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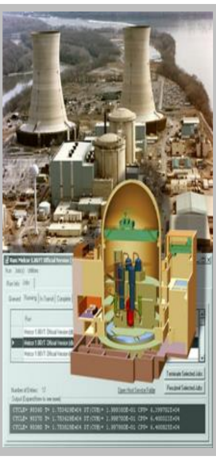
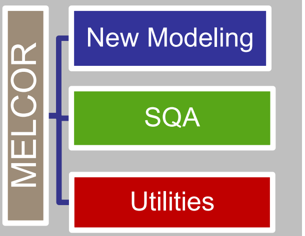




MELCOR

New Modeling

SQA

Utilities

Insights on Fukushima Damage Progression based on PCV Inspections and Implications for Decommissioning Data Collection and Code Model Refinement

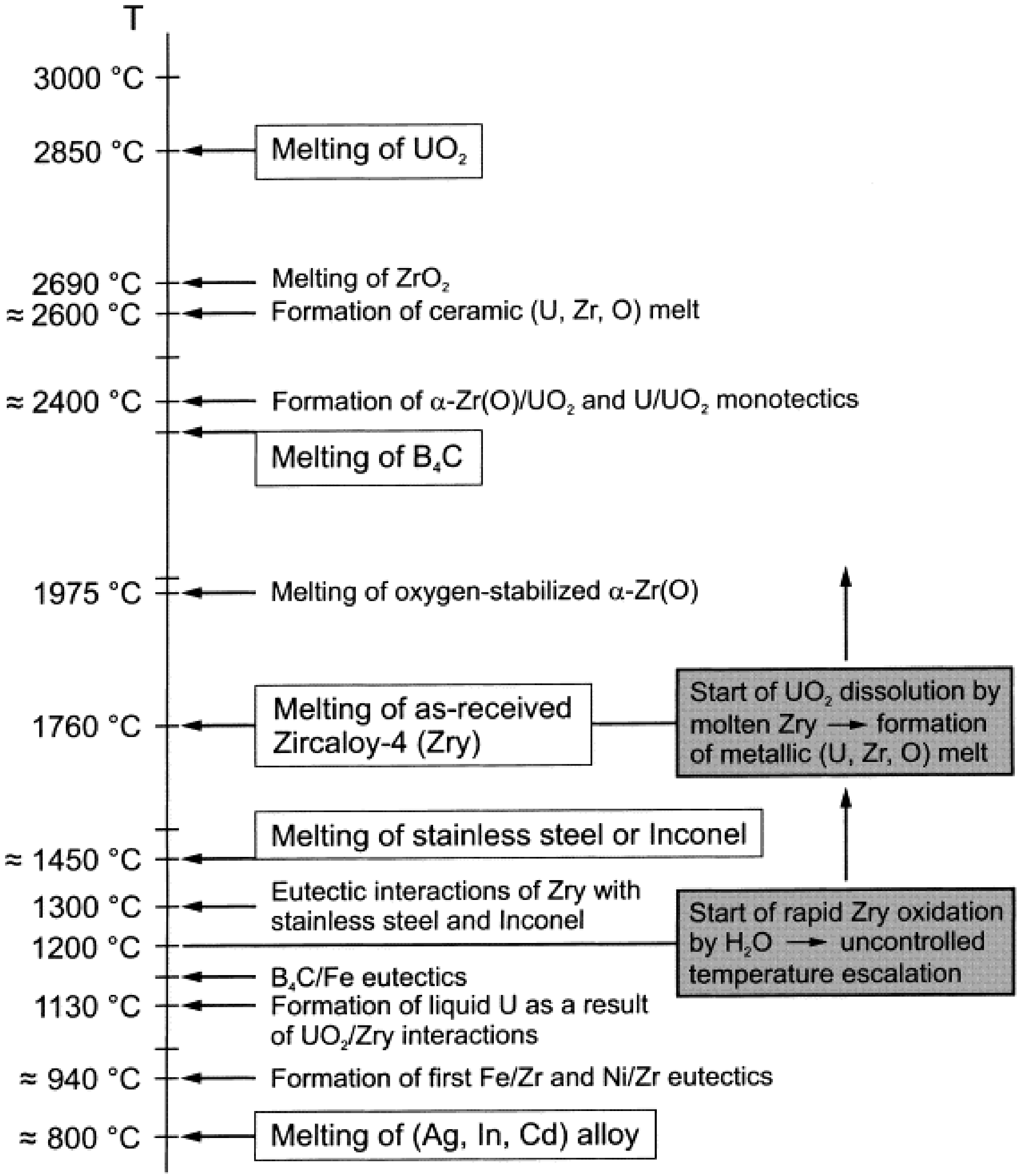
R.O. Gauntt and N. Andrews
Sandia National Laboratories

Outline and Theme of Discussions

- Review what is known from experiments and how codes are modeling phenomena
- Materials interactions are very important and key interactions will be identified and discussed
- Chronology of damage progression roughly follows in order of increasing melting/liquefaction temperatures
    - In core: control blades, cladding/canisters, fuel materials
    - Progression to core plate
    - Progression to lower head
    - Head failure
    - Melt release from head
    - Interaction with lower support structures
    - Accumulation ex-vessel
- Examine a plausible sequence to explain robotic visual examinations
- Highlight MELCOR modeling observations
- Highlight potential decommissioning phase data collection needs
- Knowledge advance is iterative process of reconciling observations with code predictions, improving code models, and comparing to emerging new observations

Important Material Interactions

(Hagen and Hoffman – KfK)



T

3000 °C

2850 °C – Melting of UO_2

2690 °C – Melting of ZrO_2

≈ 2600 °C – Formation of ceramic (U, Zr, O) melt

≈ 2400 °C – Formation of α-Zr(O)/UO_2 and U/UO_2 monotectics

Melting of B_4C

1975 °C – Melting of oxygen-stabilized α-Zr(O)

1760 °C – Melting of as-received Zircaloy-4 (Zry) – Start of UO_2 dissolution by molten Zry → formation of metallic (U, Zr, O) melt

Melting of stainless steel or Inconel

≈ 1450 °C

1300 °C – Eutectic interactions of Zry with stainless steel and Inconel

1200 °C – Start of rapid Zry oxidation by H_2O → uncontrolled temperature escalation

B_4C/Fe eutectics

1130 °C – Formation of liquid U as a result of UO_2/Zry interactions

≈ 940 °C – Formation of first Fe/Zr and Ni/Zr eutectics

≈ 800 °C – Melting of (Ag, In, Cd) alloy

Exotherimc Reaction between Zr and Steam

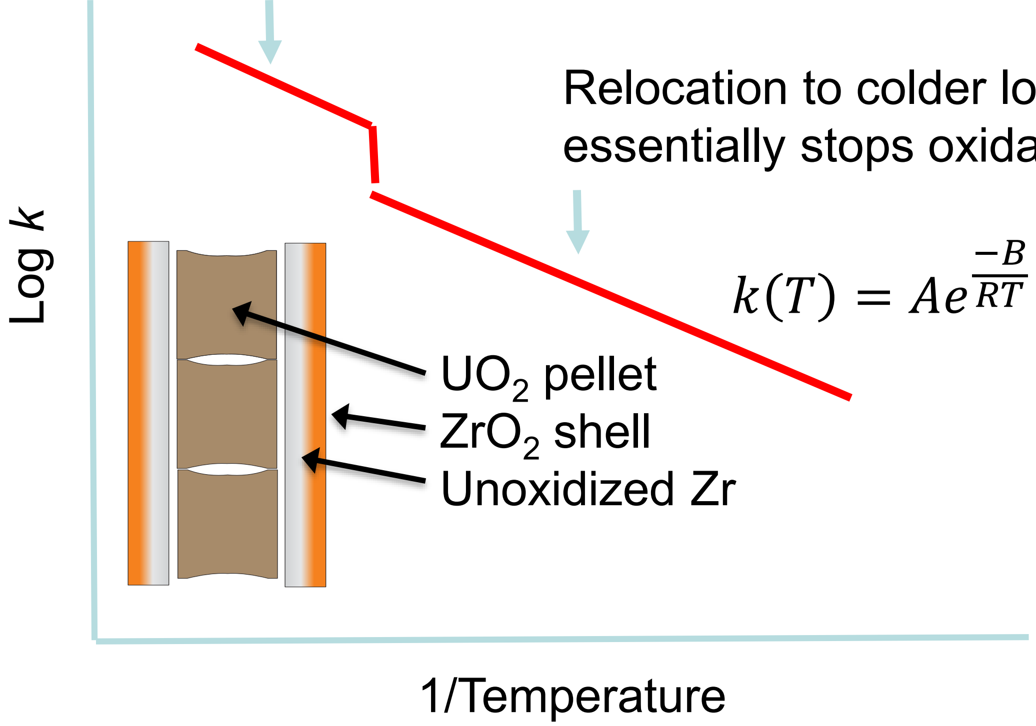
parabolic rate law

$$\frac{d\delta^2}{dt} = k(T)$$

$\delta = oxide\ shell\ thickness$

$k(T) = reaction\ rate$

Zr oxidation rate is highest at time of melting and relocation



Relocation to colder location essentially stops oxidation

UO_2 pellet

ZrO_2 shell

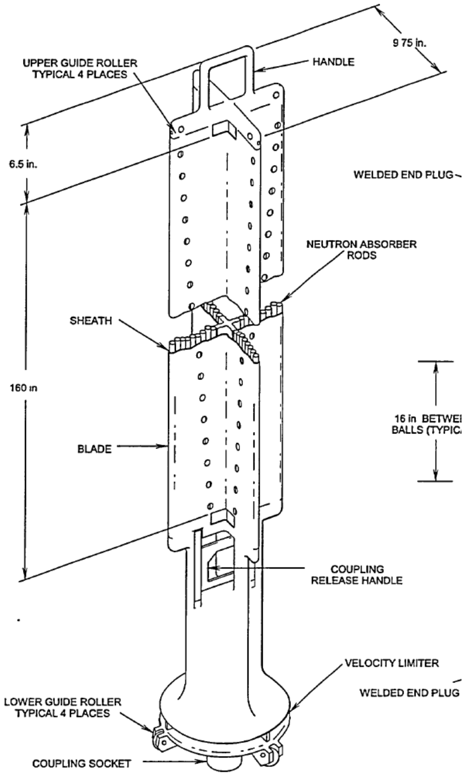
Unoxidized Zr

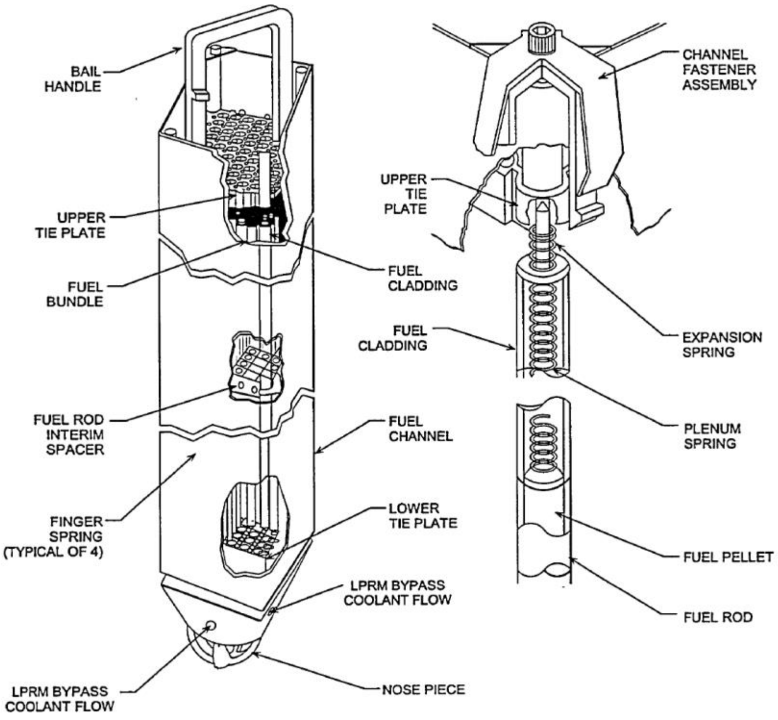
$$k(T) = Ae^{\frac{-B}{RT}}$$

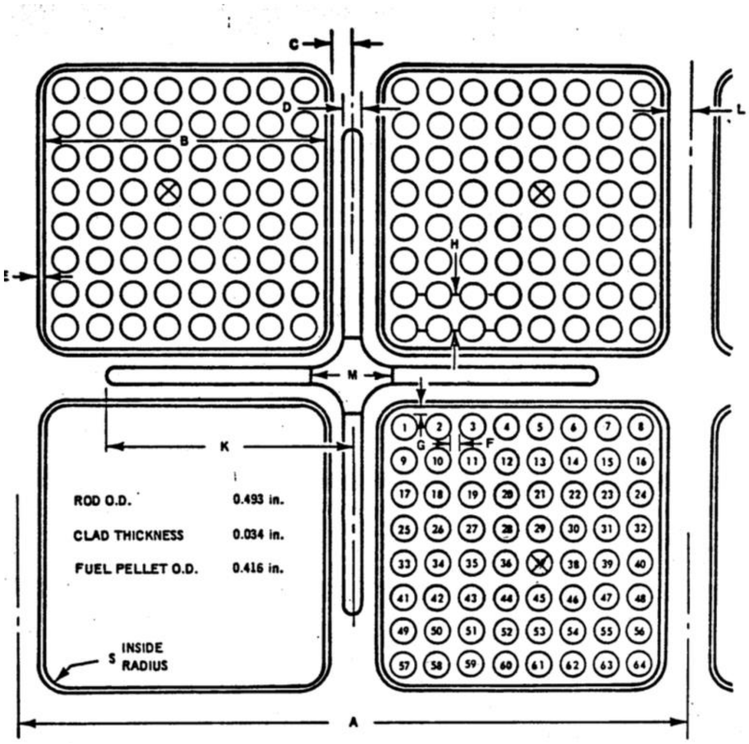
Arrhenius rate law

- $Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$ + 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 melting of Zr

