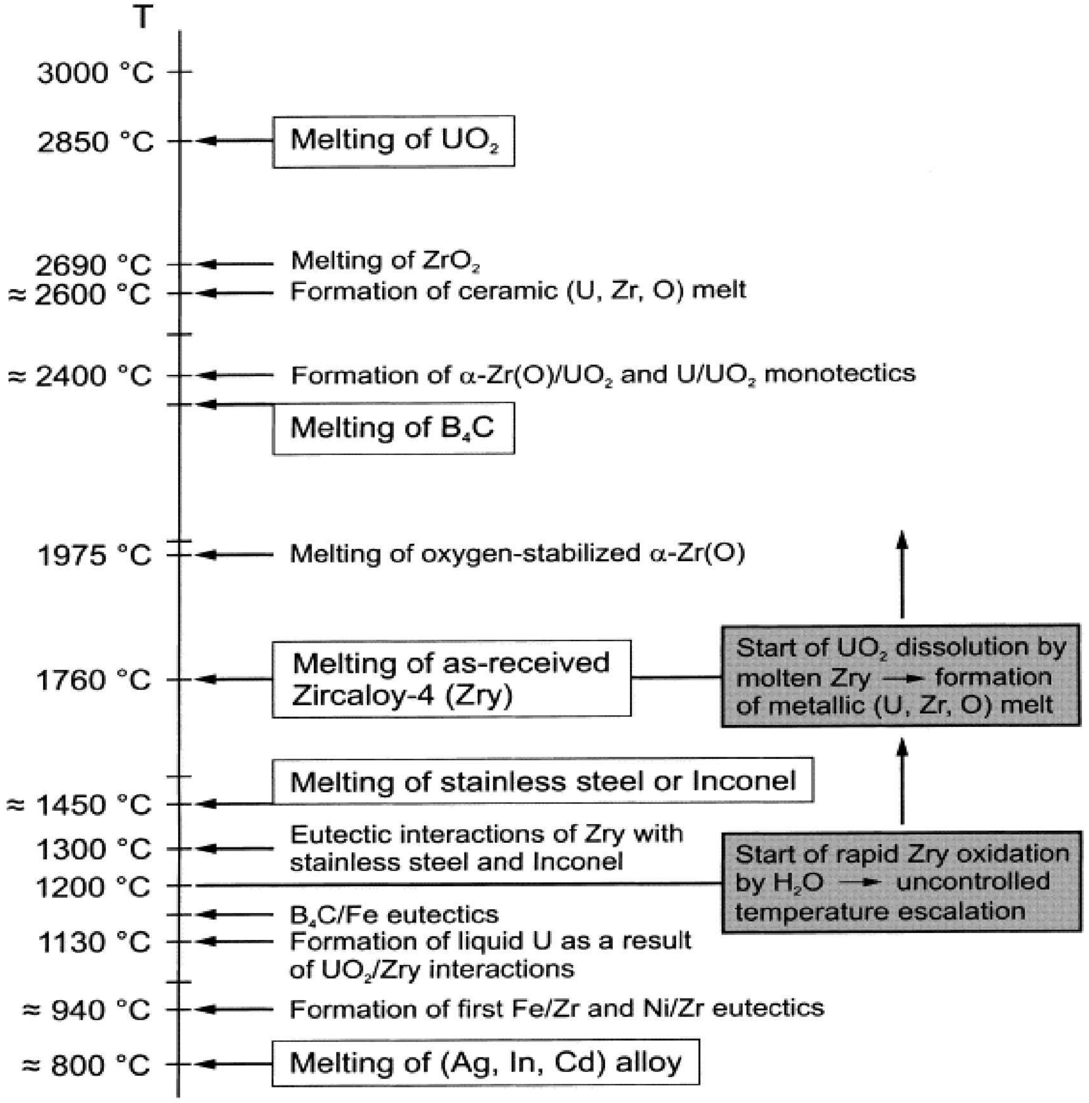
- Interplay of material chemical interactions and debris relocation mechanisms

MELCOR simulations indicate strong potential for incoherent debris slumping

- Significant relevance to explaining reactor pressure excursions at Unit 2



Important Material Interactions



Seminal work by Hagen and Hoffman (KfK)

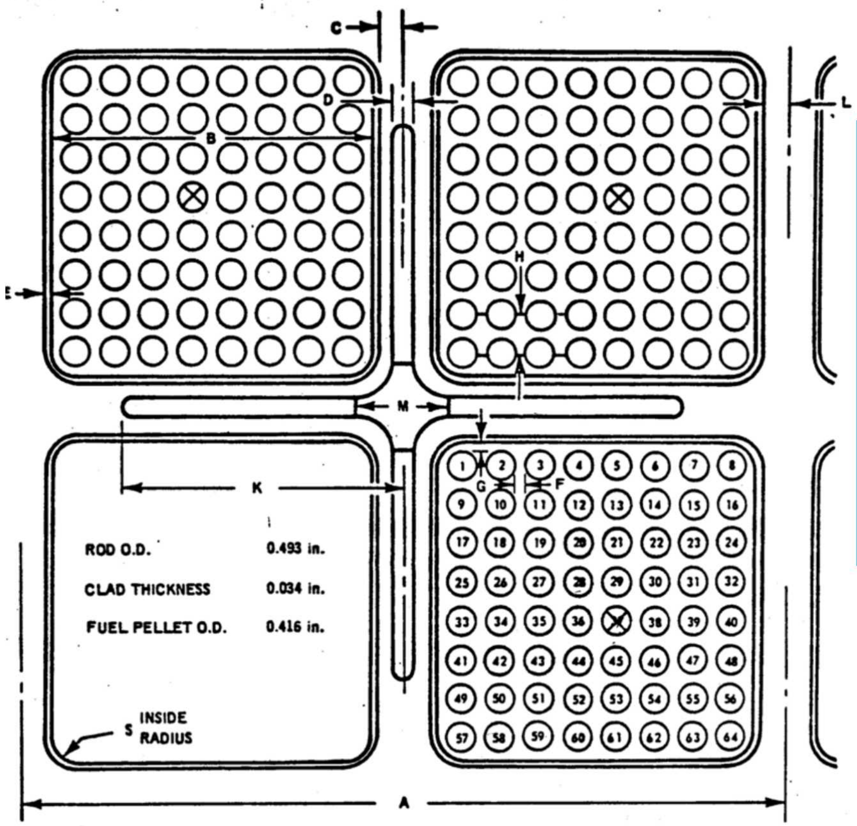
View in 1980's (STCP) assumed fuel melts at 3200K

