A modeling study of the SLOFEC™ Eddy Current system

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Outline

- Context
- The SLOFEC™ System
- Understand SLOFEC with simulation
- Calibration stage
- Lift-off effect
- Real defect modelling
- Conclusion

Context

Why Simulating a NDE process ?

- **To help for the design, optimization and implementation of the testing method:**
  - Better understanding, easy variation of parameters
  - → Better mastering of a technique and less iterations
  - → Less mock-ups, less trials
  - → Save time and money

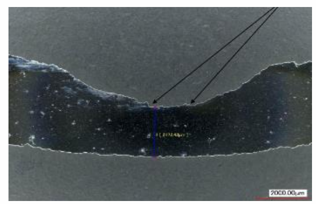
- **Expertise:** Reproduce field results to understand a complex situation and confirm/disprove a diagnosis

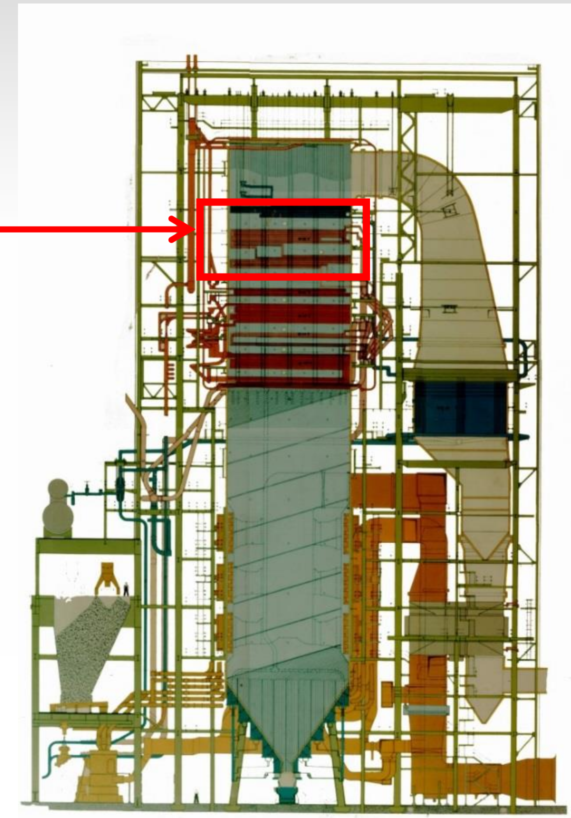
- **To ease technical discussions** between all “players” (inspector, manufacturer, end user, etc.) and **convince**

- To support performance demonstrations with study of influential parameters by simulation (and reduce mock-up tests) :
  An element of technical justification in qualification stage

Context

- **Inspection of heater and super Heater (RBT) exchangers in 600MW coal-fired French power plants**
  - Located in the upper part of boilers
  - 10s of Kms of tubes to deliver steam over 600° C
  - Subject to corrosion pitting





- **Inspection method to be qualified along EDF qualification process according european standard CEN/TR478:**
  - Experimental trials on mock ups with artificial and representative defects
  - Technical justification accounting for essential parameters

Context

Simulation study of the SLOFEC SYSTEM

- **Goal:**
  - First : **To validate** the representability of simulation results of SLOFEC (comparison with measurements)
  - To allow a future use of modelling SLOFEC for inspection feasibility study, support qualification works (to reduce experimental trials), etc.

- **Conducted by EXTENDE,** the NDT simulation company:
  - CIVA NDE 2016 CIVA software distribution and technical follow-up
  - Consulting studies

- **SLOFEC study performed on the FLUX FEM software** Flux by CEDRAT

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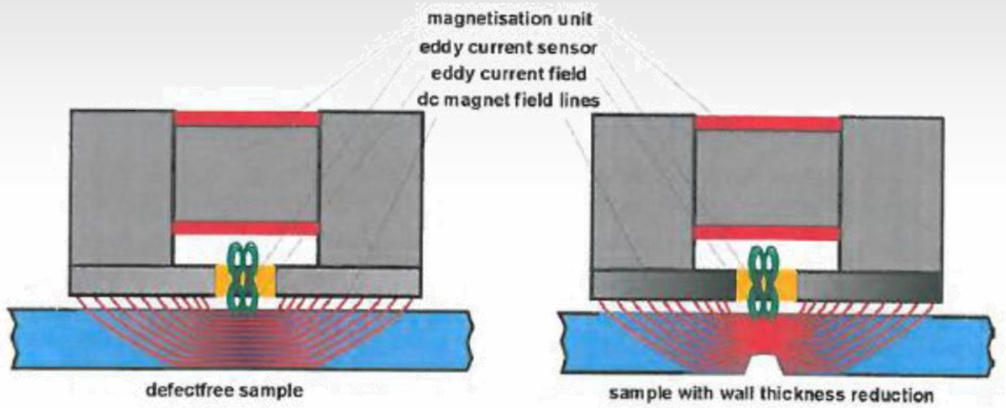
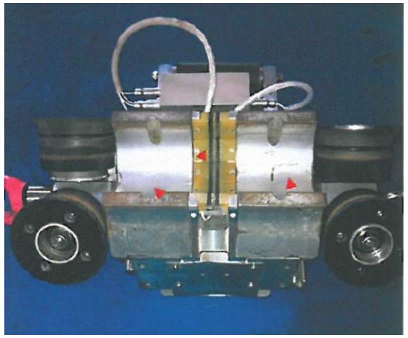
SLOFEC™ inspection system