BWR Core Components



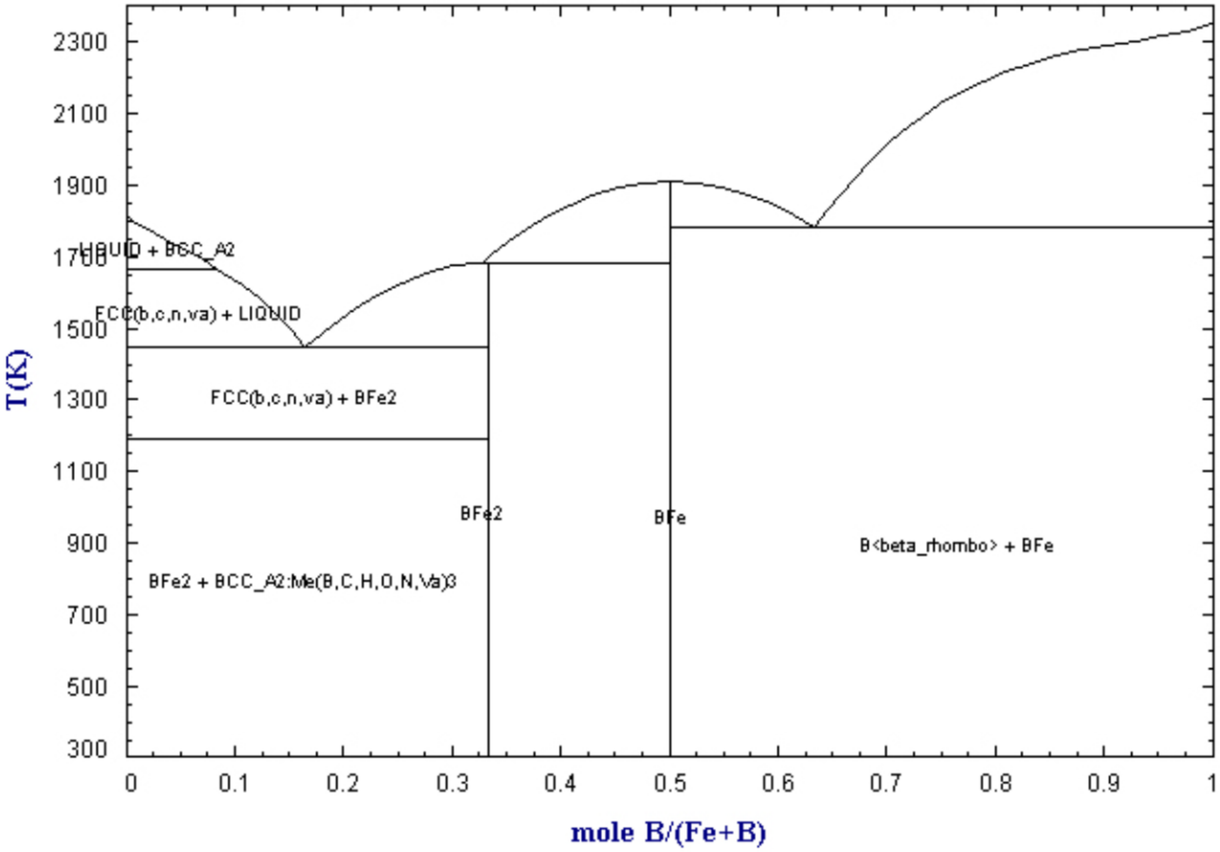




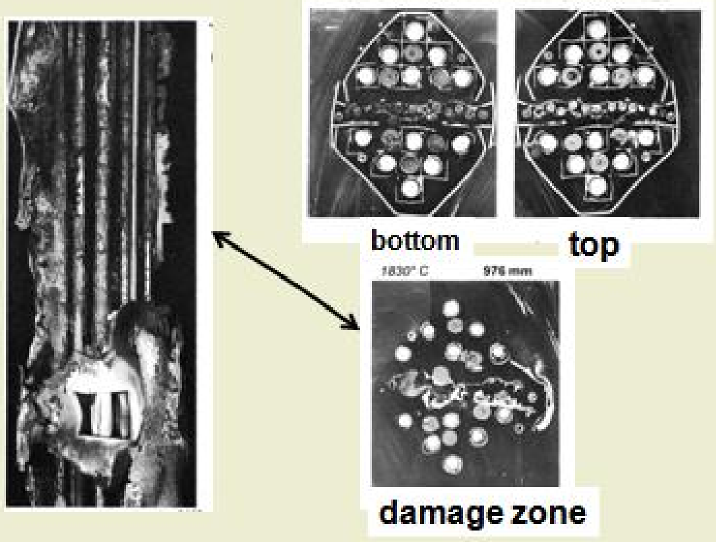
ROD O.D.	0.493 in.
CLAD THICKNESS	0.034 in.
FUEL PELLET O.D.	0.416 in.

Fe - B

Data from BINARY (SGTE) alloy databases

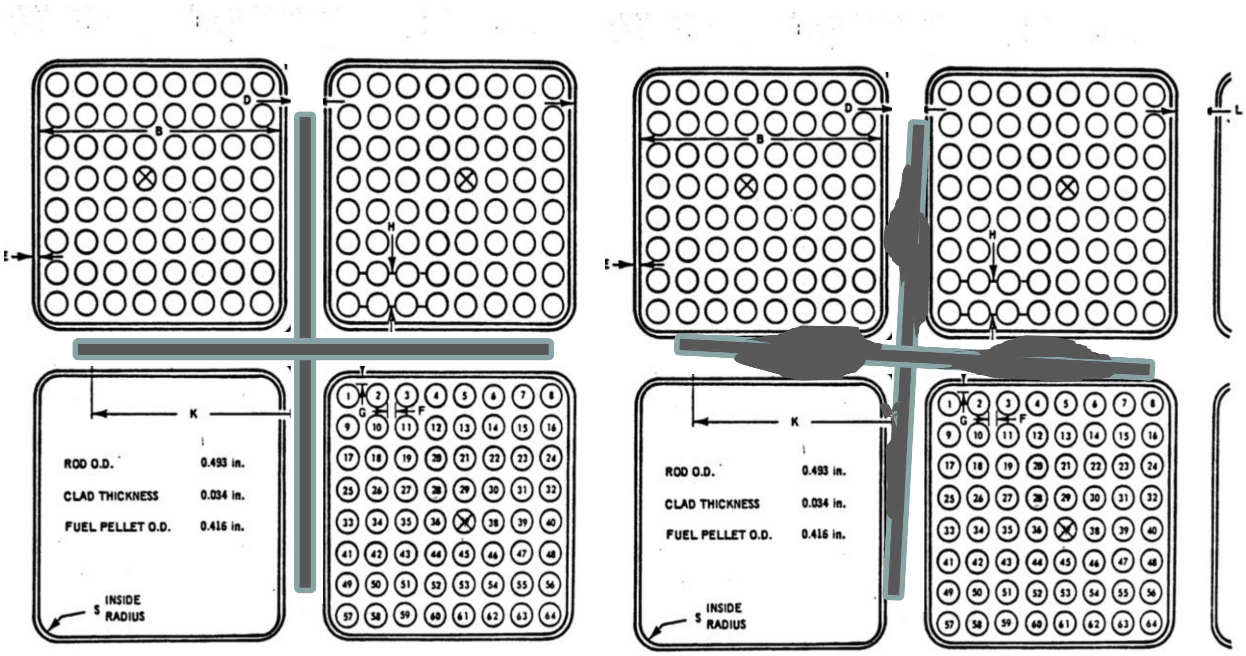


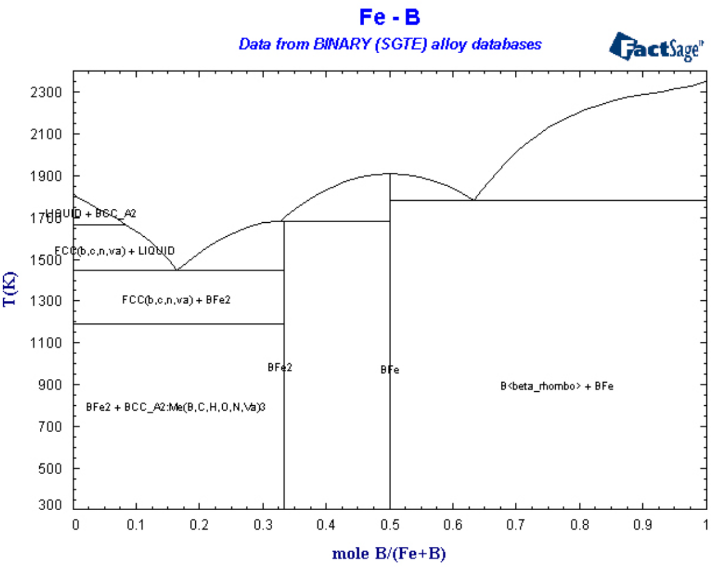
CORA BWR post test

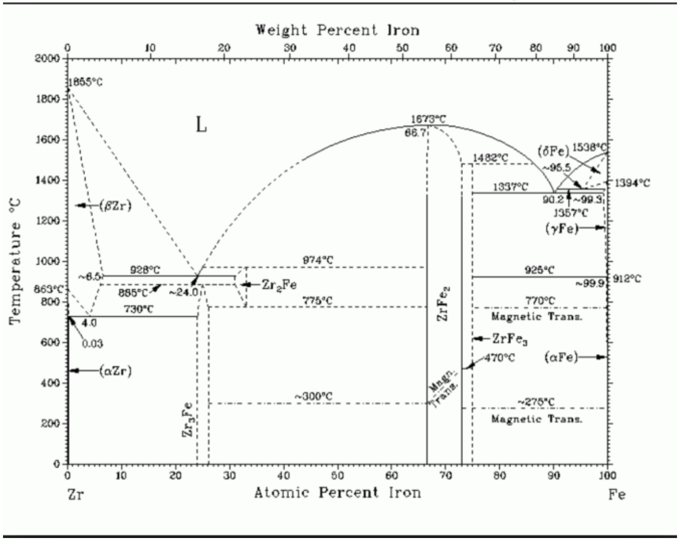


- ☐ Reaction rate seems very rapid based on experiments
- ☐ B4C seems largely consumed into eutectic melt
- ☐ B4C likely follows liqiefied SS

Initial Control Blade Liquefaction at 1500K – DF-4 Experiment

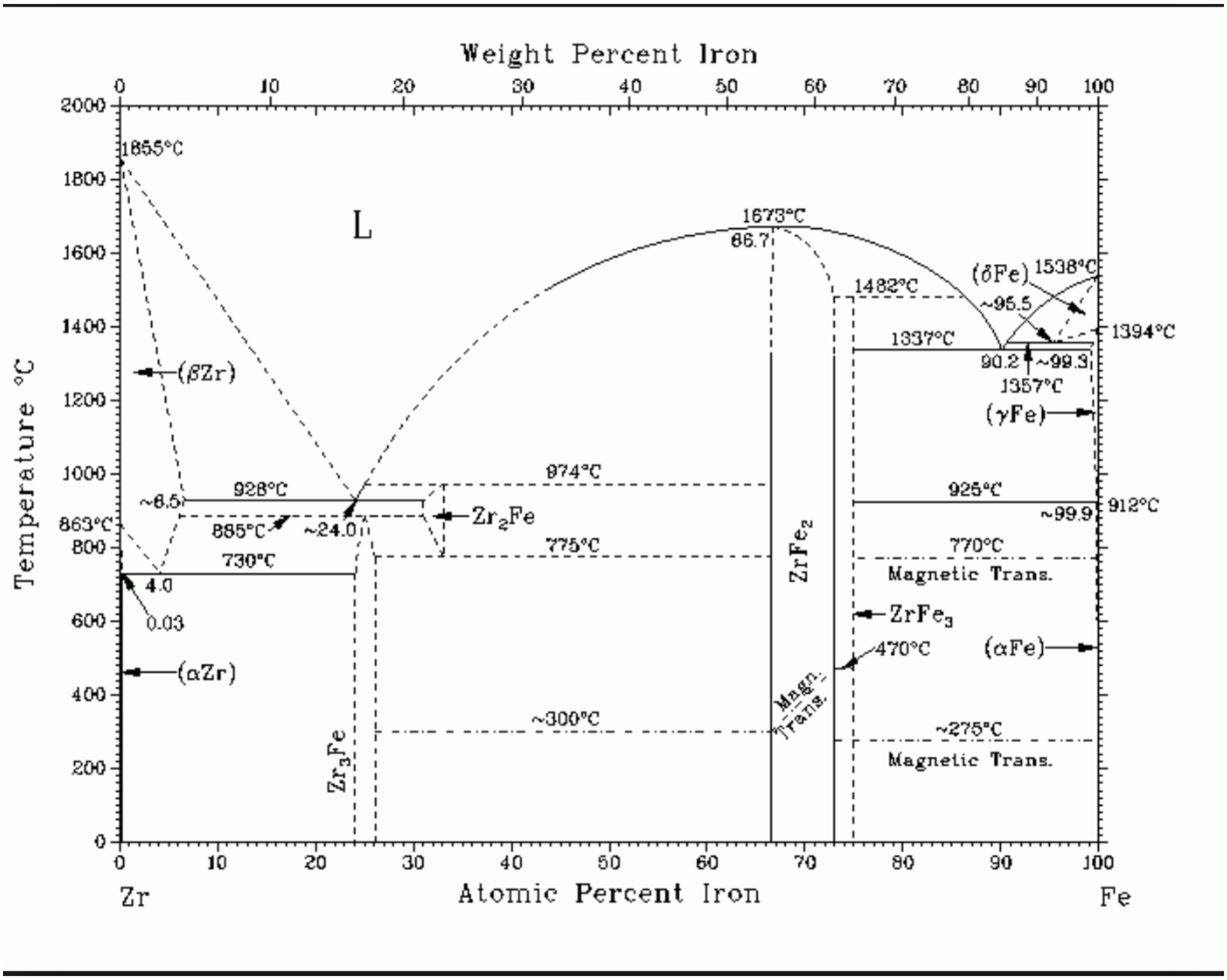






- ☐ Blade liquefied at 1500K by B_4C/Fe eutectic
- ☐ Blade distorts and melt contacts Zr channel box
- ☐ Channel box liquefied by Fe-Zr eutectic
- ☐ Liquefied materials drain downward