Early experiments showed role of material interactions showed fuel "liquefied" at lower temperatures (2400K up to 2880K)

DF-4 BWR Experiment showed B_4C/SS blades liquefy at ~1500K (compared to 1700K)

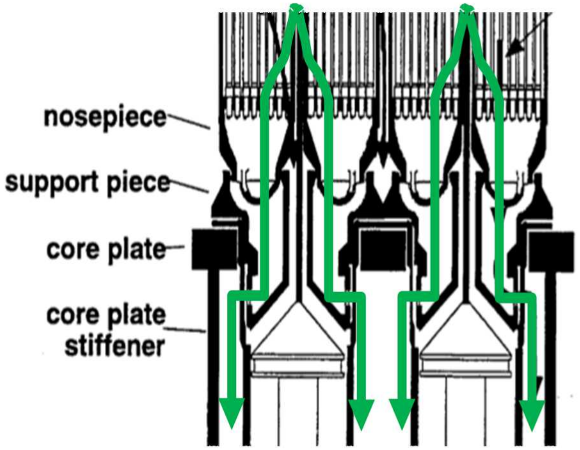
Eutectics form between Zr/SS with liquefactions as low as 1200K to 1573K

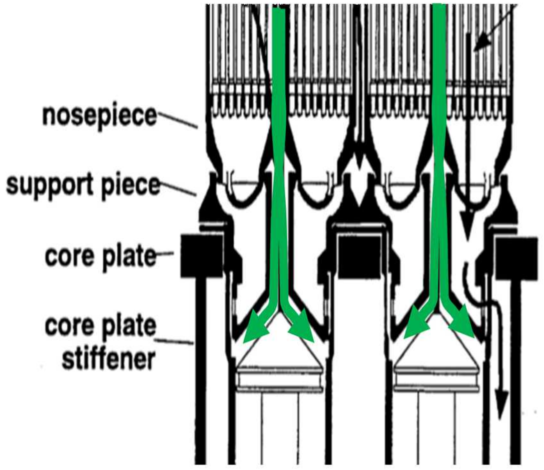
Heat of mixing of Zr/Fe is exothermic and generally not treated