- **Specific Eddy Current system developed by Kontroll Technik** for ferromagnetic tubes inspection
- **Operating principle:**
  - DC magnetization
  - AC coils sensitive to DC field disturbance due to a defect (local change of permeability)
  - Located from the outer side of tubes



- **Advantages:**
  - High sensitivity detection even for thick wall (up to 25mm)
  - High speed
  - Inspection through coating up to 10mm
  - Possible use at high temperatures
  - Inner/Outer defects distinction



- **Applications: Rising use in many industries for**
  - Boiler tubes, Buried pipes, Penstocks, tank, vessel, drum, ….

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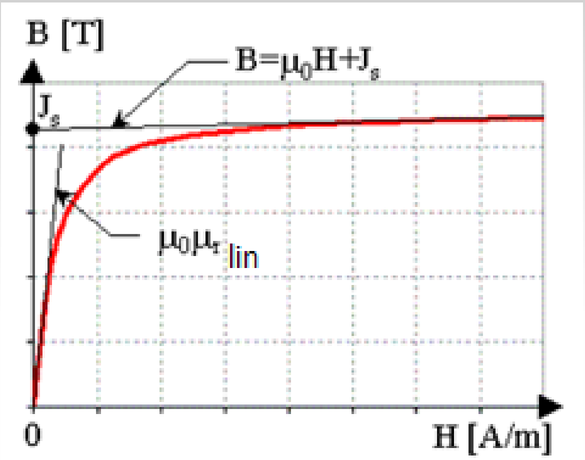
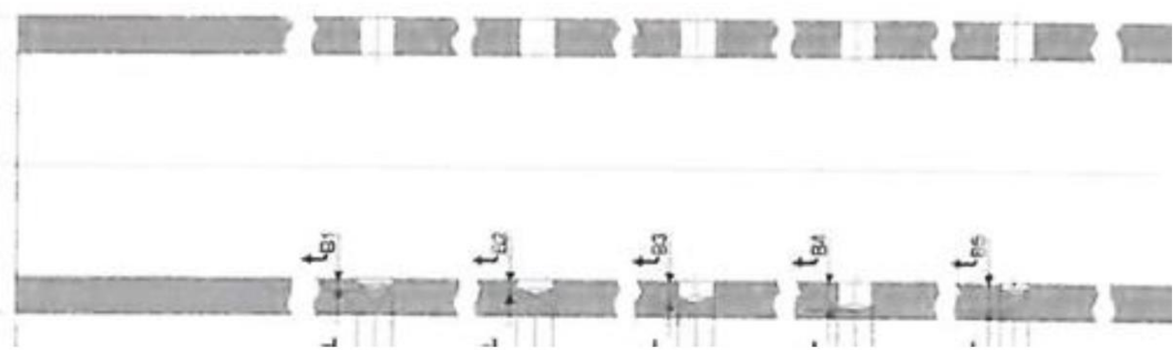
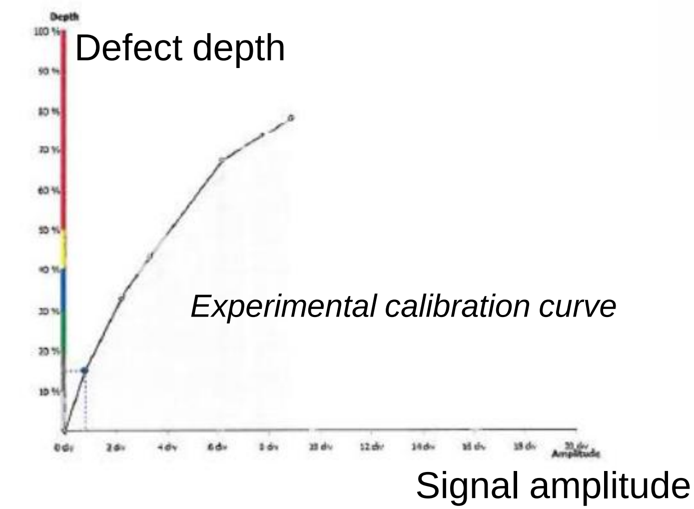
Inspected tubes

