

Electron and in-cell optical microscopy study of irradiated 20%Cr:25%Ni:Nb stainless steel

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M Levy (EDF Energy)

- UK 9 sites- 7 CAGR, 1 Magnox, 1 PWR
- Commercial Advanced Gas-cooled Reactors (CAGR)
- CO₂ coolant + solid graphite moderator
- Hollow ceramic UO₂ pellets clad with 20Cr/25Ni:Nb stainless steel alloy
- Each fuel pin is 1m length
- Pins grouped in bundles of 36, in 3 rings= 1 Fuel Element
- Graphite “sleeve”
- 8 Elements make up 1 stringer (articulated)
- High temperature cladding in comparison to LWR

Non destructive:

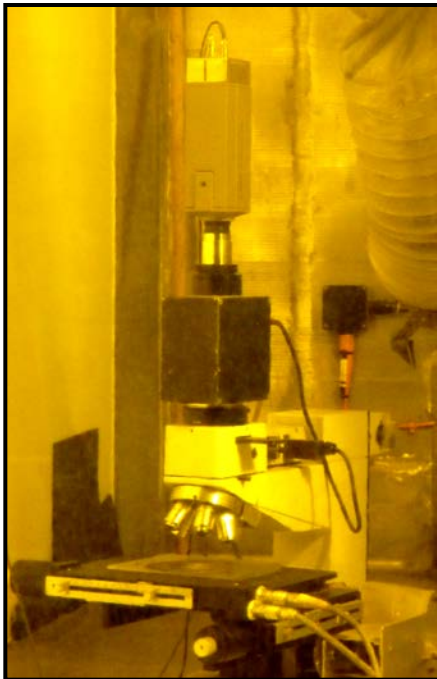
- Visual examination
- Dimensional Measurement
- Profilometry
- Gamma scanning (isotopic and total)

Destructive:

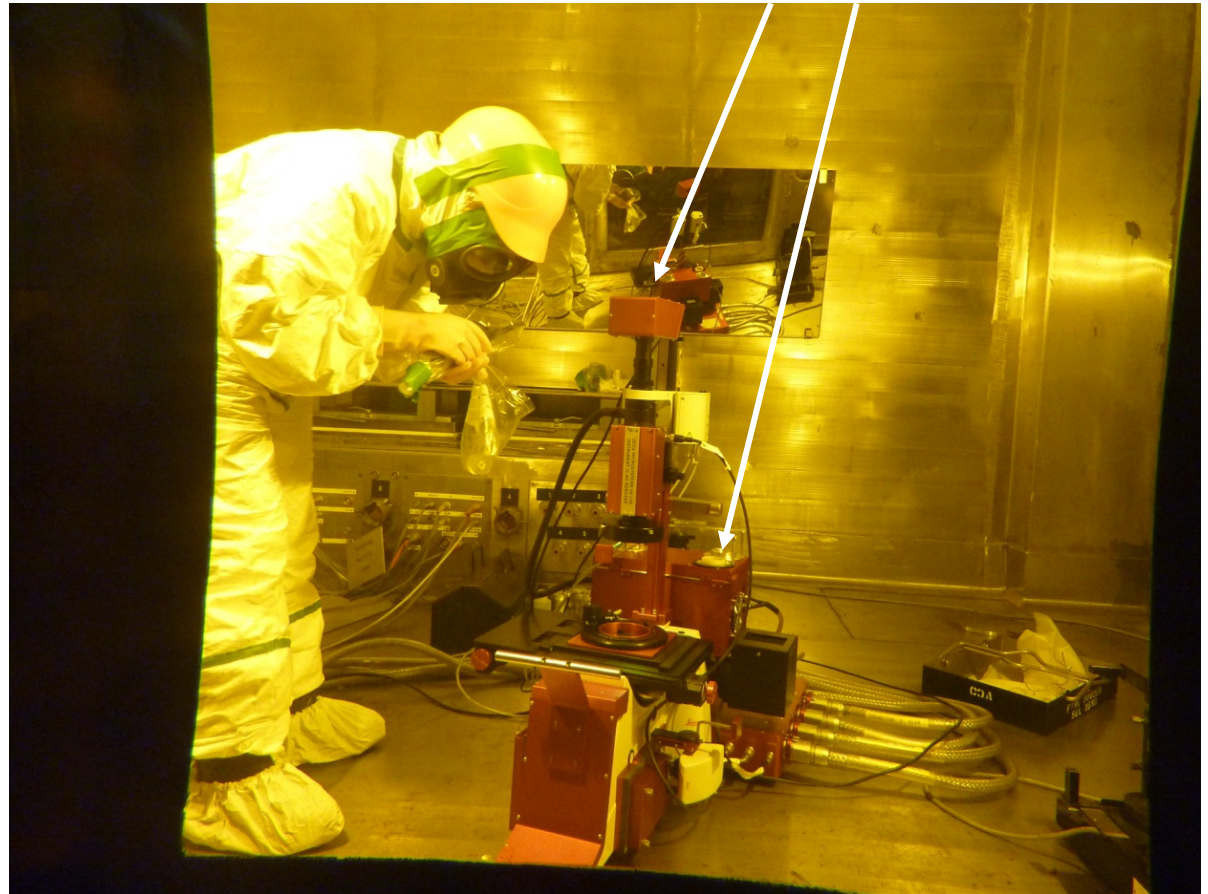
- Puncturing for fission gas sampling and analysis
 - Fission gas analysis (mass spectrometry)
 - Density
 - Raman spectroscopy
 - Thermal properties
 - Optical microscopy- polarised, fluorescent and BF
 - Electron optical examination (SEM & TEM)
 - Micro – cXRT
(FIB)
-

