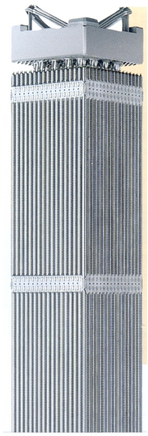
Understanding the thermal-hydraulic and related behaviour of crud-coated PWR fuel

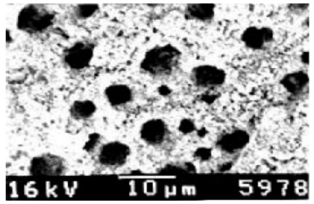
S P Walker

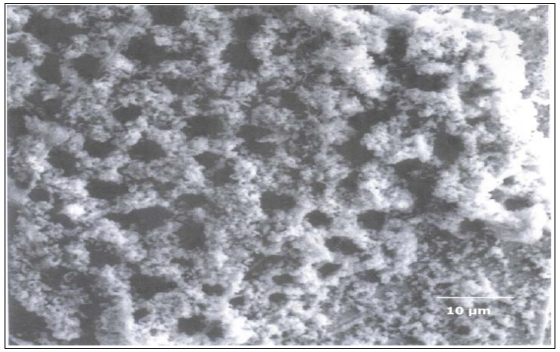
CRUD



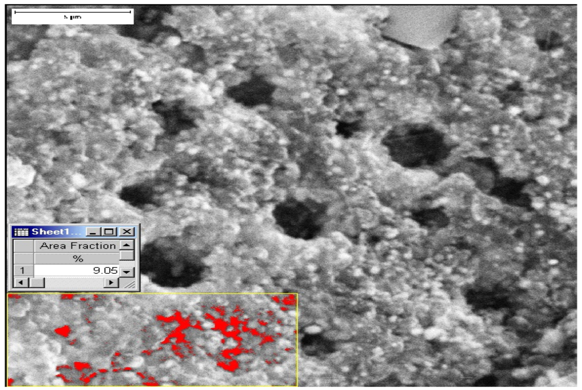
Various oxides (Metal oxides, NiO, $NiFe_2O_4$) deposit as 'CRUD' on nuclear reactor fuel pins

Porous: Crud porosity typically in the range of 70-80%.

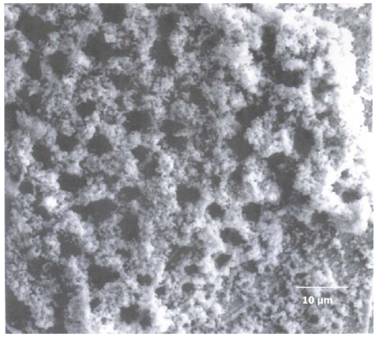


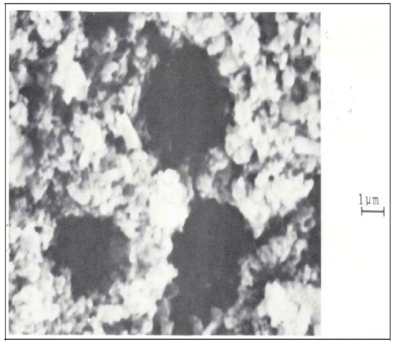


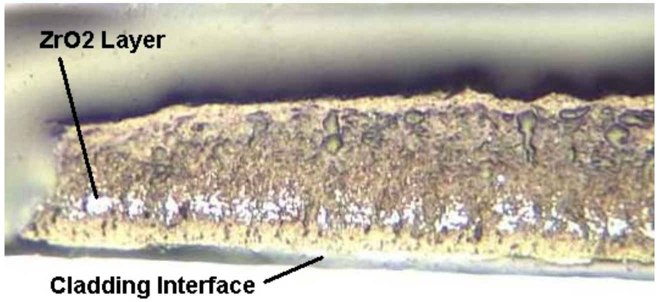
Experimentally observed chimneys in CRUD (Mahlon 2004)

