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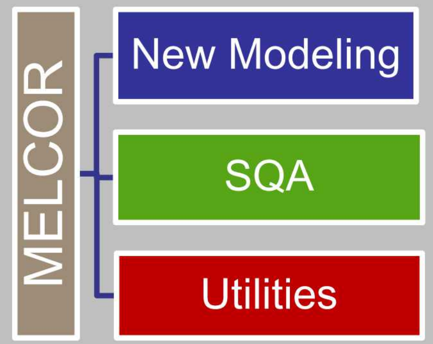

Proposed Modelling Evolution Based on Involvement in OECD/NEA Projects Related to the FDNPS Accident, Rev. 1

R.O. Gauntt, D. Luxat and N. Andrews

Sandia National Laboratories

* With Contributions from JAEA and Tokyo Tech

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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OECD/NEA Activities

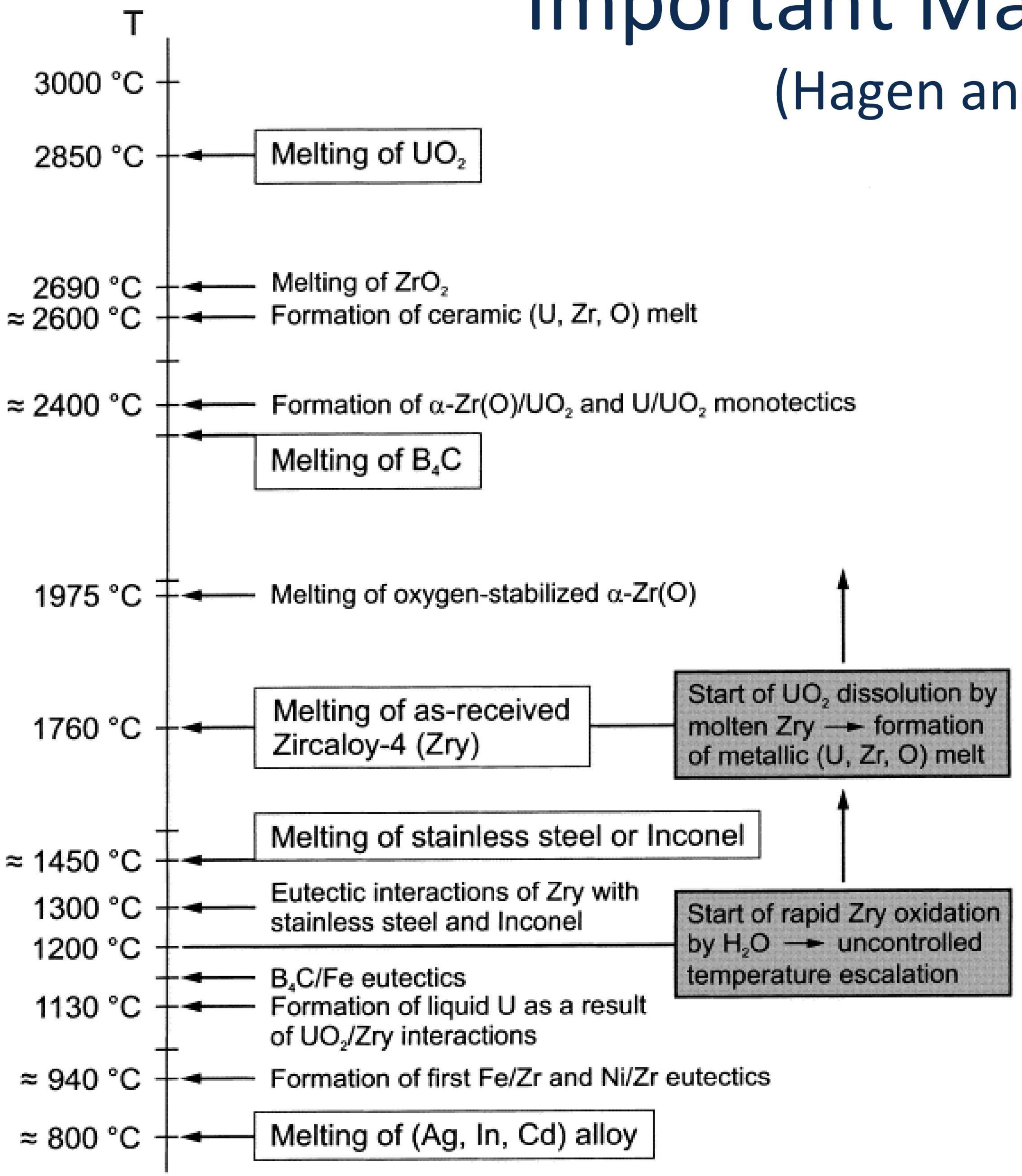
- BSAF Phase I and Phase II
  - Severe accident integral code modeling
- ARC-F
  - Sensitivity and uncertainty analyses of accidents
- TCOFF
  - Thermodynamics of materials during severe accidents
- PreADES
  - Informing sampling decisions and decommissioning
- ROSAU
  - MCCI experiments and analyses

Outline and Theme of Discussions

- What we know from experiments
- What is modeled in codes
- Important materials interactions
- Chronology of damage progression roughly follows in order of increasing melting/liquefaction temperatures
- Plausible sequence to explain 1F-2,3 robotic visual examinations
- Highlight MELCOR modeling observations
- Highlight potential decommissioning phase data collection needs

Important Material Interactions

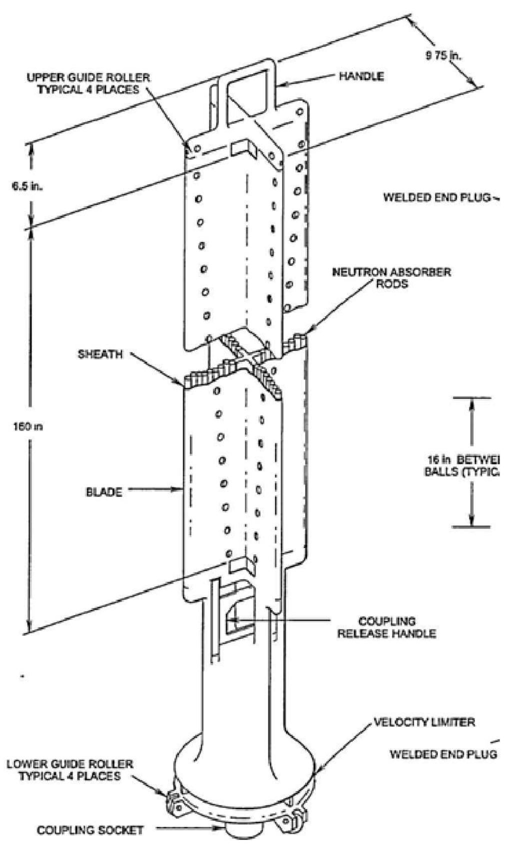
(Hagen and Hoffman – KfK)

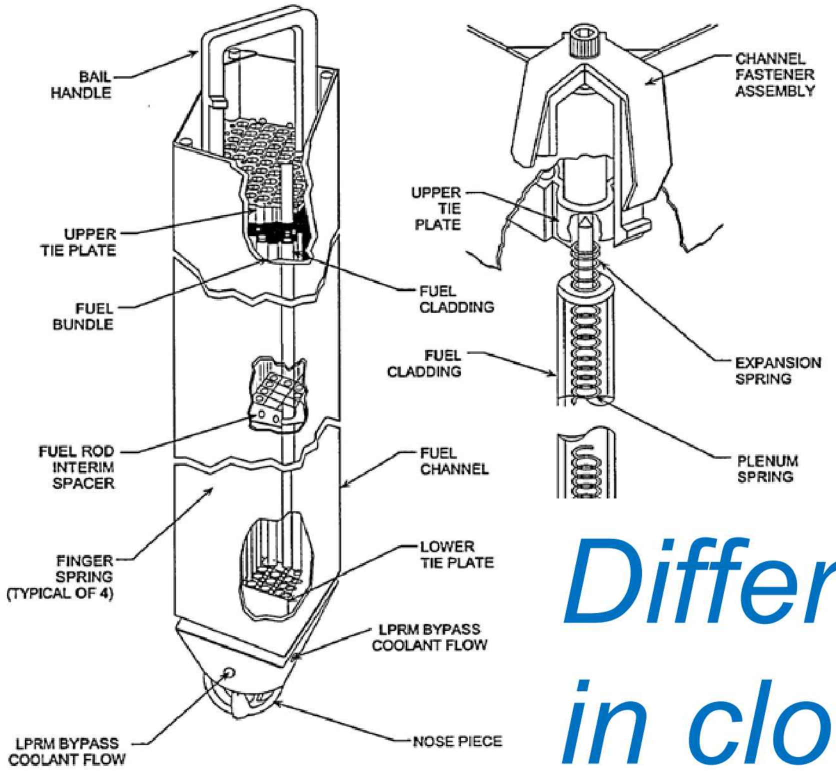


- View in 1980's (STCP) assumed fuel melts at 3200K
- Early experiments showed role of material interactions showed fuel "liquefied" at lower temperatures
  - 2400K up to 2880K
- DF-4 BWR Experiment showed B_4C/SS blades liquefy at ~1500K (compared to 1700K)
- Eutectics form between Zr/SS with liquefactions as low as 1200K to 1573K
- *Heat of mixing of Zr/Fe is exothermic and generally not treated*

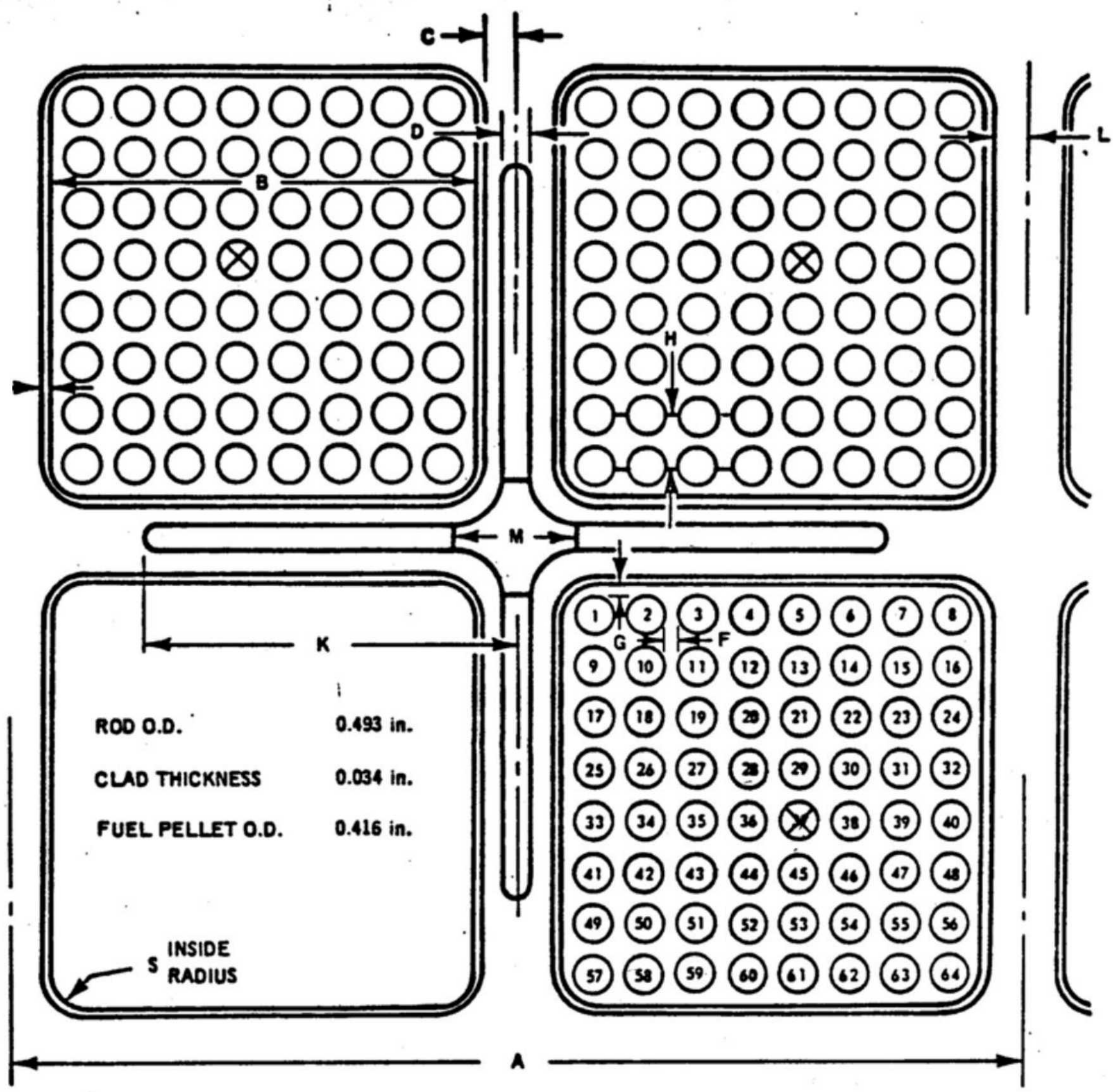
BWR Core Components

- $15\ m^3\ UO_2$
- $5\ m^3$ Zr Cladding
- $3.2\ m^3$ Zr Canisters
- $2.6\ m^3$ SS Blades





Differing Materials in close proximity



- $UO_2/Zr(O)$ liquefactions → ~2400K
- B_4C/SS liquefactions → ~1500K
- $B_4C/SS/Zr$ liquefactions → ~1200K to 1500K

