# Finite Element Modelling of Eddy Current Probes for CANDU® Fuel Channel Inspection

M. Luloff[1], J. Morelli[2], T. W. Krause[3]

[1]Royal Military College of Canada, Kingston Ontario, Canada, 9msl1@queensu.ca

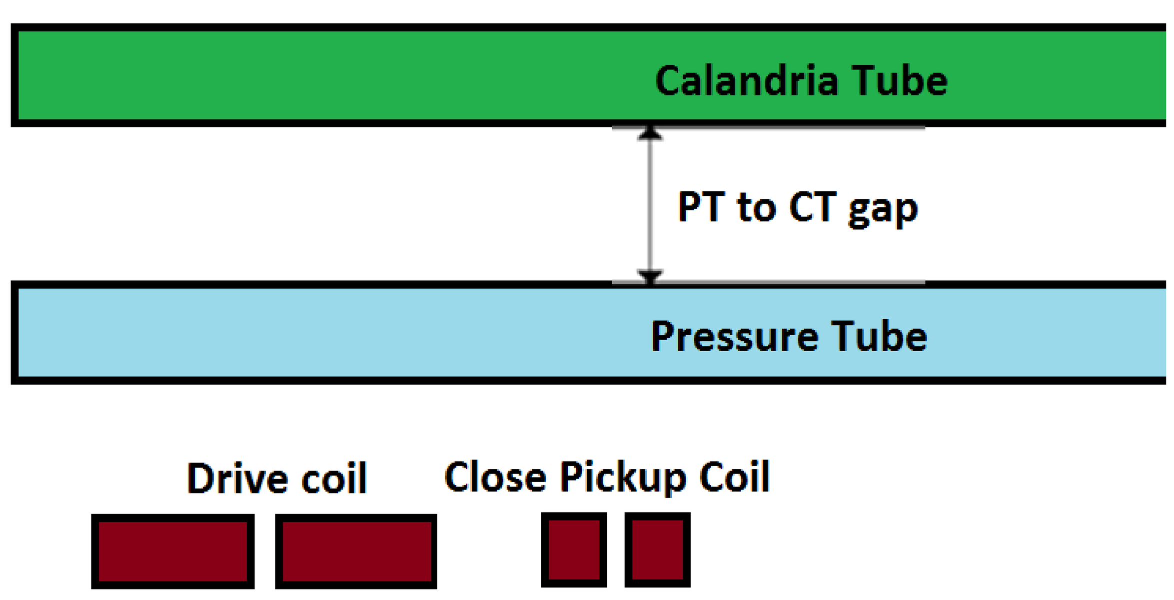
[2]Queen's University, Kingston Ontario, Canada, morelli@physics.queensu.ca

[3]Royal Military College of Canada, Kingston Ontario, Canada, Thomas.Krause@rmc.ca

## INTRODUCTION/MOTIVATION

### CANDU® REACTOR FUEL CHANNEL

- CANDU® reactor fuel bundles are contained within Pressure Tube (PT), which also carries heat transport coolant as shown in Figure 1 [1];
- A gas-filled Calandria Tube (CT) surrounds the PT and thermally isolates it from the moderator surrounding the fuel channels [1].
- The hot PT (~300°C) is separated from the cool CT (~50°C) by four annulus spacers to prevent contact, which could result in hydride blistering of the PT [1]
- Hydride Blistering lowers the fracture tolerance of the PT, which may lead to cracking of the PT;
- Monitoring the PT-CT gap is a nuclear safety requirement and is done using Eddy Current (EC) technology.




- **Figure 1:** A schematic of a CANDU® fuel channel with the EC probe.

## OBJECTIVES

The goals of this project are to:

- Develop COMSOL® FEM models to simulate the probe response for eddy current probes for future validation by experimental measurements;
- Use the FEM models to investigate probe operation under normal test conditions, comparing the response against nuclear reactor inspection specifications;

## EDDY CURRENT PROBE

- A picture of the physical EC probe used in this study is shown below in Figure 2.
- An eddy current instrument excites the drive coil of the coil pair at three frequencies.
- The pick-up coil response is filtered to isolate the response from each of the three excitation frequencies;
- Finite Element Method (FEM) used to model probe response under various in-reactor inspection conditions can be used to support activities leading to qualification of the inspection system, which is a nuclear regulator requirement [5].

