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Research on thermodynamic interaction of Corium material in lower head

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2. Analysis methodology and accident assumption

3. Material interaction and determination of corium pool configuration

4. Conclusion and discussion

1. Background

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- **In-Vessel Retention of core debris**

- **An important severe accident management strategy that has been implemented in many small/medium-sized reactors**

- **Make full use of existing systems and components to avoid complex ex-vessel severe accidents and prevent the release of fission products**

- **IVR strategy is highly compatible with CAP1400 design philosophy**

- **The IVR-relevant phenomena should be studied to maintain a modest safety margin due to huge power capacity of CAP1400**

1. Background

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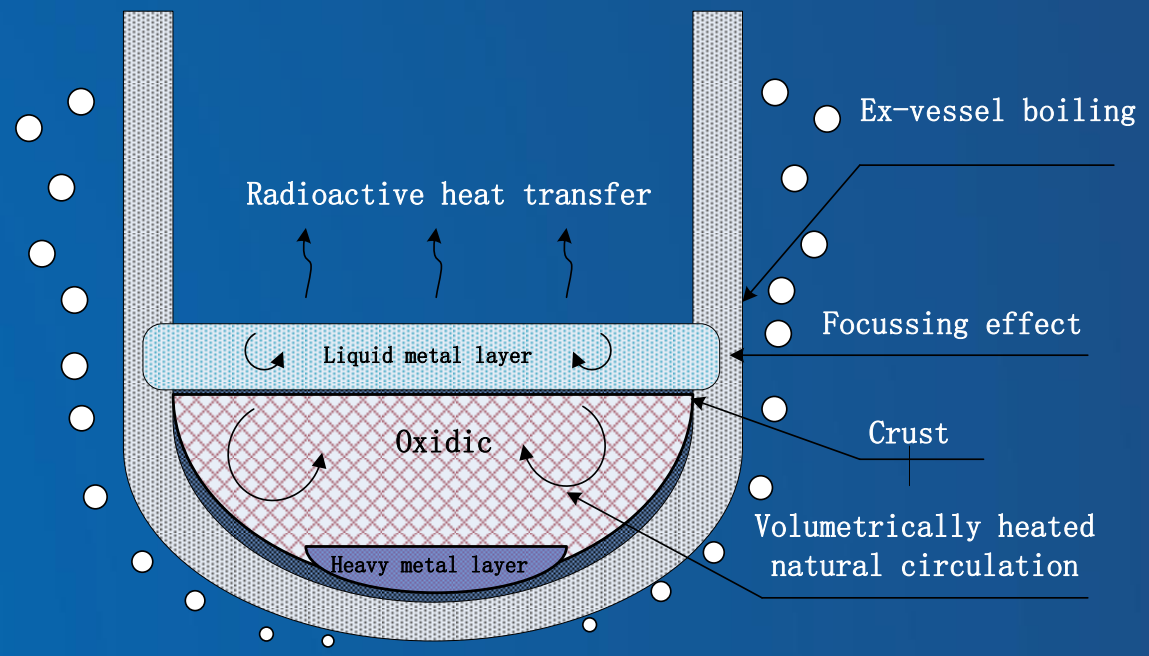
● In-Vessel Retention of core debris

- Success criteria: thermal evaluation (more limiting than structural evaluation)
  - q: Heat flux imposed to vessel wall by corium
  - q: changes with the in-vessel corium behavior
  - $q_{(CHF)}$: CHF controlled by ex-vessel flow regime and heat transfer characteristics
  - $q_{(CHF)}$: experimentally determined and has limited room for further enhancement

$$q/q_{CHF}<1$$

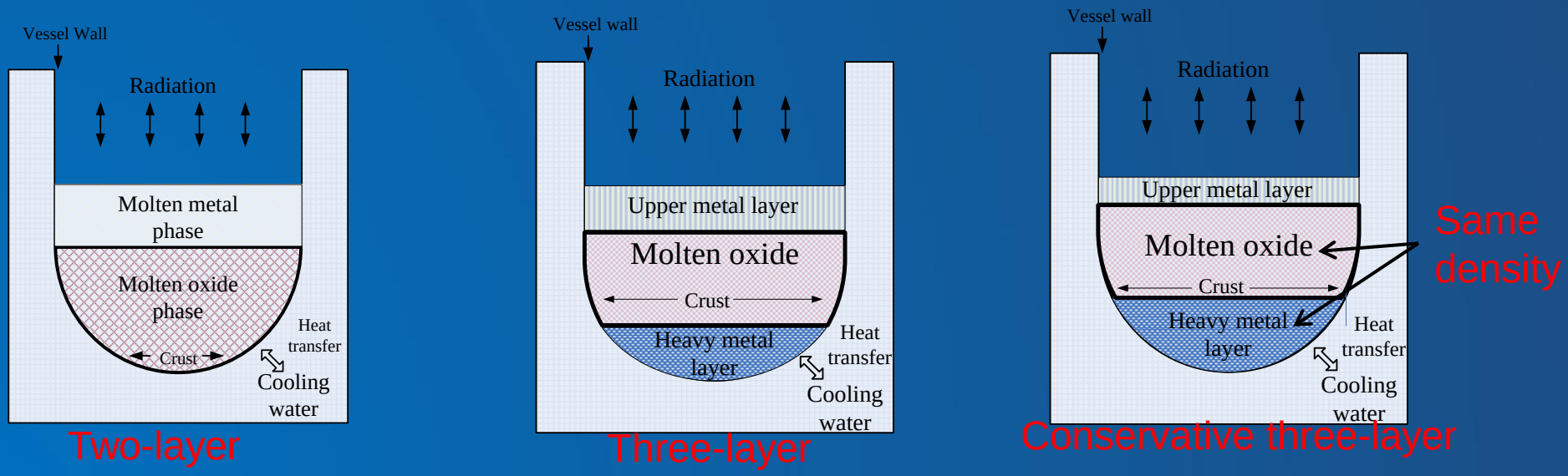


1. Background

● Corium pool configuration

- For a given decay power, corium pool configuration determines the heat flux along the vessel
  - Two-layer corium pool: widely used in current IVR analysis;
  - Three-layer corium pool: possible configuration indicated by MASCA project;
  - Conservative three-layer corium pool: minimizing top metal layer
  - Material interaction is the key point to solve the problem;