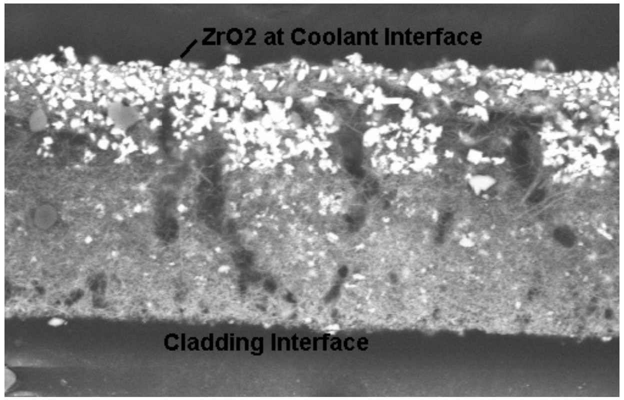


Crud from Diablo Canyon









CRUD Issues (Problems)

- Hinders heat transfer (?)
- Raises metal temperatures, worsens corrosive attack
- More fuel failures?
- More activated material around circuit?
- The neutron absorber boron, present in the coolant, is concentrated in the crud, causing local power depression
- Axial Offset Anomaly (AOA, CIPS) problems (neutron flux & power depression towards the top of the core)
- Core power output reduced

General characteristics of crud observed in different boiling facilities

Characteristics	Macbeth (1971)	Cohen (1974)	Pan (1984)	Henshaw (2006)
Shell Porosity	0.65- 0.75	0.7	0.8	0.8
Pore size (μm)	0.1-0.5	<0.1	0.5	—
Magnetite Crud Thickness (μm)	50	200	25	59
Chimney radius (μm)	2.5	2.5-5.0	2.5	2.5
Chimney density (chimneys/mm^2)	5000	5000	3000	3000
Average distance between chimneys (μm)	14	14		—

How does the presence of the crud modify the heat transfer?

How are the dissolved species concentrated by the crud?

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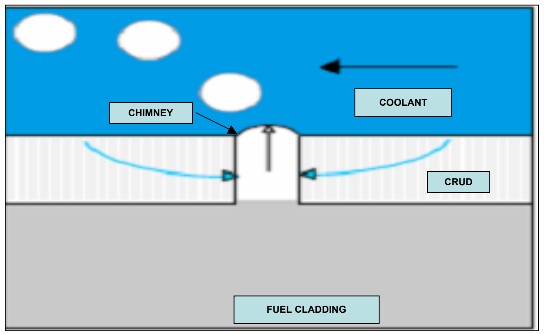
Wick Boiling

Crud may transform the heat transfer from the fuel pin to the primary coolant from wholly convection to predominantly wick boiling in penetrating chimneys. The flow through the crud is induced due to evaporative process at the chimney wall.



Idealised representation of the wick boiling process

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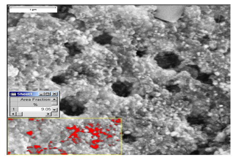

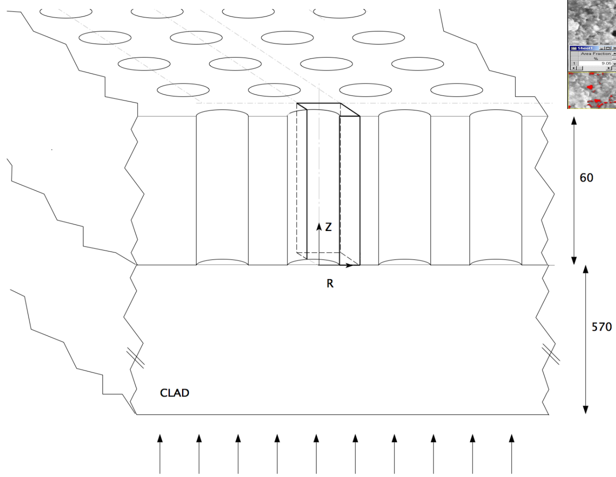

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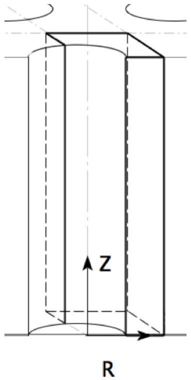
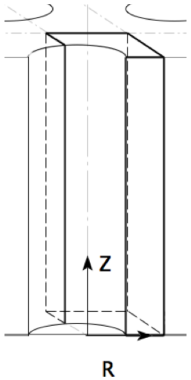
The physical processes I