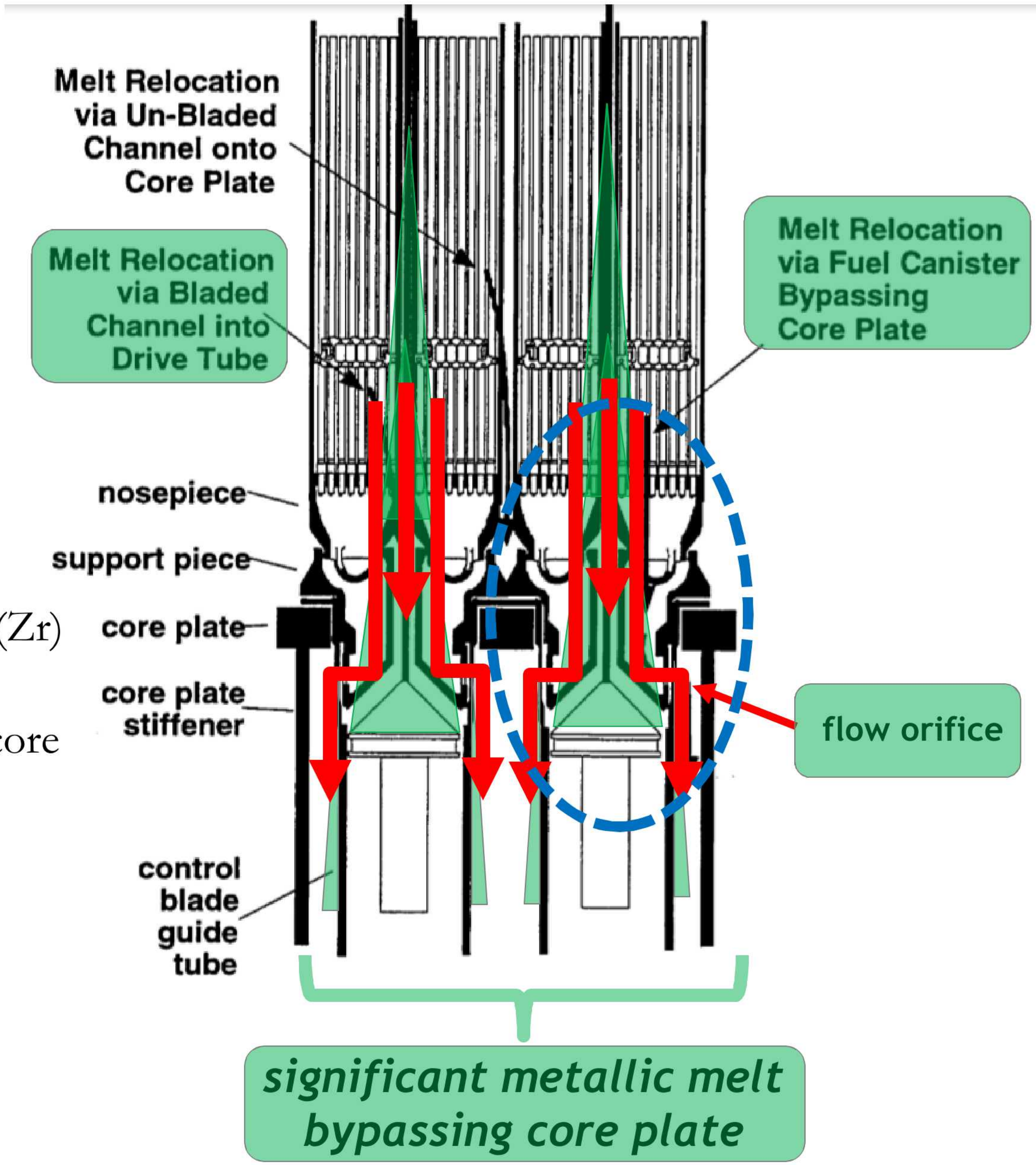


Differing materials in close proximity

Blade/Canister Melt Draining Inside and Within Fuel Canister







Liquefied blade (SS) and banister (Zr) can enter fuel rod canister

Drain into nose pieces and fuel support piece

Exit support piece through flow orifices

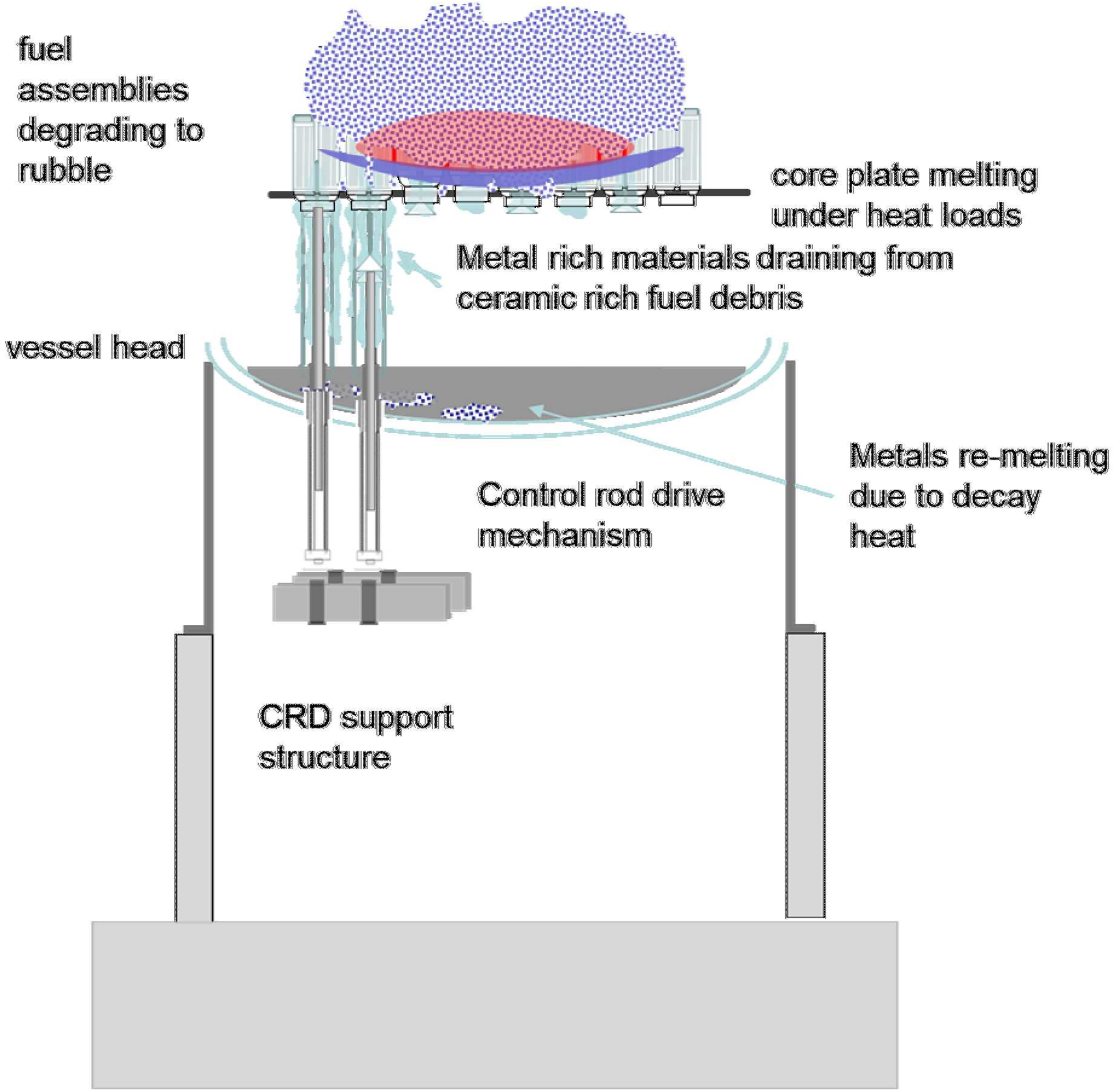
Drain down outside of guide tubes

Liquefied blade (SS) and canister (Zr) can also drain down blade region

Drains into bladed region below core plate

Melt will accumulate on velocity limiter

Revised Conception of In-Core Accident Progression Scenario



In-core structures and some fuel experience early liquefaction

- Relocation to core plate and slumping to lower plenum

Fuel rods degrade and slump onto core plate

- Localized in-Core TMI-2 like crucible could also form

Debris slumping to lower plenum

- Initial debris pours quenched in lower plenum water

Continued injection at Units 2 and 3 would keep much of the debris bed frozen

Subsequent debris pours not into deep lower plenum water pool

- Peripheral pours of hot molten material could pose challenge to lower head wall
- Absence of strong quenching effect due to slumping into deep water pool