Different Focusing Effect



1. Background

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● Material interaction research

□ **Purpose:**

- **Detailed analysis of material interaction in CAP1400 lower head;**
- **Determination of possible corium pool configurations;**
- **Providing an input for subsequent heat transfer calculation imposed by corium;**
- **Establishing the foundation for comprehensive evaluation of CAP1400 IVR strategy;**

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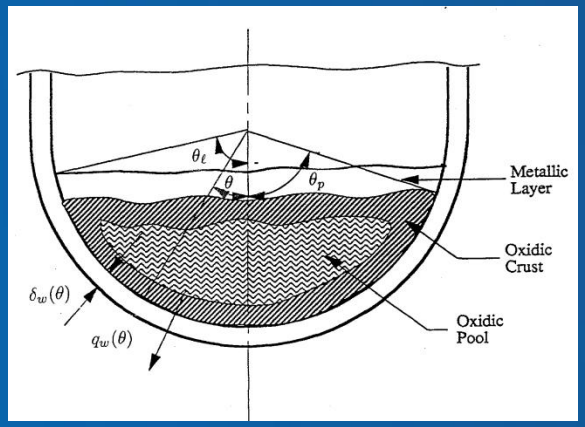
2. Analysis methodology and accident assumption

- **Analysis methodology**

- **Software: material thermodynamic code to analyze the equilibrium state by minimizing the Gibbs energy;**
- **Corium material interaction and separation: immiscibility gap from the scientific branch of materials**



2. Analysis methodology and accident assumption

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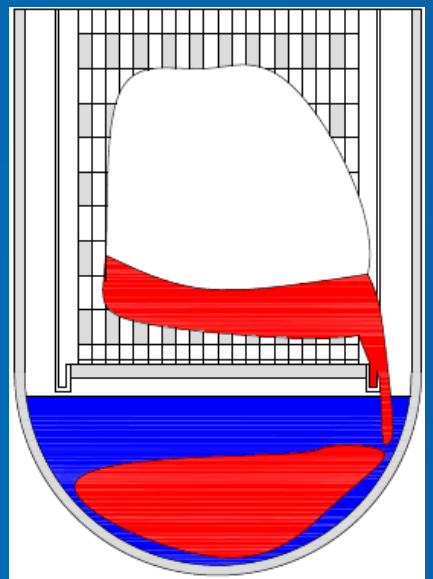
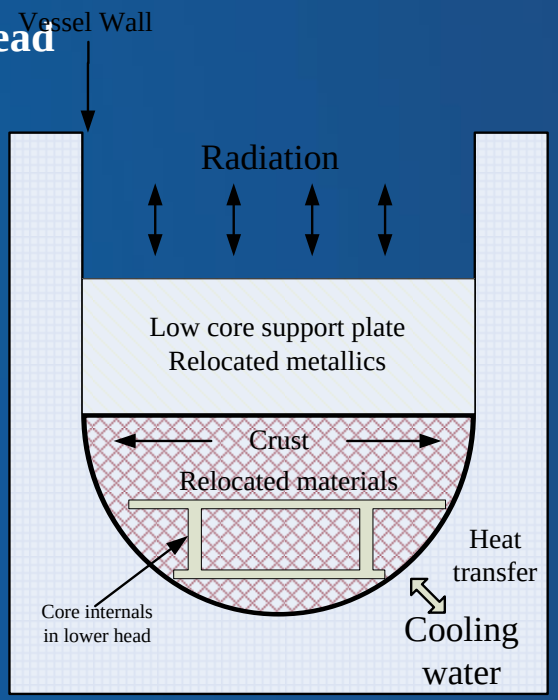
- **Accident scenario**

- **Initial condition of material interaction is closely related to the core relocation process;**
- **The sidewards relocation mode is dominant in CAP1400;**
- **Relocated corium should accumulate to a high level before contacting low core support plate (LSP);**
- **Crust will be formed between relocated corium and LSP;**
- **Portion of core materials will be entrained with corium to lower head**





2. Analysis methodology and accident assumption

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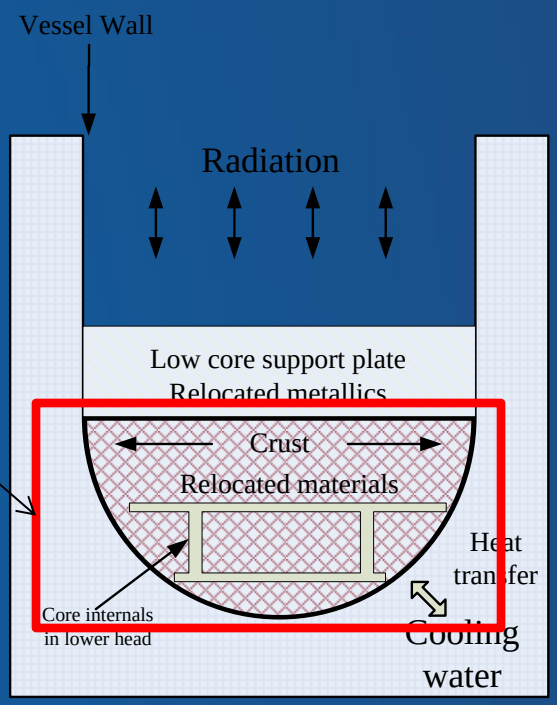
- **Accident scenario-1**