Control Blade/B4C & SS/Zr Interactions

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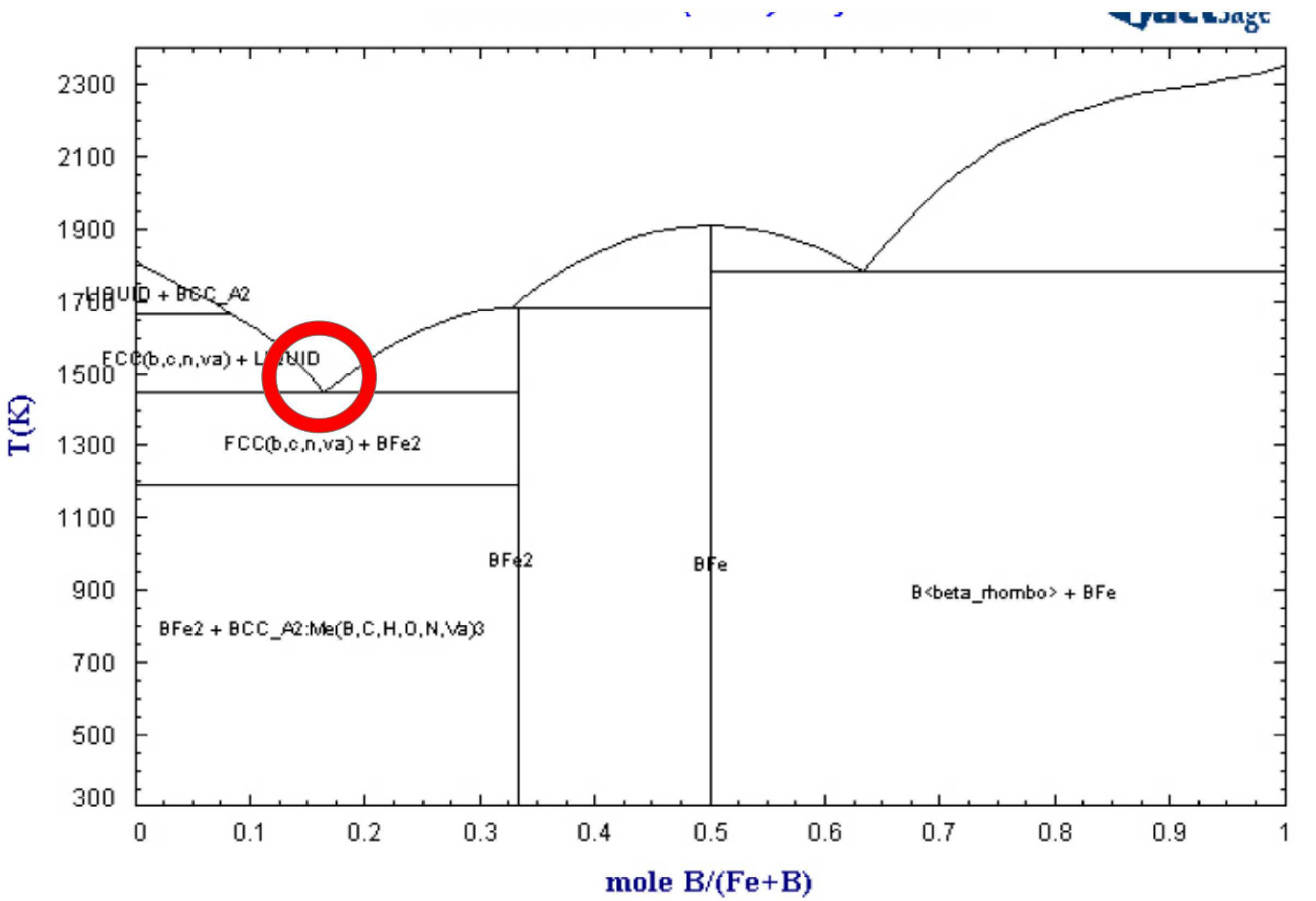
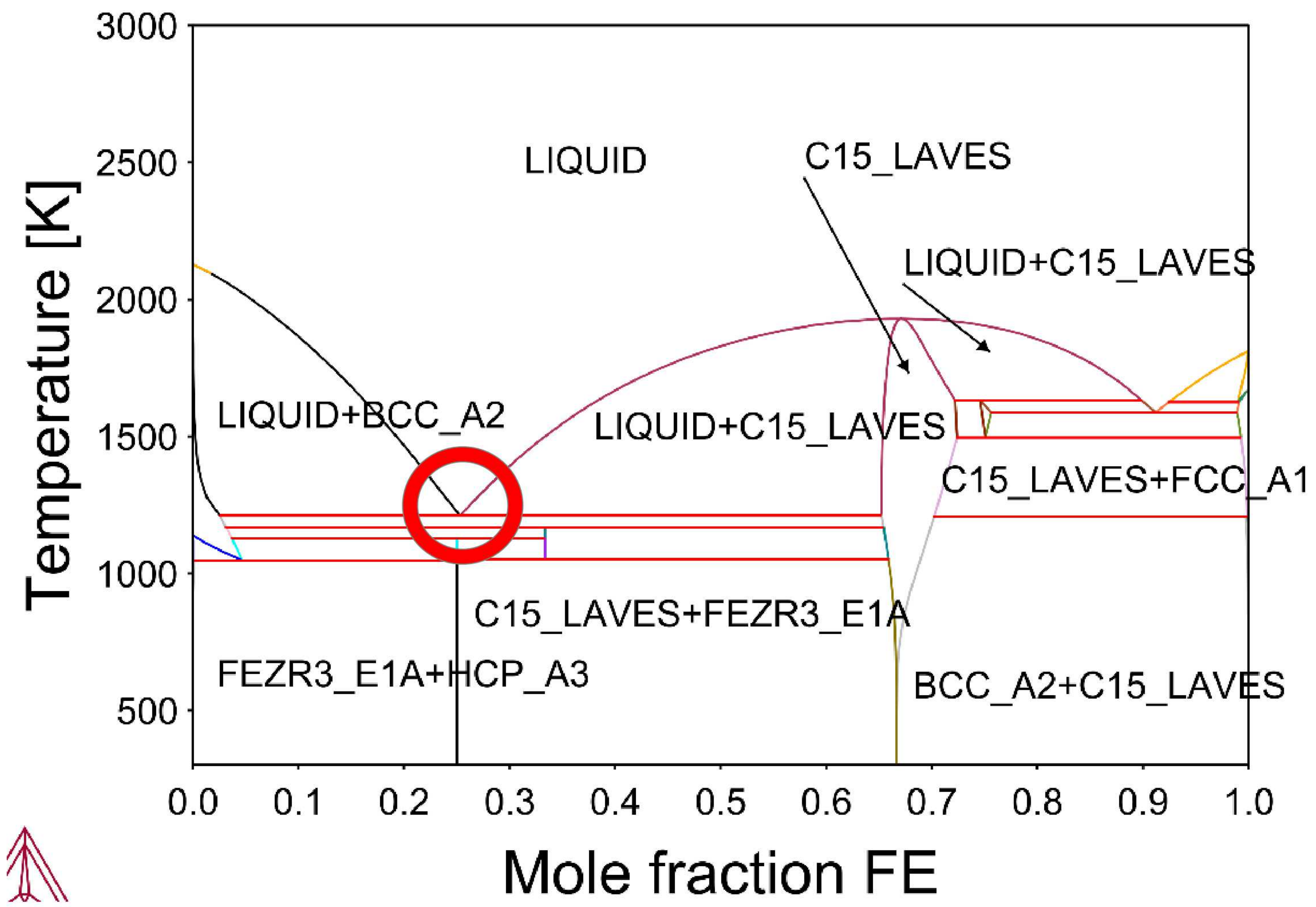


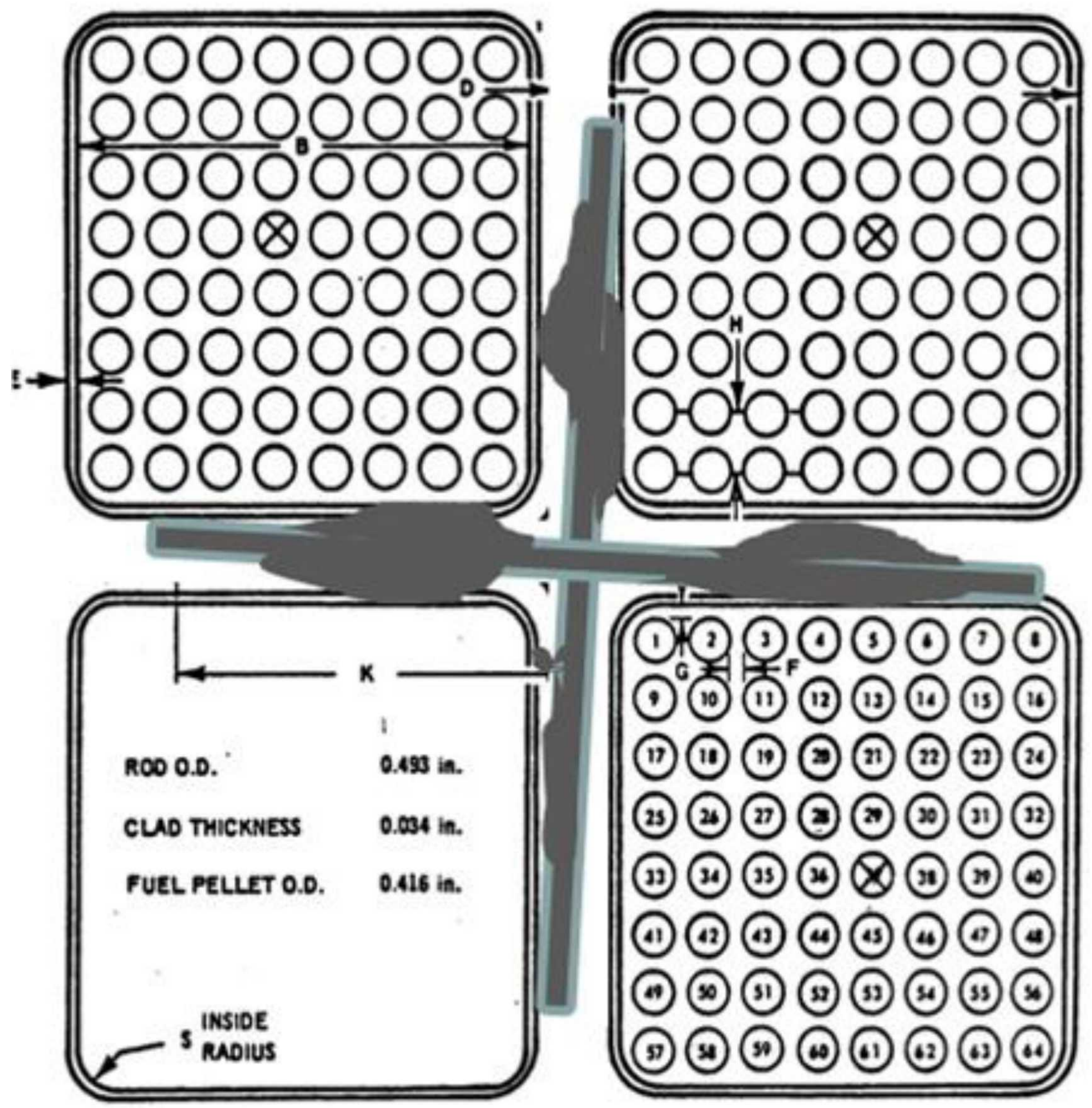


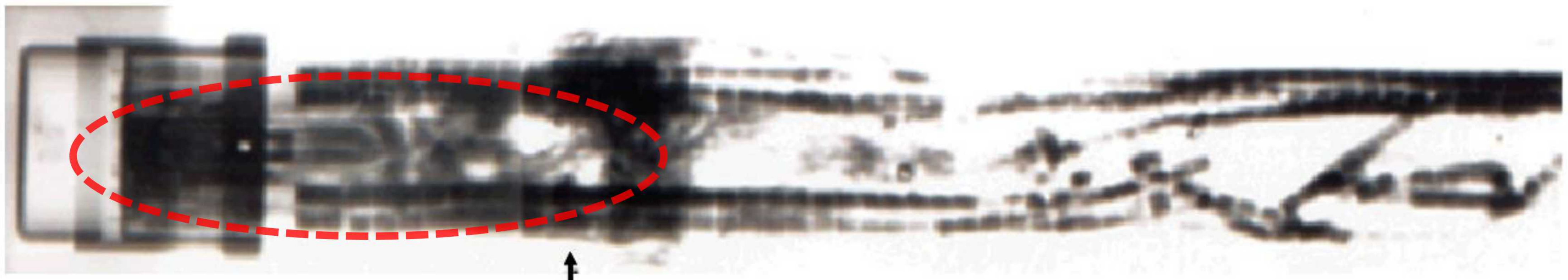
- Reaction rate seems very rapid based on experiments
- B_4C seems largely consumed into eutectic melt
- B_4C likely follows liquefied SS

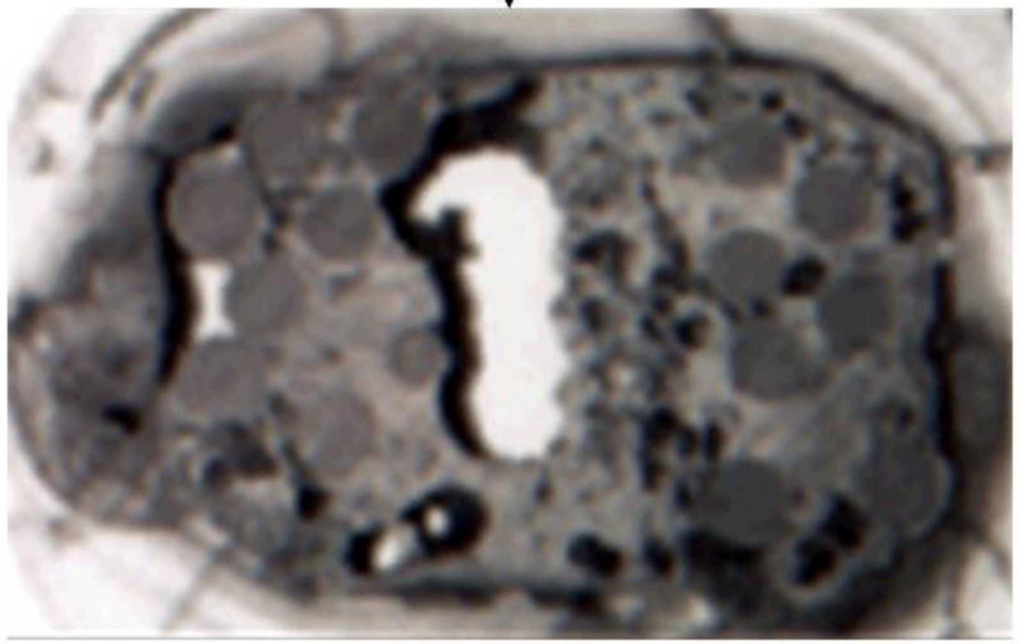
- Blade distorts and melt contacts Zr channel box
- Channel box liquefied by Fe-Zr eutectic (1200K)
  - Channel box "unzips"
- Liquefied materials drain downward
  - Inside channel box and outside channel box

Attack of Channel Box (Zr) by Liquefied Blade Material (SS/B4C)

DF-4 BWR Experiment in ACRR (SNL)



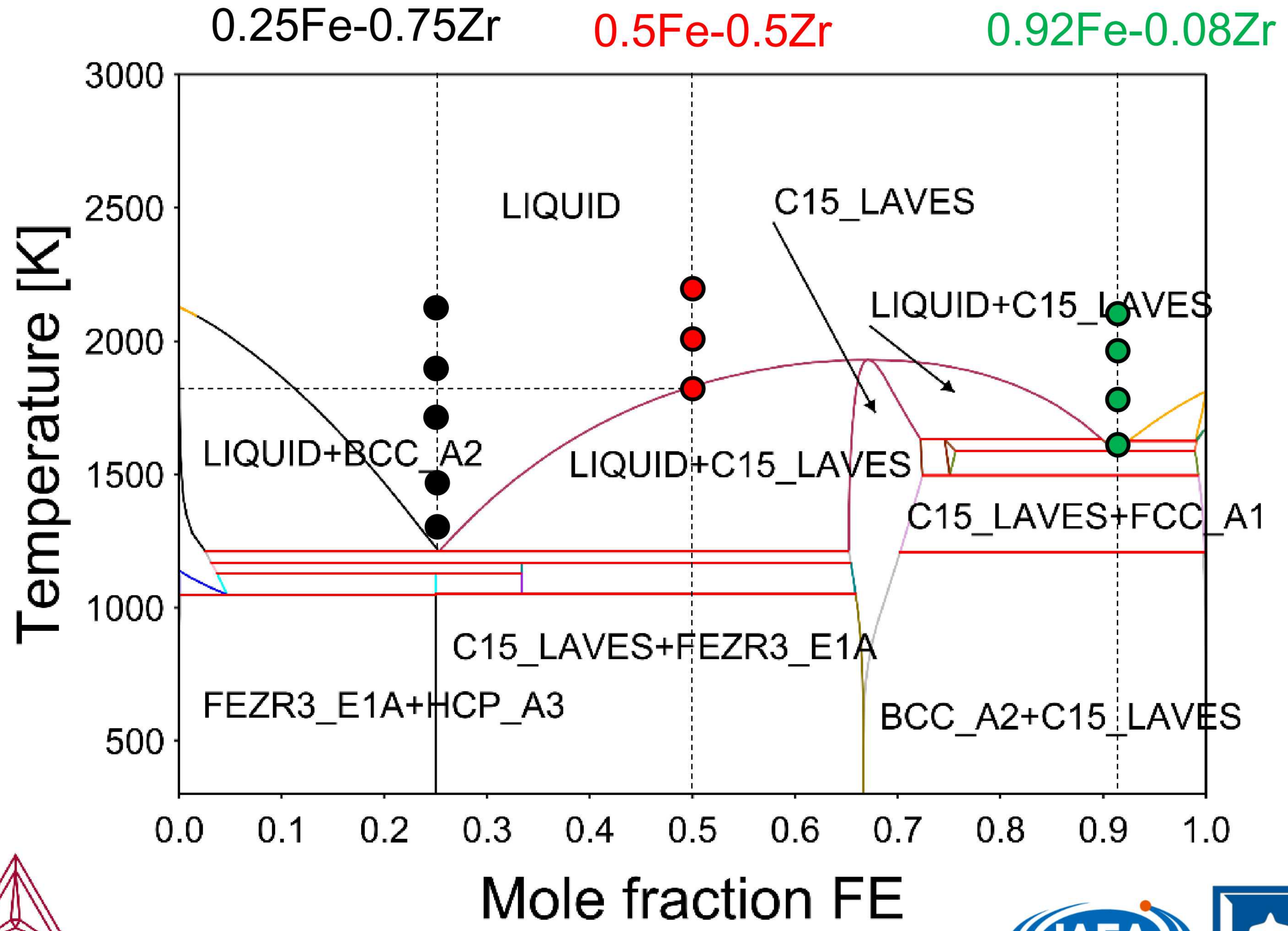




- Channel and blade obliterated over most of length
  - Slight remnant at bottom
  - Blade material at bottom