- **“RBT” tubes:**
  - **Dimensions:** Φ 60.3mm, 4mm wall thickness
  - **Material:** Low alloy carbon steel
    - $\sigma \sim 6$ MS/m
    - Ferromagnetic but relative permeability curve difficult to know → parameters estimated by curve fitting vs experimental calibration curve (variation of Js and μr lin)



- **Targetted defects:** Corrosion pits
- **Reference defects**: Conical Bottom Holes Φ 4mm from 20% to 77% depth
  - Amplitude/depth calibration curve is plotted





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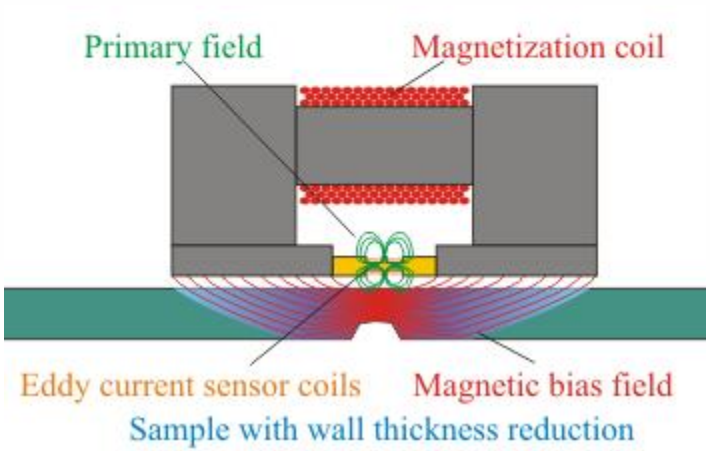
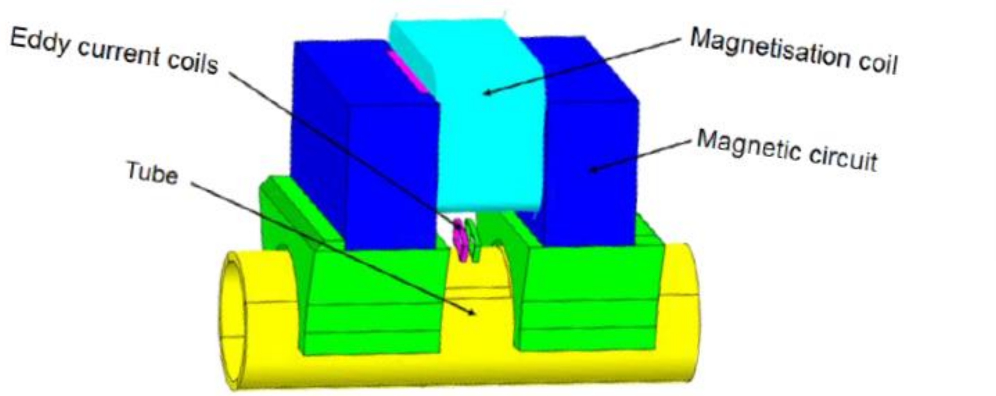
Understand SLOFEC™

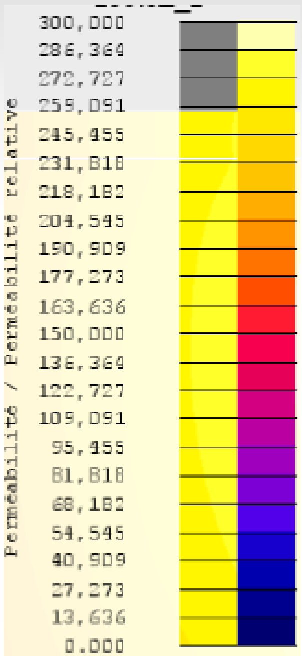
- **Core principle with SLOFEC: Inspection sensitivity linked to disturbance on component permeability due to defect**
  - AC coils will be sensitive to field change due to the modification of local permeability due to local DC magnetic field
  - Eddy currents are not directly disturbed by the defects (generally no penetration of EC at the flaw depth at this frequency, here 70kHz)