- **Crust is assumed to separate and stop the interaction between LSP and relocated corium;**
- **No unoxidized zircalloy is entrained by corium to lower head;**
- **Interaction concentrates in the region bounded by crust;**
- **Cladding oxidation fraction has no impact on the results;**
- **Arbitrary assumption of 50% for oxidation fraction;**

Thermodynamic interaction

- UO_2
- ZrO_2
- Fe (stainless steel)



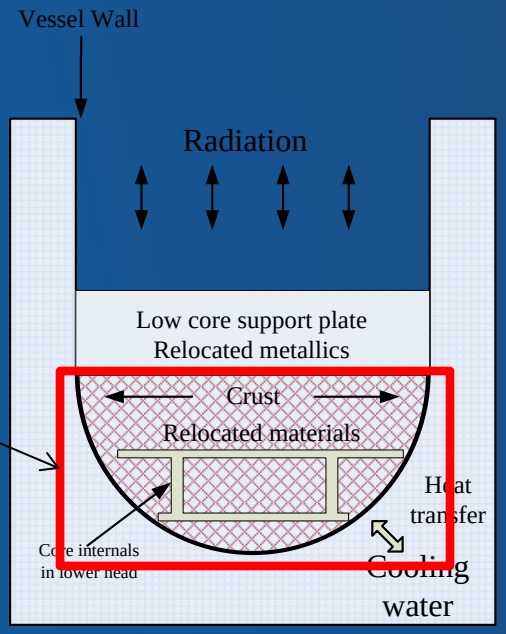
2. Analysis methodology and accident assumption

- Accident scenario-2

- Crust is assumed to separate and stop the interaction between LSP and relocated corium;
- 40% unoxidized zircalloy is entrained by corium to lower head;
- Interaction concentrates in the region bounded by crust;
- Cladding oxidation fraction changes the amount of Zr for interaction;

Thermodynamic interaction

- UO2
- ZrO2
- Zr
- Fe (stainless steel)



2. Analysis methodology and accident assumption

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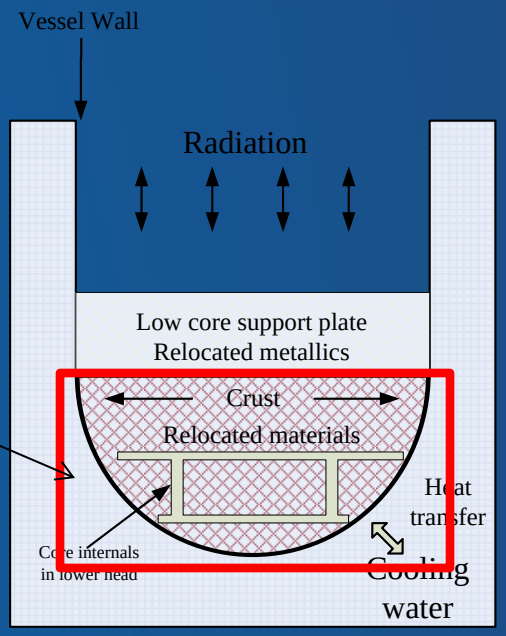
- **Accident scenario-2**

- **Case-1: Cladding oxidation fraction is 15%;**
- **Case-2: Cladding oxidation fraction is 75%;**
- **Two cases significant change the content of unoxidized Zr for thermodynamic interaction;**

Thermodynamic interaction

- UO2
- ZrO2
- Zr
- Fe (stainless steel)



2. Analysis methodology and accident assumption

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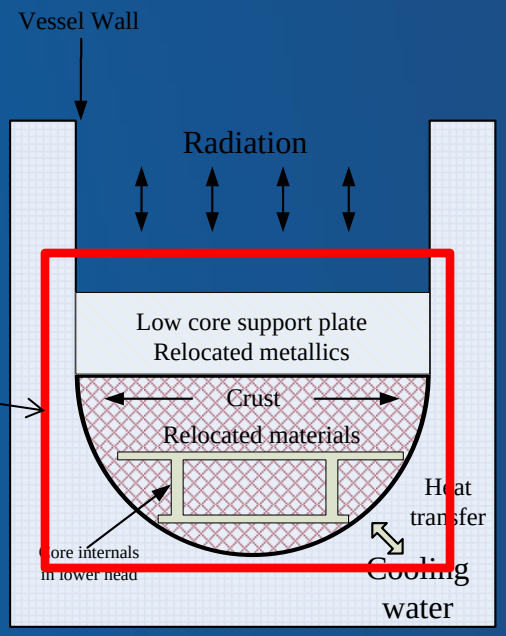
- Accident scenario-3

- Material infiltration and mixing through crust is assumed;
- All the materials in the lower head can be interacted without barriers;
- Different Cladding oxidation fractions are assumed:
  - ✓ 15%
  - ✓ 75%

Thermodynamic interaction

- UO2
- ZrO2
- Zr
- Fe (stainless steel)



2. Analysis methodology and accident assumption

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- **Others**

- **All the UO2 and ZrO2 are assumed to relocated into lower head;**
- **Material temperature: 3000K;**
- **Pressure: 2atm;**