- Heat is conducted through the wet crud to cause evaporation at the chimney wall. (Boiling IN the crud is inhibited by the very small pore sizes)
- This mass loss causes coolant to be drawn into the crud to replace it
- The coolant brings (tries to bring) with it the dissolved species
- These have nowhere to go, as they are (mostly) left behind when the water evaporates at the chimney

The physical processes II



- A high concentration builds up, until the diffusive flow of the dissolved species back down this concentration gradient balances the advective flow.
- This high concentration raises the local saturation temperature
- This modifies the spatial distribution of conductive heat flow
- This modifies the spatial distribution of evaporative loss
- This modifies the of advection of the dissolved species
- Which in turn modifies the concentrations reached
- And so on and so on….; a coupled, non-linear problem

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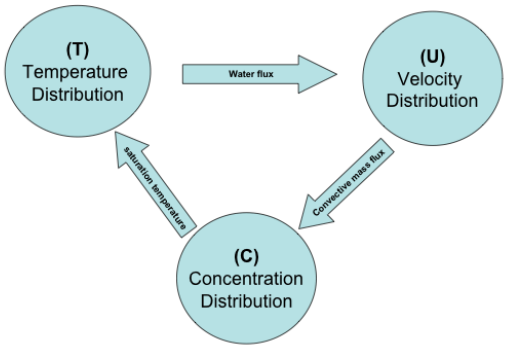

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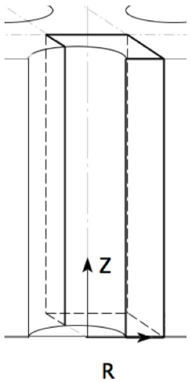
Modelling this:



- Temperature: $$\nabla^2 T = 0$$
- Flow: $$\mathbf{u} = -k\nabla p$$
- Advection & diffusion
$$\mathbf{J} = -D\nabla C + \mathbf{u}C$$
$$\nabla \cdot \mathbf{J} = 0$$
$$-D\nabla^2 C + \mathbf{u}\cdot\nabla C = 0$$

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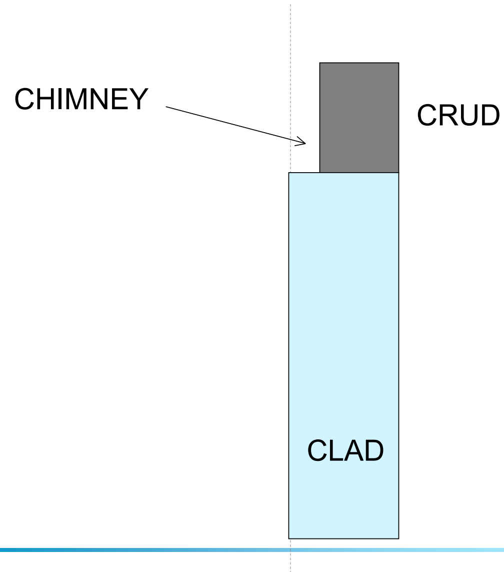
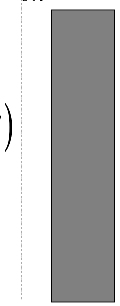