SS-Zr Interactions are not generally modeled in SA Codes



- ❑ Liquefied SS/B4C contacts Zr channel box walls
- ❑ "Eutectic" liquefaction of Zr possible at 974C (1247K) below B4C/SS liquefaction temperature
- ❑ Exothermic heat of mixing of SS/Zr could accelerate Zr box wall erosion

Comment on Modeling in MELCOR

- 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 molten Fe-Zr not modeled (when oxidation rate should be highest) – MELCOR redistributes molten components to some cooler lower location where oxidation rate is now much lower

Information Needs from Decommissioning Activities

- ☐ Need evidence of SS/B4C content from metallic debris
    - ☐ Confirm behavior of B4C with control blade steel
    - ☐ Determine location of Boron – criticality?
- ☐ Need to quantify Zr/SS ratio in metallic melts
    - ☐ Identify if SS-Zr intermetallic compounds form and if control blades attack channel boxes
    - ☐ Help identify effective melting points of eutectic materials

Exotherimc Reaction between Zr and Steam

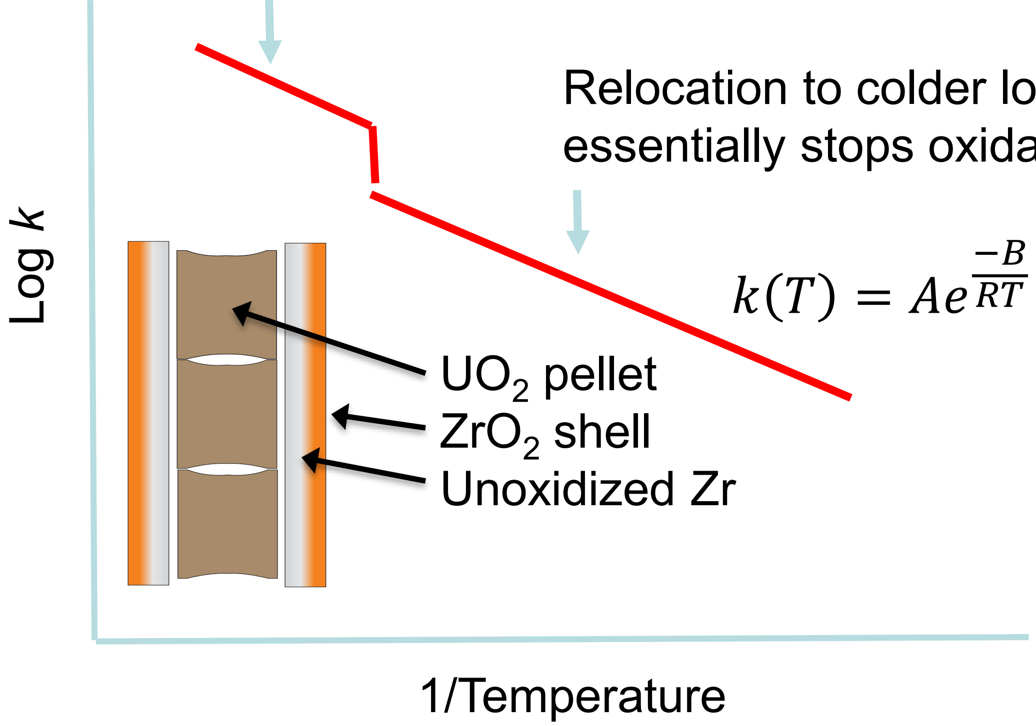
parabolic rate law → $$\frac{d\delta^2}{dt} = k(T)$$

$\delta = oxide\ shell\ thickness$

$k(T) = reaction\ rate$

Zr oxidation rate is highest at time of melting and relocation

Relocation to colder location essentially stops oxidation



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

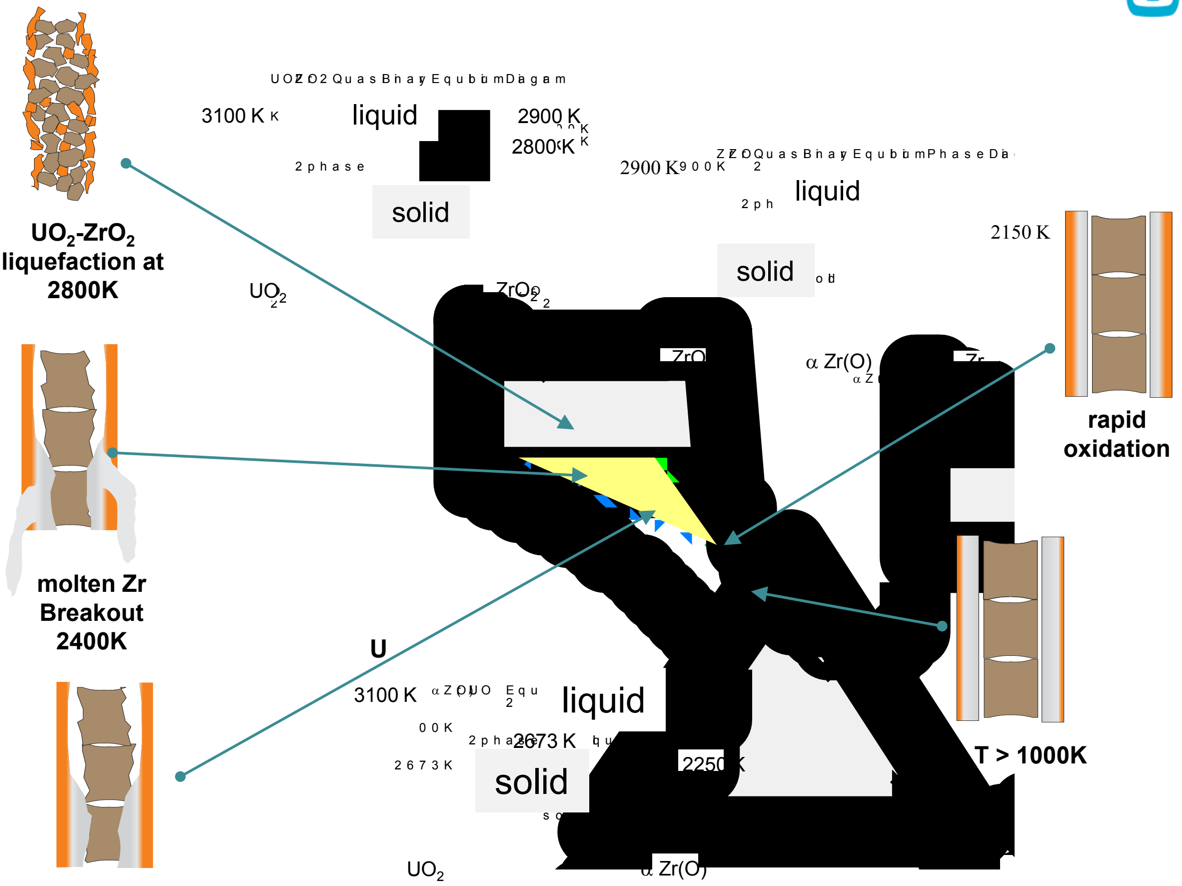
UO_2 pellet

ZrO_2 shell

Unoxidized Zr

- ❑ $Zr + 2H_2O \rightarrow ZrO_2 + 2H_2 +$ 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 melting of Zr

U/Zr/O Material Interactions



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

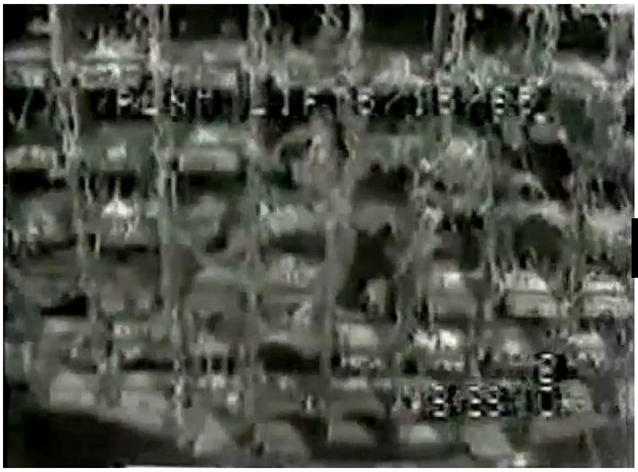
Comments on MELCOR Modeling

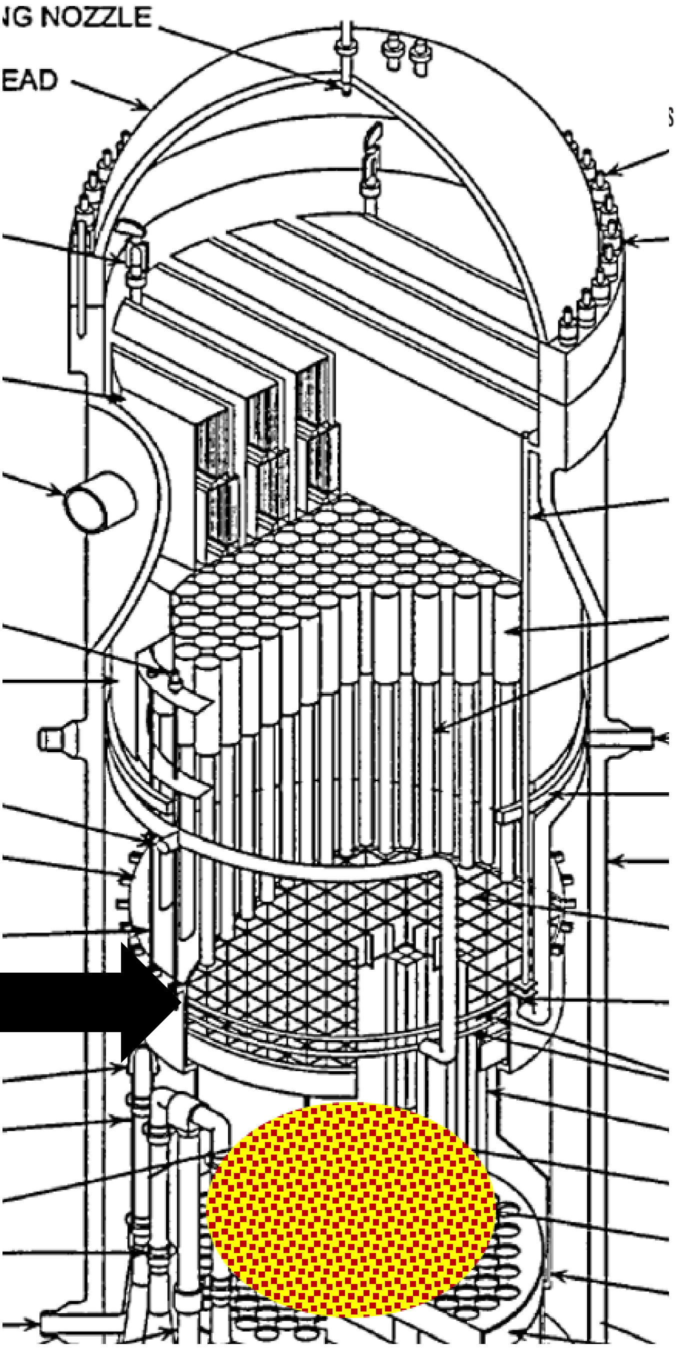
- As metallic components in core segregate from fuel components, more PWR-like fuel remnants remain
  - Modeled in MELCOR
- Zr-cladding oxidizes and melts under outer Zr-oxide shell (~2100K)
  - Modelled in MELCOR
- Molten clad wets fuel pellets and enters cracks
  - Not modeled explicitly in MELCOR
- U-Zr-O interactions form liquid mixtures ~2500K
  - Effect is treated by Eutectic effects on melting points
  - Eutectic composition not well controlled
- U-Zr-O fluidized phase drains slowly when ZrO2 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

Information Needs from Decommissioning Activities

- ☐ Need evidence of U/Zr content from fuel debris
  - ☐ Identify eutectic behavior between Zr and UO_2 and effective melting and freezing points
  - ☐ Characterize net erosion of fuel by molten cladding and distribution of decay heat
- ☐ Need to characterize U-Zr-O proportions of ceramic-like fuel debris or presence of undamaged UO_2 pellets
  - ☐ Understand fuel rod degradation behavior
- ☐ Characterize spatial (axial) segregation of various melts and phases in vessel (1F2)
  - ☐ Does this affect order or sequence of melt release from failed lower head?
- ☐ Examine lower head remnants for evidence of exothermic Zr-Fe attack (possible failure mode?)