Optical Microscopy

Modified components
coloured red



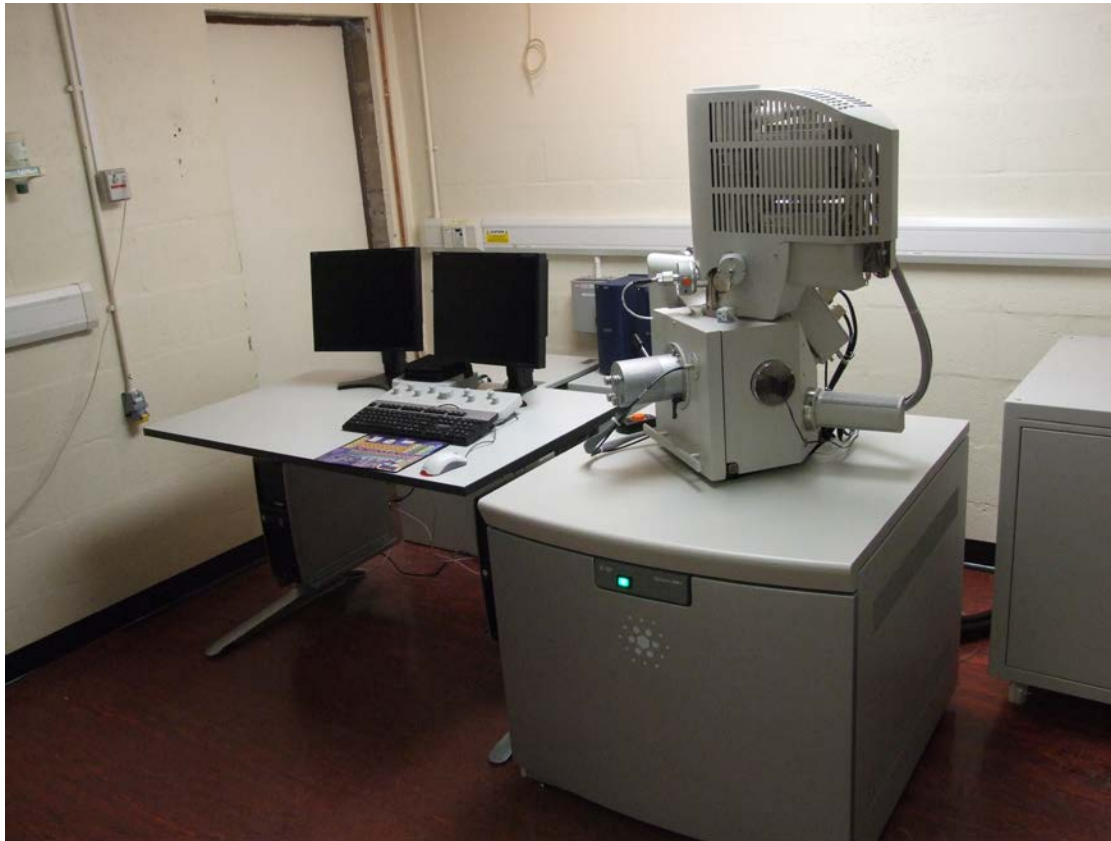
Ergolux



Leica DMI5000

Scanning Electron Microscopy

- FEI Quanta 200 FEG SEM with Oxford Instruments SDD EDX detector

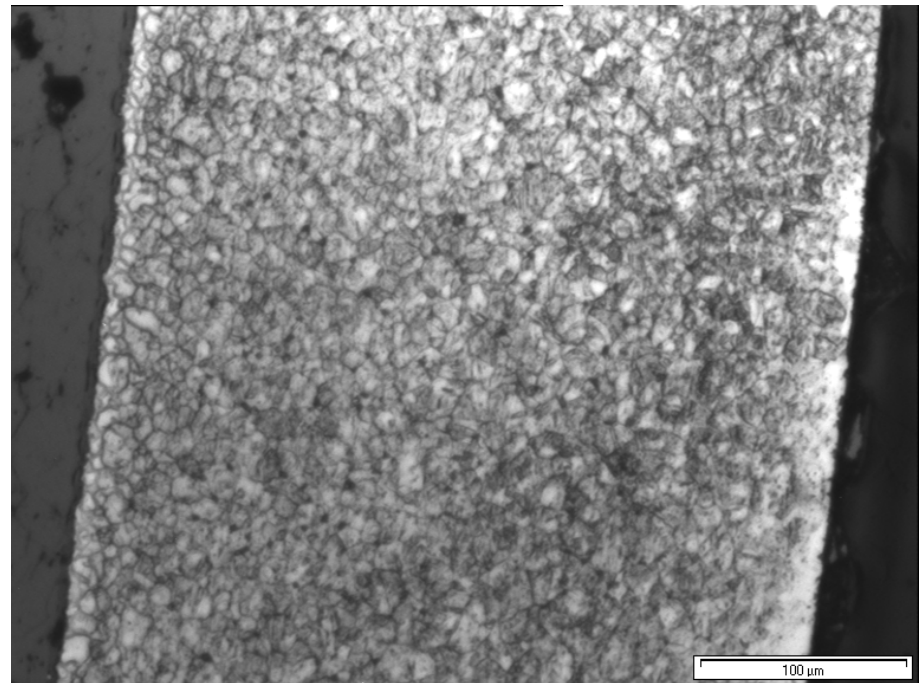


Cladding:

- 20%Cr:25%Ni:Nb stainless steel (austenitic polycrystalline face centred cubic (fcc) solid solution alloy)
- Contains dispersed Nb(C) precipitates
 - In reactor (with increased T) these precipitates coarsen
 - $M_6C/M_{23}C_6$, G phase ($Ni_{16}Nb_6Si_7$), complex carbonitrides, silicides
 - Only observable using electron microscopy
- Sigma (σ) phase formation also occurs (triple points)
 - σ phase can be used to indicate operational T