Loss of water injection leads to lower plenum water boil-off

- Progressive exposure of lower head to hot debris and hot Zr

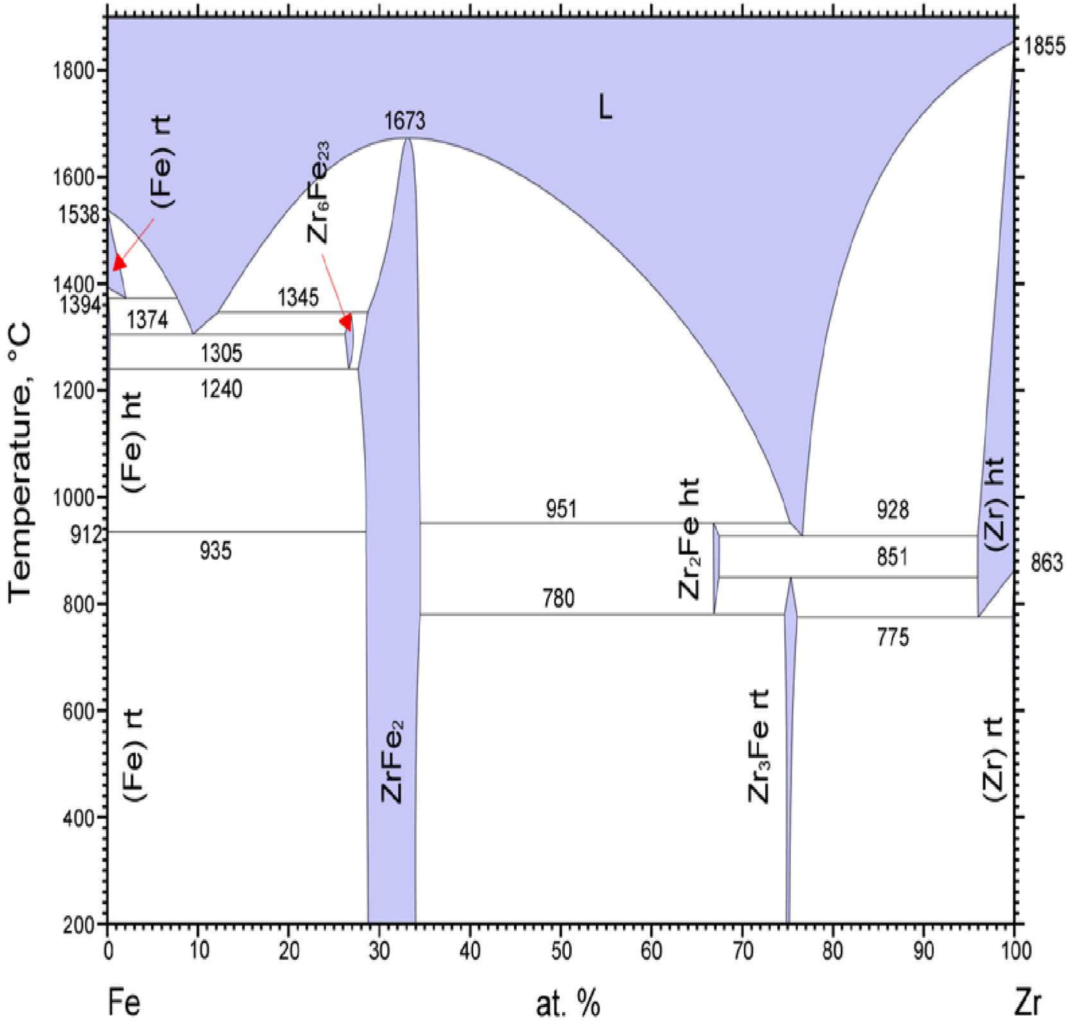
Lower Head Failure

Fe-Zr Chemical Interactions and Phase Diagram

Fe-Zr eutectics
- 928°C (1201 K) on Zr rich side
- 1305°C (1578 K) on Fe rich side

Substantially lower melting temperature than pure materials
- 1538°C (1811 K) Fe
- 1855°C (2128 K) Zr

Description of effect
- "The Laves phase, $ZrFe_2$, is very stable indicative of strong interactions between iron and zirconium probably involving electron transfer from zirconium to iron. This strong interaction also occurs in the liquid phase and gives rise to exothermic heat of mixing"



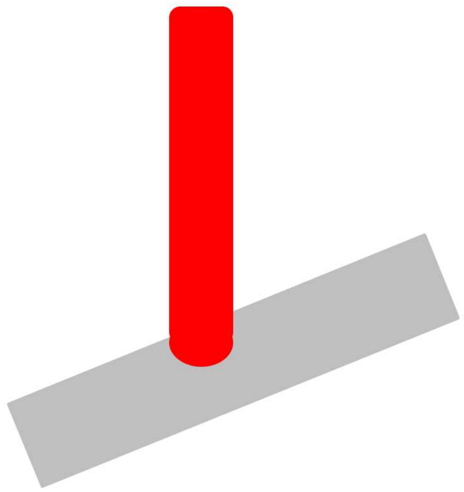
Relevant Configurations for Assessing Implication for Fe-Zr Chemical Interaction

Melt jet impacting vessel

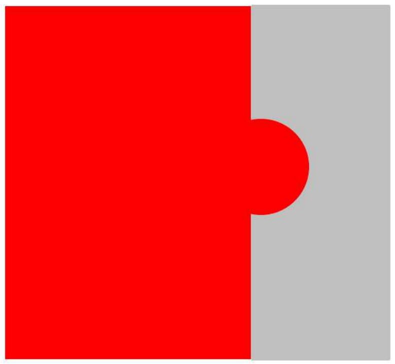
- Release of held up configuration
- Small melt mass
  - reaction effect on ablated amount
- Large melt mass
  - Reaction effect on penetration timing

Corium pool in contact with vessel wall

- Reaction effect on erosion rate
- Locally higher Zr concentrations (layers) can affect local erosion