Boundary conditions; heat transfer

$$\nabla^2 T = 0$$

$$k\frac{\partial T}{\partial n} = -h\left(T - T_{BULK}\right)$$

$$T = T_{SAT}\left(C\right)$$



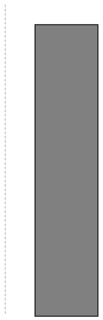
$$k\frac{\partial T}{\partial n} = 0$$

$$k\frac{\partial T}{\partial n} = -\dot{q}''$$

Boundary conditions; fluid flow

$$p = p_{coolant}$$

$$\frac{\partial p}{\partial n} = \frac{-1}{\kappa \rho h_{fg}} k \frac{\partial T}{\partial n}$$



$$\frac{\partial p}{\partial n} = 0$$

$$\frac{\partial p}{\partial n} = 0$$

Boundary conditions; advection & diffusion (species concentration)

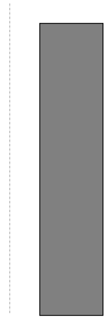
$$\mathbf{J} = -D\nabla C + \mathbf{u}C$$

$$\nabla \cdot \mathbf{J} = 0$$

$$-D\nabla^2 C + \mathbf{u} \cdot \nabla C = 0$$

$$C = C_{BULK}$$

$$J_n = -D\frac{\partial C}{\partial n} + \mathbf{u} \cdot \mathbf{n} C = 0$$



$$D\frac{\partial C}{\partial n} = 0$$

$$D\frac{\partial C}{\partial n} = 0$$

- Coupled r-z finite volume code written
- Outermost iterative loop, in which it solves sequentially for each of
  - Temperature
  - Pressure / flows
  - Concentrations
- Updated values used in the next solution, until a converged solution is found

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Typical values employed in the analyses

Crud thickness	μm	60
Chimney centres	μm	20
Chimney diameter	μm	5
Crud porosity	%	80
Crud / water mean thermal conductivity	W $m^{-1}K^{-1}$	0.506
Heat flux into base of crud	MWm^{-2}	1.5
System pressure	MPa	15.5
Boric acid diffusion coefficient	m^2s^{-1}	1.05E-08
Tortuosity		0.4
Coolant boron concentration	ppm (gm^{-3})	1200 (4637)
Coolant heat transfer coefficient	W $m^{-2}K^{-1}$	1.2E04
Bulk coolant temperature	K	590

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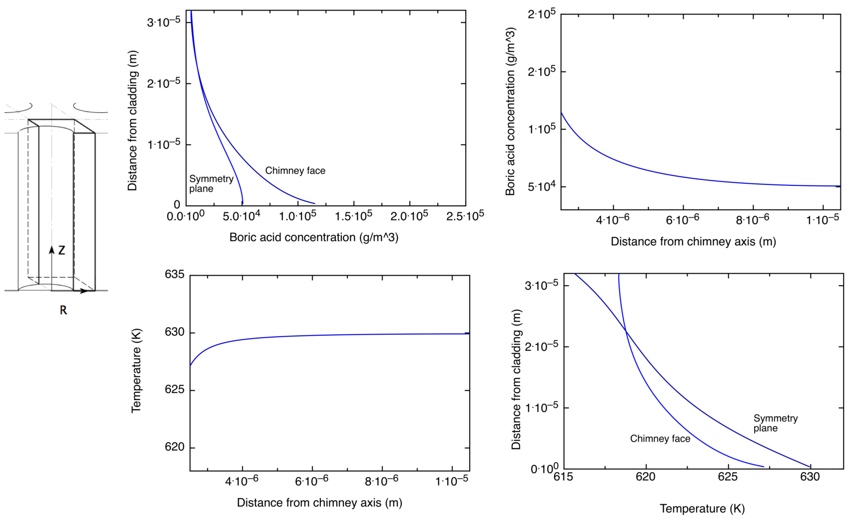