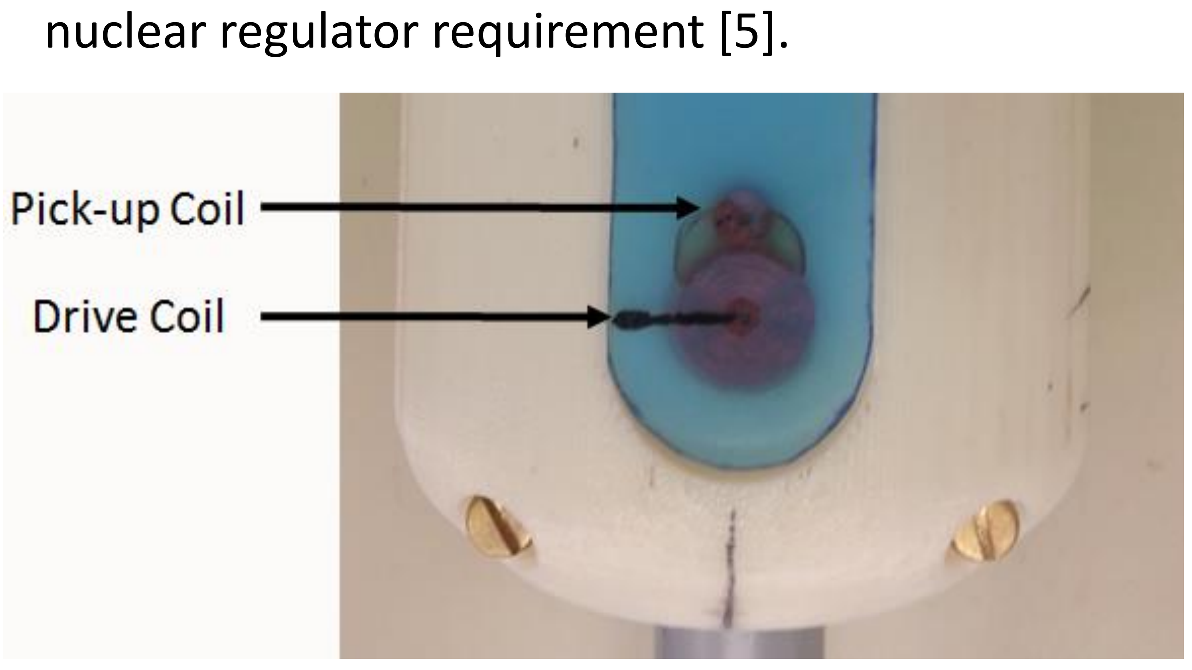



**Figure 2:** A photograph of the experimental EC probe.

## COMSOL® MULTIPHYSICS

- As shown in Figure 3, three 3D COMSOL® models (COMSOL® version 5.1) were made: a planar-geometry approximation, a growing CT approximation [2,3] and one model with the actual fuel channel dimensions;
- The Magnetic Fields (mf) physics node in the AC/DC module was used in conjunction with a Frequency Domain study;
- The coils were cut into fifths and connected to a pull up or pull down resistor using the Electrical Circuit interface. By turning on the right "fifth coils" , one can develop a liftoff profile;
- A stack of CTs were placed about the PT. Turning the material resistivity to 10 S/m or the correct resistivity developed the PT-CT gap profile;
- The coils were modelled as multi-turn coils, with the drive coil was connected to a 10 V AC-source;
- The pickup coils were constrained to be in an open circuit configuration.