TMI-2 Melted upper fuel assembly grids





- Core exit gas temperatures >2000K
- Melting of shroud and separators as well as dryers expected
- Molten steel drains to core region and contributes to materials released from failed vessel – *Not Modeled in MELCOR yet*

Information Needs from Decommissioning Activities

- Need examination of upper shroud, separators and dryers
    - See if melting and SS oxidation occurs
    - Establish peak core exit gas temperatures for SA codes

Focus on Lower Vessel Plenum, Lower Head, and Structures Below Vessel

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Recent Observations from Drywell Robot Examinations Are Challenging Our Codes Ability to Predict Observations

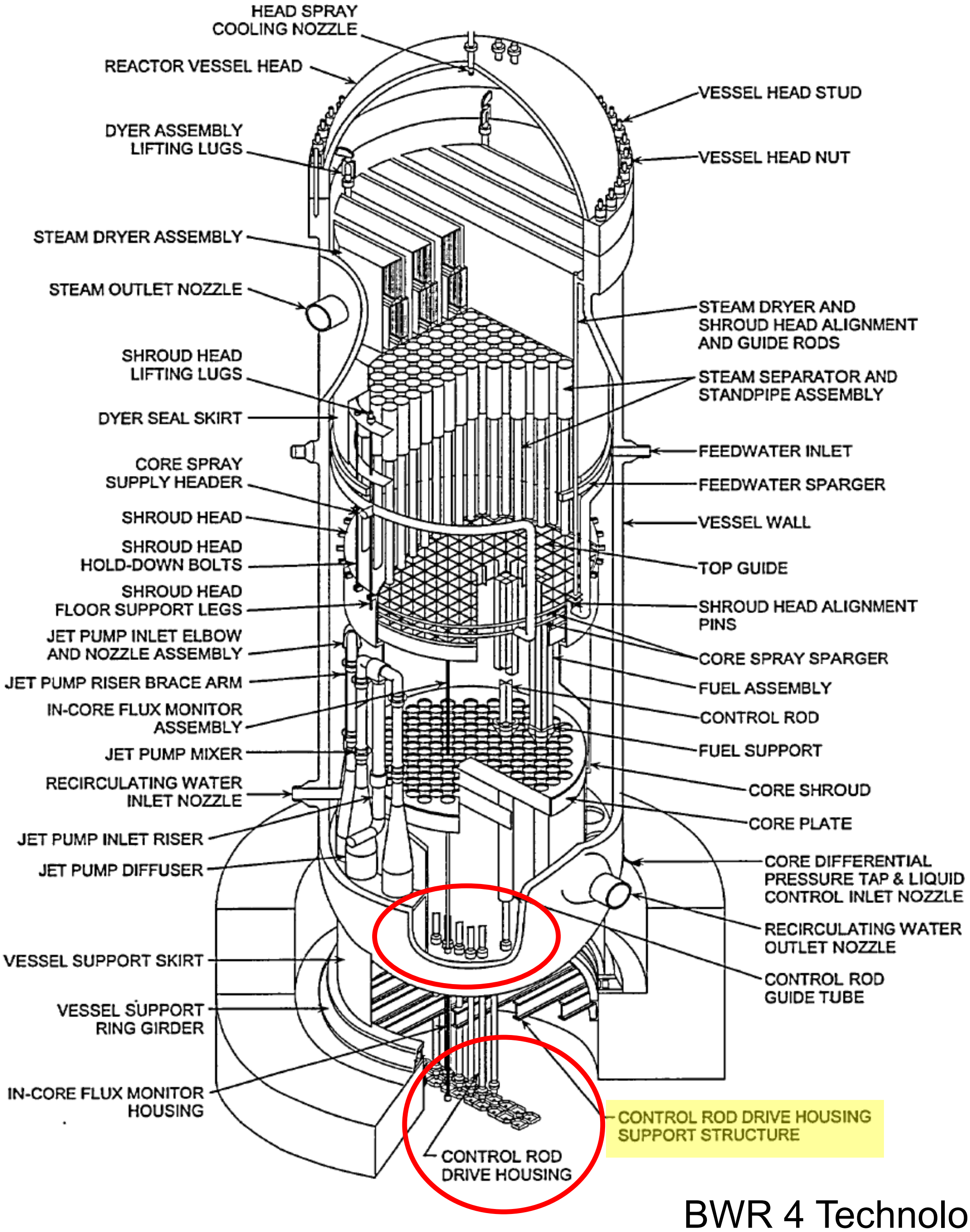
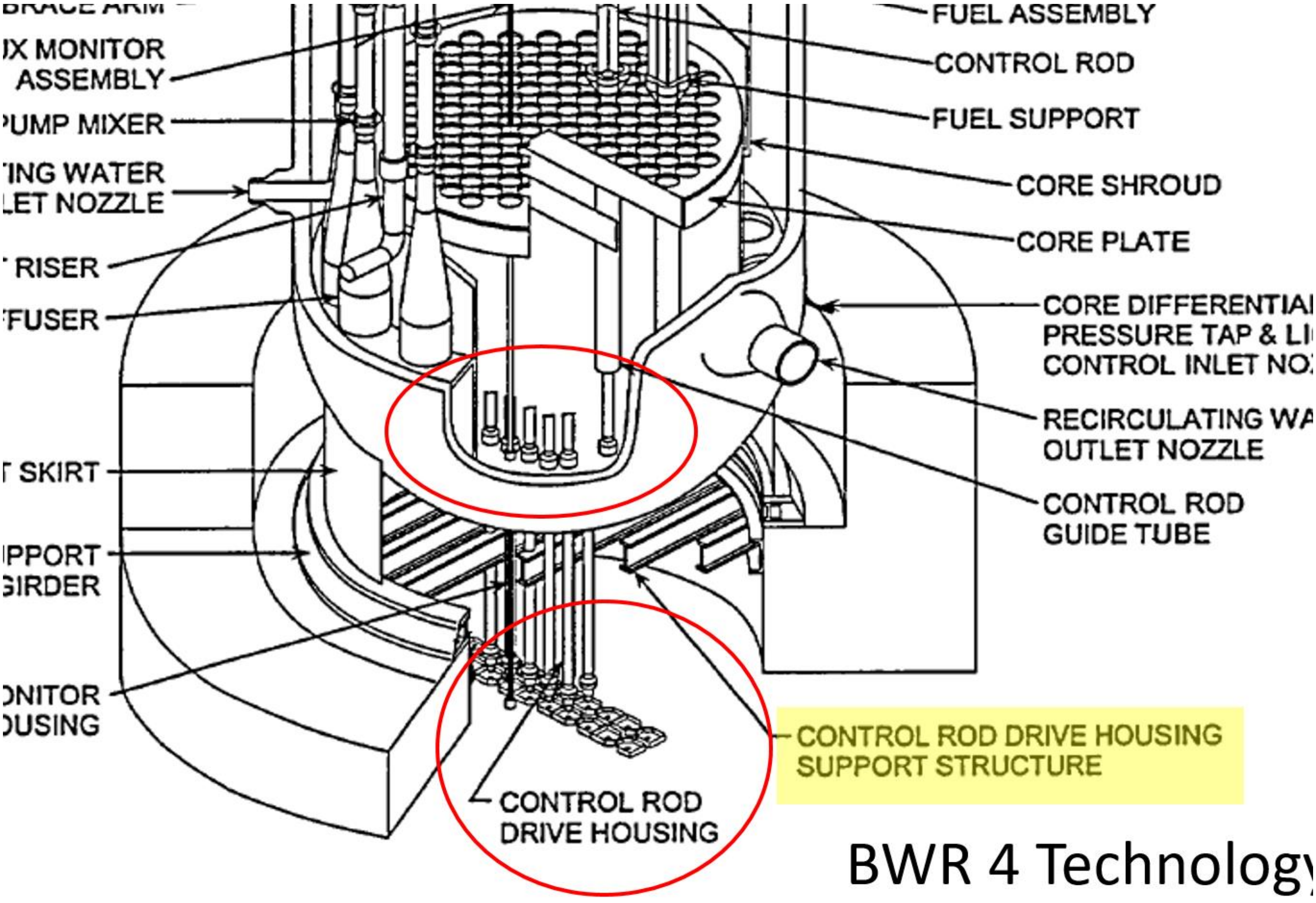


Figure 2.1-1 Reactor Vessel Cutaway

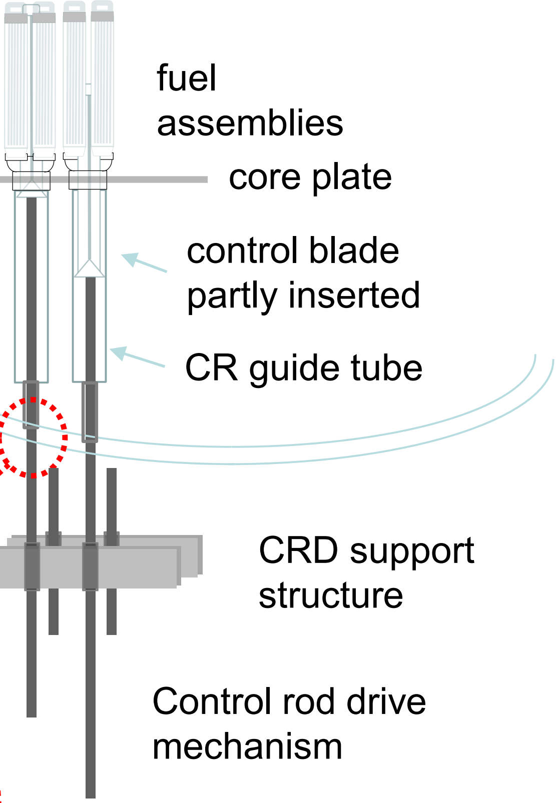
BWR 4 Technology Manual

- Current 1F observations challenge current models for core degradation and lower head failure
- This presentation now focuses on aspects of the core, lower head and structures below the vessel