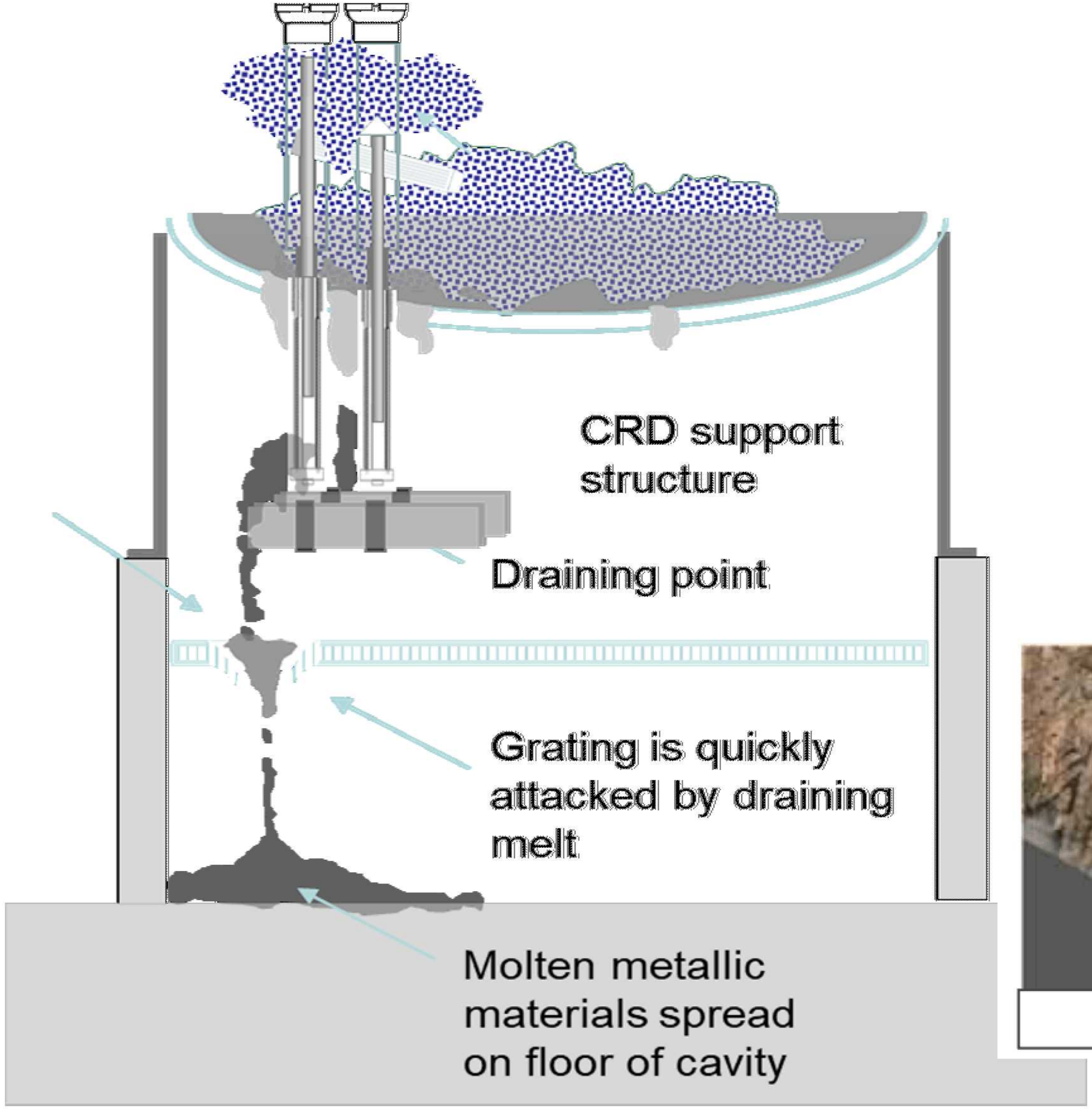


Melt jet wall interaction



Corium-pool wall interaction

Molten Debris Attack of Lower Head Wall – Unit 2



Reference : Platform grating

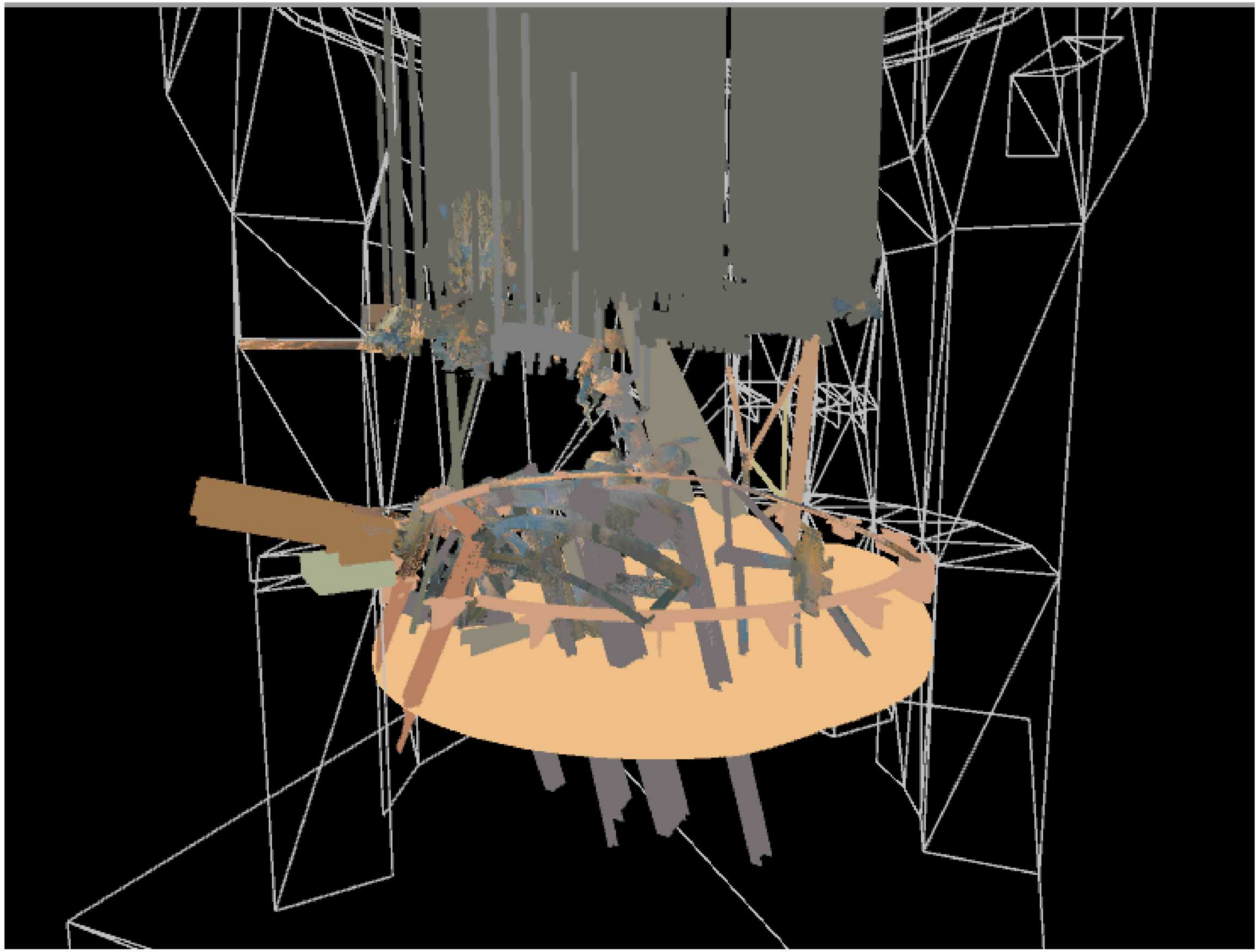
Localized failure at upper portion of lower head
- Draining peripheral metallic core material
- Potential for localized Fe-Zr interactions

Remainder of lower head wall largely undamaged

CRDs largely undisturbed at Unit 2

Platform grating attacked at periphery of vessel
- Draining metallic melt locally attacked grating