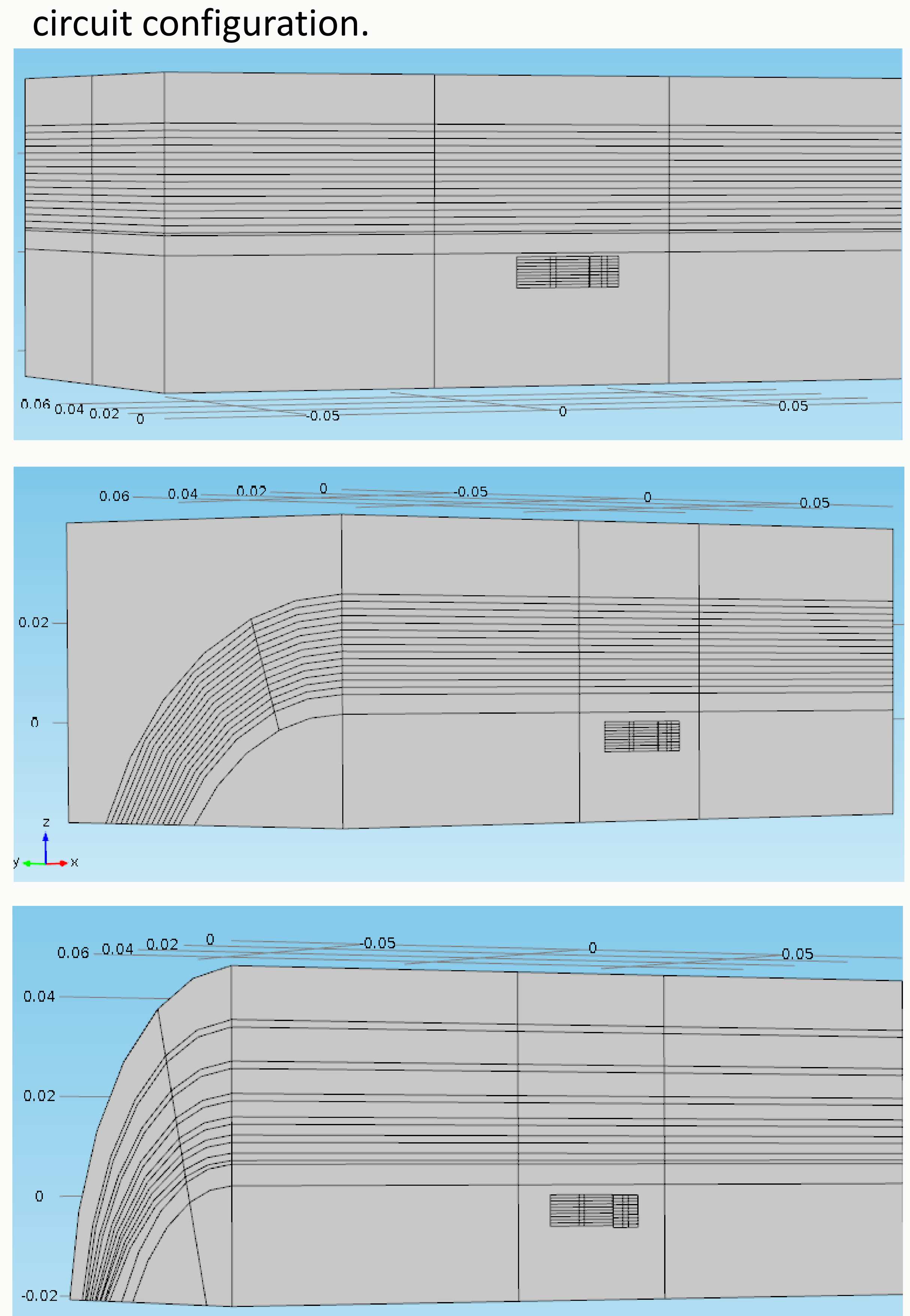


**Figure 3:** The flat-plate and growing CT COMSOL® models to replicate analytic solutions (top and middle) and the real geometry model (bottom).