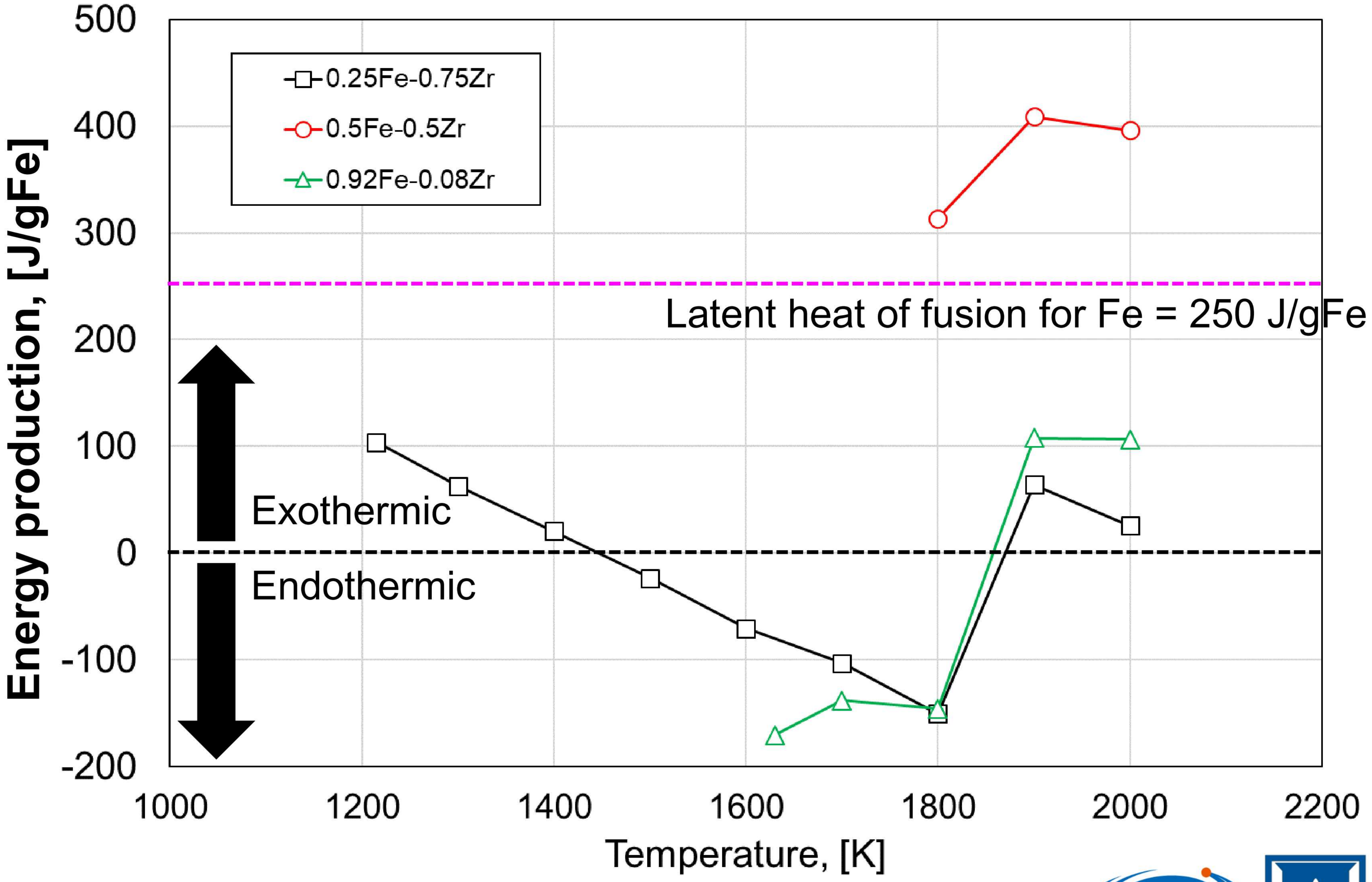
Fe/Zr Binary System – Potential Material Combinations

- Is the Fe/Zr combination exothermic, compared to non-mixed metals?
- Representative combinations of Fe and Zr
  - Two separate eutectic materials combinations
  - 50/50 mixture
- Representative temperatures

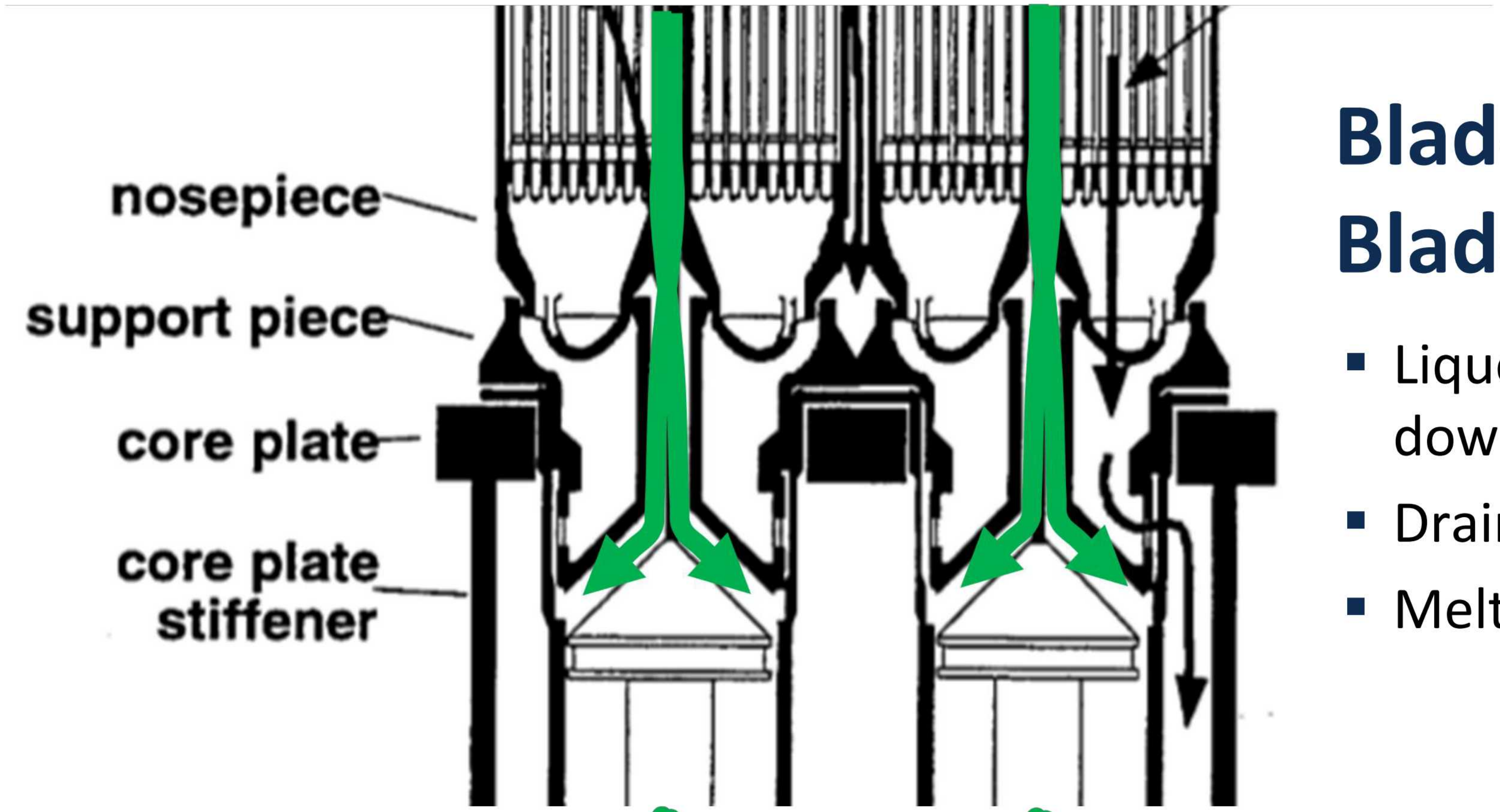


Fe/Zr Binary System – Can be Exothermic

- Exothermic before runaway oxidation starts at ~1500K
- Exothermic at elevated temperatures just before or after fuel degradation has occurred
- Not addressed in SA codes

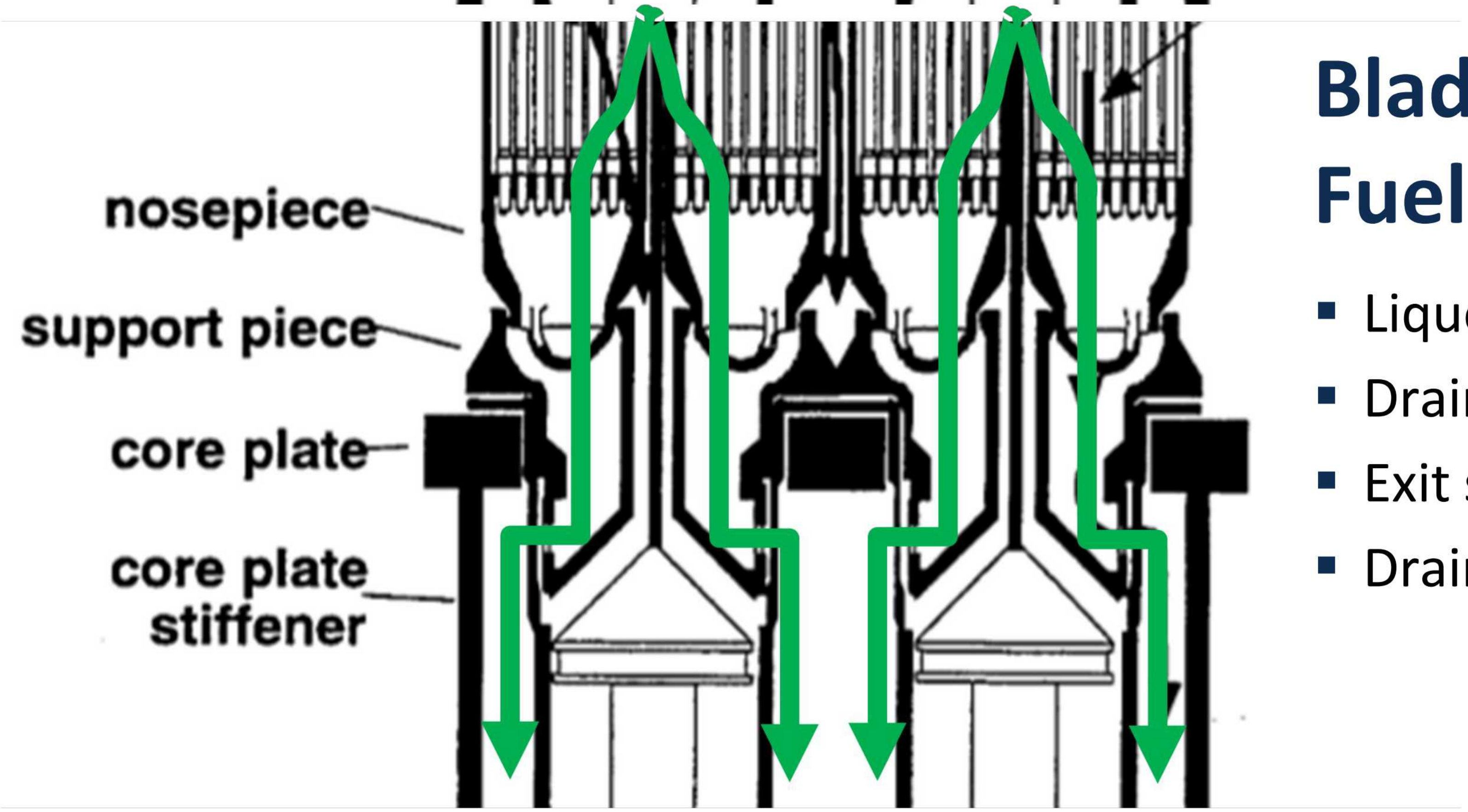


Energy production = -1*dH per 1g of Fe, [J/gFe]



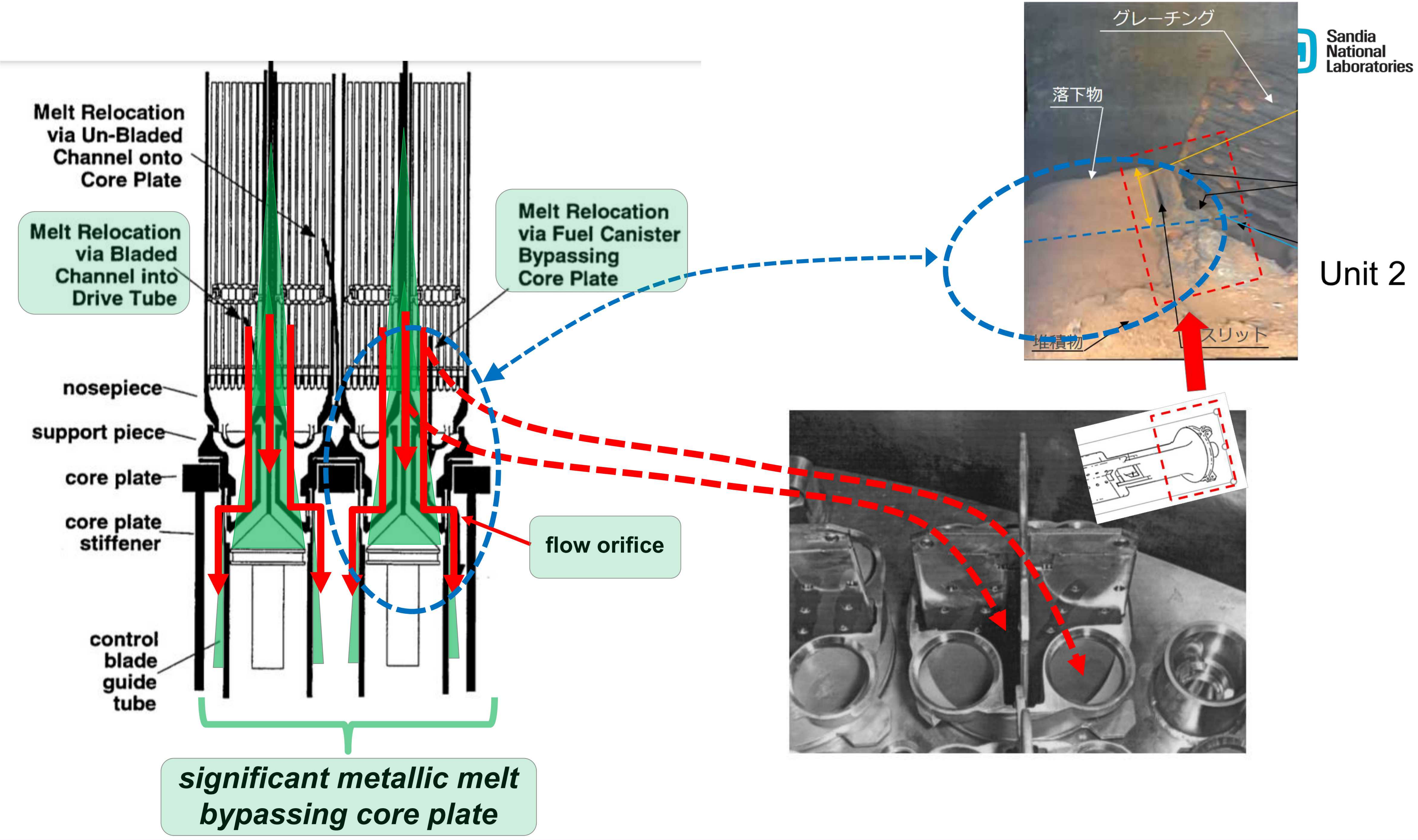
Blade/Canister Melt Draining Within Blade Region