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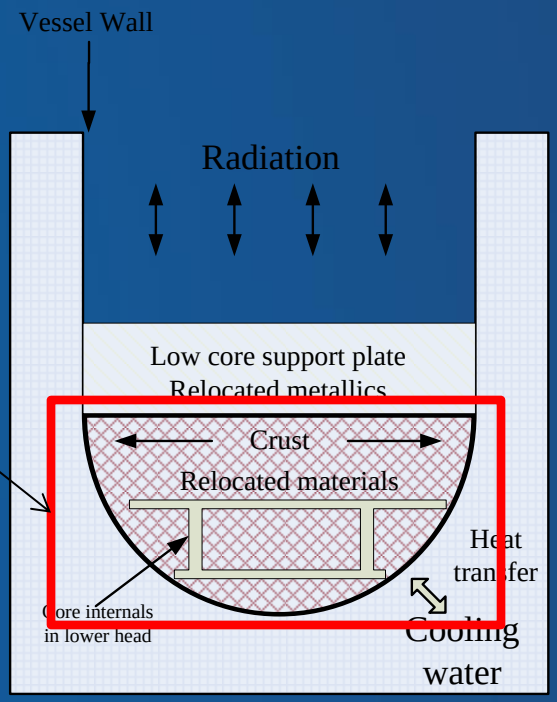
3. Material interaction and determination of corium pool

- Accident scenario-1

- Crust separation;
- No unoxidized zircalloy for interaction;
- 50% cladding oxidation fraction;

Thermodynamic interaction

- UO2
- ZrO2
- Fe (stainless steel)



3. Material interaction and determination of corium pool

- **Material interaction**

- **Accident Scenario-1**
  - ✓ **Corium materials are separated into two phases: Oxygen rich phase (oxidic) and oxygen starving phase (metallic);**
  - ✓ **Oxidic phase accounts for 95% interacted corium;**

3. Material interaction and determination of corium pool

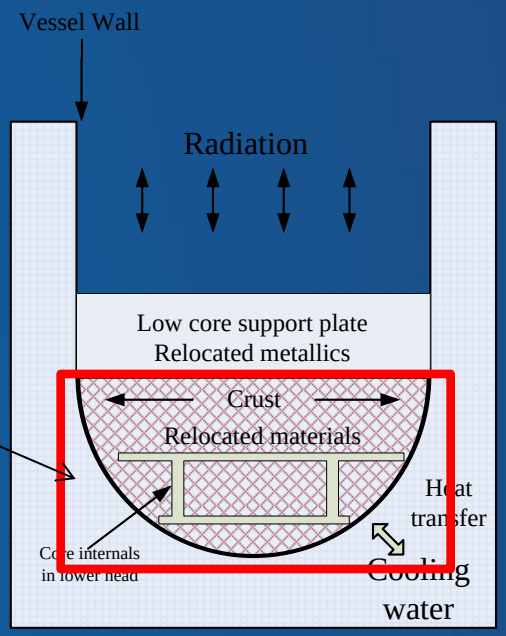
- Accident scenario-2

- Crust separation;
- Unoxidized zircalloy for interaction;
- cladding oxidation fraction:
  - ✓ Case-1: 15%
  - ✓ Case-2: 75%

the ratio of Zr

Thermodynamic interaction

- UO2
- ZrO2
- Zr
- Fe (stainless steel)



3. Material interaction and determination of corium pool

- **Material interaction**

- **Accident Scenario-2**
  - ✓ **Low cladding oxidation fraction leads to :**
    - **Increase of metal phase;**
    - **Increase of Uranium element content in metal phase;**
  - ✓ **Cladding oxidation fraction has only slight impact on oxidic phase composition;**

3. Material interaction and determination of corium pool

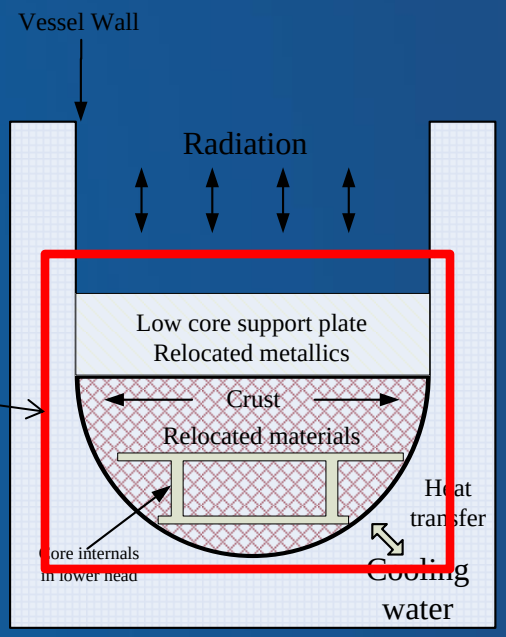
- Accident scenario-3

- Integral interaction (LSP participation);
- cladding oxidation fraction:
  - ✓ Case-1: 15%
  - ✓ Case-2: 75%

the ratio of Zr

Thermodynamic interaction

- UO2
- ZrO2
- Zr
- Fe (stainless steel)



3. Material interaction and determination of corium pool

- **Material interaction**

- **Accident Scenario-3**
  - ✓ **Introduction of LSP to thermodynamic interaction leads to:**
    - **Significant increase of metal phase;**
    - **Significant increase of iron content in metal phase;**
  - ✓ **Cladding oxidation fraction has only slight impact on oxidic phase composition;**