Molten Debris Attack of Lower Head Wall – Unit 3



Gross deformation of Unit 3 lower head observed

- CRD tubes displaced
- Reflects creeping of vessel wall

Multiple relocation points through lower head wall

- Boil-down of water in lower plenum
- Progressively exposed lower head to thermal transient

Complete loss of platform grating at Unit 3

Substantial debris accumulation under center of lower head

- Gross creep failure of lower head wall
- Prior to substantial formation of molten debris in lower plenum

Scenario 1

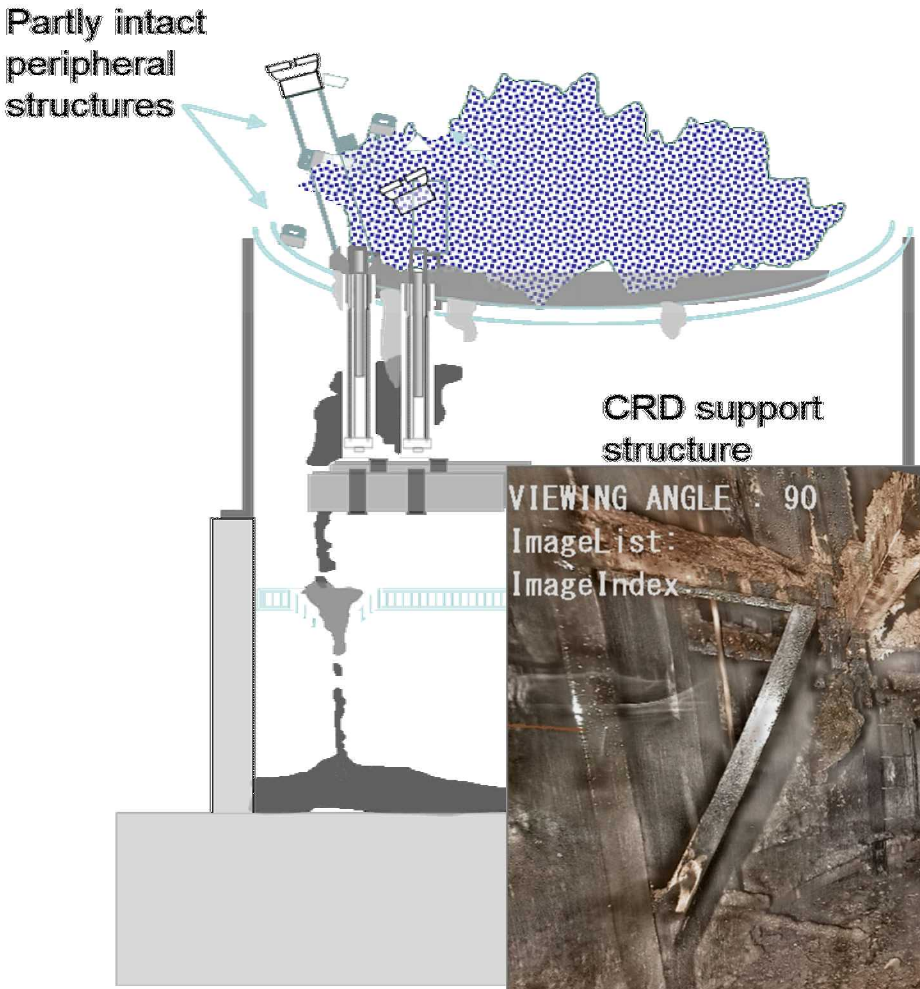
- Progressive relocation of molten debris with progressive failure of lower head wall

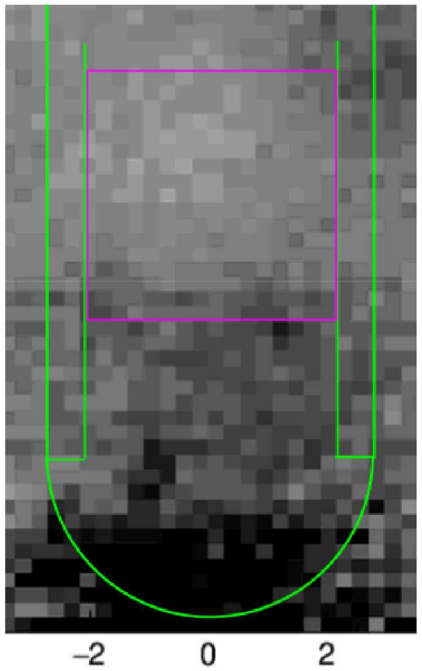
Scenario 2

- Gross creep failure of lower head brought substantial mass of debris down on grating
- Failure occurred prior to substantial accumulation of molten debris in lower plenum
- Weakening of lower head wall through interaction of Fe with interfacing Zr-rich debris layers

Ex-Vessel Debris Relocation

Unit 2 End State





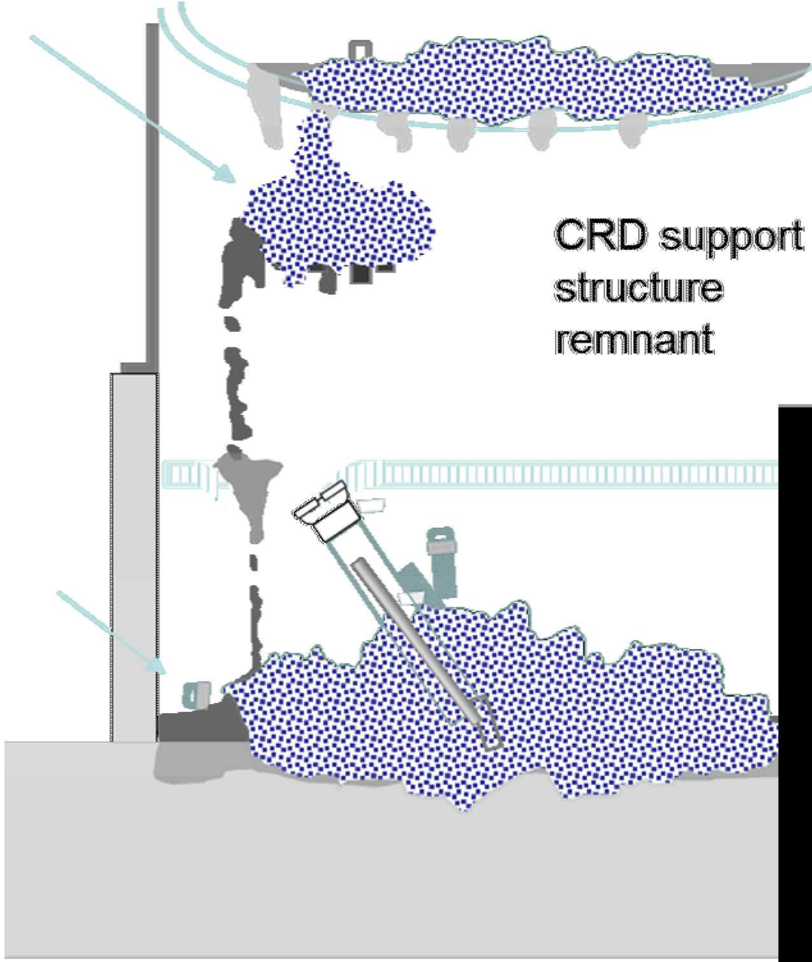
Peripheral structures may be partly intact at edge of core and fall to lower head – MELCOR *could* capture this with code modifications