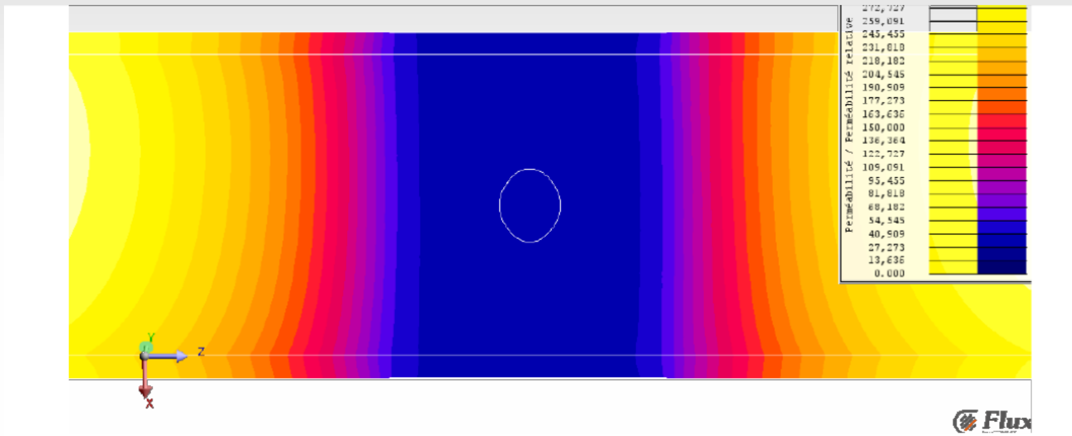


Understand SLOFEC™

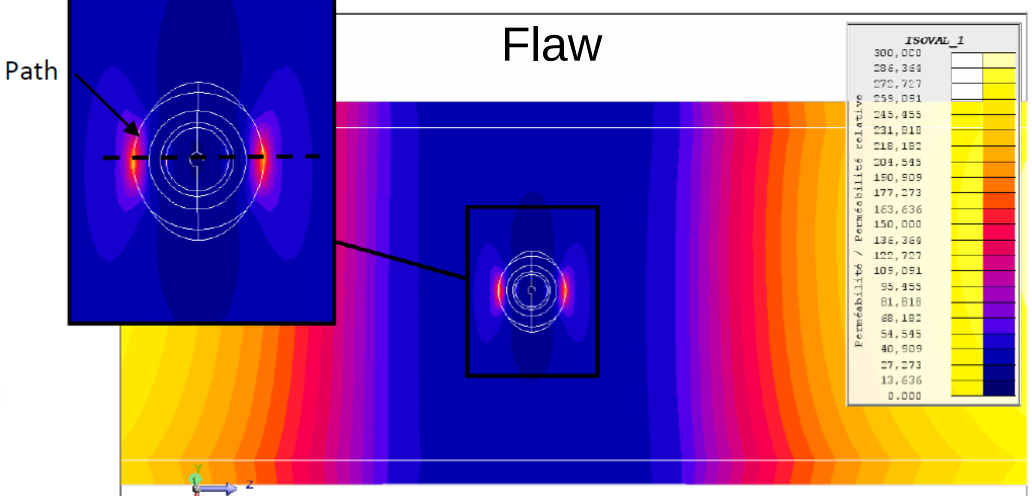
- **Relative permeability distribution with and without (inner) flaw**
  - Color chart view from the inner side of the tube (between magnetization poles):