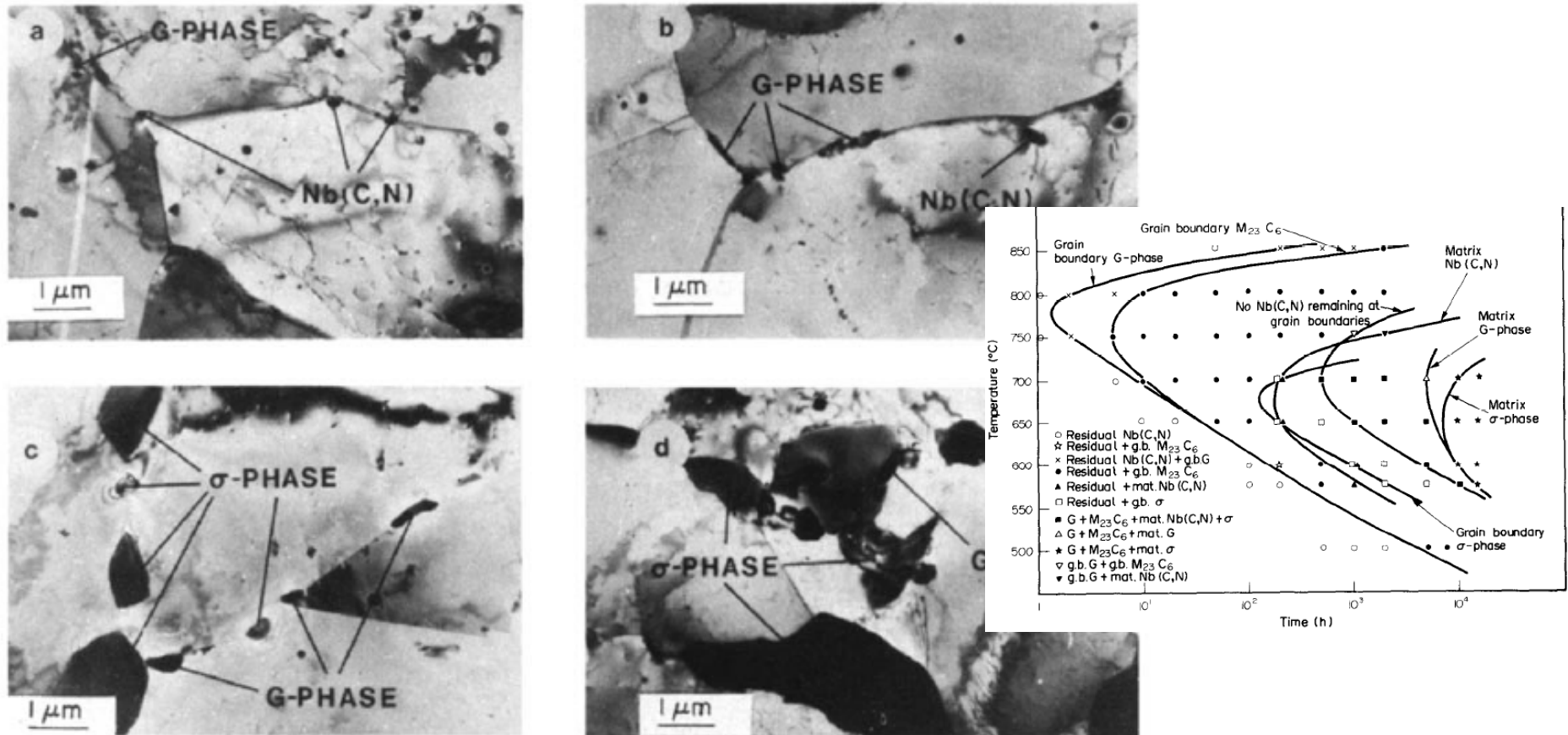
Cladding:

- Radiation induced segregation (RIS)
 - Result of irradiation at low temperatures ($<550^{\circ}\text{C}$)
 - Migration of Cr away from the grain boundaries-sensitisation (similar to thermally aged steels).
 - (Ni,Si)-rich precipitates form (10nm to 60nm) similar to the formation of γ' in other hi Ni alloys
 - Manifests as optically irresolvable 'dark' phase
 - Can also be used to estimate operational temperatures



LOM image

Previous work



Transmission electron micrographs showing the microstructural changes as a function of time at 650°C. (a) 100 h, (b) 500 h, (c) 5000 h, (d) 15,000 h.