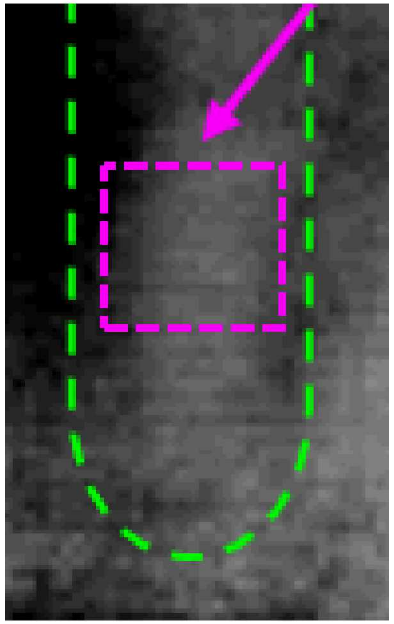
Metallic melt spreads to walls of cavity – MELCOR can do

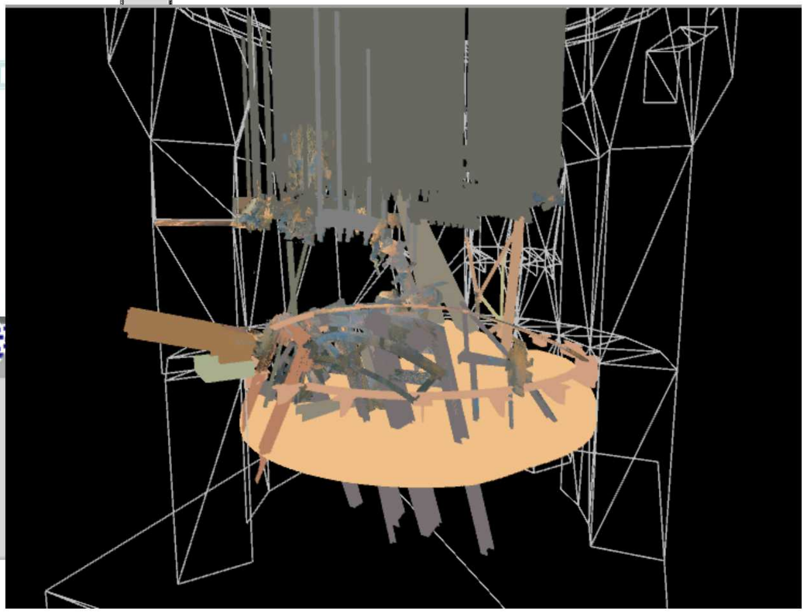
Unit 2 lower plenum likely did not boil dry may have been arrested by this time leaving a mostly level metallic layer on cavity floor – 1F2

Some intact parts apparently fell through largely disintegrated lower head – 1F3

Unit 3 End State







Substantial mass of solid debris relocated into reactor pedestal

- Accumulation of debris pile beneath center of lower head
- Supports extensive creep deformation and failure of vessel wall

Substantial deformation of Unit 3 lower head observed

- Supports condition for substantial debris release to reactor pedestal

Substantial debris release to CRD support structure

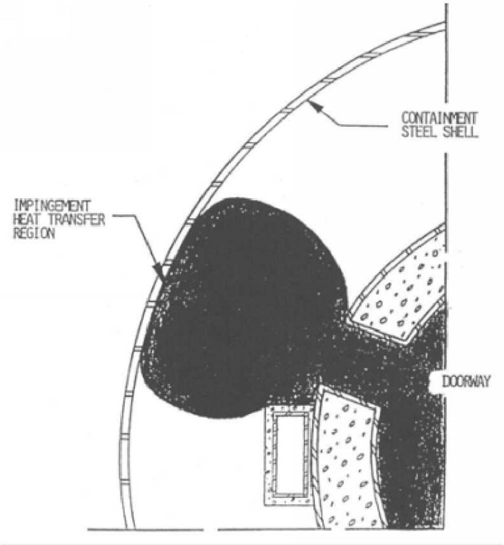
- Loss of CRD support structure
- Allows in-core drive tube structures to drop into reactor pedestal

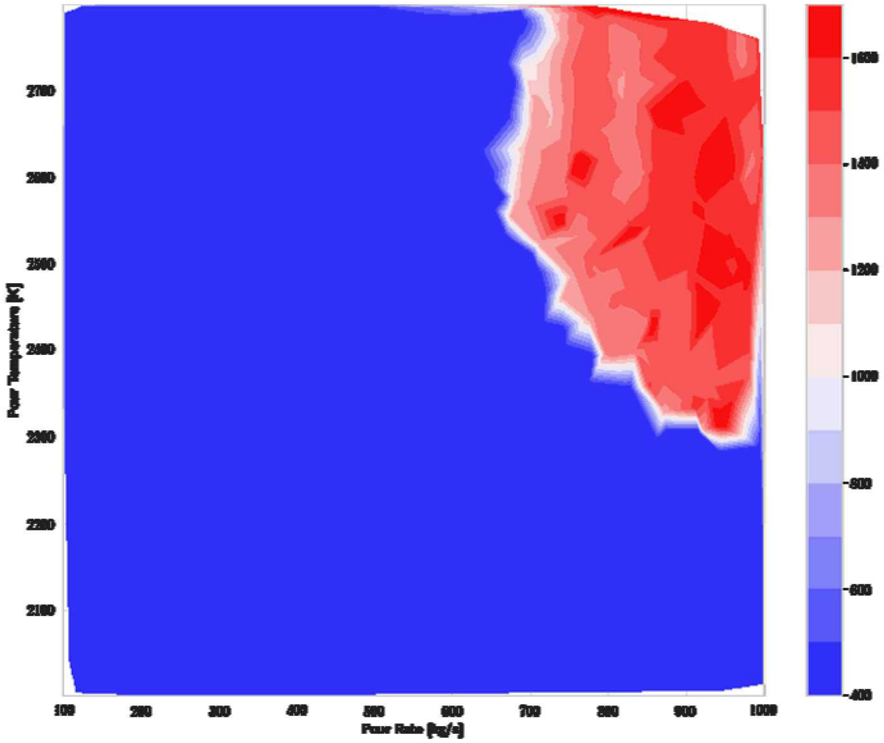
Implications for Ex-Vessel Debris Relocation Scenarios