3. Material interaction and determination of corium pool

- **Determination of corium pool configuration**

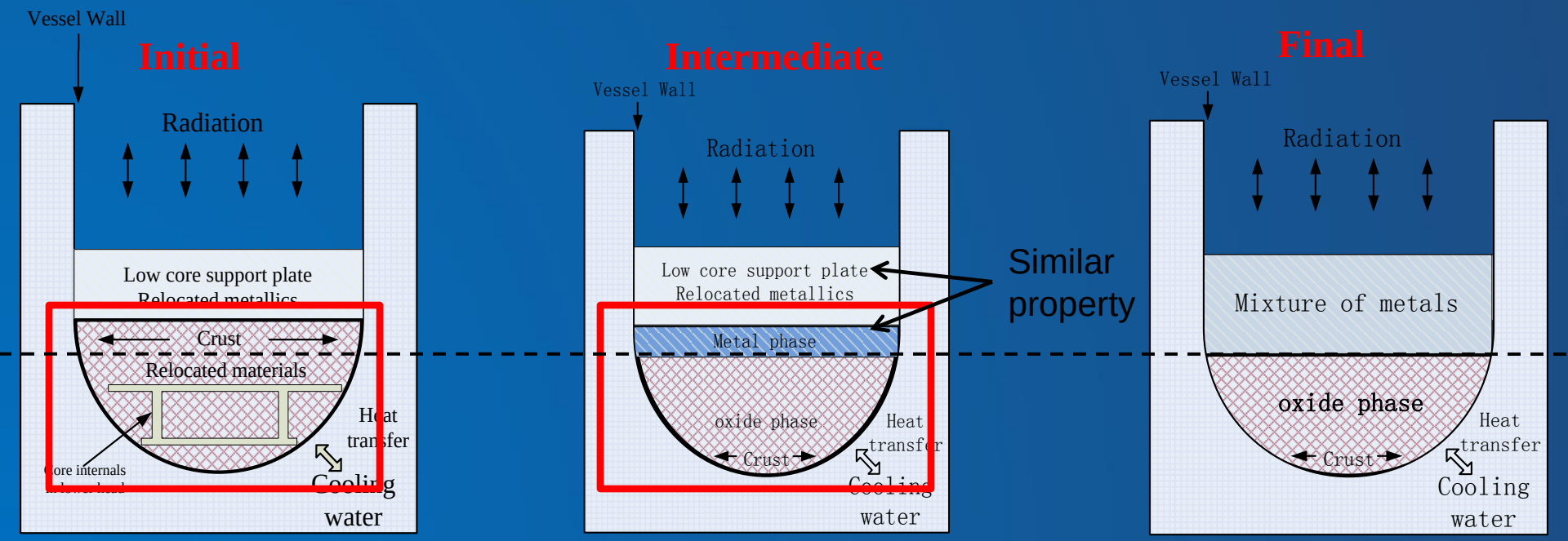
- **Empirical density correlation derived from MASCA project**

3. Material interaction and determination of corium pool

- **Determination of corium pool configuration**

- **Accident scenario-1**
  - ✓ **Density of oxidic phase is above metal phase**
    - ➢ **Merge with the uninteracted LSP**

Two-layer corium pool

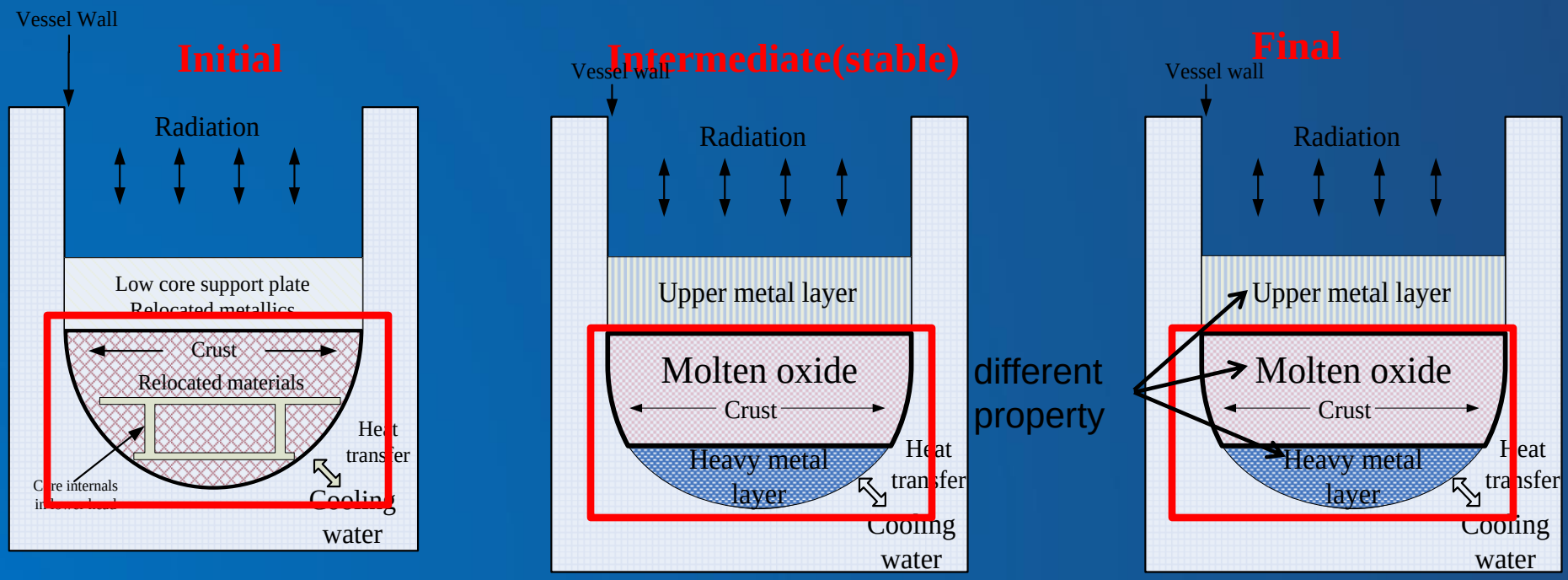


3. Material interaction and determination of corium pool

- **Determination of corium pool configuration**

- **Accident scenario-2: case-1 (15%)**
  - ✓ **Density of oxidic phase is below metal phase**
  - ✓ **Two metal phases are sandwiched by oxidic phase**