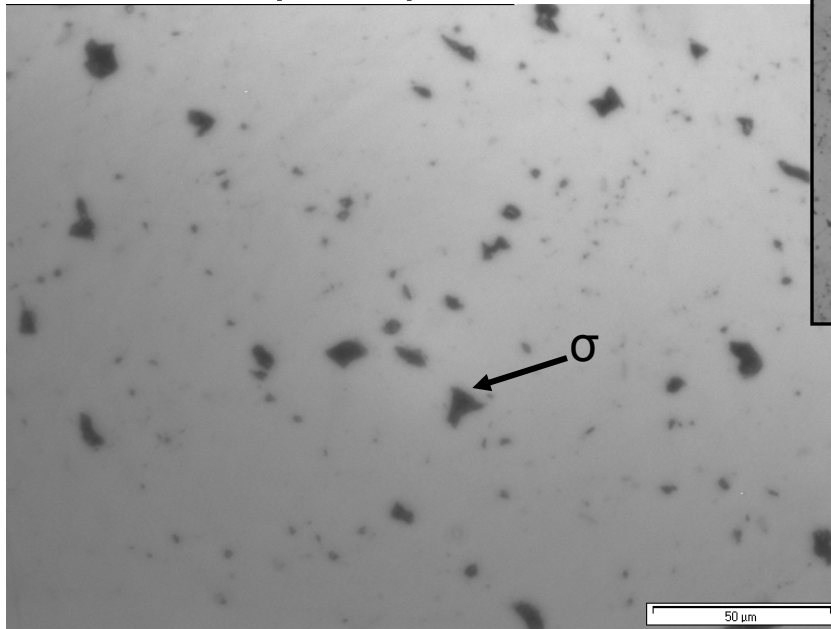
TEM images- unirradiated steels

Reactor irradiated CAGR cladding

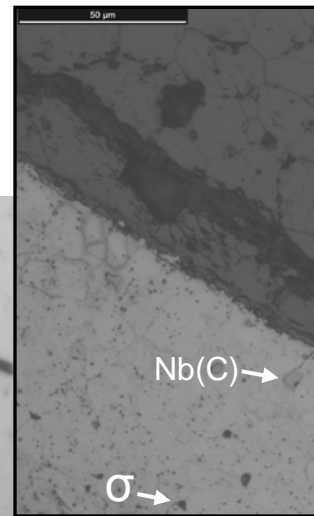
- 20Cr:25Ni:Nb
- In-reactor Temperature range $\sim 400 \leq 700^{\circ}\text{C}$
- Carbon dioxide (CO_2) atmosphere
- $\sim 30\text{GWd/tU}$ burn-up
- ~ 2500 days in core (60,000hrs)

Cladding:

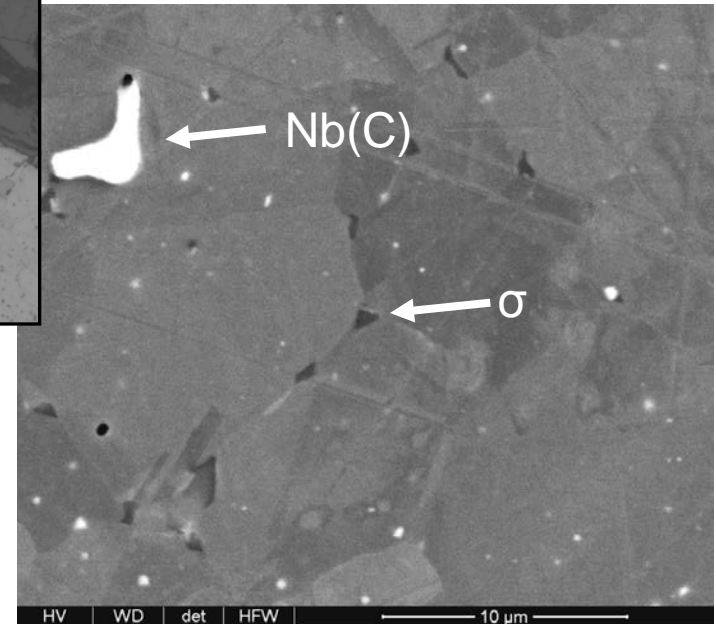
- Sigma (σ) phase
- Nb(C) precipitates



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