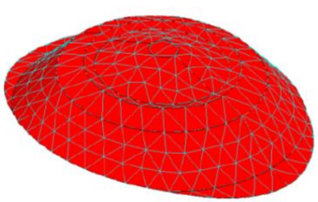


No Flaw

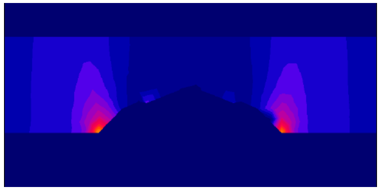


Flaw





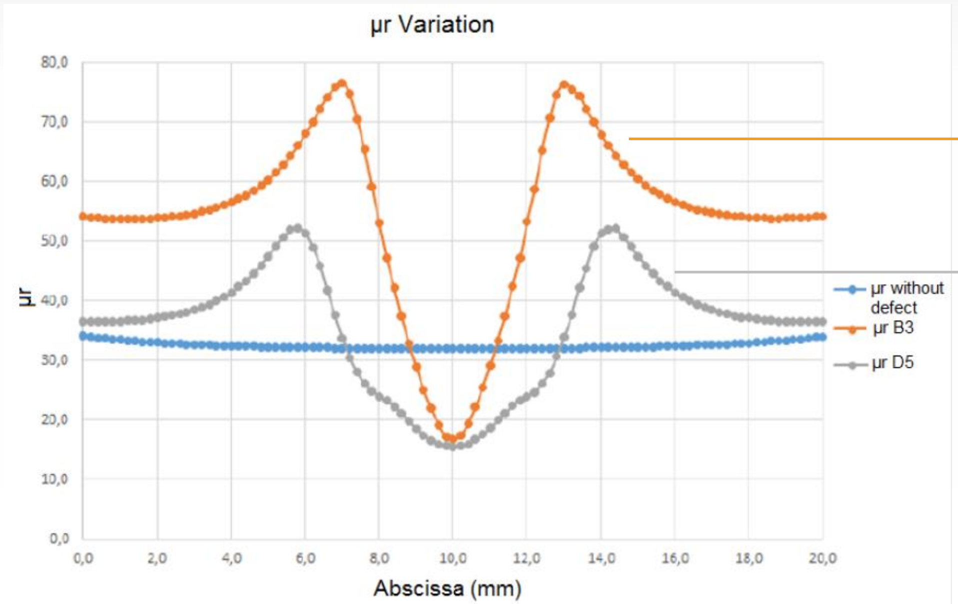
Corrosion pit geometry in the FEM model

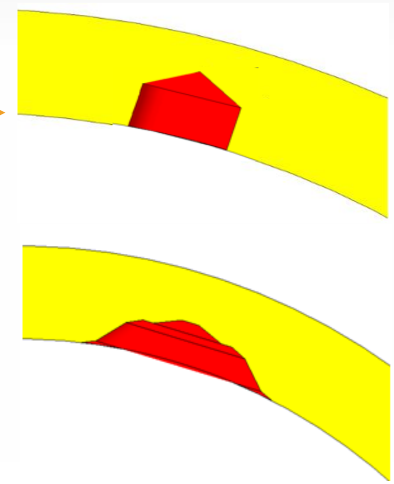


Cross section view

Understand SLOFEC™

- **Curves of permeability values along a path between flaw and outer side**
  - Defect leads to flux lines modification (orientation and concentration):
    - If field density increases → closer to saturation level → drop of local permeability
    - If field density decreases → further from saturation level → increase of permeability





Φ 4mm, Depth 2.7mm

Φ ~9mm, Depth 1.8mm

- Profile of permeability variation will depend on flaw depth and diameter
- Amplitude of variation (i.e. sensitivity) will be also **dependent on the magnetization level and the material properties (magnetization curve)**

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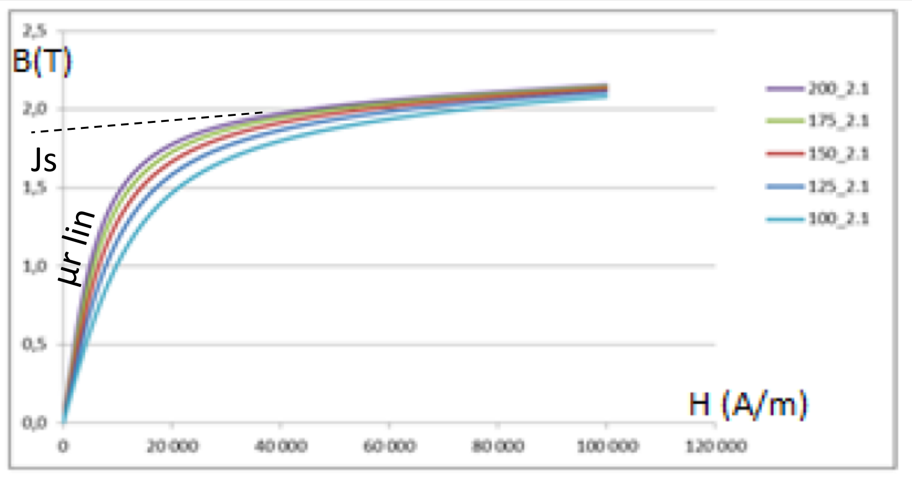
Understand SLOFEC™

- **Influence of the Magnetization curve of the material**
  - Output signal amplitude for a given defect when linear B(H) curve properties change



Permeability coefficient (µr lin)	100	125	150	175	200
Signal amp.	11 div.	10,5 div.	10 div.	9,6 div.	9,2 div.