BWR 4 Technolog

Figure 2.1-1 Reactor Vessel Cutaway



fuel assemblies

control blade fully inserted

core plate

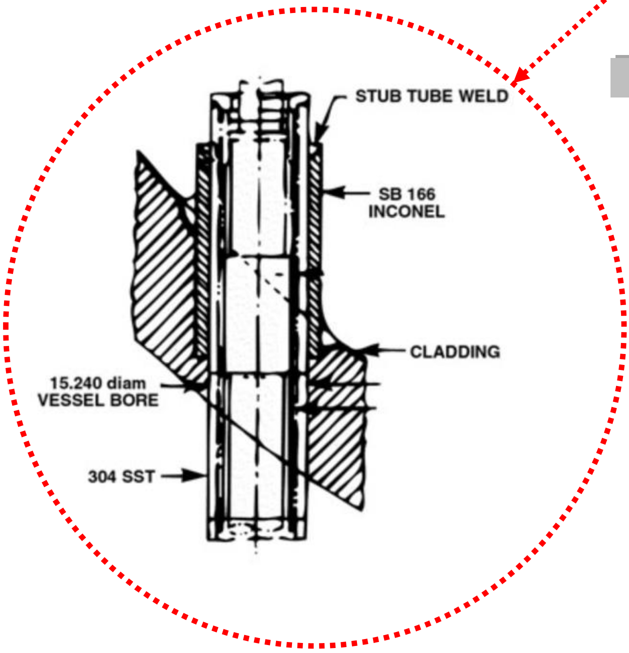
control blade partly inserted

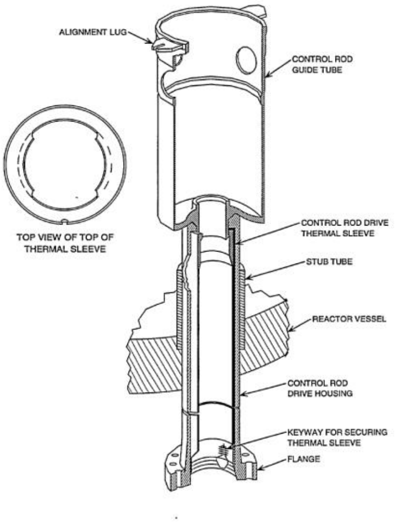
vessel head

CR guide tube

CRD support structure

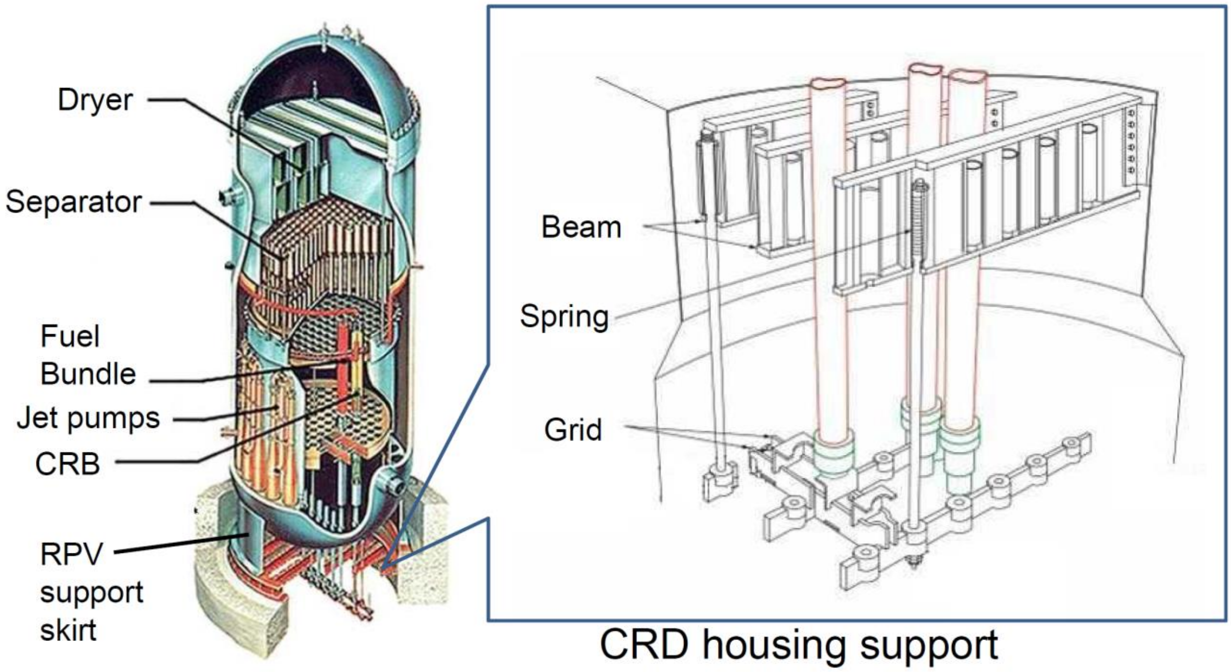
Control rod drive mechanism



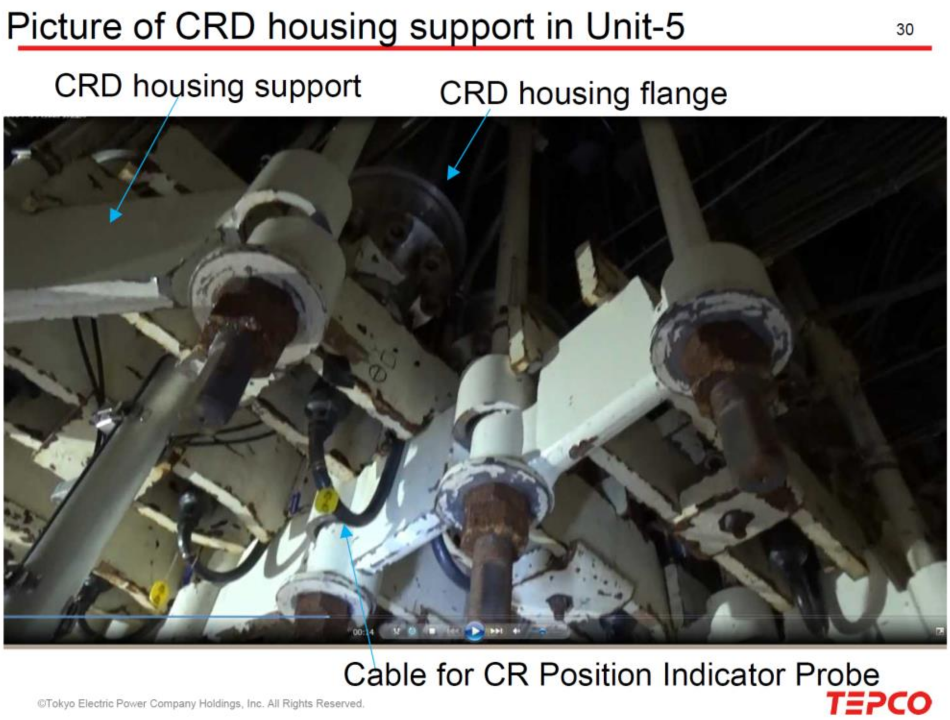


- ☐ Penetration failure is often proposed as a focus for initial head failure, however…..
- ☐ BWR CRD Penetrations could be large heat sinks and lagging in heatup and failure compared to the head wall itself
  - ☐ No detailed treatment of CRD penetrations exists in MELCOR

Views of CRD Housing Support



CRD housing support



Picture of CRD housing support in Unit-5

30

CRD housing support

CRD housing flange

Cable for CR Position Indicator Probe

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CRD Structures below vessel have been Neglected by SA Codes

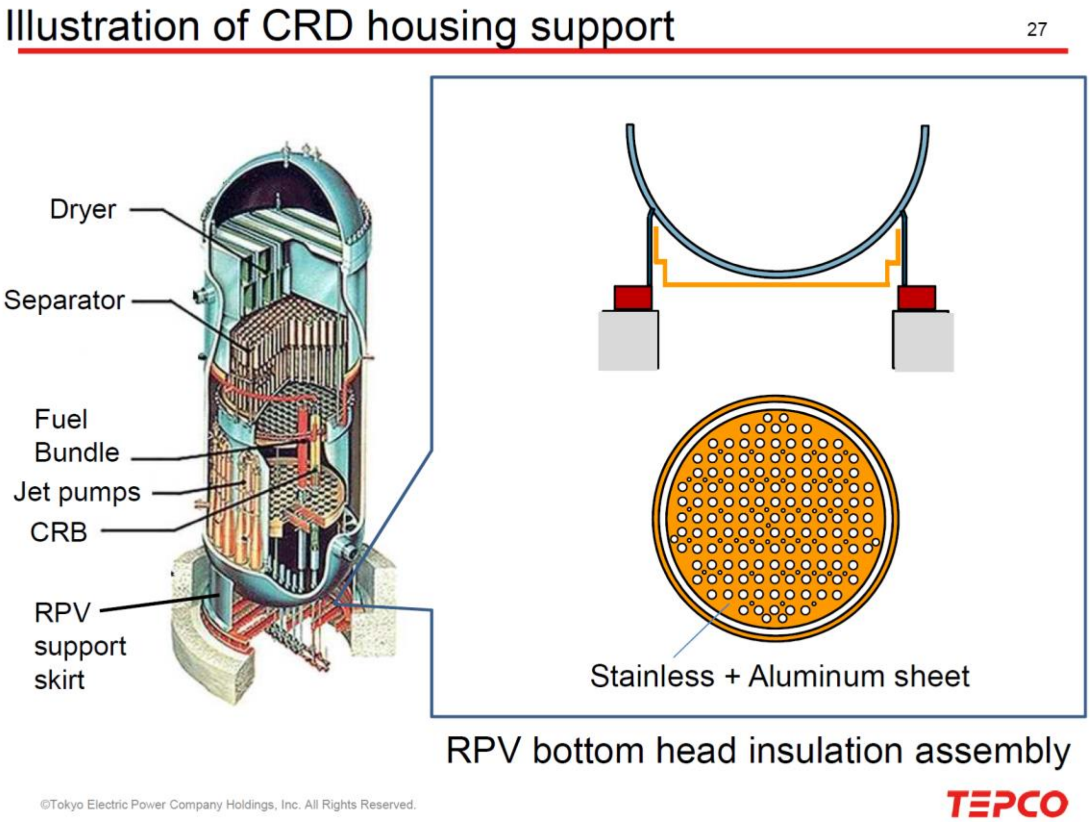

Illustration of CRD housing support

27

Dryer

Separator

Fuel Bundle

Jet pumps

CRB

RPV support skirt

Stainless + Aluminum sheet

RPV bottom head insulation assembly

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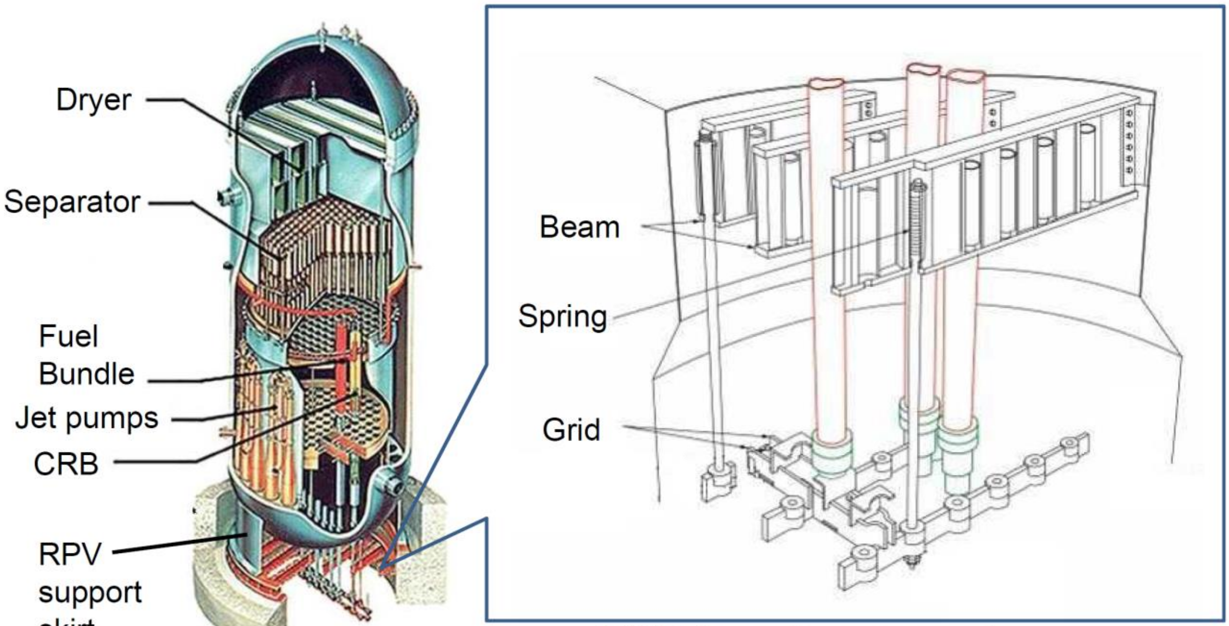
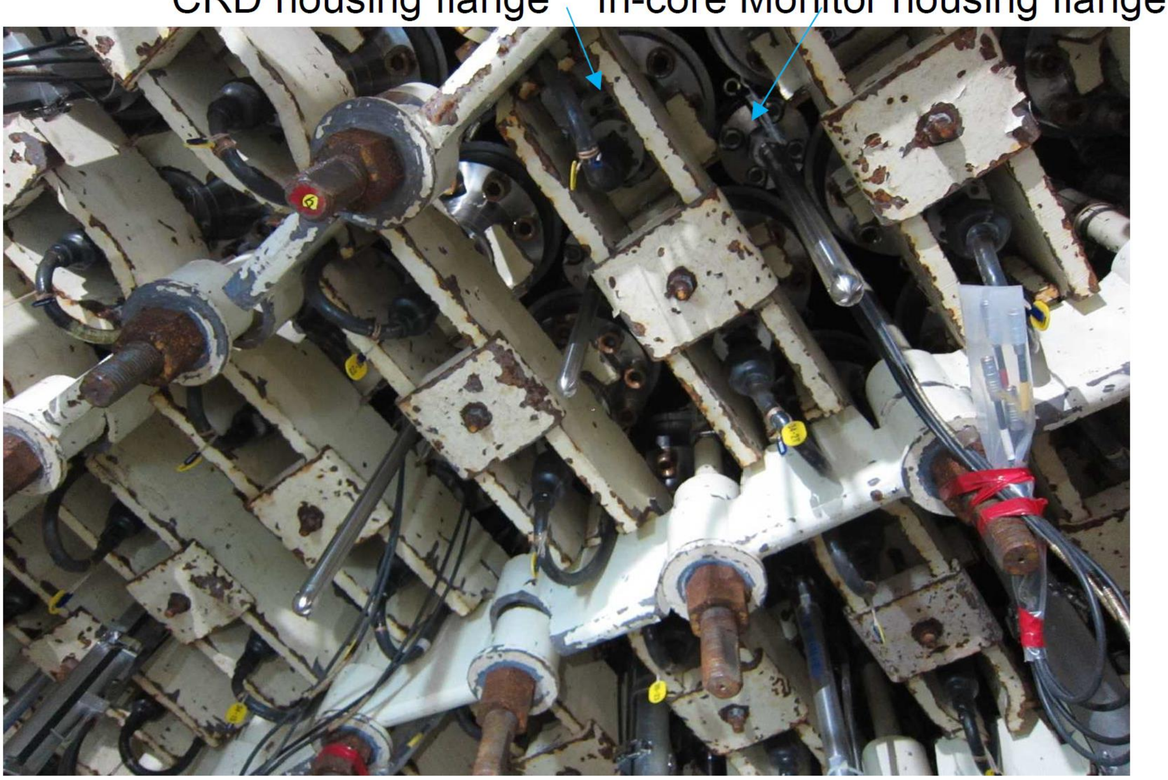
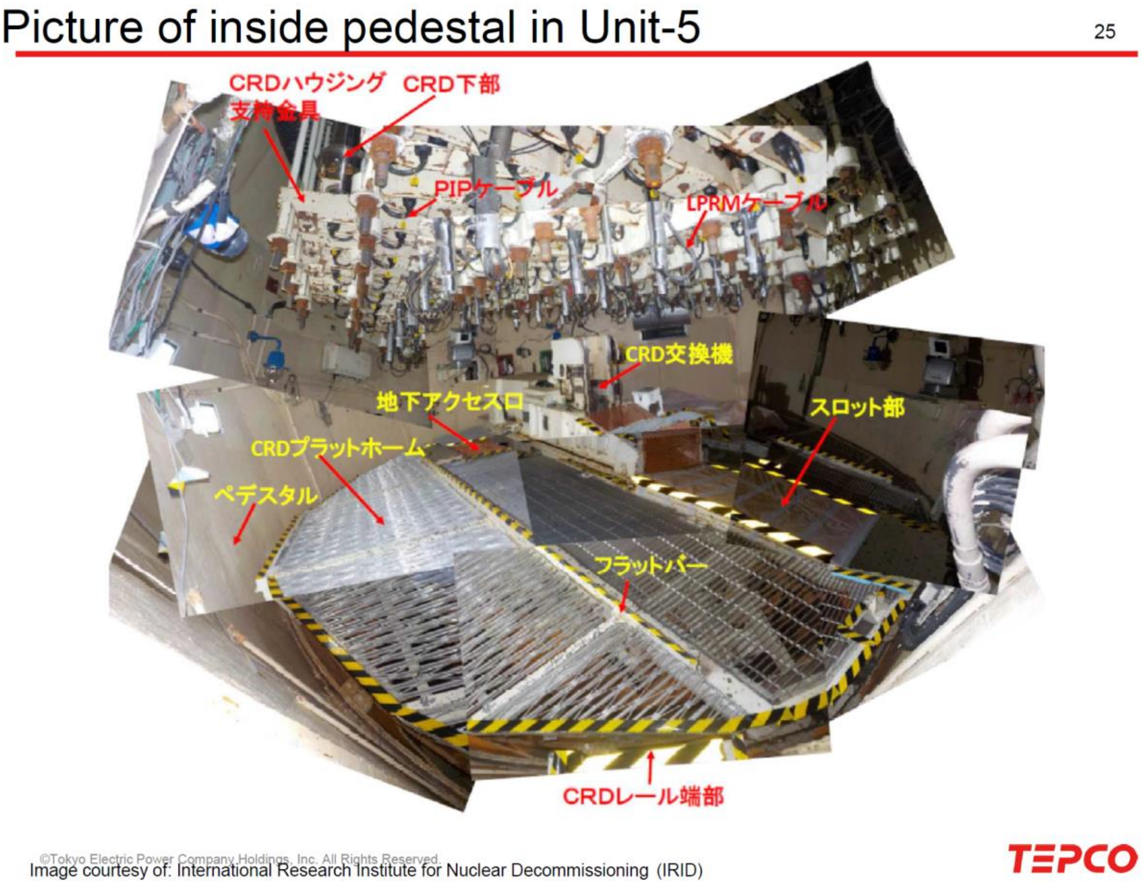