- Liquefied Blade (SS) and Canister (Zr) can also drain down the blade region
- Drains into bladed region below core plate
- Melt will accumulate on velocity limiter



Blade/Canister Melt Draining Inside Fuel Canister

- Liquefied Blade (SS) and Canister (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



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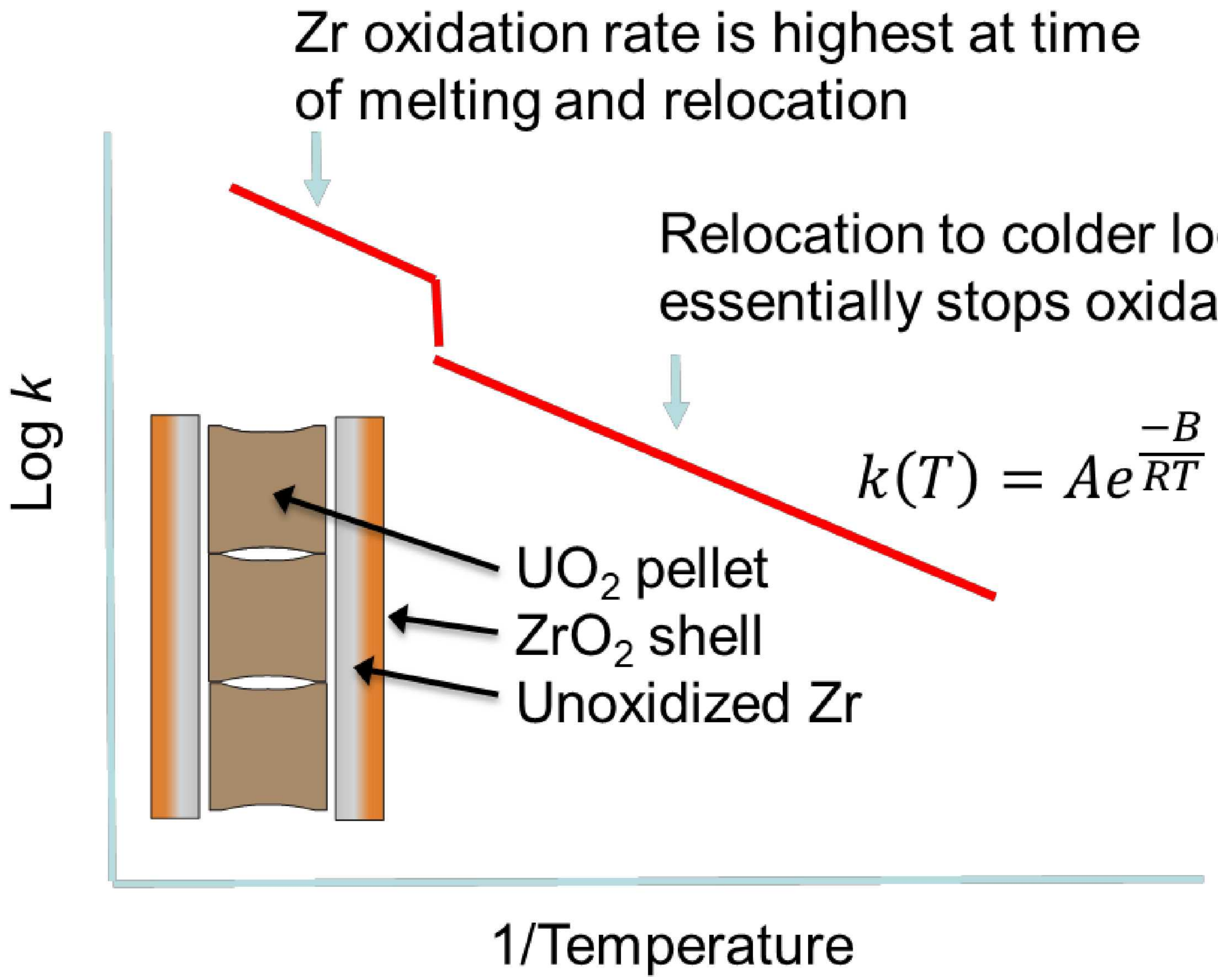
Exotherimic Reaction between Zr and Steam

parabolic rate law $\Rightarrow$ $$\frac{d\delta^2}{dt} = k(T)$$

$\delta = oxide\ shell\ thickness$

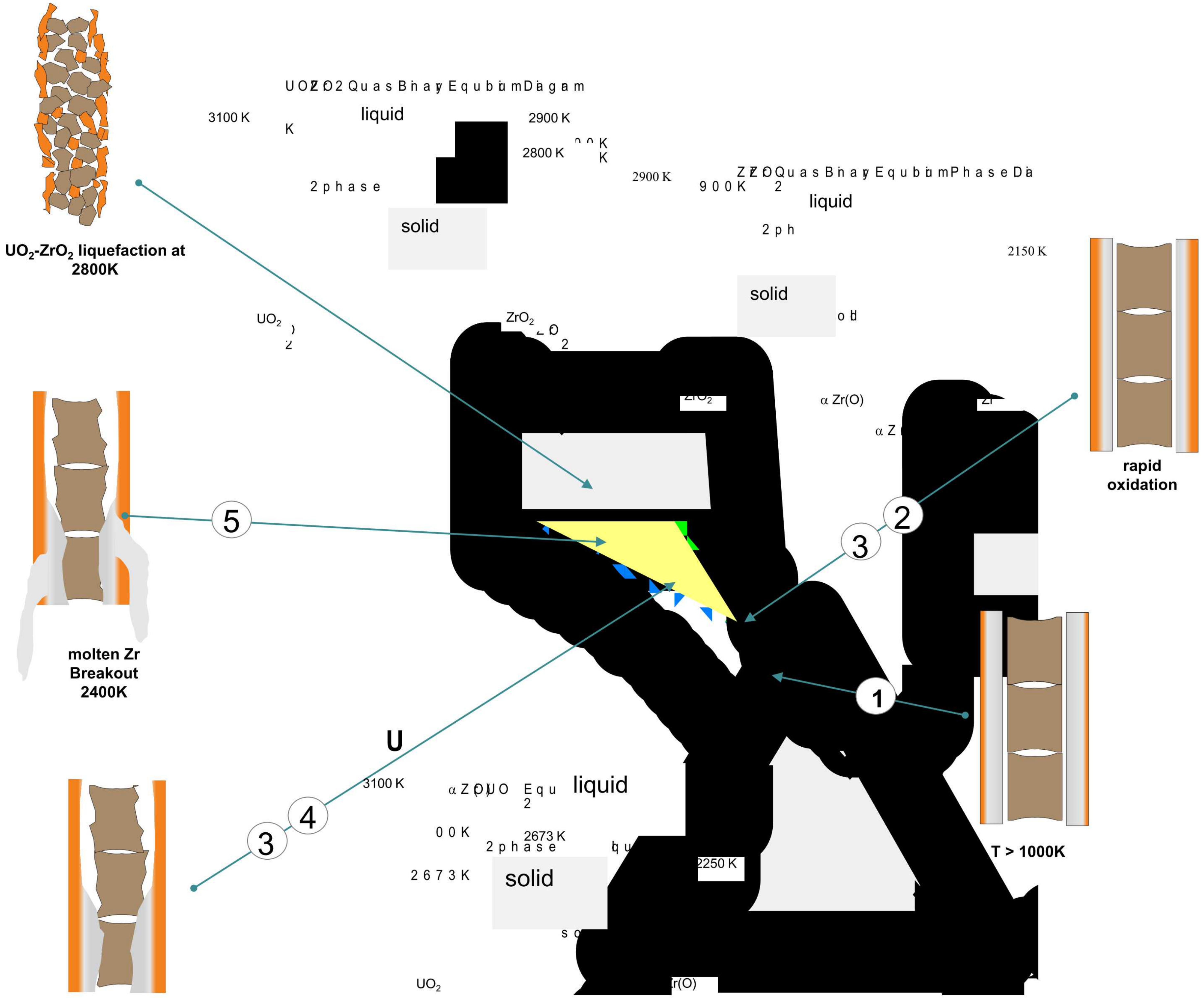
$k(T) = reaction\ rate$



$$k(T) = Ae^{\frac{-B}{RT}}$$ $\Leftarrow$ *Arrhenius rate law*

- $Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$ + energy
- Reaction rate is autocatalytic (accelerates with T)
- Decay power heatup rate ~1K/s
- Oxidation power heatup rate ~15K/s
- *Short time between start of oxidation and relocation of liquefied Zr*

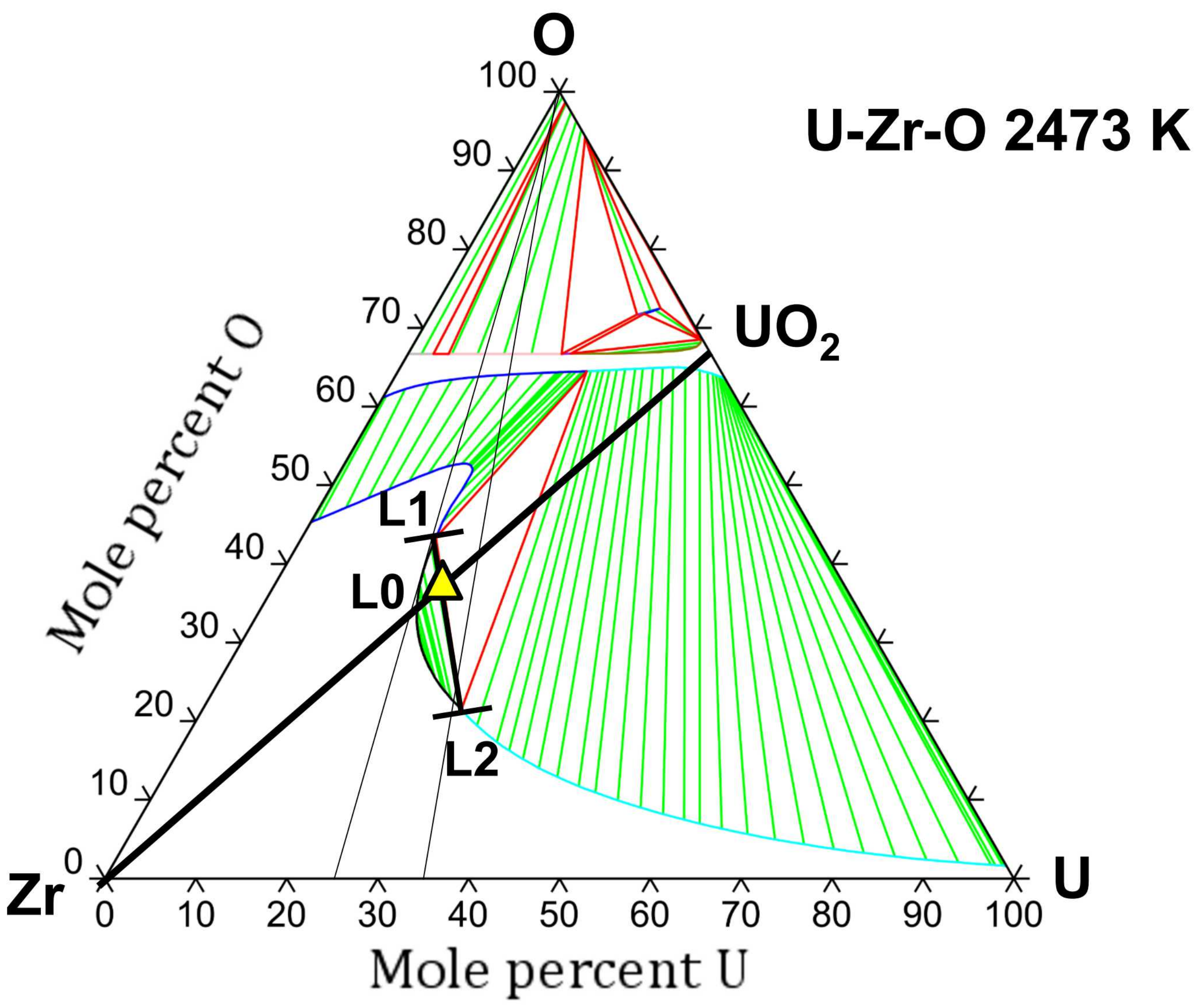
U/Zr/O Material Interactions



1. Zr cladding begins to oxidize with steam at ~1000K
   - ❑ ZrO_2 outer shell forms
   - ❑ Underlying Zr-metal takes on dissolved oxygen
2. α Zr(O) melts at ~2100K confined under ZrO_2 shell
3. Molten α Zr(O) wets and interacts with cracked UO_2
   - ❑ UO_2 dissolved into α Zr(O) (U-Zr-O)
4. Equilibrium dissolution or rate limited ?
   - ❑ Parabolic interaction rate measured by Hoffman (MELCOR option)
5. ZrO_2 shell breaks at ~2400K releasing molten U-Zr-O
   - ❑ Metallic U-Zr-O segregates from oxidic UO_2/ZrO_2

U/Zr/O Ternary System – Potential Material Combinations

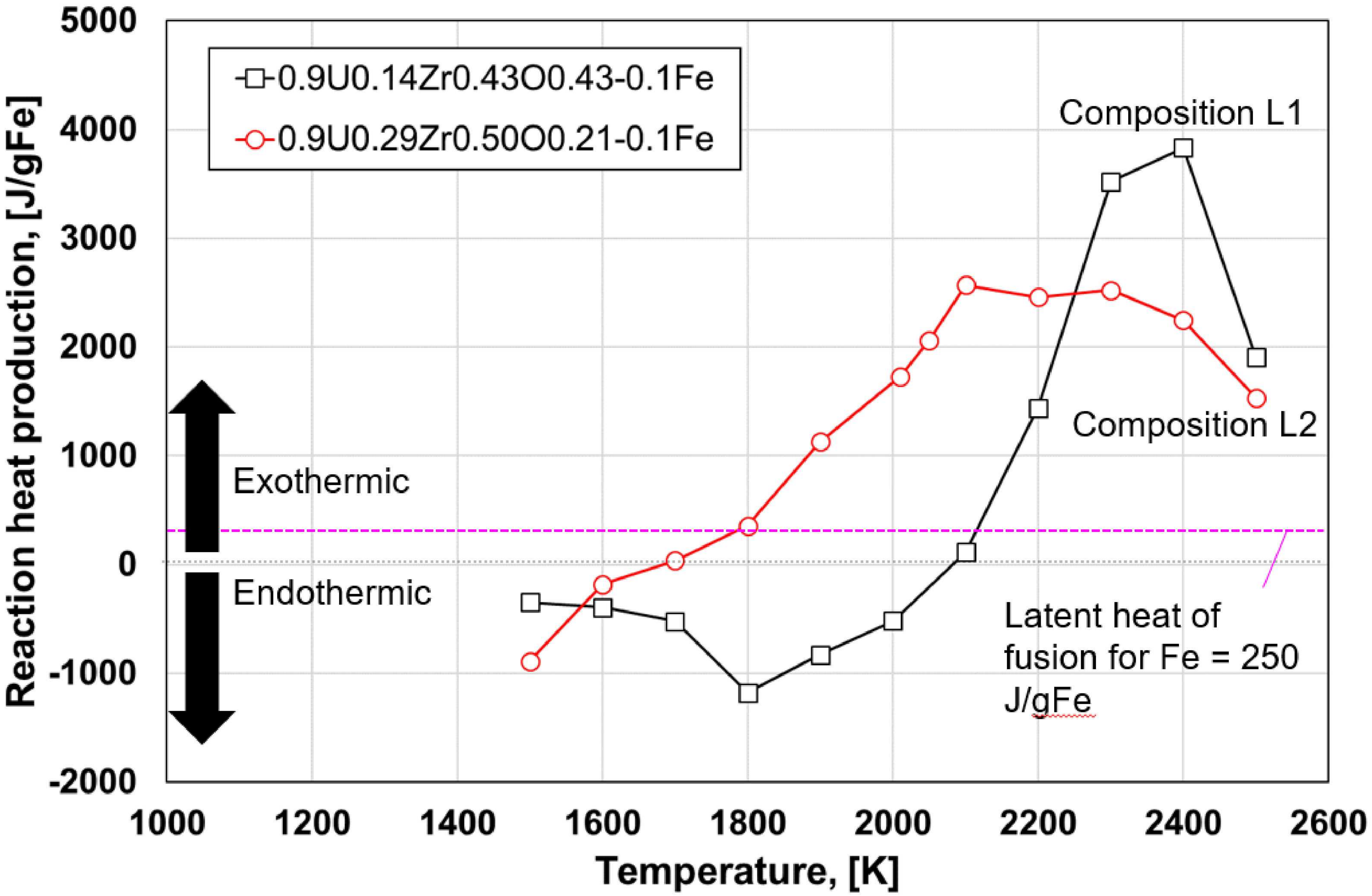
- What is the uranium content of a liquid U-Zr-O system?
  - MELCOR currently has a default value of the U/Zr wt% ratio of 0.2 (max of 1.0)
- L1, L2 and L0 all show a significant amount more uranium content
  - 0.84 to 1.5 U/Zr wt%
  - U-Zr-O liquid contain significantly more decay heat than currently modeled in MELCOR
- What occurs when U-Zr-O interacts with Fe in the core plate or lower head?