MELTSPREAD code used to assess impact of debris pour transients on ex-vessel debris state

Comparison against observed Unit 2 and Unit 3 ex-vessel damage conditions

- Forensic insights to evaluate lower head failure and relocation transient





Implications for Reactor Safety

BWR Mark I liner melt attack issue

- Containment failure soon after lower head failure
- Failure gives rise to more severe off-site consequences

What does Fukushima Daiichi say about the potential for this failure mode?

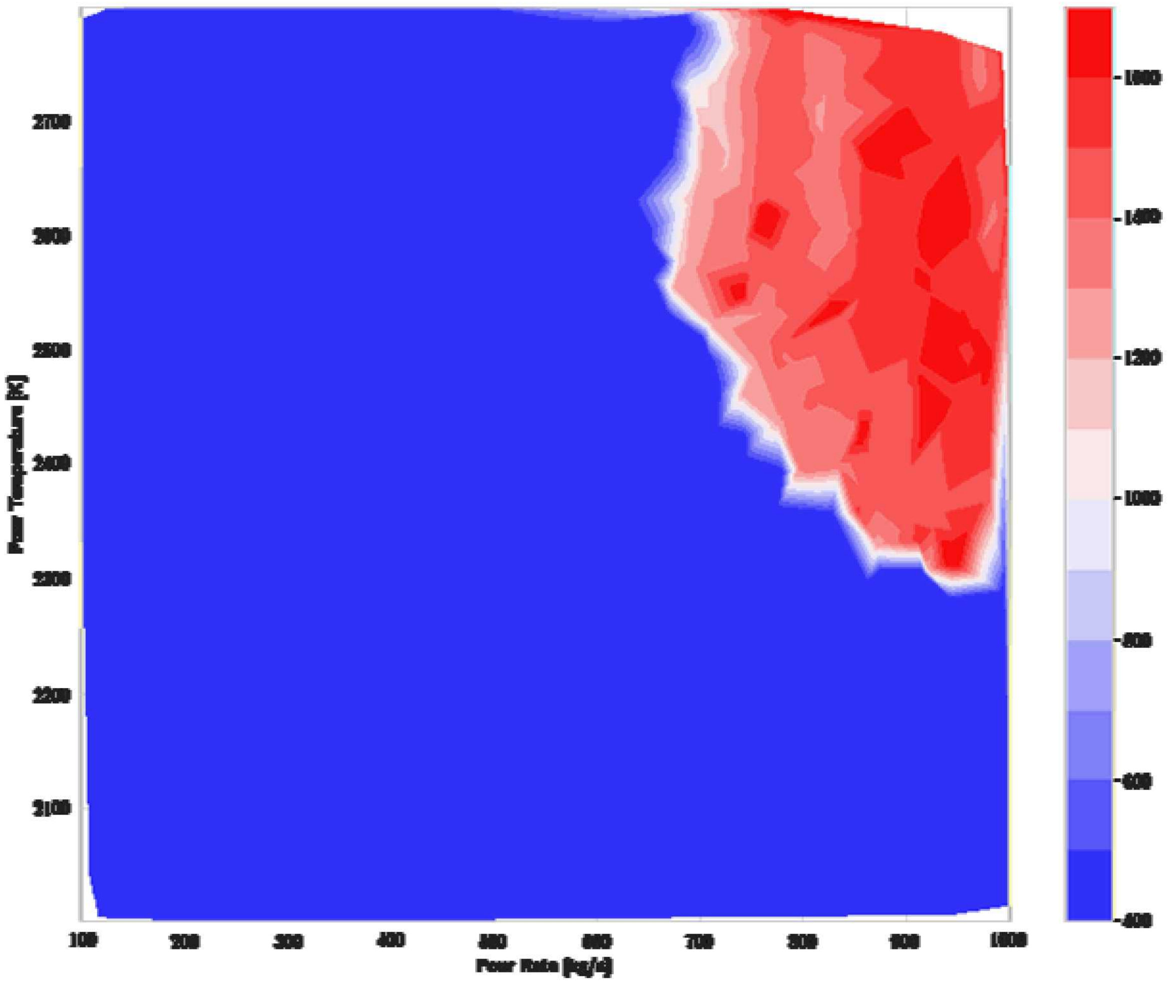
Vessel failure tends to be more progressive

Molten debris tends to relocate out of the vessel

- More gradually
- In bursts due following core slumping

Debris relocation transient tends to lead to less significant ex-vessel spreading

- Challenge to drywell liner lower



Future Insights from Fukushima Daiichi

Lower plenum debris in Unit 2 has potential to significantly enhance understanding of debris slumping to lower plenum

- Are bottom layers of lower plenum debris more metallic?
- This would be consistent with a scenario in which metals formed from early eutectic dissolution drain into lower plenum prior to significant slumping of majority of fuel debris

State of Unit 2 lower head wall around failure of critical interest

- Does it support potential for chemical interaction between molten Zr in debris pour and Fe in lower head wall?

State of Unit 3 lower head wall

- Did Zr-Fe chemical interactions promote earlier and more extensive thermal loading of lower head?
- Did these promote rapid creep and gross failure at the bottom of the lower head?

Units 2 and 3 ex-vessel debris sampling critical to confirming insights regarding lower head failure and debris relocation