CRD housing support

Picture of CRD housing support in Unit-5



Other Features below vessel



Picture of inside pedestal in Unit-5

25

Image courtesy of: International Research Institute for Nuclear Decommissioning (IRID)

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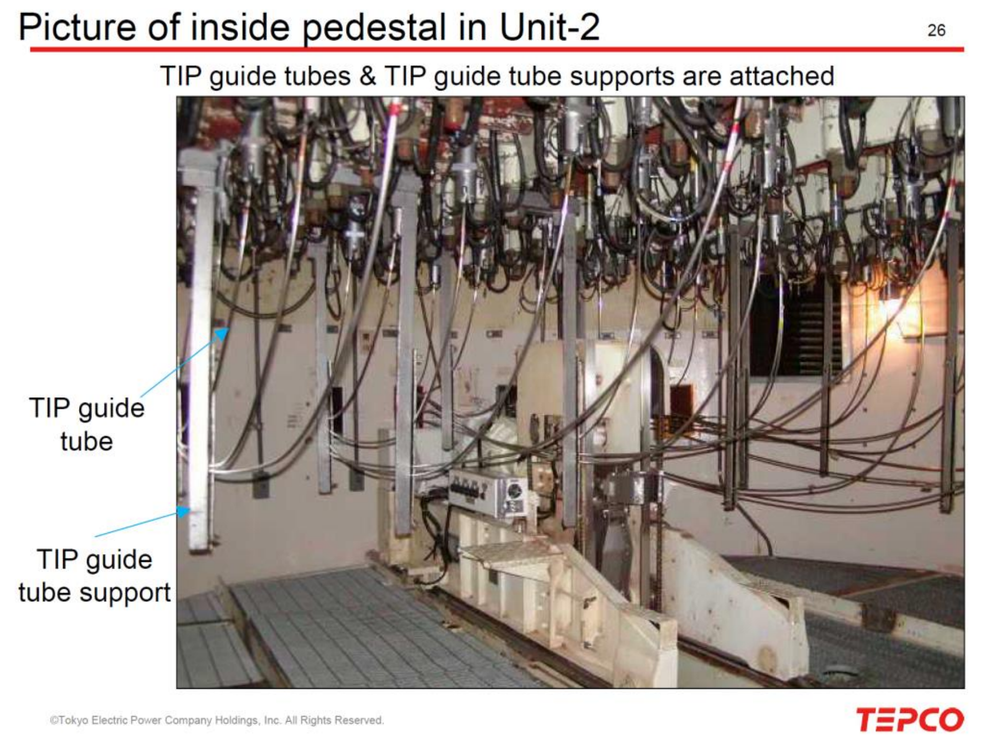

Picture of inside pedestal in Unit-2

26

TIP guide tubes & TIP guide tube supports are attached

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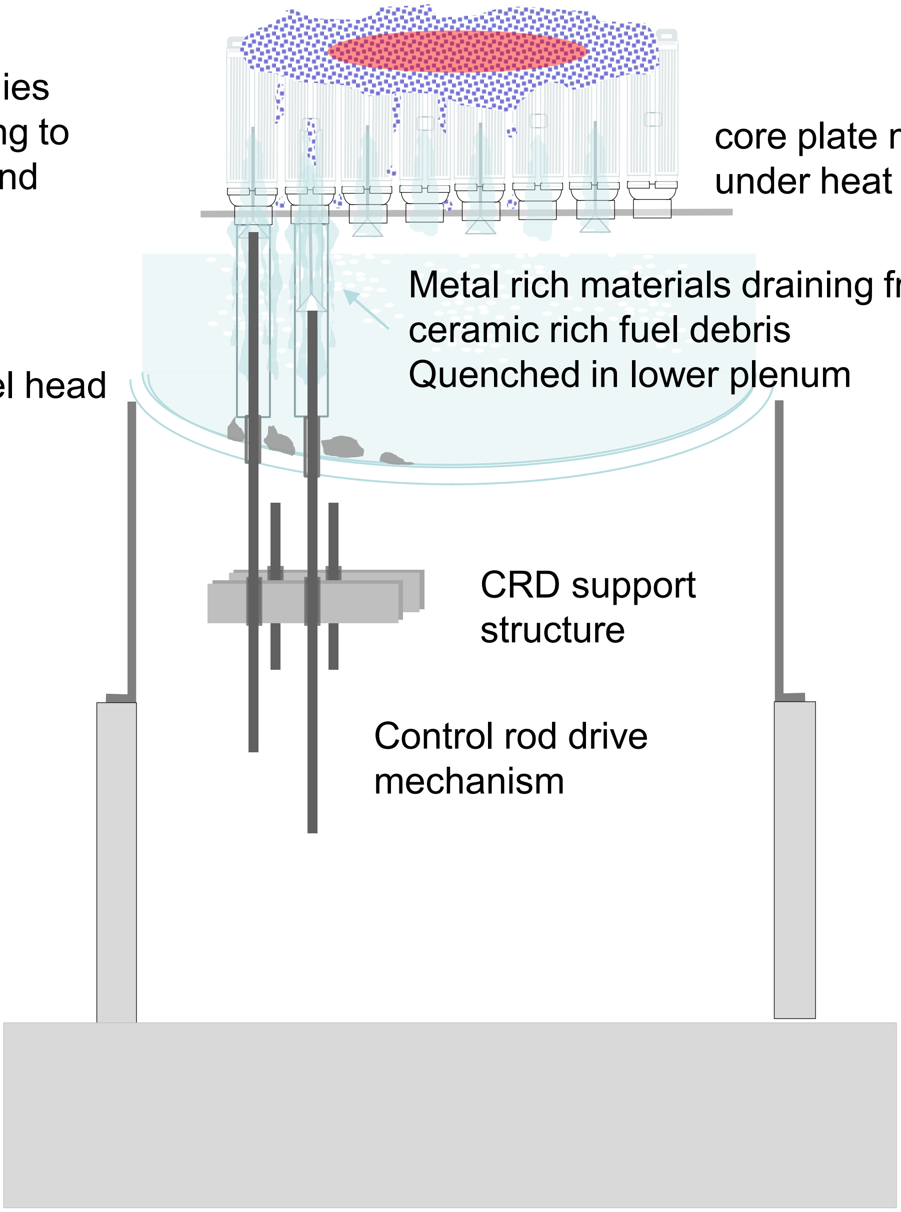
Potential Ways our Codes Can Capture Observations from Drywell Below Vessel



fuel assemblies degrading to rubble and melt

core plate melting under heat loads

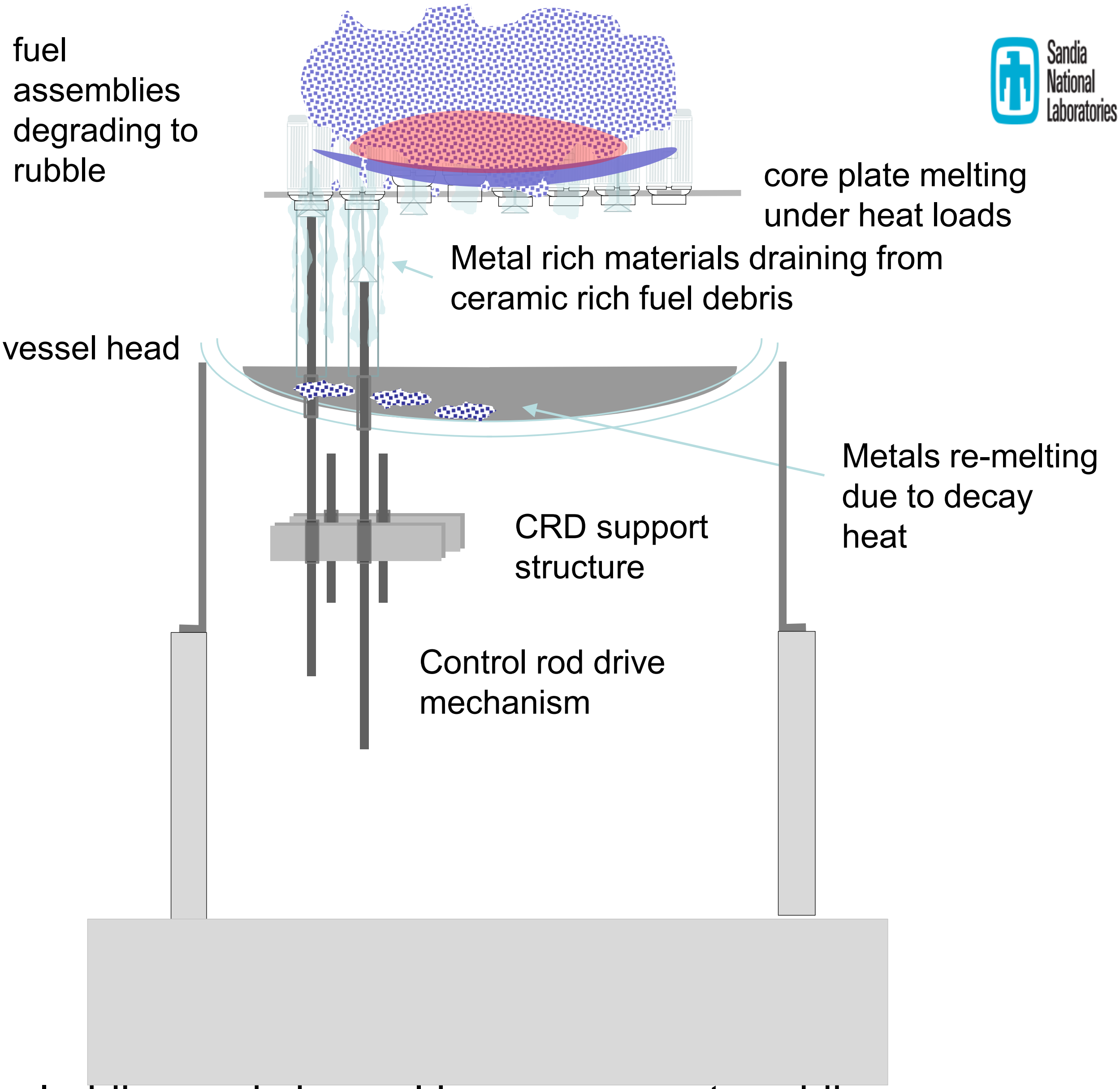
Metal rich materials draining from ceramic rich fuel debris
Quenched in lower plenum

vessel head

CRD support structure

Control rod drive mechanism

- ☐ 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
- ☐ Zr could float to top of iron due to lower density – not considered by MELCOR
- ☐ Core debris region progresses down at same time as metallic are accumulating on lower head – a race



fuel assemblies degrading to rubble

core plate melting under heat loads

Metal rich materials draining from ceramic rich fuel debris

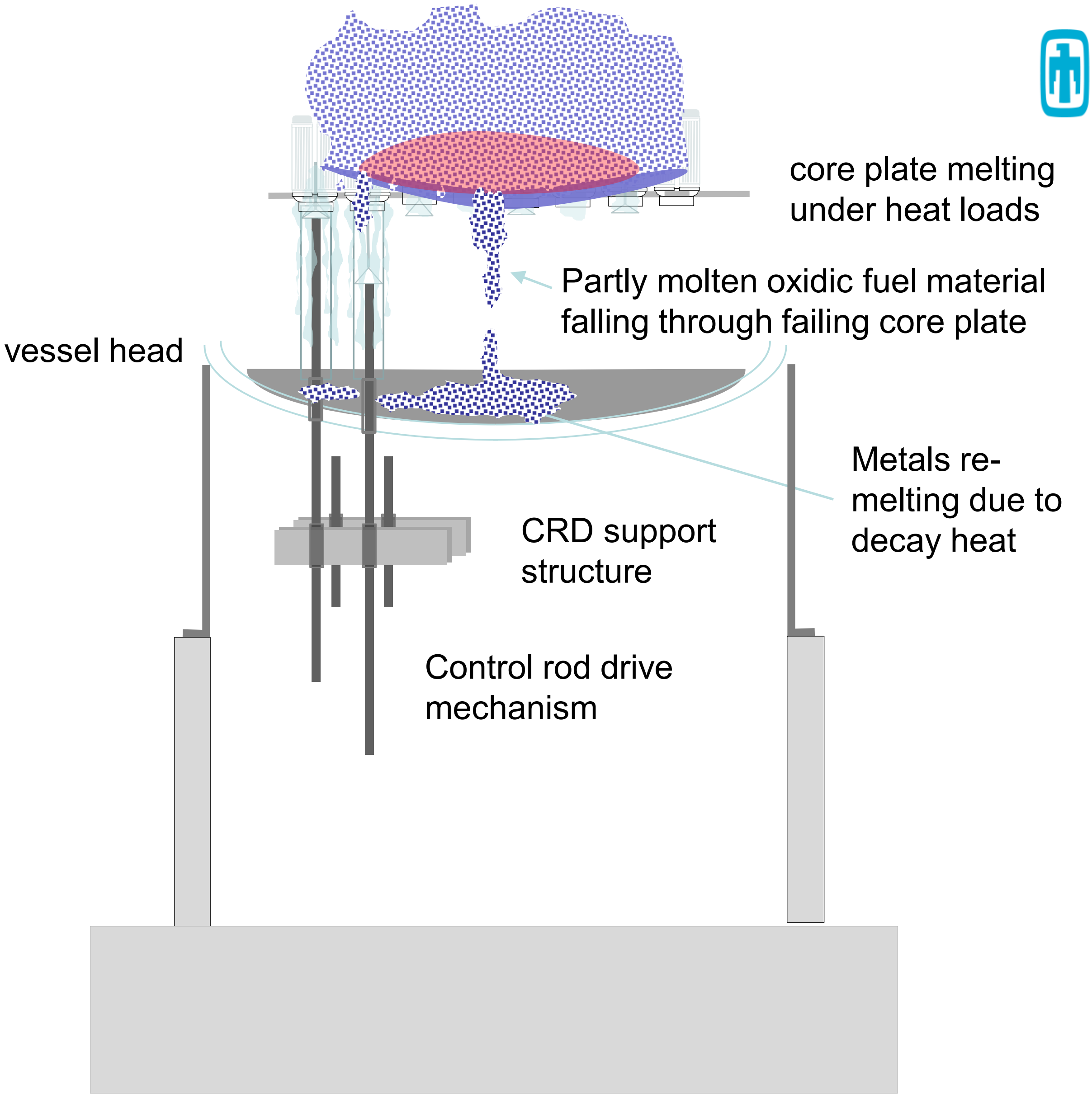
vessel head

Metals re-melting due to decay heat

CRD support structure

Control rod drive mechanism

- 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
- CR Drive tubes and rods may also melt and incorporate into metallic-like (metallo-ceramic?) melt