L1: X(U,O,Zr) = (0.14,0.43,0.43) (mol) → U/Zr wt. = (0.14*238)/(0.43*91)=33/39=**0.84**
L2: X(U,O,Zr) = (0.29,0.21,0.50) (mol) → U/Zr wt. = (0.29*238)/(0.50*91)=69/45=**1.5**
L0: X(U,O,Zr) = (0.19,0.38,0.43) (mol) → U/Zr wt. = (0.19*238)/(0.43*91)=45/39=**1.1**

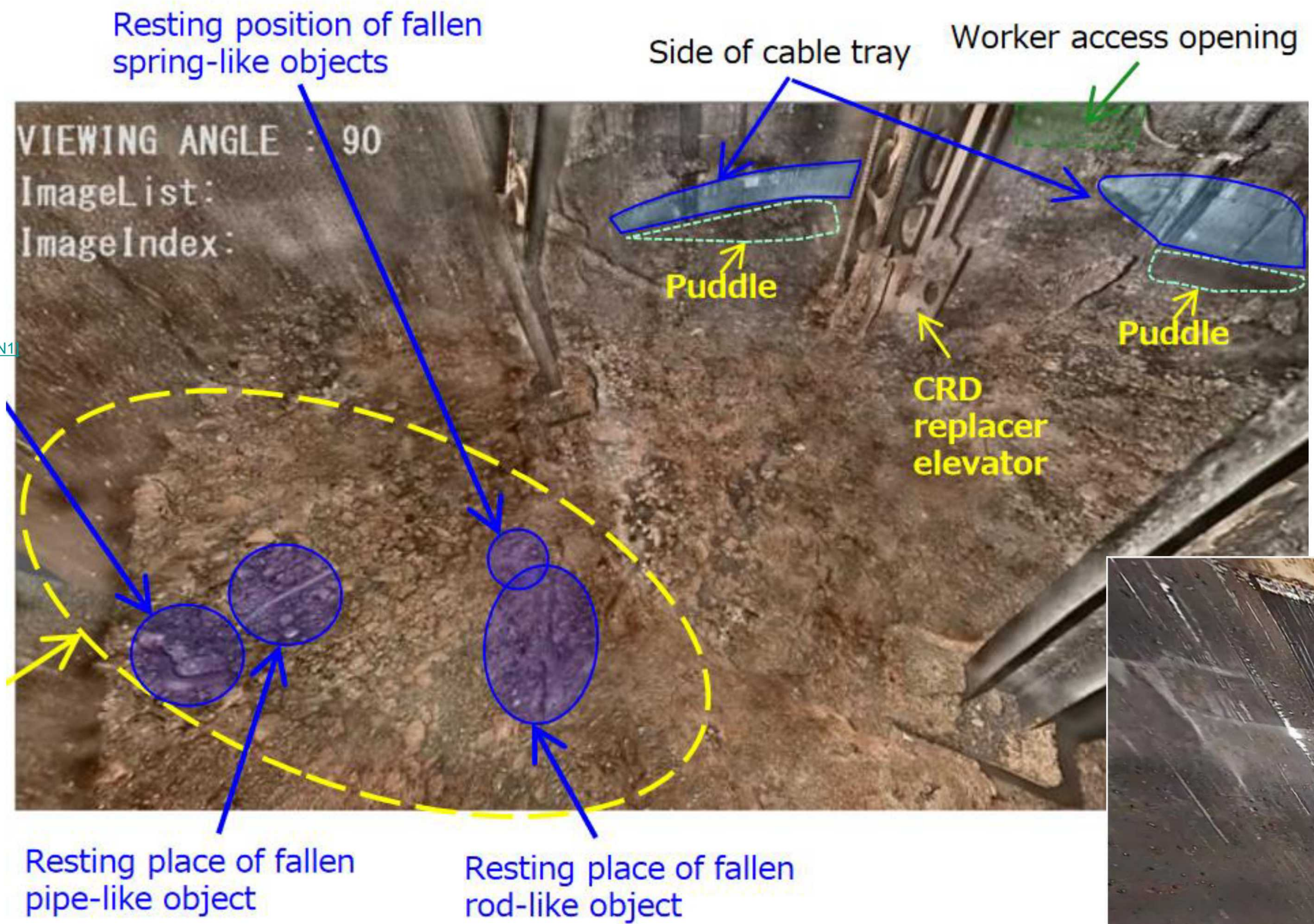
Fe/(U-Zr-O) Quaternary System – Can be Exothermic

- Comparison of heat production in case of 10 mol% Fe with U-Zr-O liquids (L1 & L2)
- Interaction is exothermic at elevated temperature that would exist during and after significant core degradation has occurred
- Provides an addition challenge to the core plate and lower head
  - Additional heat
  - New material interactions
- Not accounted for in SA codes

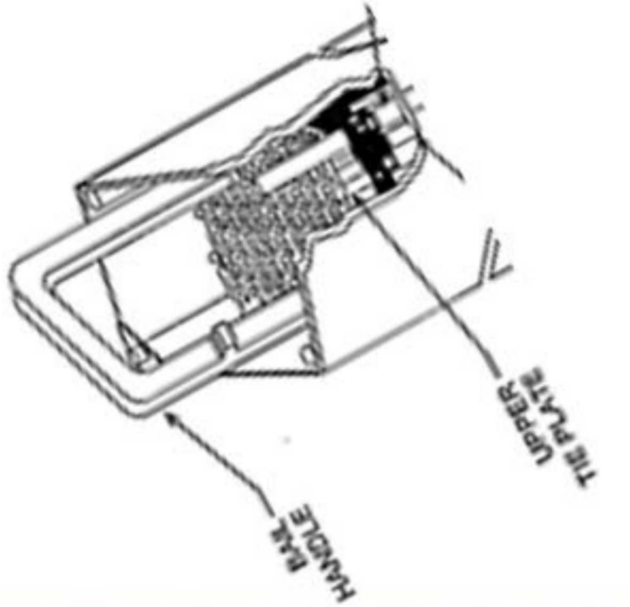


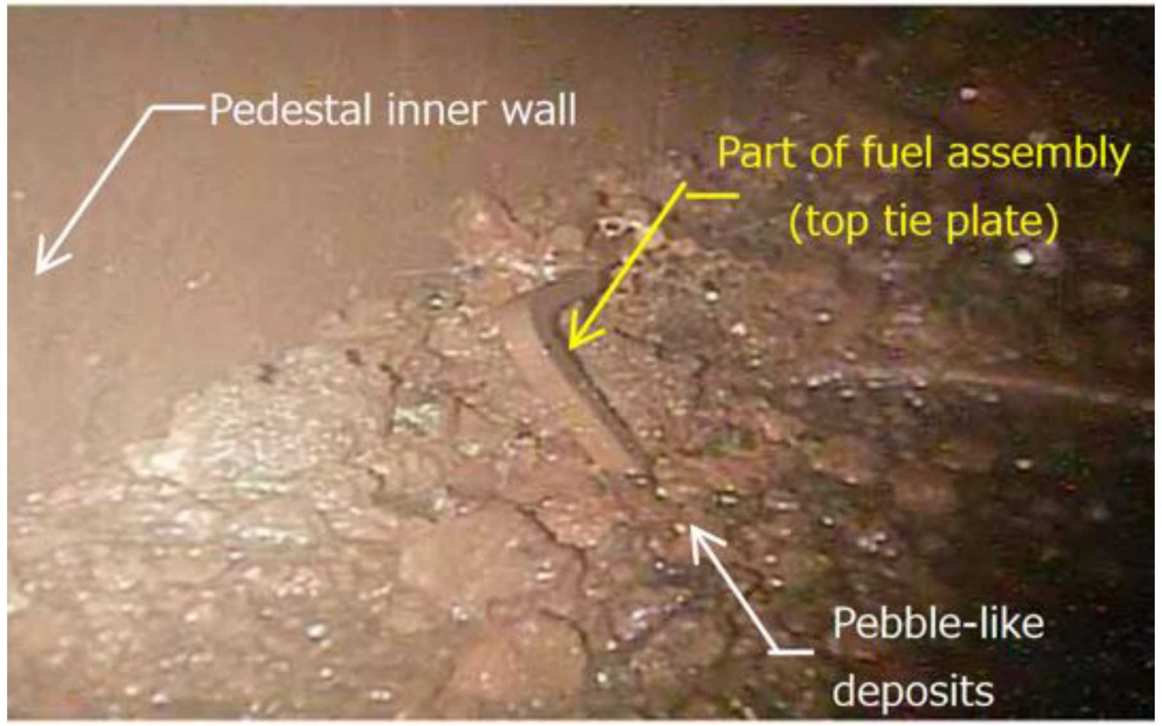
Unit 2

[AN1]

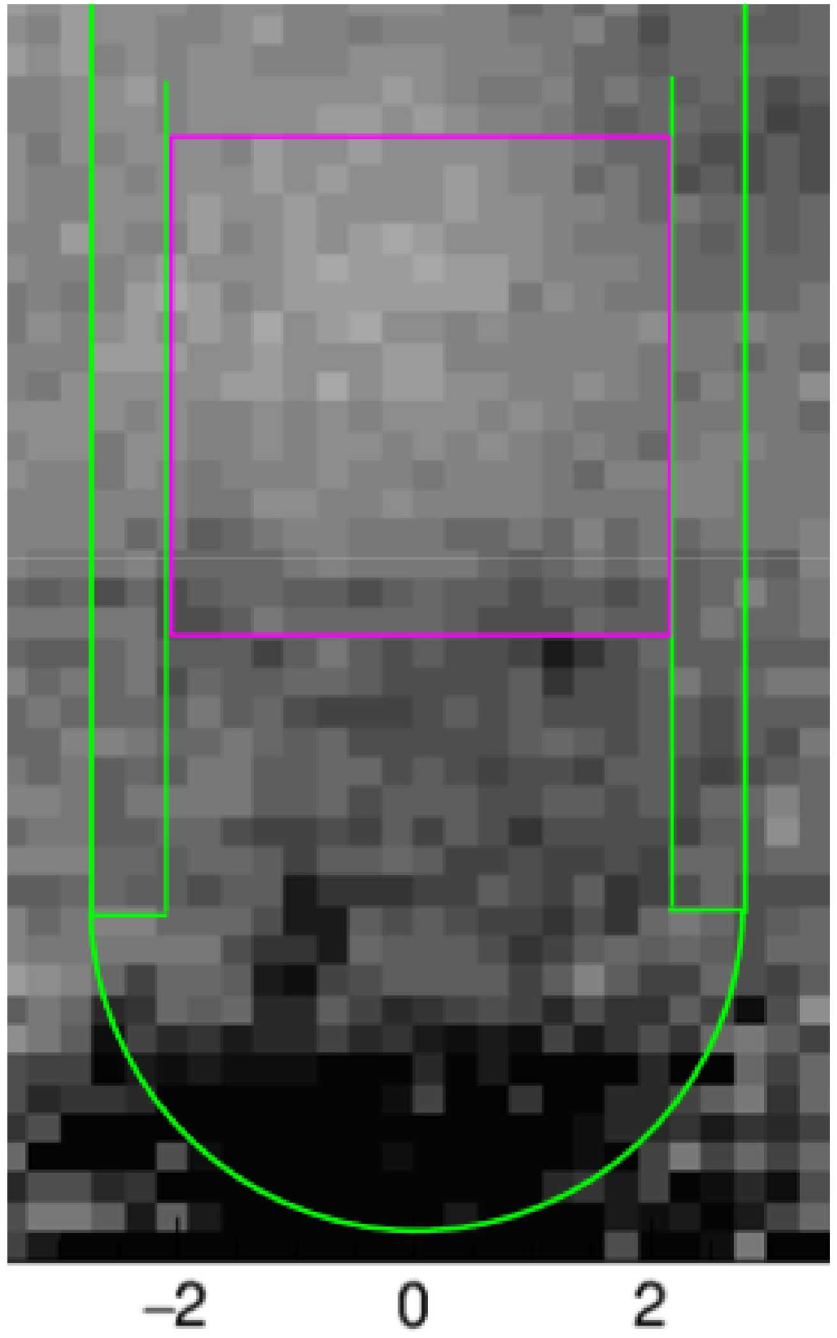

Resting position of fallen spring-like objects
Side of cable tray
Worker access opening
VIEWING ANGLE : 90
ImageList:
ImageIndex:
Puddle
Puddle
CRD replacer elevator
Resting place of fallen pipe-like object
Resting place of fallen rod-like object