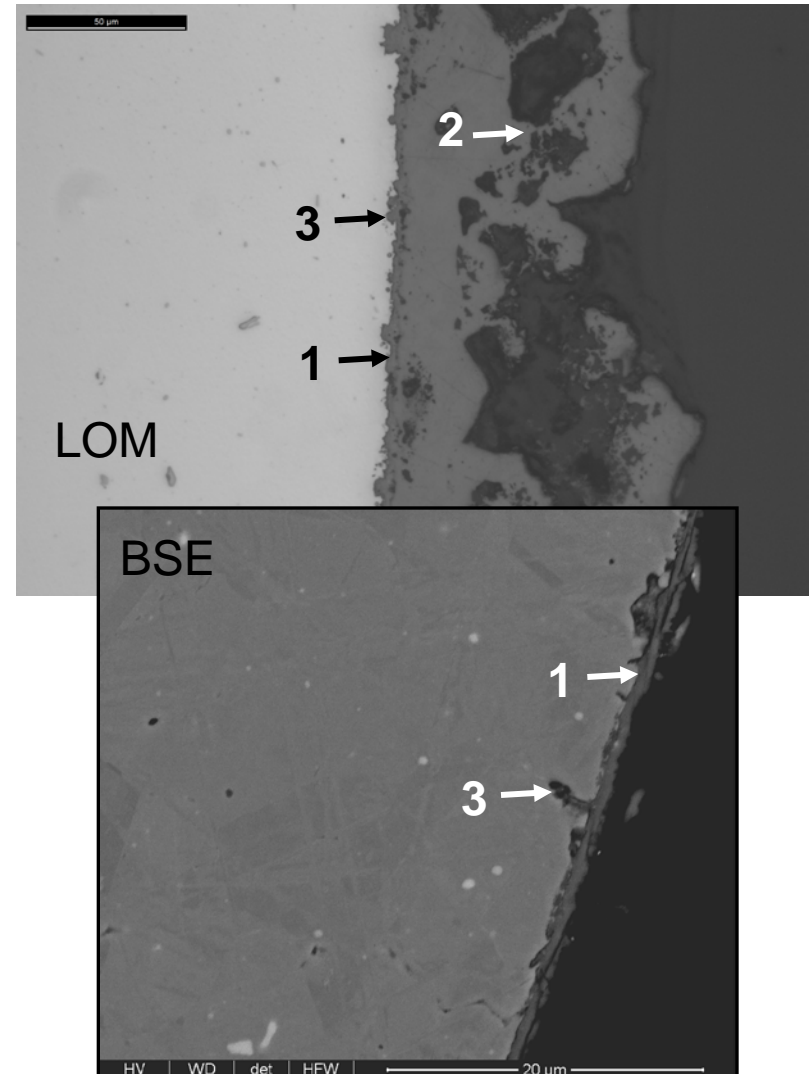


BSE

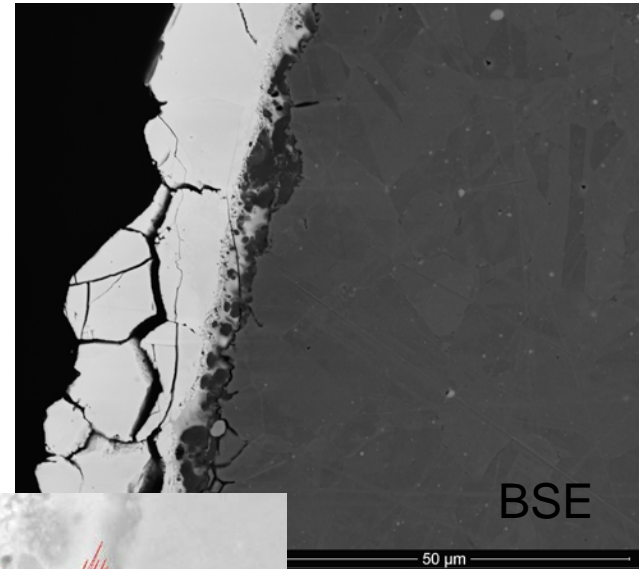
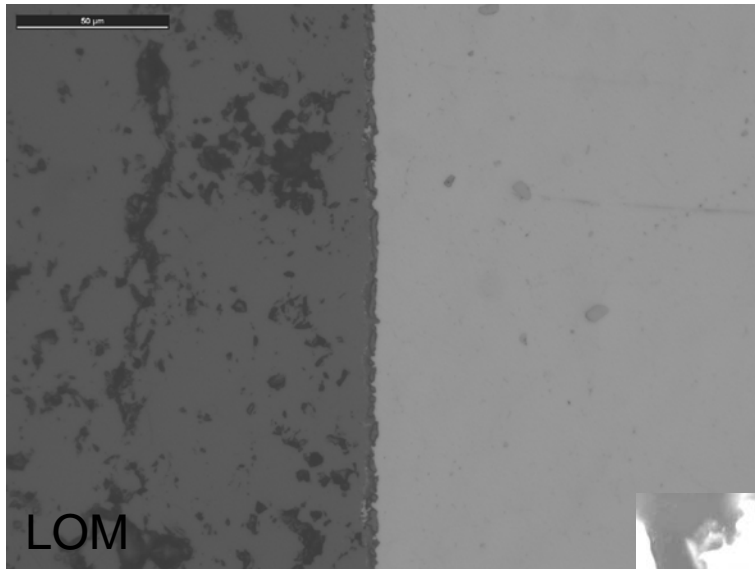
CAGR Features