Closer to saturation, lower is the sensitivity (lower permeability contrast due to the flaw)

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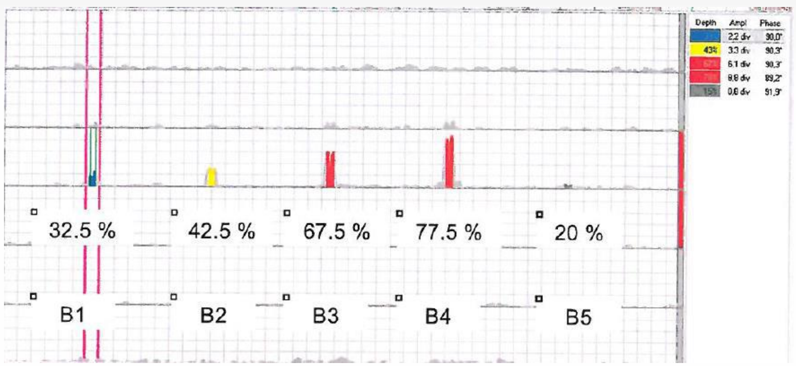
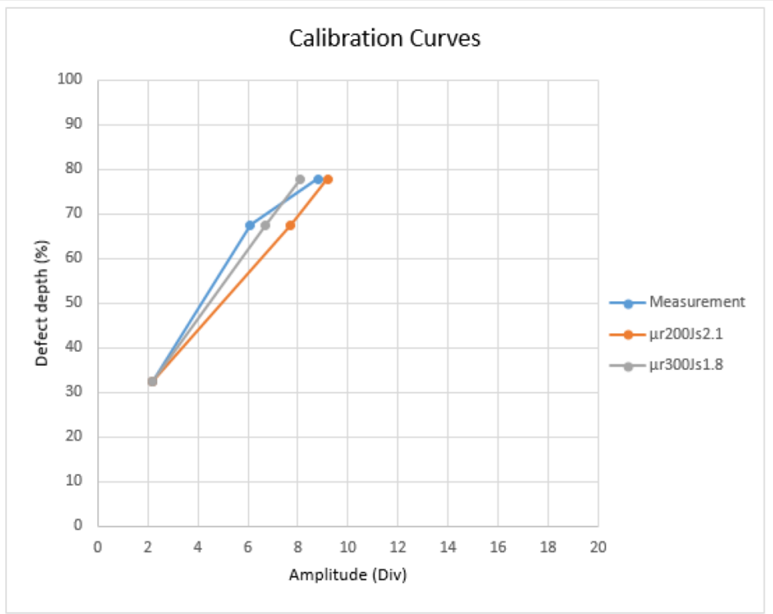
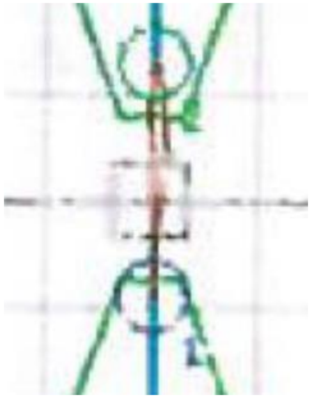
Calibration results

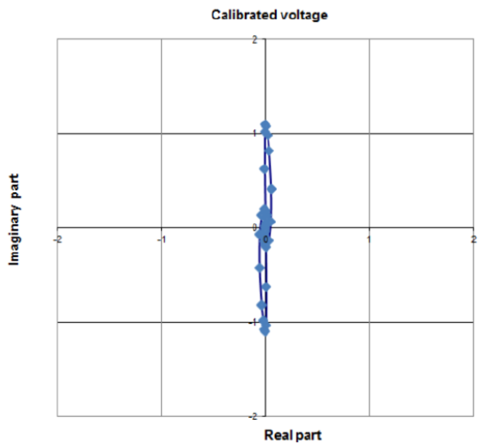
- **Simulated calibration curve and experimental calibration curve:**
  - Material properties fixed vs calibration curve fitting (on Conical Bottom Holes response):
    - Less than 10% discrepancy with Js=1,8T and µr lin = 300