Unit 2

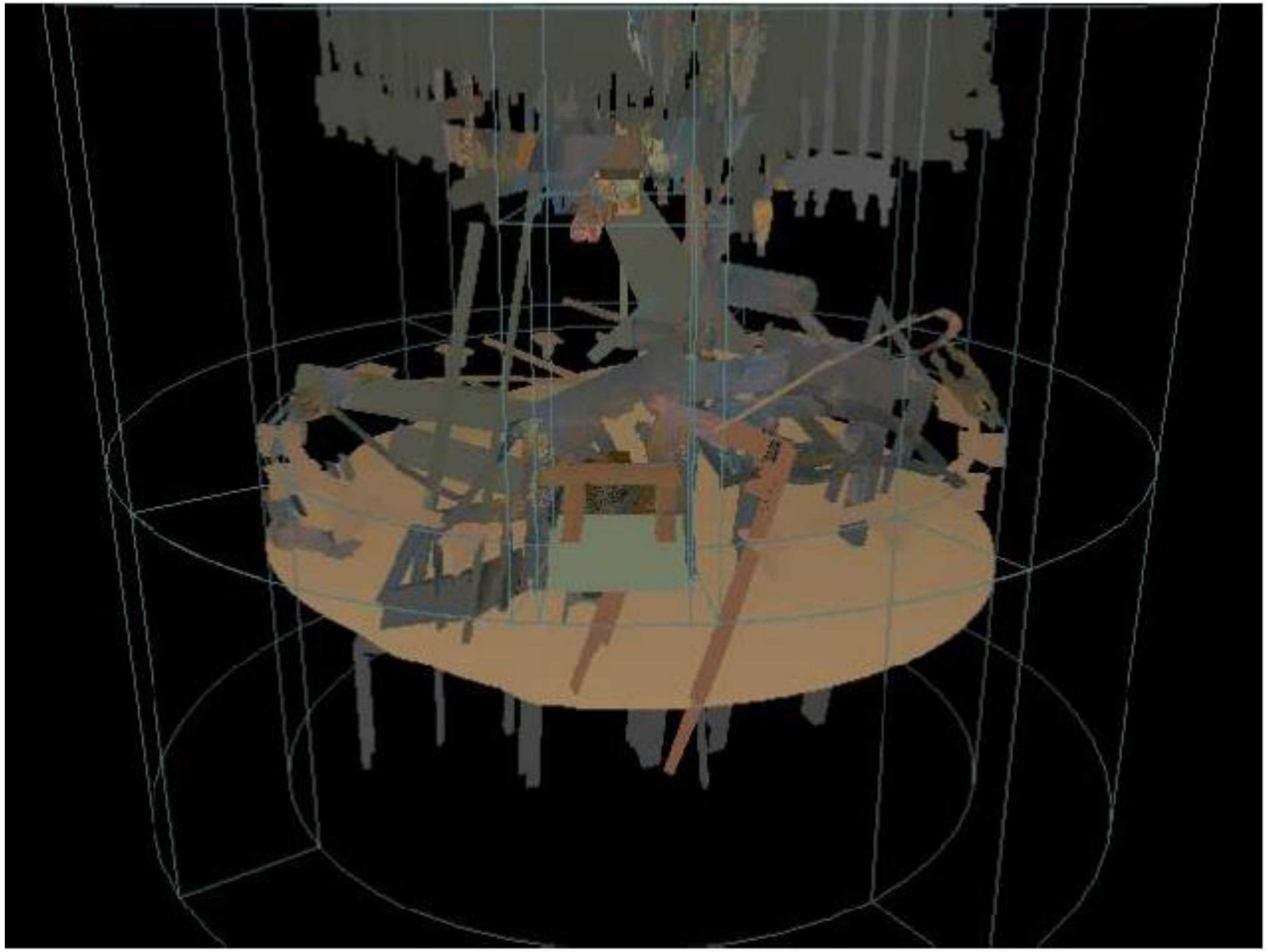

UPPER
TIE PLATE
BAIL
HANDLE

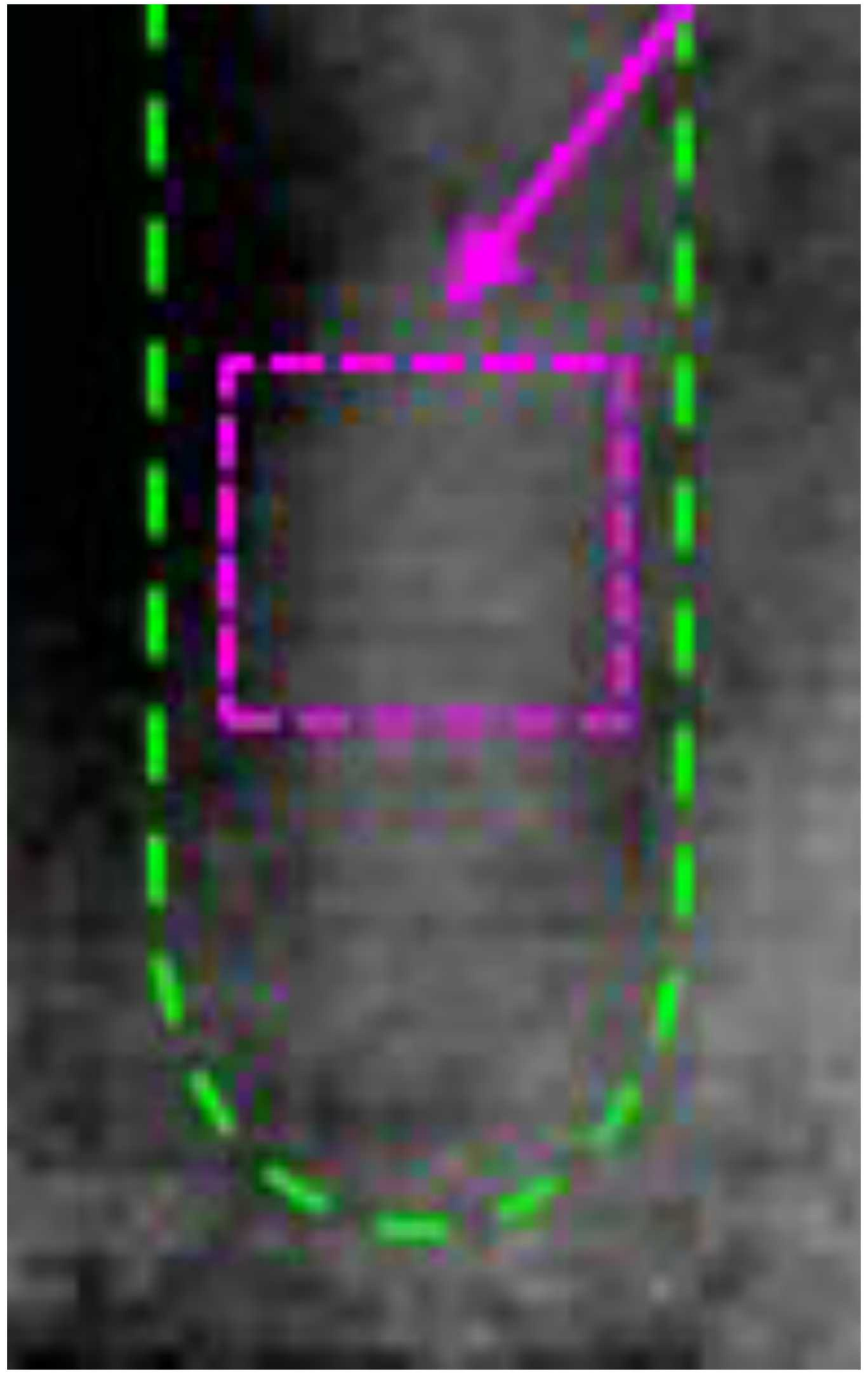

Pedestal inner wall
Part of fuel assembly
(top tie plate)
Pebble-like
deposits


PAN -069
TILT +078

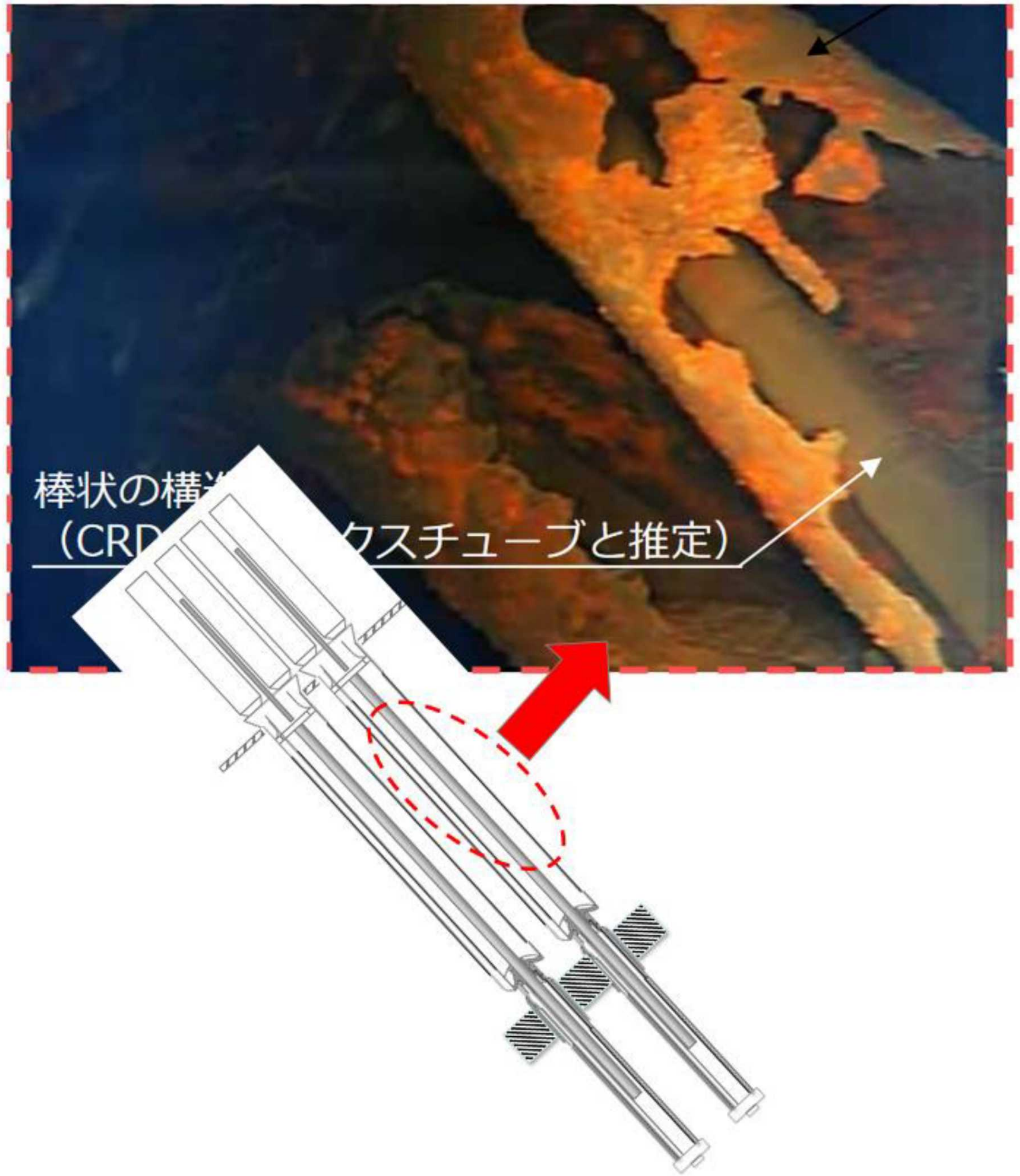

–2
0
2

Unit 3

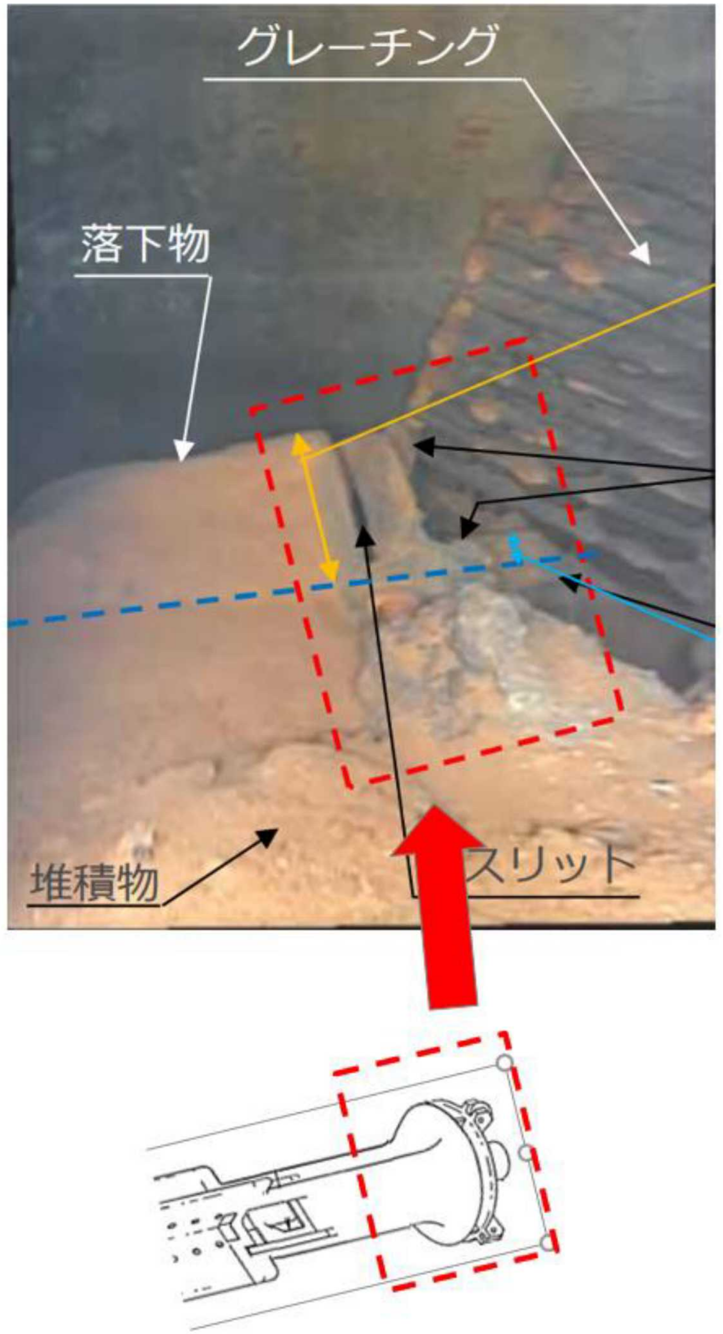




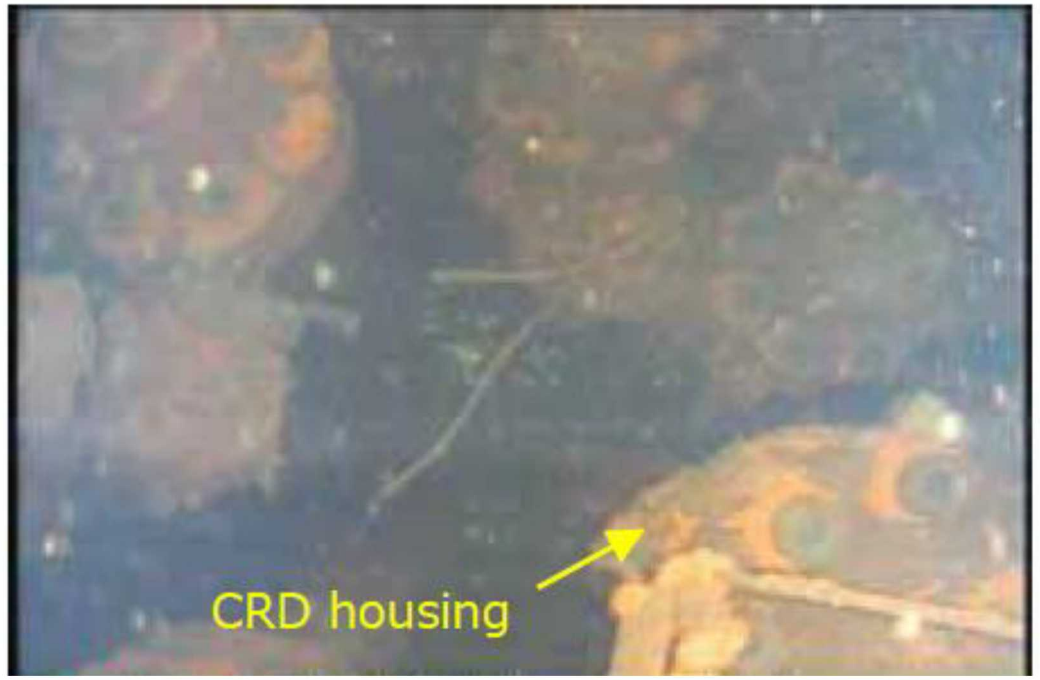
Unit 3



棒状の構
（CRD
クスチューブと推定）

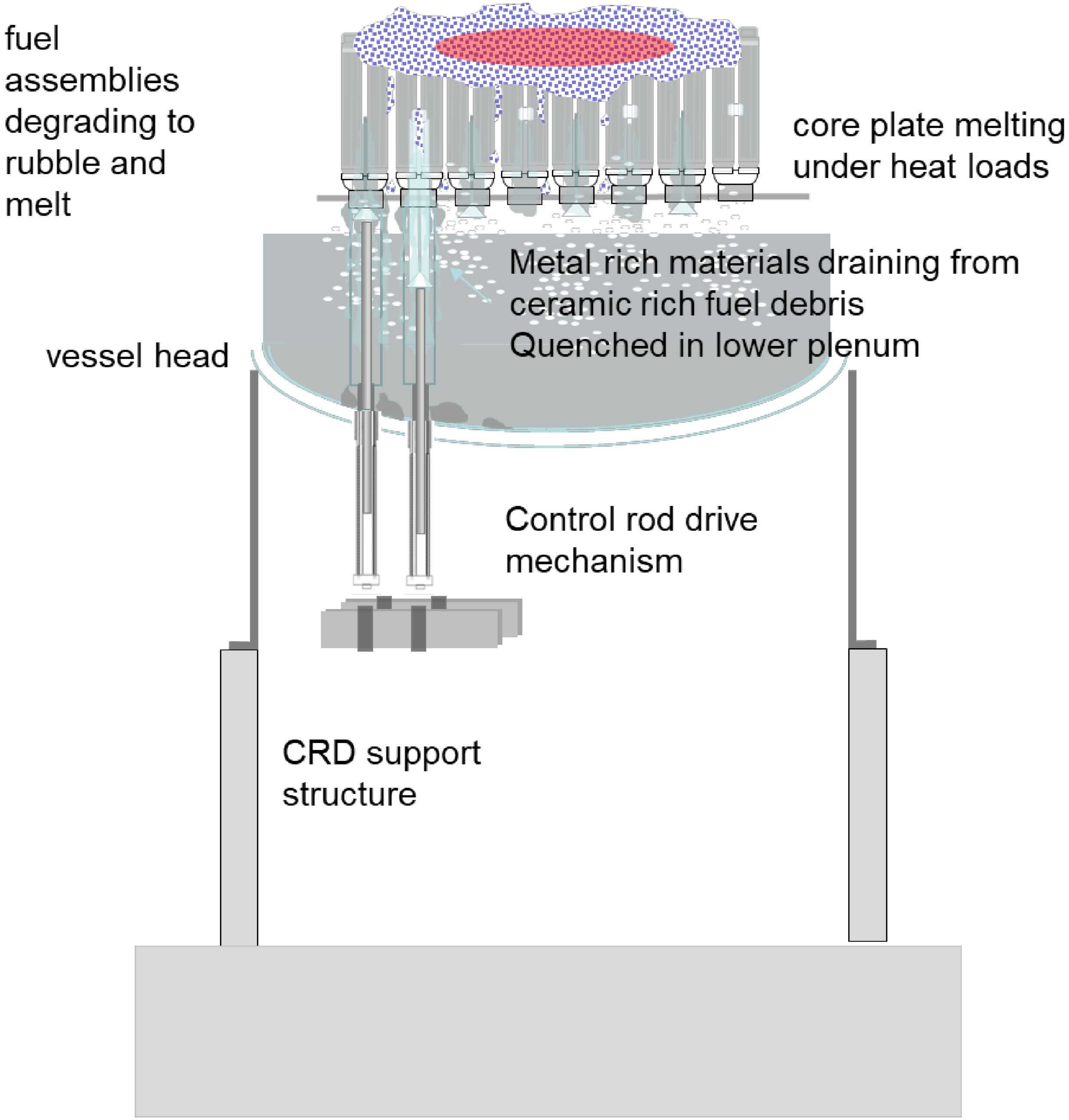


グレーチング
落下物
堆積物
スリット

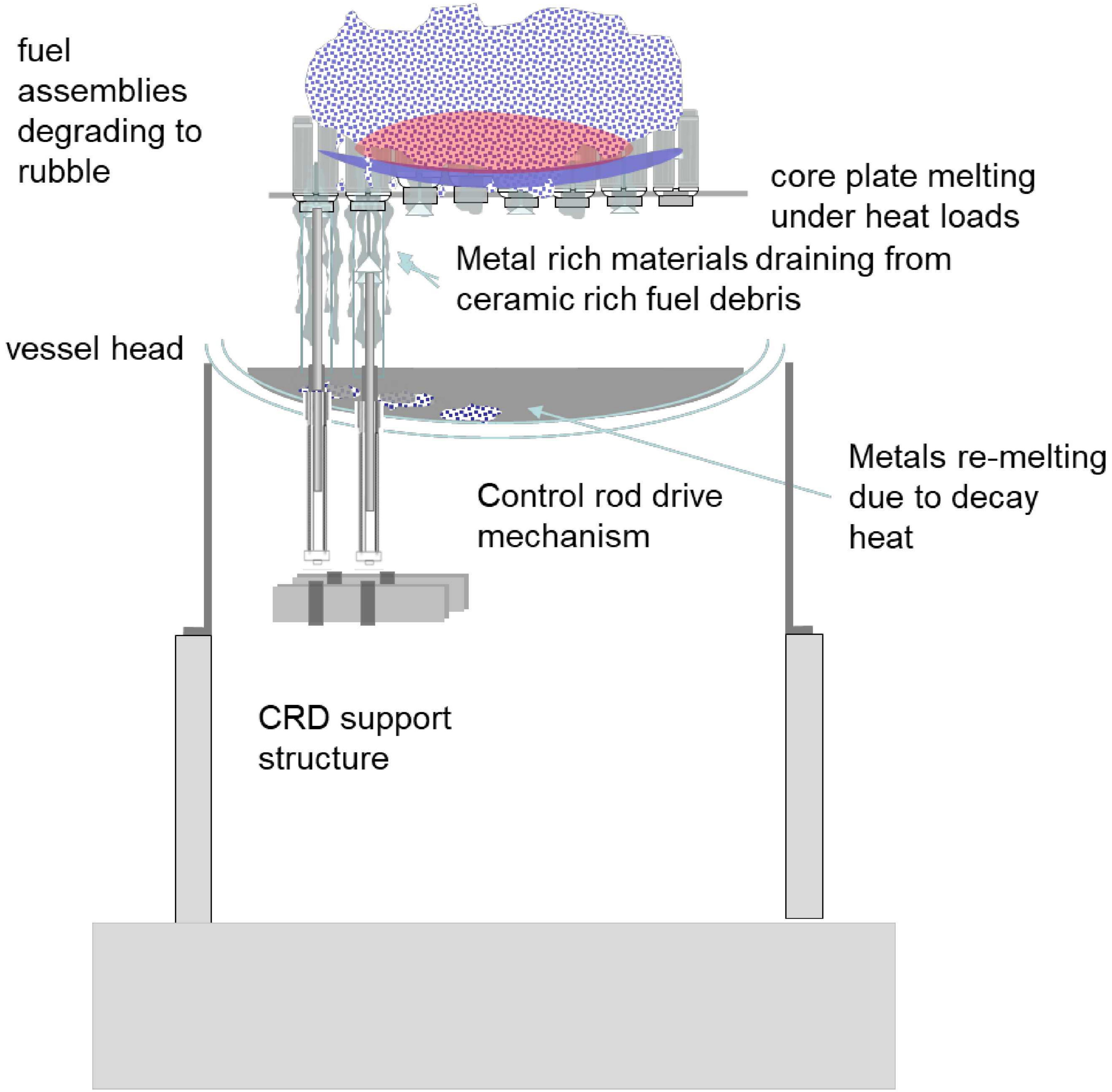


CRD housing

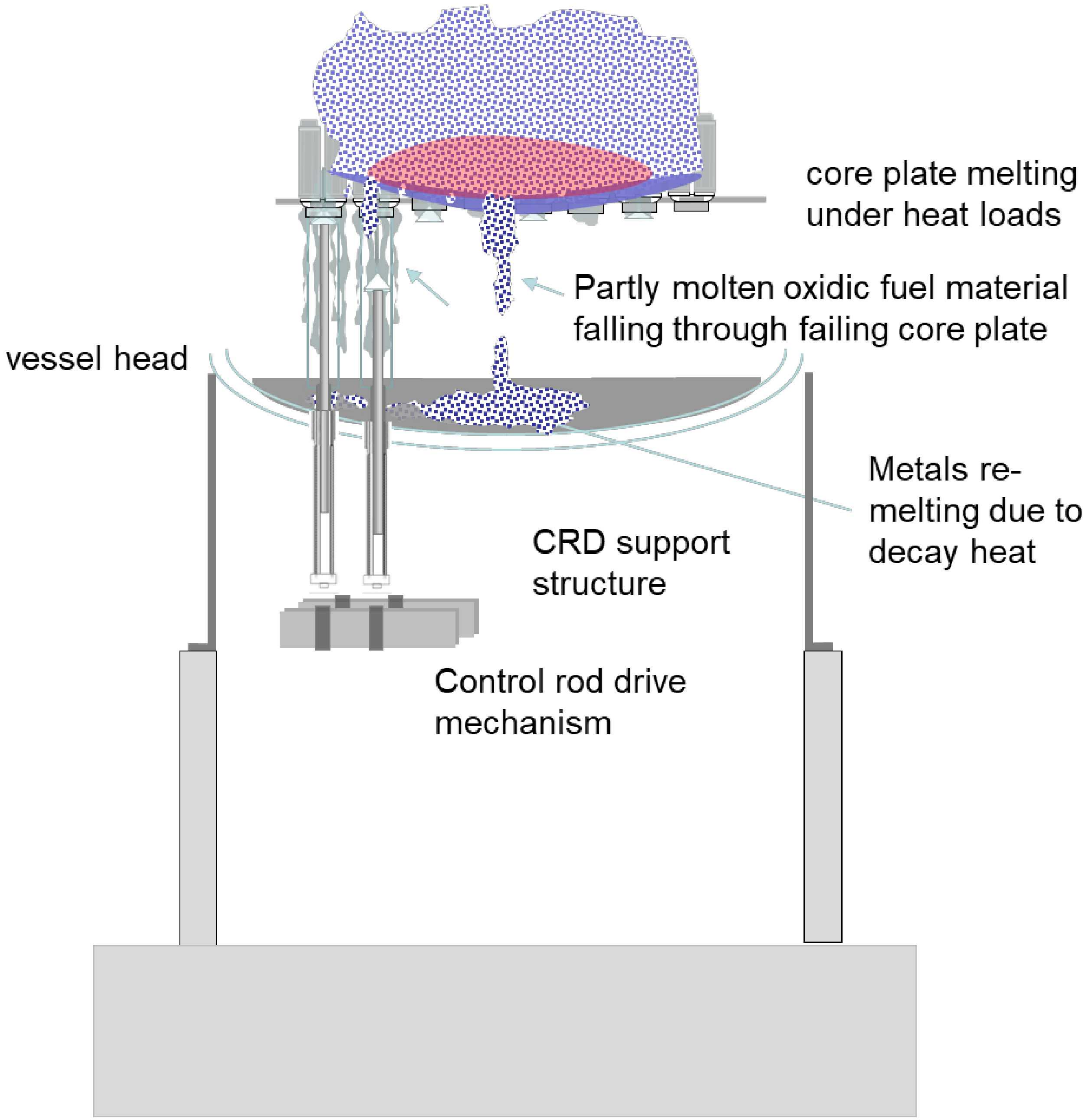
CRD housing
Supporting
clamp



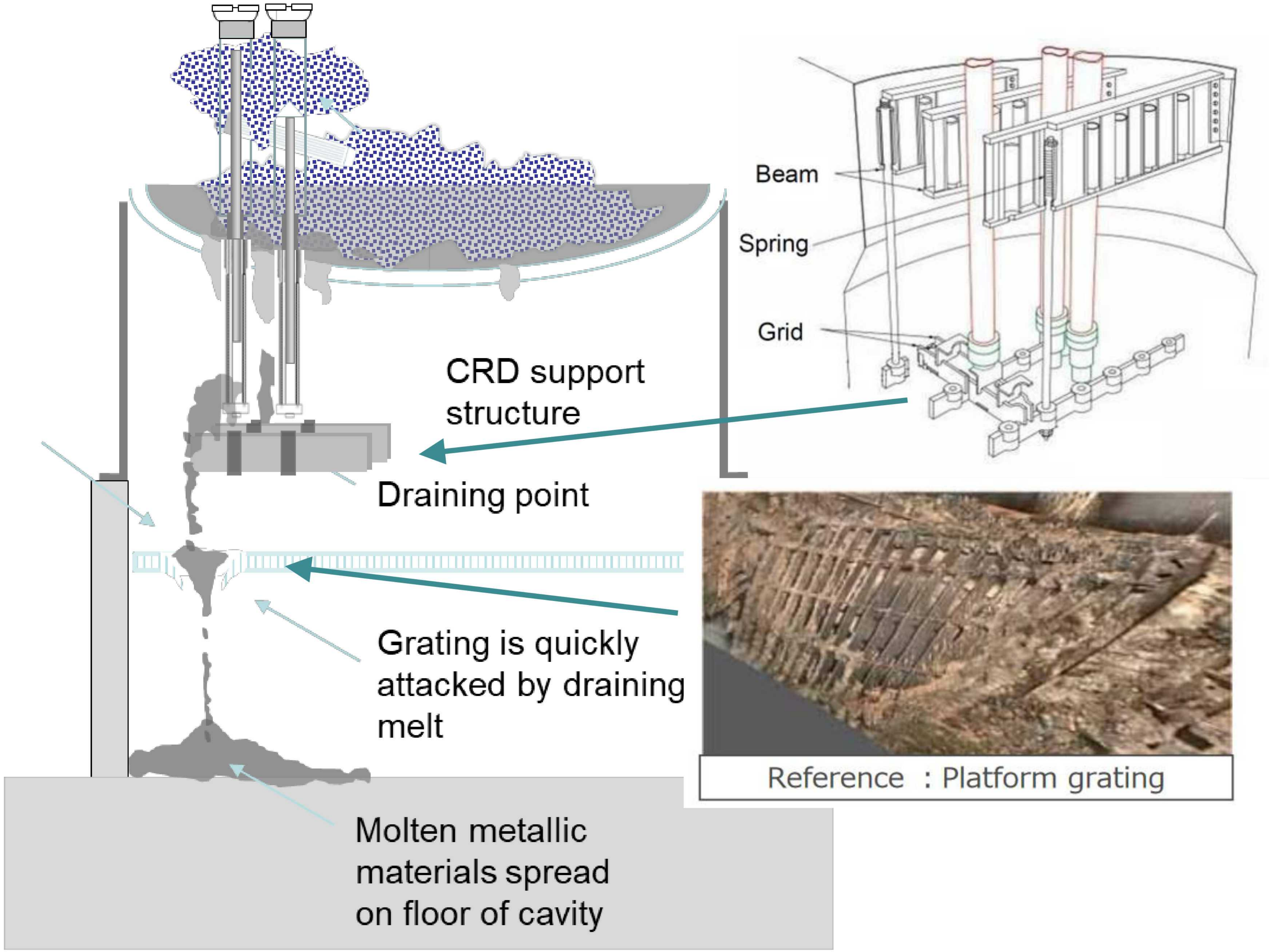
- Control blades melt first and drain away from fuel materials, falling through core plate and nose pieces DF4 and XR2-1.
- Interaction with and dissolution of Zr channel boxes are expected – not considered by MELCOR
- Metals drain to lower head and may quench in water
- Core debris region degrades as metallic are accumulating on lower head – a race



- Zr-cladding and channel boxes remnants oxidize
- Fuel rods degrade and slump, either
  - onto core plate, or
  - In-Core TMI-2 like crucible could also form
- Lower head water evaporates and metals (SS-Zr + U-Zr-O) accumulations heat and remelt
  - Dissolved UO2 content could will increase heat loads to lower head