Three-layer corium pool



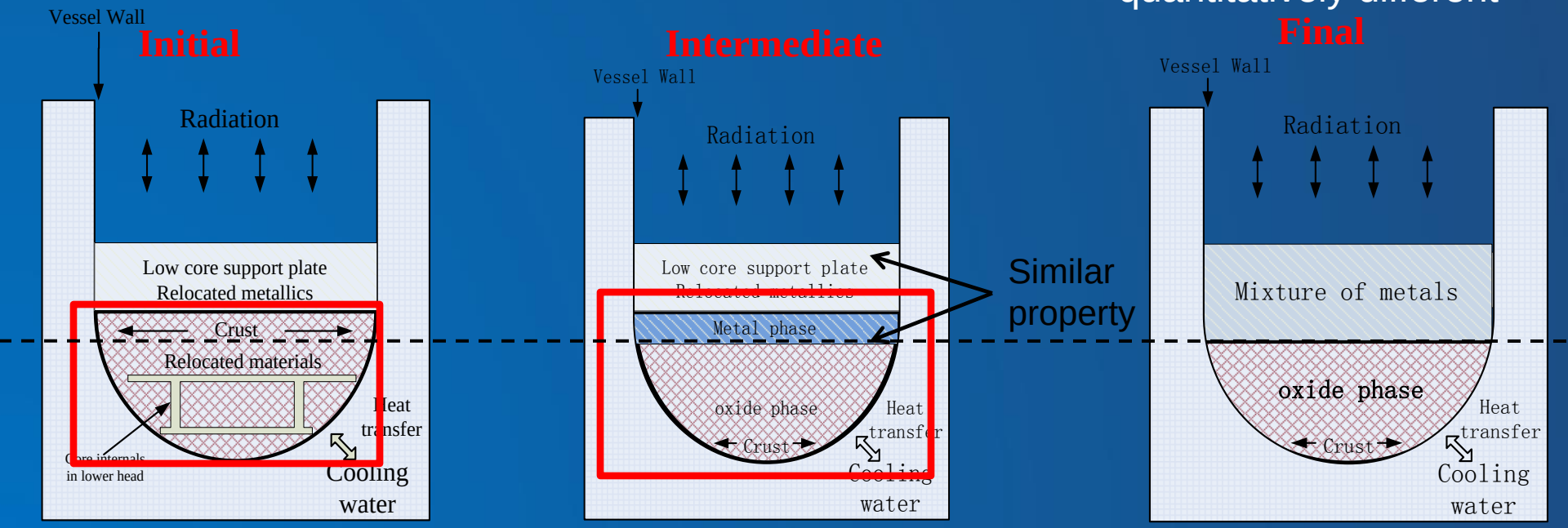
3. Material interaction and determination of corium pool

- **Determination of corium pool configuration**

- **Accident scenario-2: case-2 (75%)**
  - ✓ **Density of oxidic phase is above metal phase**
    - ➢ **Merge with the uninteracted LSP**

Two-layer corium pool

Element fractions in each layer are quantitatively different



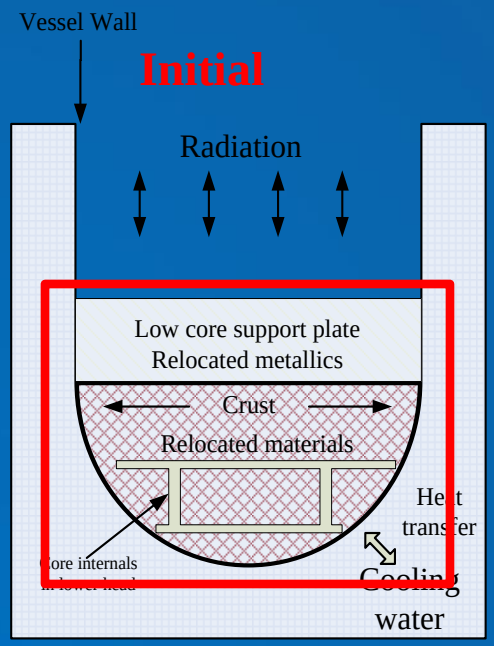
3. Material interaction and determination of corium pool

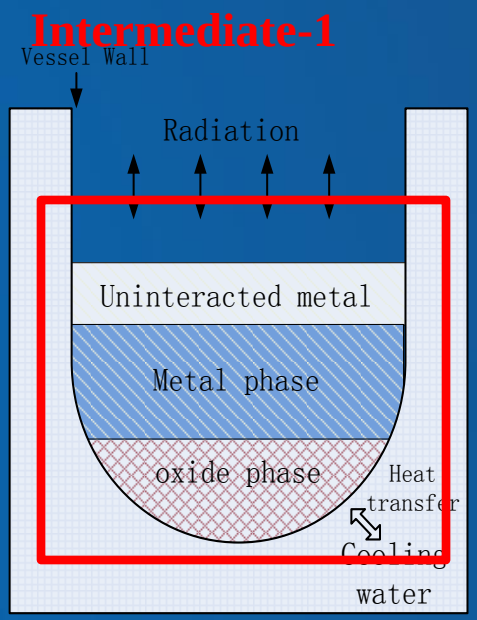
- **Determination of corium pool configuration**