- **Experimental signal compared with simulated one :**





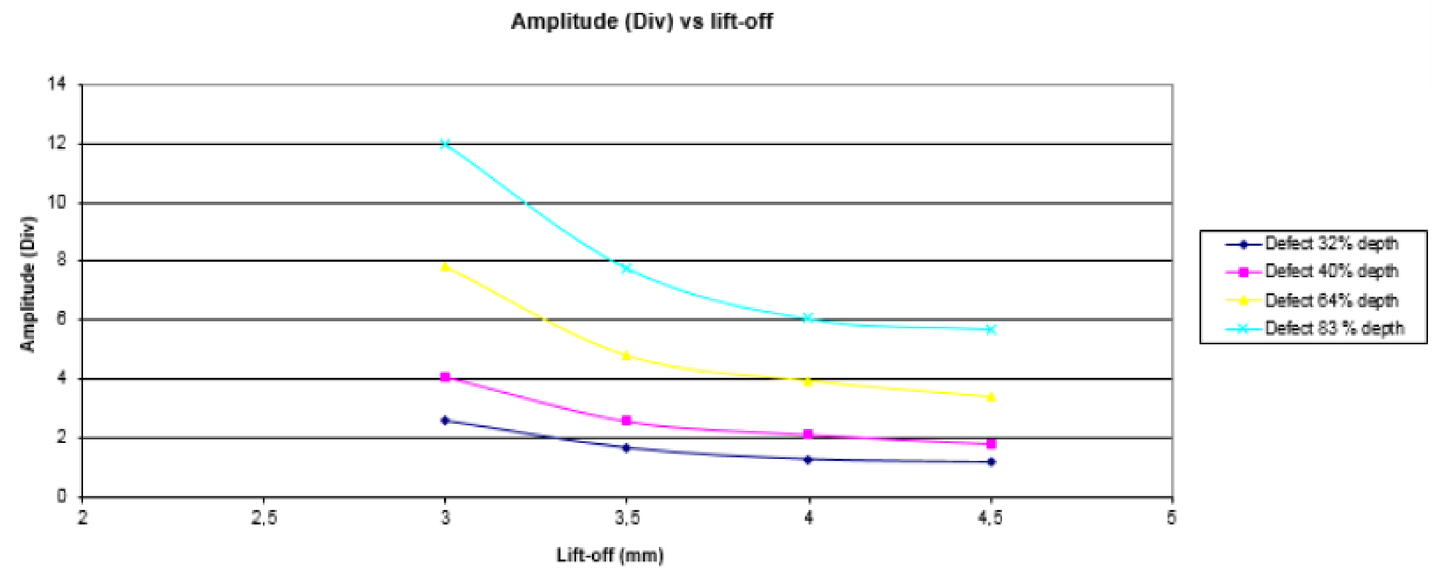
Lift-off influence

- **Signal amplitude vs lift-off variation**
  - Simulation on calibration defect 2,7mm depth:

Lift-off (mm)	Amplitude	Phase
3	6,7 div.	88,4°
4,5	3,1 div.	88,3°

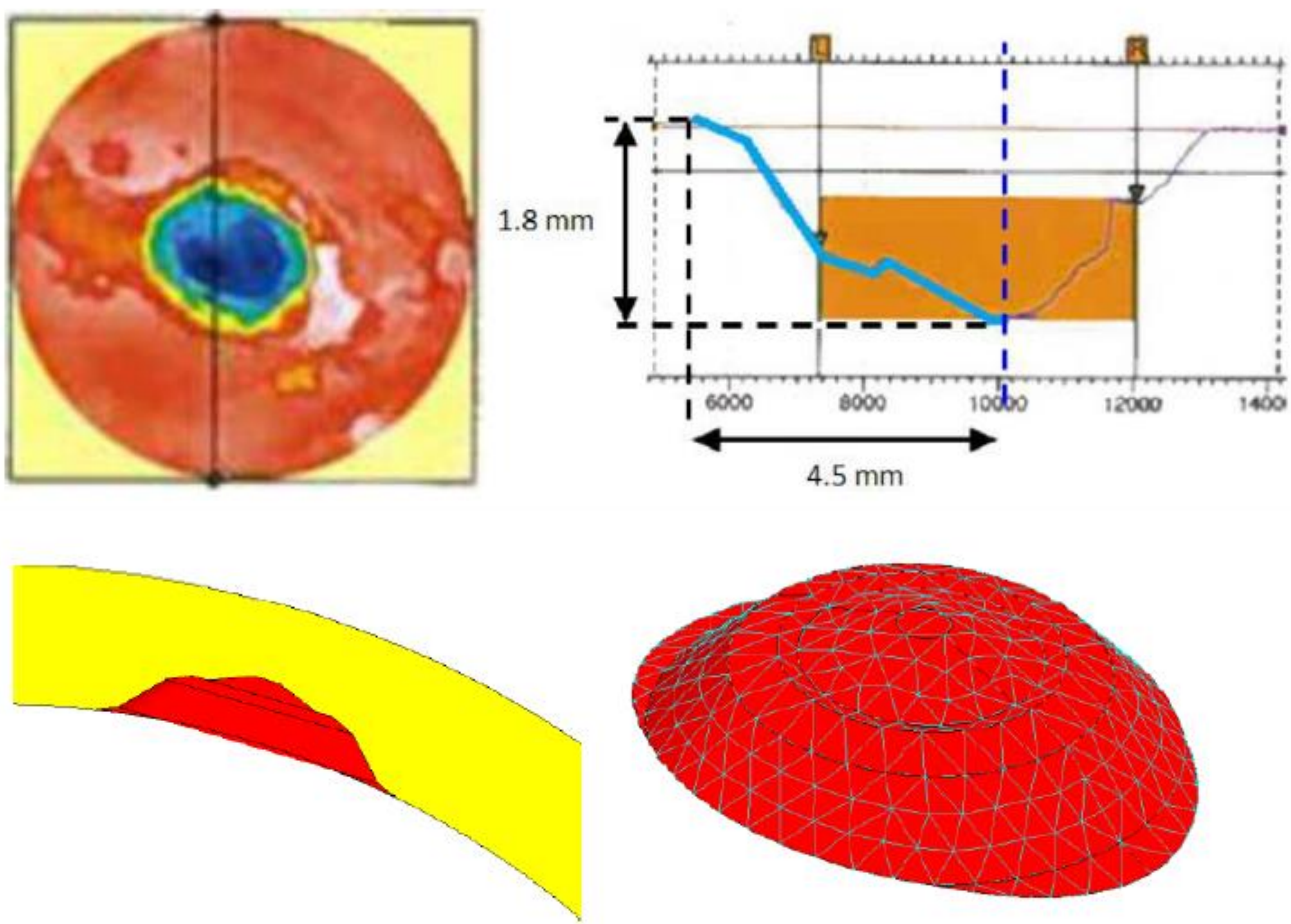
54% amplitude drop for 50% lift-off increase