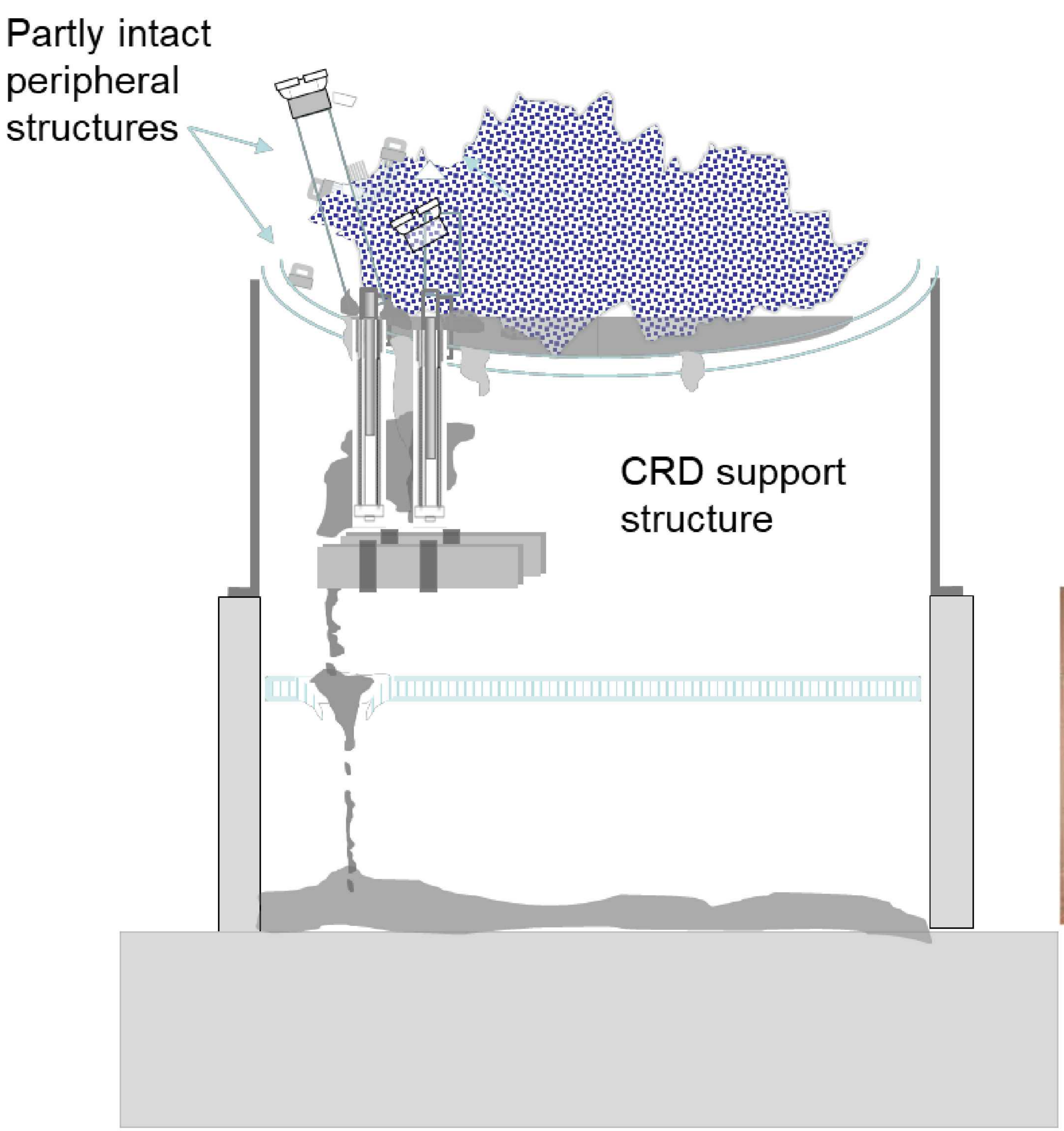


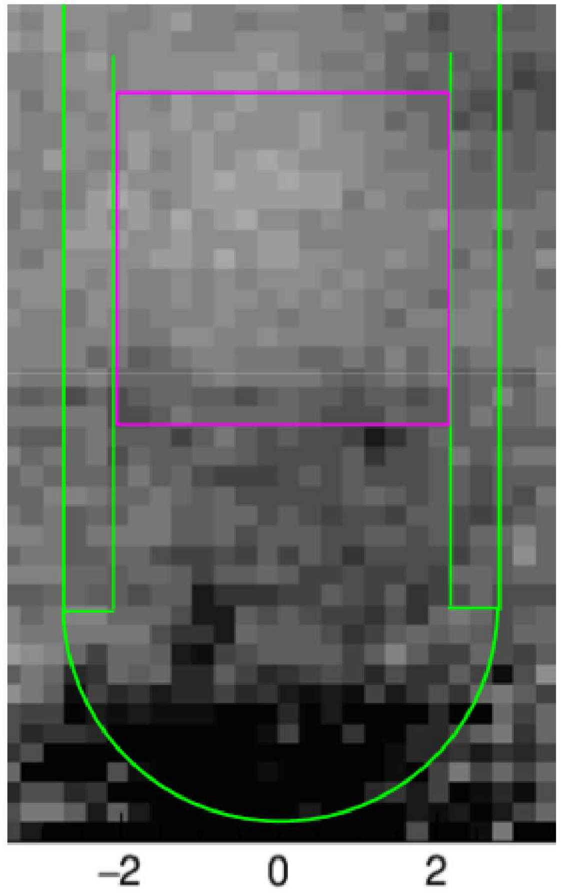
- Partly molten/partly solid fuel oxidic fuel materials heat metals above carbon steel melting temperature
- Configuration resembles “hot rocks in molten soup of Zr-SS metal”
- Heat conduction to vessel wall begins to melt wall
- Intermetallic reactions and heat of mixing (Fe-Zr) may be very exothermic and drive progressive attack of vessel wall
- Competition in collapse of core with failure of lower head

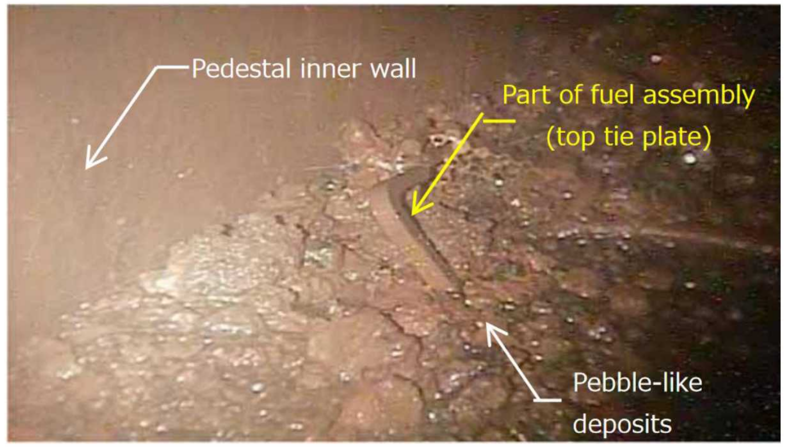


- ❑ Vessel wall melted or yielded away leaving drive tube remnants standing, supported by CDR support structure below vessel head
- ❑ Molten Fe-Zr-U-O metals drain from multiple holes in vessel head
- ❑ Accumulations form on CRD support structure and find draining point
- ❑ Underlying grating structures attacked by draining melt
- ❑ Vessel wall may be largely disintegrated leaving only CRD drive tubes and penetration nozzles supported by CRD support structure

Unit 2 End State

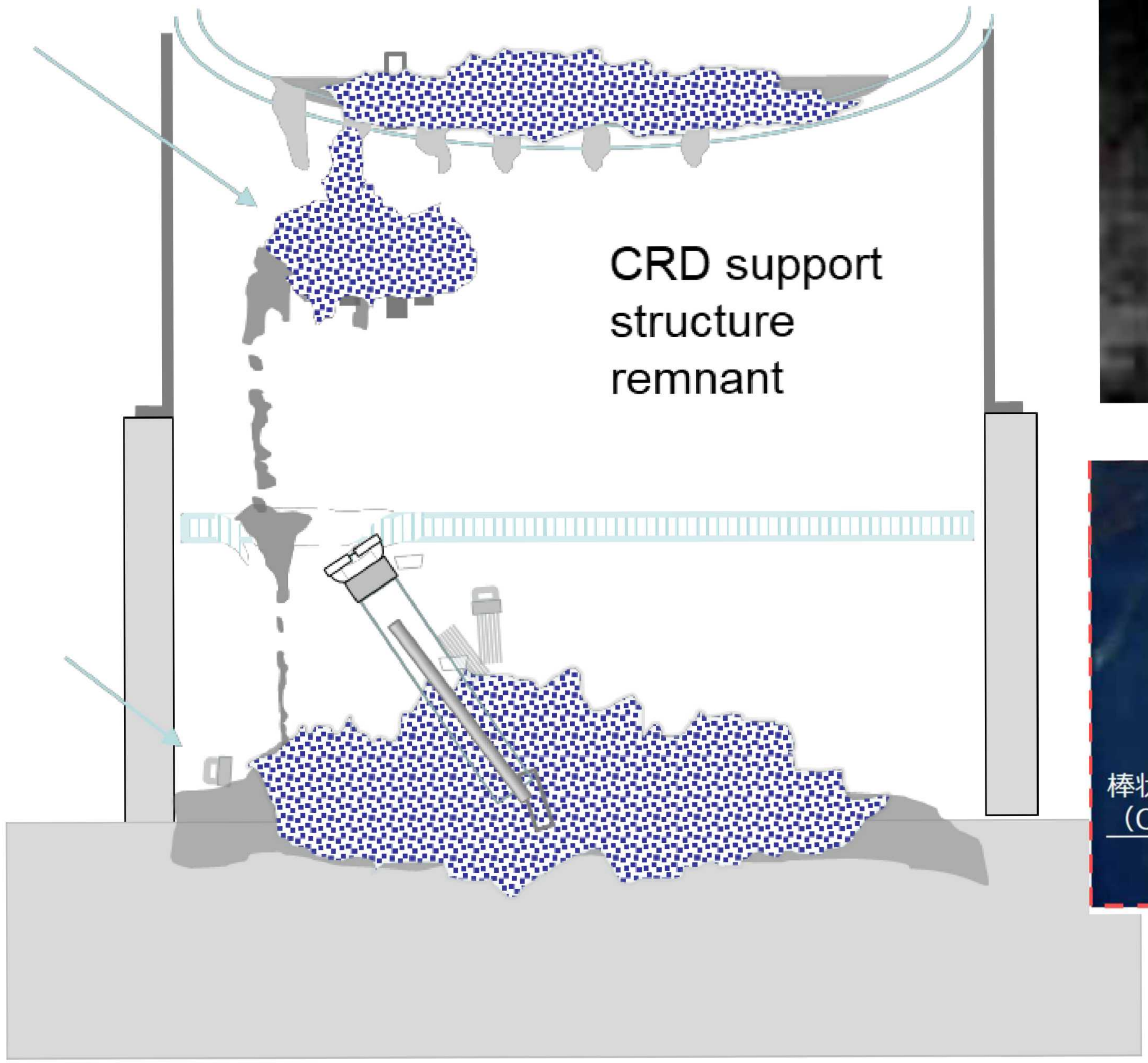


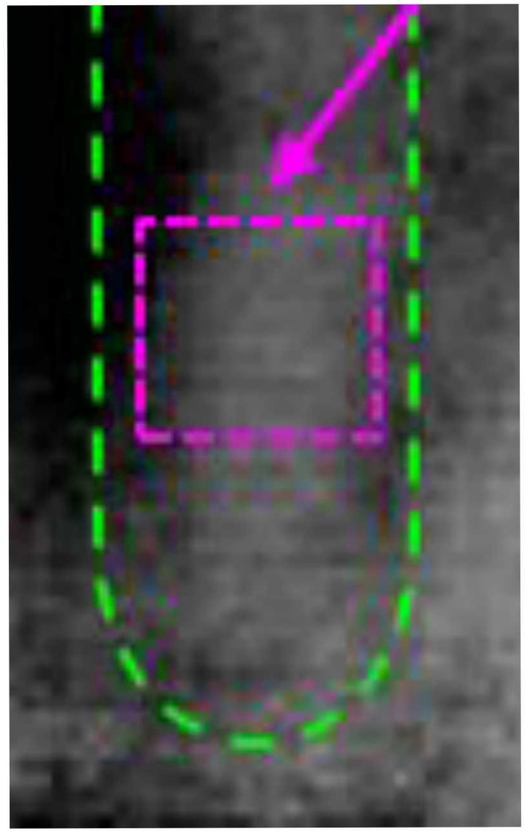




- ❑ Peripheral structures may be partly intact at edge of core and fall to lower head – MELCOR *could* capture this with code modifications
- ❑ Metallic melt spreads to walls of cavity – MELCOR can do
- ❑ 1F2 may have been arrested by this time leaving a mostly level metallic layer on cavity floor – 1F2
- ❑ Some intact parts apparently fell through largely disintegrated lower head – 1F3

Unit 3 End State





- Increasing melt release to C/R support structure fails structure, finally allowing dropping of in-core drive tube structures
- Lower head must be largely melted/slumped away allowing large in-core structures to fall to cavity floor

Comment on Modeling in MELCOR

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- ✔ ❑ Control blade liquefaction at 1500K by Boron-Iron eutectic effect *is* currently modeled in MELCOR
- ✘ ❑ Slumping and interaction of liquefied SS blade and Zr Channel boxes *is not* modeled
  - ❑ Modeling effect would open channel boxes to lateral steam flow
  - ❑ Modeling effect would create a molten SS-Zr component that would drain downwards
  - ❑ Draining melt inside fuel canister can enter nose pieces and flow to lower plenum
  - ❑ Draining melt outside of fuel canisters fall to core plate
- ✘ ❑ Continued oxidation of draining molten Fe-Zr *is not* modeled (when oxidation rate should be highest) – MELCOR redistributes molten components to some cooler lower location where oxidation rate is now much lower

Comments on MELCOR Modeling

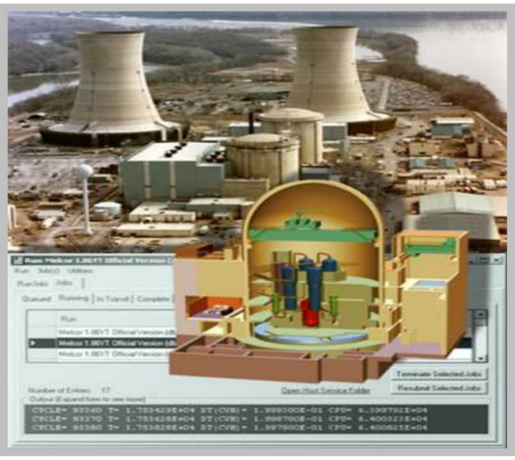
- As metallic components in core segregate from fuel components, more PWR-like fuel remnants remain
  - Modeled in MELCOR
- Zr-cladding oxidizes and melts under outer Zr-oxide shell (~2100K)
  - Modelled in MELCOR
- Molten clad wets fuel pellets and enters cracks
  - Not modeled explicitly in MELCOR
- U-Zr-O interactions form liquid mixtures ~2500K
  - Effect is treated by Eutectic effects on melting points
  - Eutectic composition not well controlled
  - Decay heat content of U-Zr-O may be significantly underestimated
- U-Zr-O fluidized phase drains slowly when ZrO_2 layer breaks (~2550K +/-)
  - Modeled in MELCOR
- Phase should continue to oxidize while draining down
  - Not modeled in MELCOR – we are missing important source of hydrogen here
- Last fuel remnants potentially $(U,Zr)O_{2-x}$ mixed in with U-Zr-O
  - Not clear what actually happens in MELCOR PD/Conglomerate fields – no phase diagram exists yet

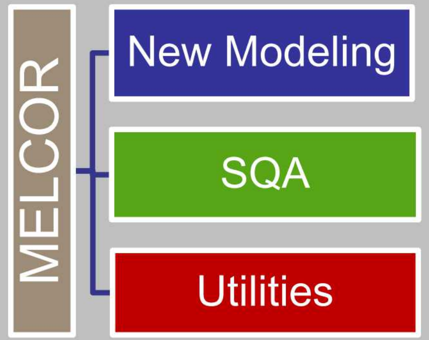
Summary

- Material interactions potentially more significant in BWR melt progression compared to PWR
- Control blade liquefaction by B_4C interaction at 1500K
- Model for channel box attack by molten control blade SS needed
- UO2 dissolution by molten Zr creates lower temperature heat bearing molten phase – need kinetics model for dissolution
- Metallic melts (SS/Zr) can segregate from core fuel and relocate to bottom head – models for head failure need attention
  - Heat of mixing for Zr-Fe possible head failure phenomena

Acknowledgements

- This work was funded by the USNRC
- Tokyo Tech
  - Ayumi Itoh, Prof. Kobayashi
- JAEA
  - Kurata-san, Nagae-San, Ogi-san
- KTH
  - S. Bechta, A. Komlev





Questions and comments?