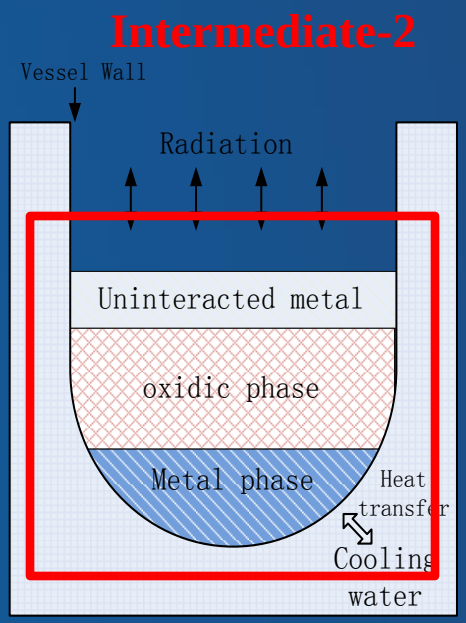
- **Accident scenario-3: case-1 (15%)**
  - ✓ **Density of oxidic phase is similar to metal phase density**

Final

Unable to determine final state







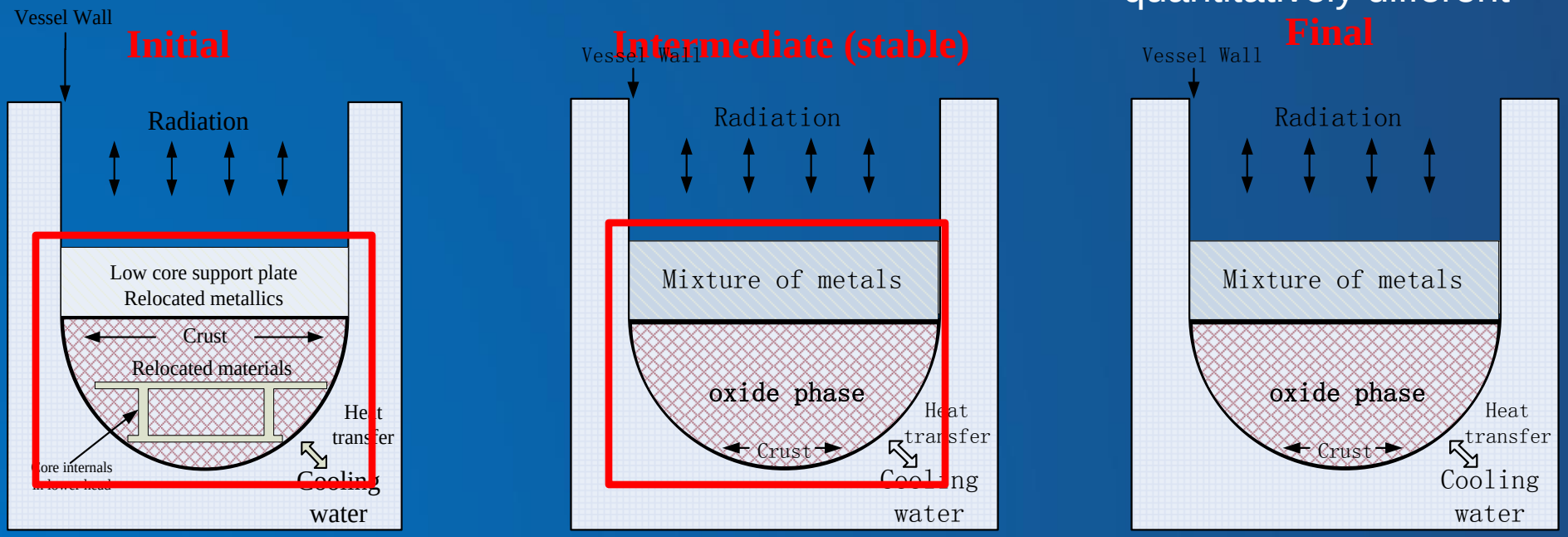
3. Material interaction and determination of corium pool

- **Determination of corium pool configuration**

- **Accident scenario-3: case-2 (75%)**
  - ✓ **Density of oxidic phase is above that of metal phase**
    - ➢ **Limited unoxidized Zr**

Two-layer corium pool

Element fractions in each layer are quantitatively different



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4. Conclusion and discussion

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Conclusion

- The molten corium is separated into two liquid phases under prototypical accident conditions. The oxidic and metallic phases are distinguished based on the oxygen content.

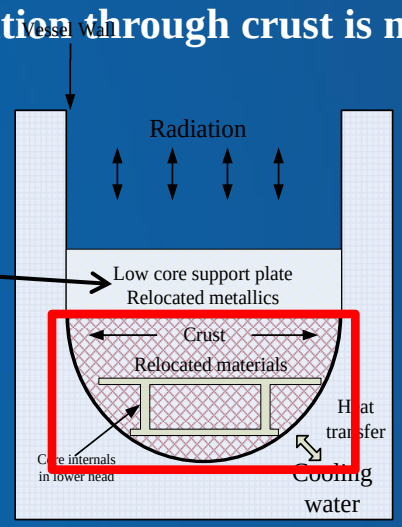
- Unoxidized zirconium has a strong capability of extracting uranium element from oxidic phase to metallic phase. The cladding oxidation fraction has impact on the amount of unoxidized zirconium for interaction.