core plate melting under heat loads

Partly molten oxidic fuel material falling through failing core plate

vessel head

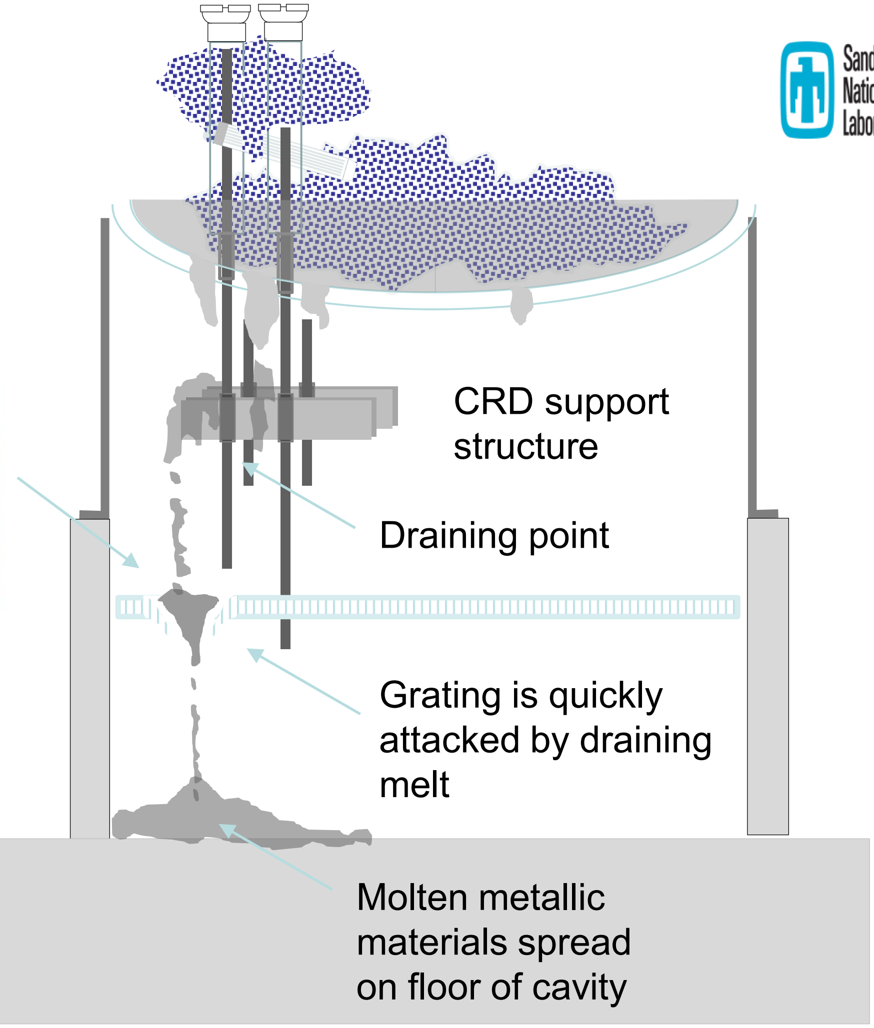
Metals re-melting due to decay heat

CRD support structure

Control rod drive mechanism

- 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

Reference : Platform grating



CRD support structure

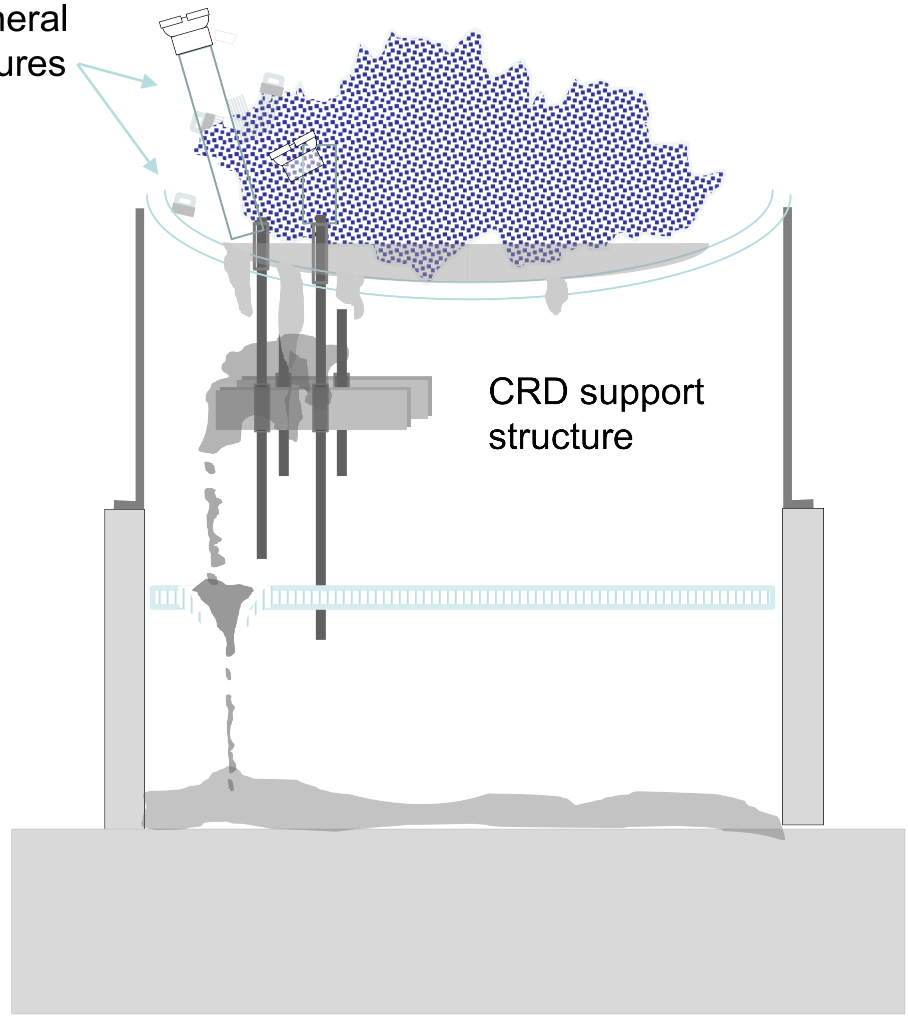
Draining point

Grating is quickly attacked by draining melt

Molten metallic materials spread on floor of cavity

- 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

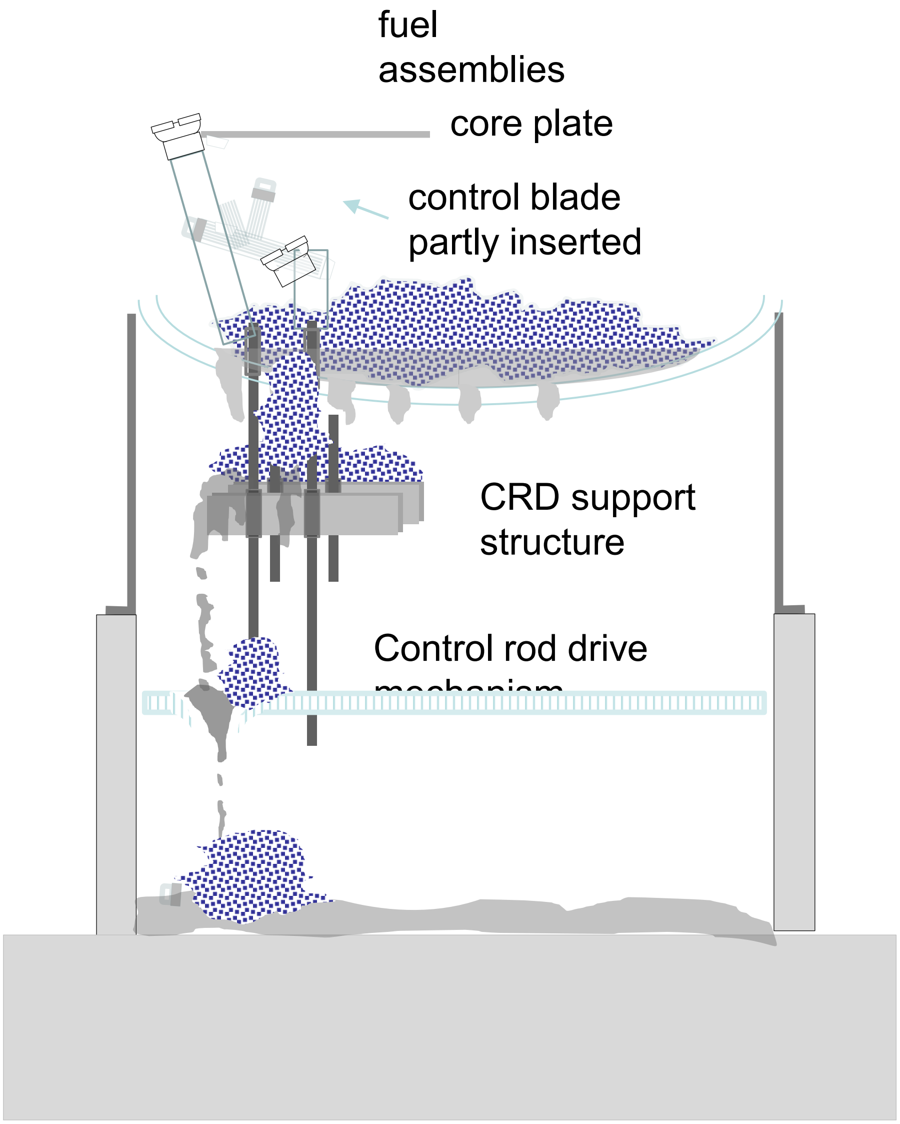
Unit 2 End State



Partly intact peripheral structures

CRD support structure

- 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
- Some intact parts apparently fell through largely disintegrated lower head – 1F3
- 1F2 may have been arrested by this time leaving a mostly level metallic layer on cavity floor – 1F2



fuel assemblies

core plate

control blade partly inserted

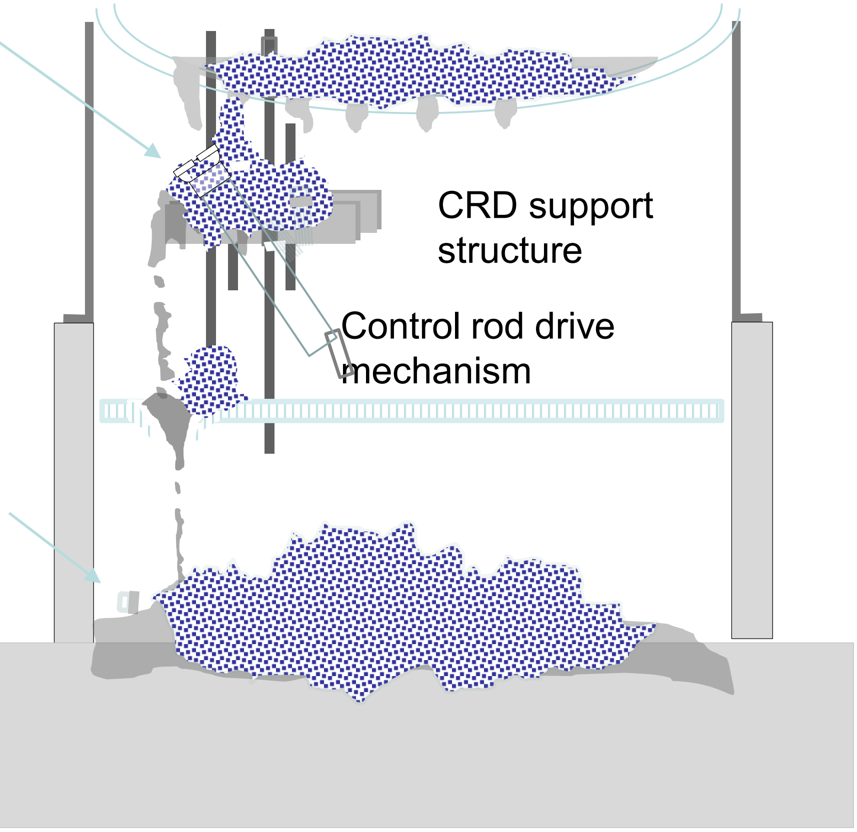
CRD support structure

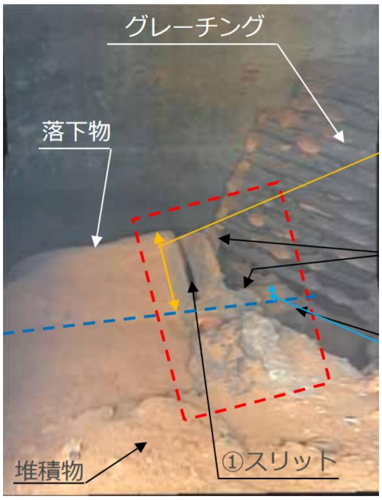
Control rod drive mechanism

☐ Without cooling, ceramic debris becomes mobile (partly molten perhaps) and falls from vessel