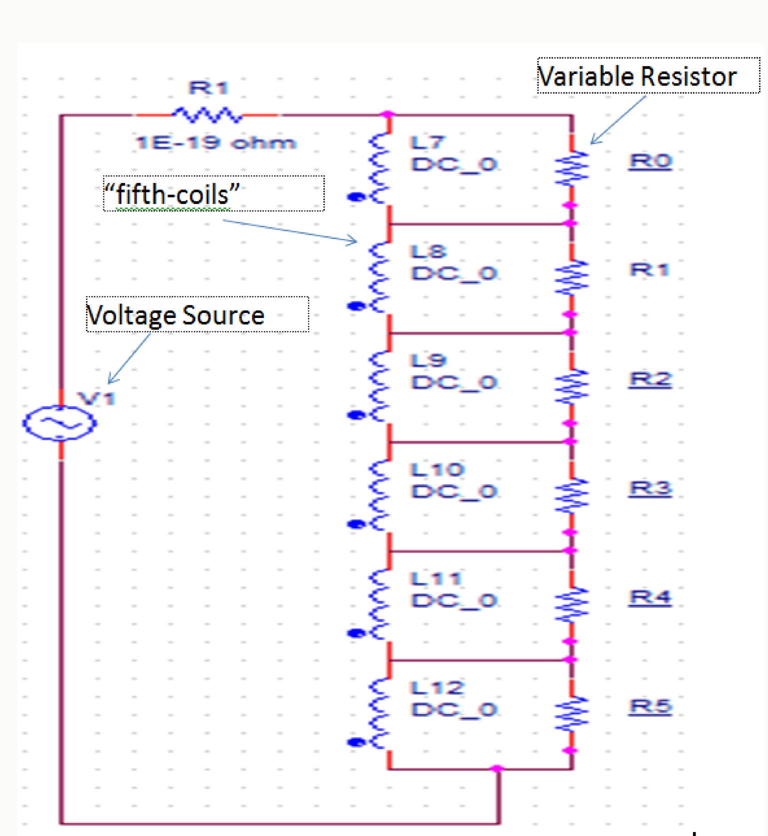



**Figure 4:** A circuit diagram showing how the "fifth-coils" of the drive coils are connected to a pull-up or pull-down resistor.

## RESULTS

- FEM model results (see Figure 5) always show that the ECs are localized above the drive coil, thereby reducing the effect of geometric curvature in the model;
- As shown in Figure 6, the impedance plane display of the PT-CT gap response was calculated for the planar approximation, the growing CT approximation and real geometry of the fuel channel when the probe was operated at 4 kHz;
- It was found that all three models yield a similar shape response, however:
  - The flat-plate model (infinite curvature) does not predict the phase of the PT-CT gap profile accurately;
  - For small PT-CT Gaps (< 5.5 mm) the growing CT approximation agrees well with the real geometry model but deviates at larger gaps.