4. Conclusion and discussion

Conclusion

- Accident sequences that material infiltration through crust is not considered:
  - ✓ Cladding oxidation fraction is low - three layer corium pool
  - ✓ Cladding oxidation fraction is high - two layer corium pool
  - ✓ No unoxidized Zr for interaction - two layer corium pool
- CAP1400 has increased mass of LSP. Such design ensures thickened top metal layer to prevent strong focusing effect if material infiltration through crust is not considered.

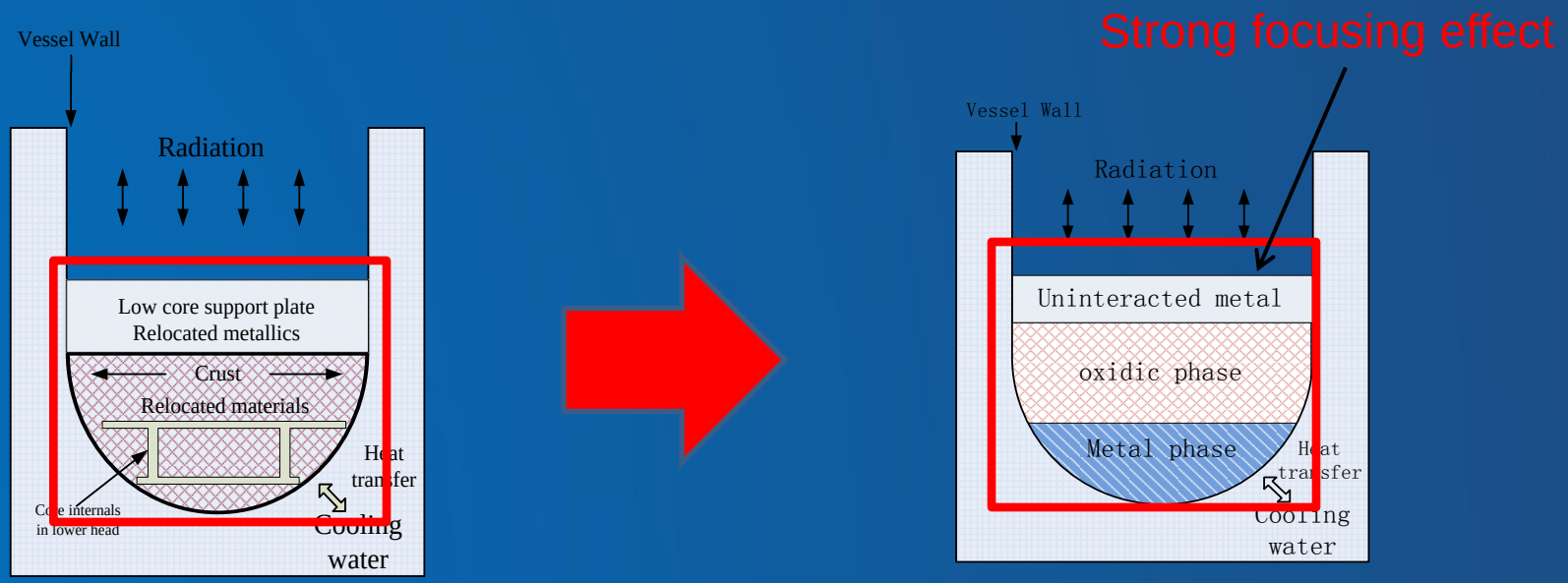
Thickened LSP



4. Conclusion and discussion

Discussion

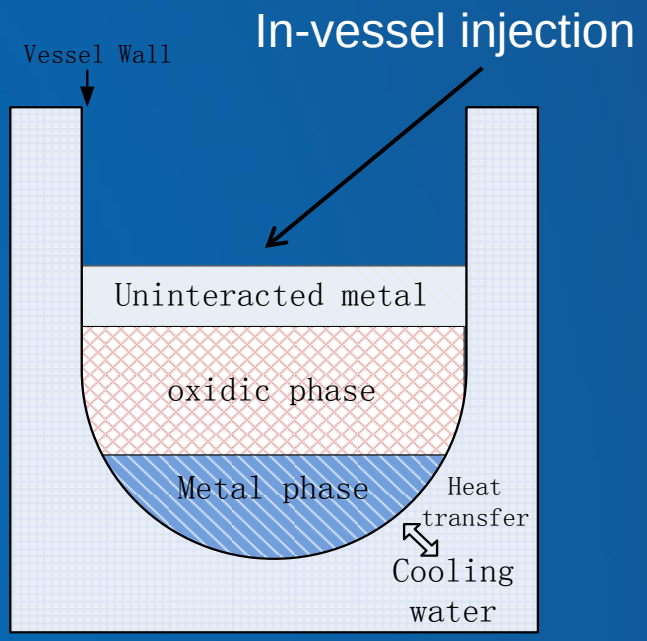
- Accident sequences that material infiltration through crust is assumed:
  - ✓ Safety margin provided by increasing LSP mass has the possibility to be compromised
  - ✓ Reaction rate through crust should be considered
  - ✓ The possibility of forming conservative three-layer corium pool in transient process can not be excluded if cladding oxidation fraction is not very high



4. Conclusion and discussion

- **Discussion**

- **For conservative three-layer corium pool, in-vessel injection is needed to take the decay heat and relieve the focusing effect.**
- **CAP1400 IVR analysis methodology postulates the formation of conservative three-layer corium pool in the transient process if material infiltration through crust is assumed.**



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Thank you for your Attention!

Any questions?