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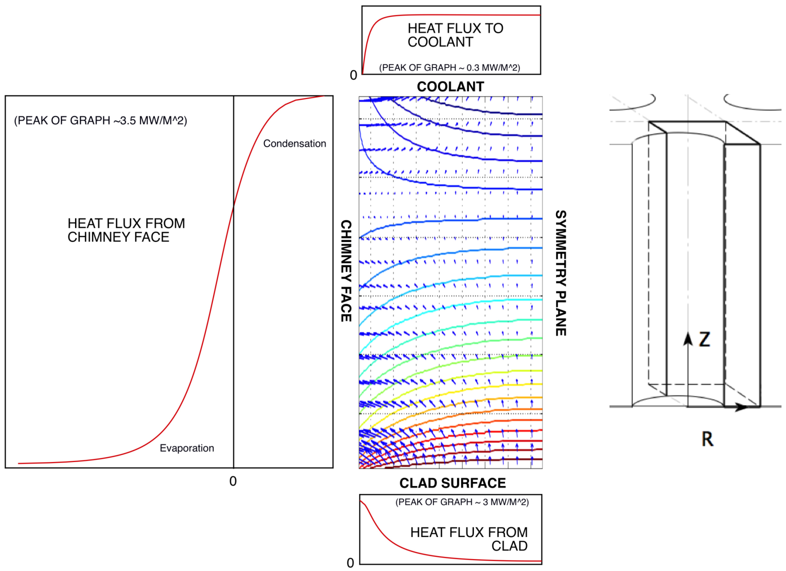

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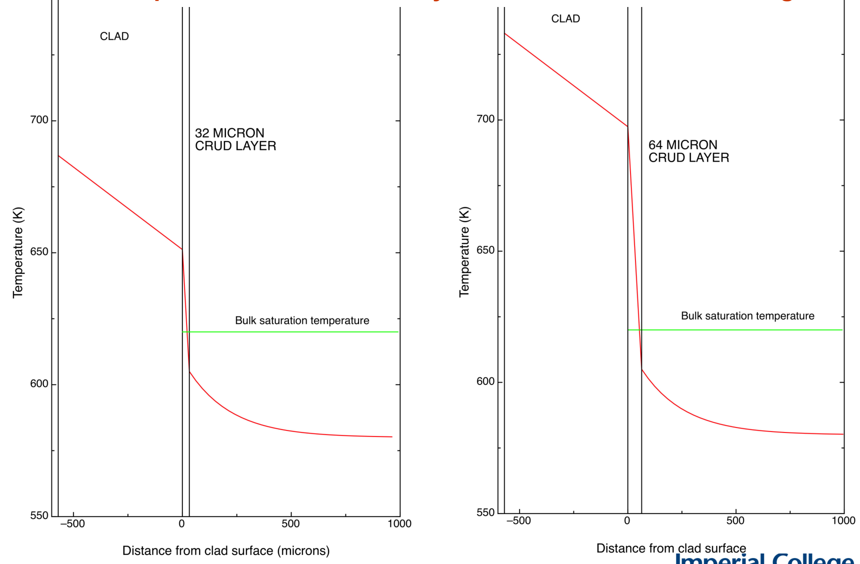
-How does all this affect fuel performance, heat transfer & temperatures?

-Can we characterise ‘macroscopic’ performance using this detailed model?

Simple “thermal conductivity of wet crud”: -no wick boiling



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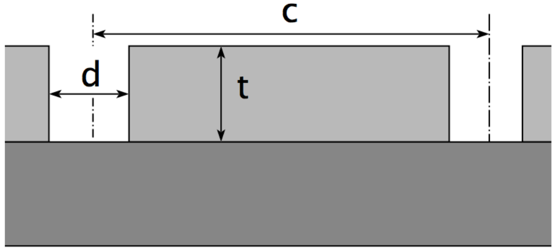

Notation to characterise:-
-crud thickness
-chimney diameters
-chimney separations

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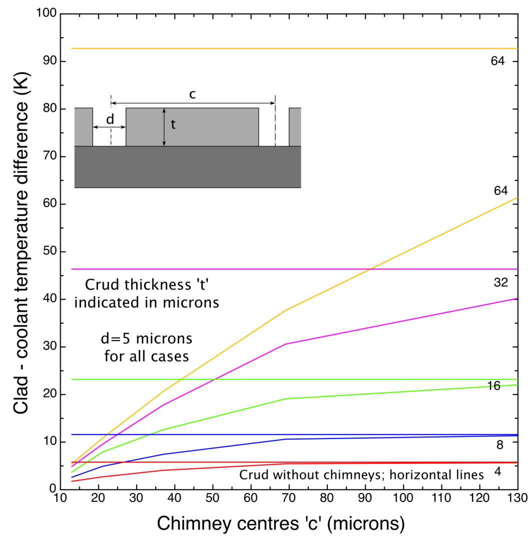