Outer Cladding Surface:

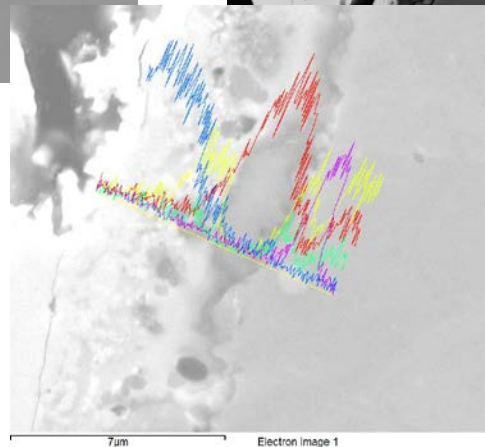
- Protective layer Cr_2O_3 [1]
 - Between 2-8 μm
 - Thin, adherent
 - May contain
 - silica, oxide, spinel
- Carbonaceous deposition [2]
 - Coolant additives CH_4 and CO breakdown
 - Deposit builds on some can surfaces
 - Impairment of heat transfer from fuel to coolant
 - May nucleate on small surface oxide pits [3]



Cladding to fuel interface:



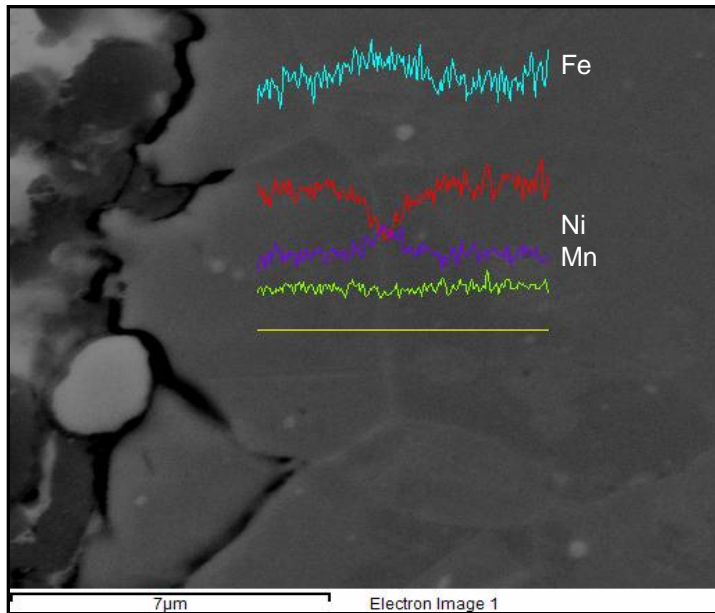
Fe, Cr and U



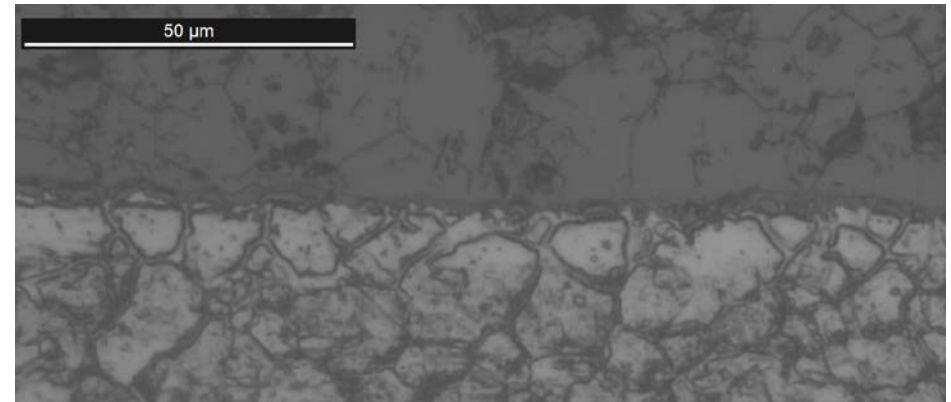
Cladding Study

Cladding grain boundaries:

- Some localised enrichment at clad-fuel interface
- Uniform through bulk



BSE



LOM

- WDS on clad-fuel interface- comparison with EDX to eliminate contribution of Fe-55 to Mn
- Quantitative TEM on smaller samples
- Non-active TEM
- Non-active FIB

Acknowledgements

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