☐ Modeling under-vessel structure may be key to capturing Unit 3 containment pressure signature

Unit 3 End State





- Ceramic attack on remnants in lower head and on CRD support structure allows large relocation of fuel debris
- Peripheral less damaged structures, such as upper fuel tie plates and partly damaged CDR guide tubes and drive components can fall through holes in head, CRD support and grating

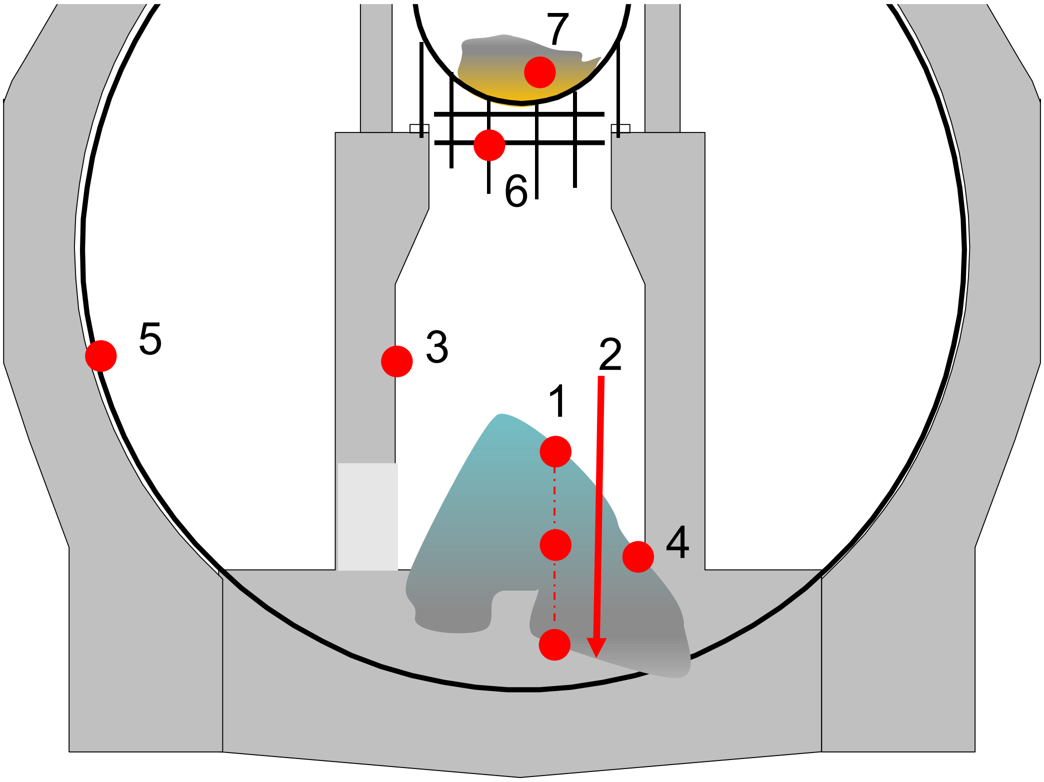
MELCOR Modeling of Lower Head Failure and Material Transfer to Cavity

- Head failure considered ring-by-ring in MELCOR
  - Under Depressurized conditions…
    - Not much difference in global failure from melting, loss of strength or penetration failure
    - Penetration failure models are too crude and not appropriate for BWR and depressurized RPV
    - Control function failure allows user control
- Head failure allows release material from the lower head to the cavity with some options:
  - Option 1 – Release everything all at once whether molten or solid
  - Option 2 – release only molten components until Tpfail temperature is exceeded (penetration) where upon everything is release over a 1 sec period
  - Dissolved UO2 will also exit with molten Zr fraction retaining the undissolved solid fraction
  - Seems option 2 allows some flexibility for modeling protracted releases
- MELCOR flexibility would seem to allow capability to explore potential behaviors in Unit 2 and Unit 3
  - Release molten metals and dissolved UO2 and retain balance of UO2
  - Eventually release everything

Information Needs from Decommissioning Activities

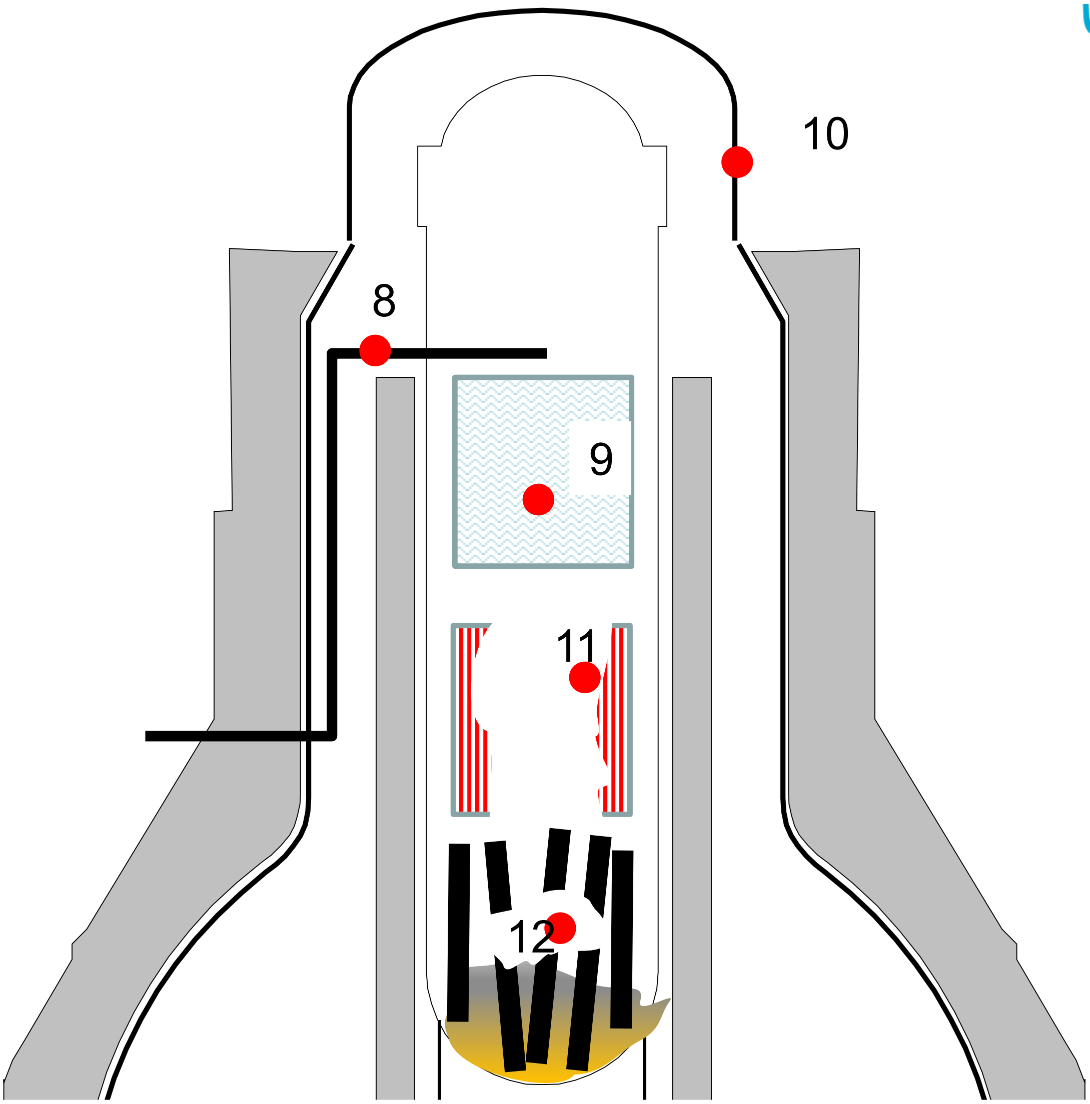
- Examine nature of lower head melting and attack
  - Melting
  - Intermetallic attack by Zr
  - Hole sizes and locations
- Characterize damage to CRD supporting structure
  - Nature of melt interaction
  - Potential for adding mass to cavity
- Determine Unit 2 cavity deposit composition – SS/Zr/B4C
- Determine Unit 3 cavity deposit composition
  - Metal layer on bottom?
  - Evidence of MCCI
  - Dispersion of boron affecting recriticality or material hardness

Key Location of Potential Samples



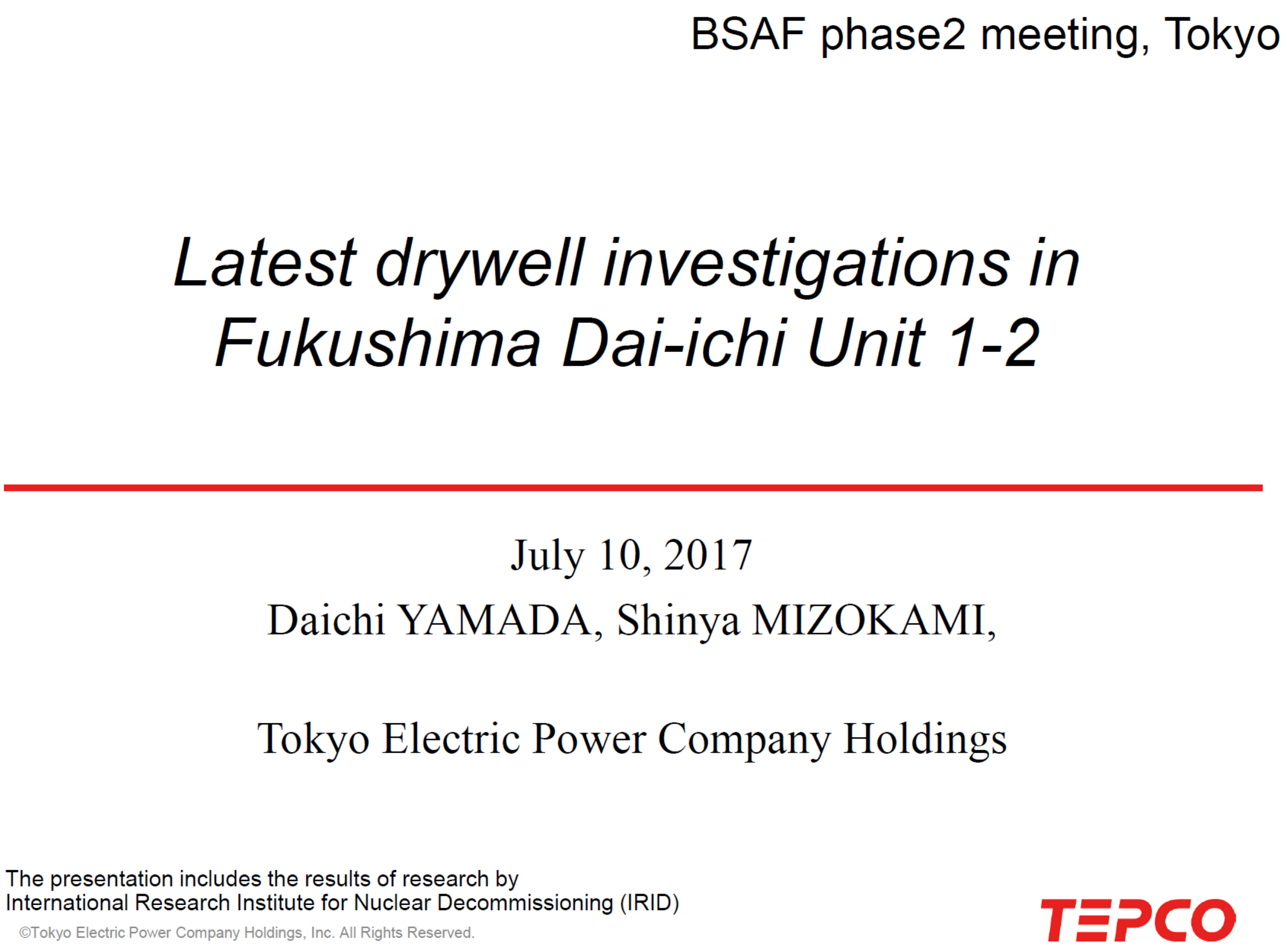
Location	Description	Knowledge Gain
1	Sample of cavity debris every 1 m depth	Segregation of debris layers (metallic and ceramic) within the cavity region
2	Bored sample of full debris depth	Segregation of debris layers (metallic and ceramic) within the cavity region
3	Interior of pedestal wall	Fission product (Cs, Te, Sr, etc..) deposition information
4	Wall and debris bed intersection	Characterization of potential for pedestal wall attack by molten materials
5	Interior of drywell wall	Fission product (Cs, Te, Sr, etc..) deposition information
6	Deposited materials on structures below lower head	Core debris relocation behavior and material distribution
7	Lower plenum	Core debris relocation behavior and material distribution

Key Location of Potential Samples



Location	Description	Knowledge Gain
8	Main steam line	Validate the possibility of a main steam line rupture from hot gasses
9	Steam dryer area	Extent of oxidation and melting of the steam dryers – could be a major unaccounted for source of hydrogen and metal during core degradation
10	DW head flange	Extent of damage on this structure – confirm a major likely PCV failure location
11	Images or samples of core region	Information on the extent of core damage, (i.e. whether or not all fuel failed)
12	Images or samples of CRDs in lower RPV	Extent of damage to the

Photos and Illustrations Taken From…..



BSAF phase2 meeting, Tokyo

Latest drywell investigations in Fukushima Dai-ichi Unit 1-2

July 10, 2017
Daichi YAMADA, Shinya MIZOKAMI,

Tokyo Electric Power Company Holdings

The presentation includes the results of research by
International Research Institute for Nuclear Decommissioning (IRID)