- **Similar to what was observed experimentally**
  - Amplitude drop between 52% and 56% whatever the defect depth



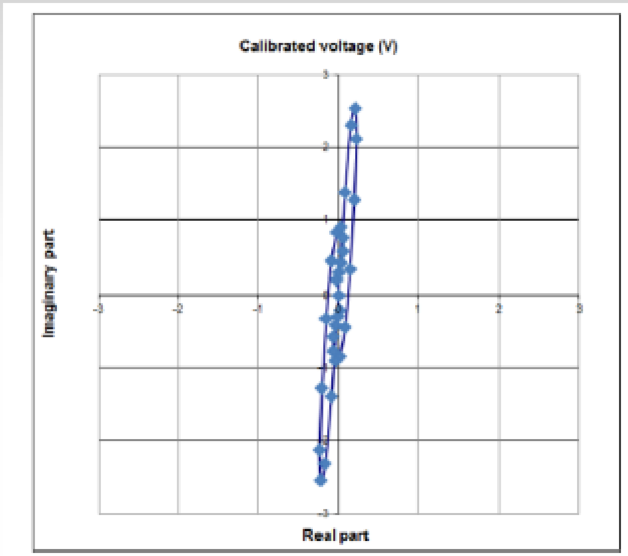
Real defect simulation

- **CAD profile defined from metrologic analysis of a corrosion pit:**
  - From the real defect to the CAD model : 1,8mm depth (45% wt), Φ ~9mm



Real defect simulation

- **Signal obtained by simulation:**



5,1 divisions
--> 55% depth from
calibration curve = 2,2mm

- **Results comparison:**

Metrology		UT		SLOFEC Experimental		SLOFEC modelling	
Depth (mm)	Depth (%)	Depth (mm)	Depth (%)	Depth (mm)	Depth (%)	Depth (mm)	Depth (%)
1,8	45	2,2	55	2,2	55	2,2	55

Both NDT methods overestimates defect depth in this case (large diameter flaw vs calib), & modelling reproduces this

Conclusion

- Simulation study of SLOFEC Eddy Current Inspection system in the context of NDT technical justifications for heater tube inspection in a French coal fired PP

- Good agreement between modelling results and experimental results
  - But necessity to know or estimate ferromagnetic properties of the component (possible with calibration curves)

- Simulation helps the physical analysis of SLOFEC and understanding influential parameters for such inspection: Lift-off or other typical ET parameters but also importance of the magnetization level and magnetization curve material properties to **maximize permeability local contrasts due to a flaw**

- This first validation opens the door for wider supported simulation works with SLOFEC:
  - Predict the response of real flaw using his real shape
  - Feasibility studies
  - Design and procedures optimization
  - Qualification works
  - ….

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