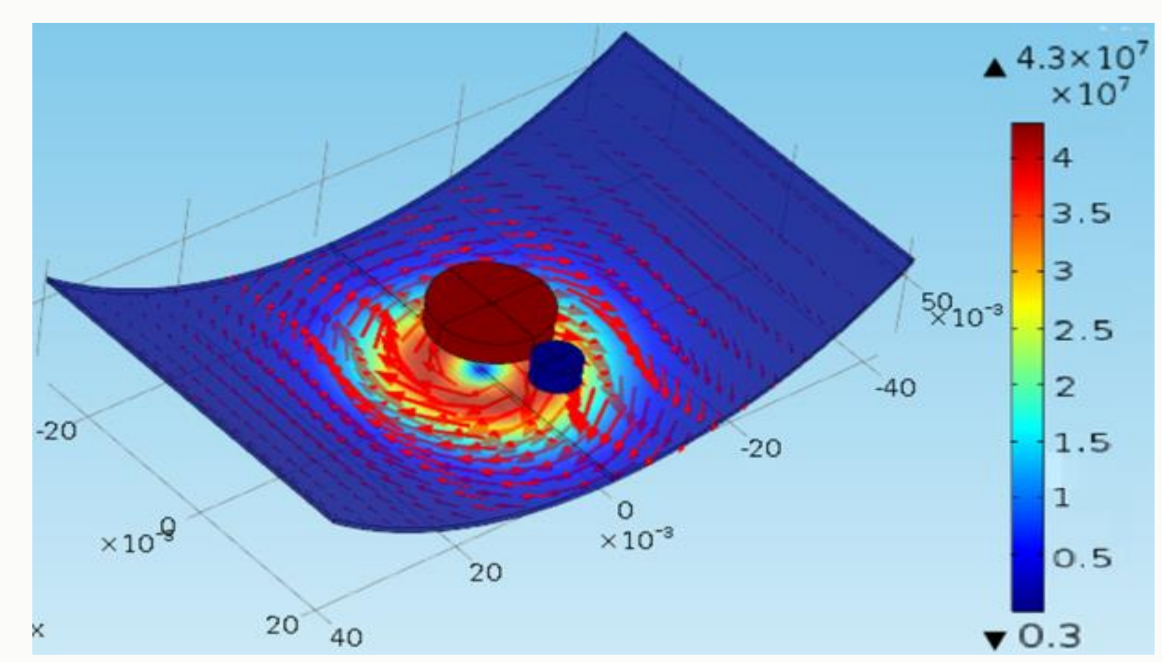



**Figure 5:** The PT eddy current distribution from a conventional EC probe. Colour axis given in units of A/m².

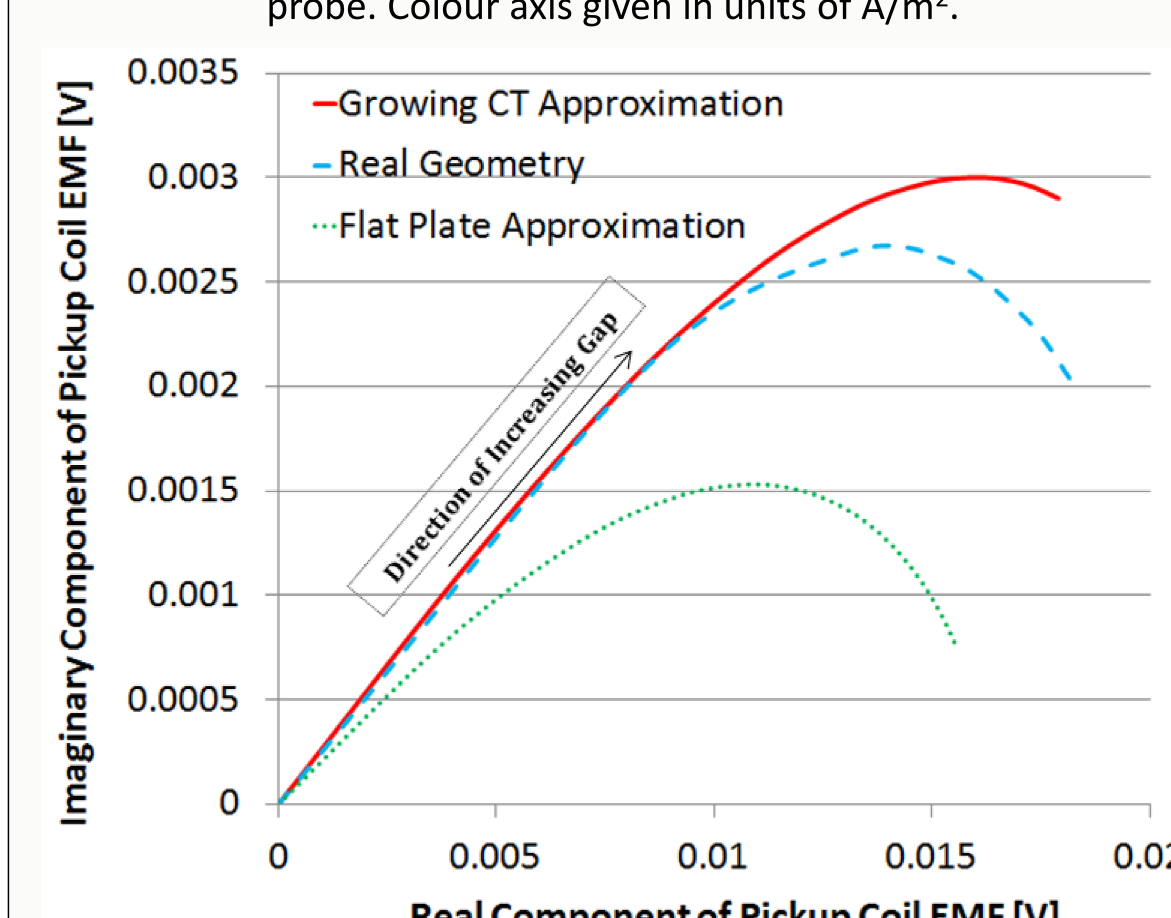



**Figure 6:** Impedance plane display of PT-CT gap response (0-20 mm) for the planar geometry approximation, the growing CT approximation and real geometry of the fuel channel as predicted by COMSOL®.

## CONCLUSIONS

- The effect of fuel channel curvature must be taken into account as the flat-plate model (infinite curvature) does not predict the phase of the PT-CT gap accurately;
- The effect of curvature however is smallest at small gaps (<5.5 mm)

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