Horizontal lines: simple ‘wet crud thermal conduction delta-T for various crud thicknesses

Curves: Crud delta-T as a function of chimney separation, using wick boiling model

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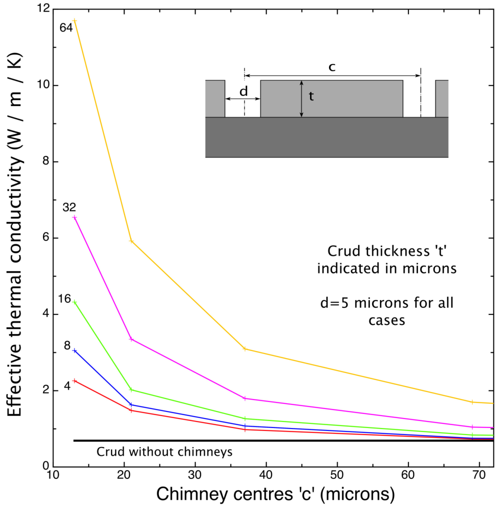
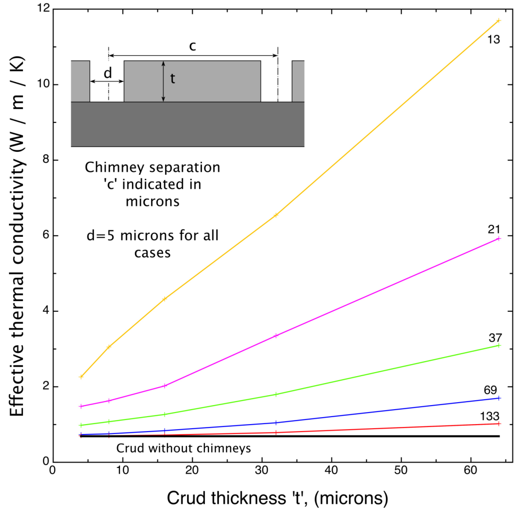


Effective thermal conductivity MUCH higher than a simple wet crud thermal conduction model would indicate



Effective thermal conductivity MUCH higher than a simple wet crud thermal conduction model would indicate

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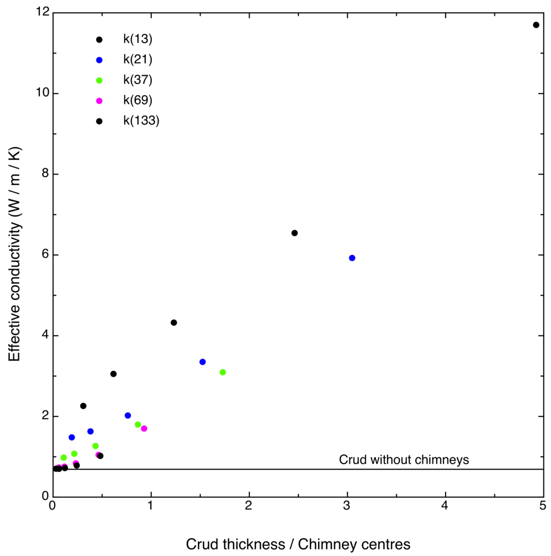

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Next steps:

- Experimental validation?
- Much more complex chemistry needs to be added
  - ionisation of water
  - metal ion hydrolysis
  - boric acid equilibrium
  - precipitation and dissolution of different species
  - radiolysis chemistry of water
- Vapour layer formation?
  - Boiling may NOT be totally inhibited. Need to develop an additional outermost iterative loop allowing for steam formation adjacent to the clad, to determine a self-consistent vapour - wet crud interface

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