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# Simulation of a Permeability Probe to Estimate Hot Corrosion Zone Size

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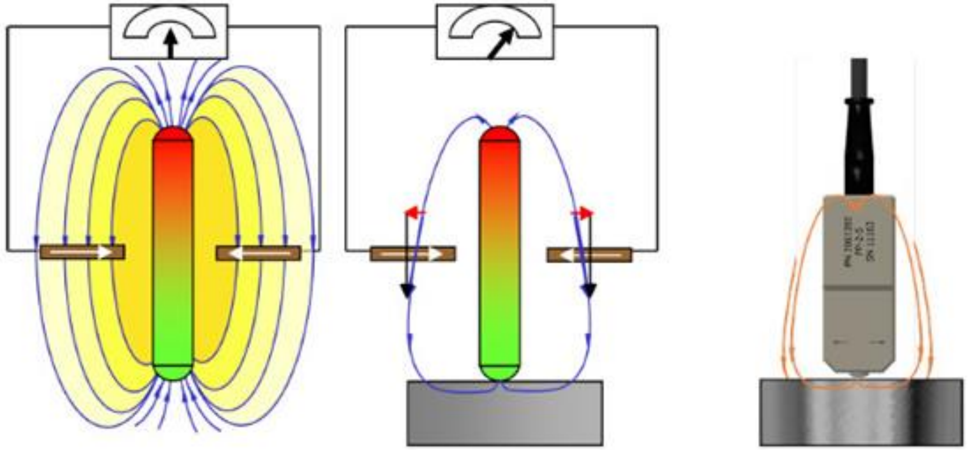
# Introduction

- Sulfidation corrosion of Nickel based super-alloys components is one form of corrosion that affects performance
- This corrosion results in the formation of a hot corrosion zone with a high relative permeability
- Hot corrosion zones can be detected by a permeability probe, Magnetoscop 1.070, in this work, and used to determine whether a component should be removed from service
- Measurements from the probe do not provide details on the hot corrosion zone area or depth

# Magnetoscop 1.070

- The Magnetoscop 1.070, made by FOERSTER, is a portable magnetometer system that measures relative permeability
- An addition of a material with a relative permeability greater than 1 will affect the magnetic field, and change its horizontal component at the measurement locations
- The probe is therefore an effective, non-destructive testing tool for detection of hot corrosion zones

**Relative Permeability = 1  Relative Permeability > 1**



**KK&S Instruments. (2016). *The Probe* [Brochure]. Retrieved from [http://www.kks.com.au/24-2016-october-december-probe/](http://www.kks.com.au/24-2016-october-december-probe/)**

# Magnetoscop 1.070 Operation

- The Magnetoscop 1.070 probe, circled in red below, works by contacting its tip with the surface of a component or cylindrical calibration block (ideally perpendicular to the surface)
- The probe outputs the magnetic flux density, or effective relative permeability, of an object that generates magnetic flux
- The output reading is displayed in the attached instrument shown to the right
- This probe is suitable for relative permeability values in the range of 1.00 to 2.00


**Foerster. (n.d.). *Magnetoscop 1.070: Product Information*. Retrieved from https://www.fluxgate-magnetometer.com/assets/foerster/media/Downloads/Magnetoscop%201.070/1070_PI_EN_MAGNETOSCOP.pdf**

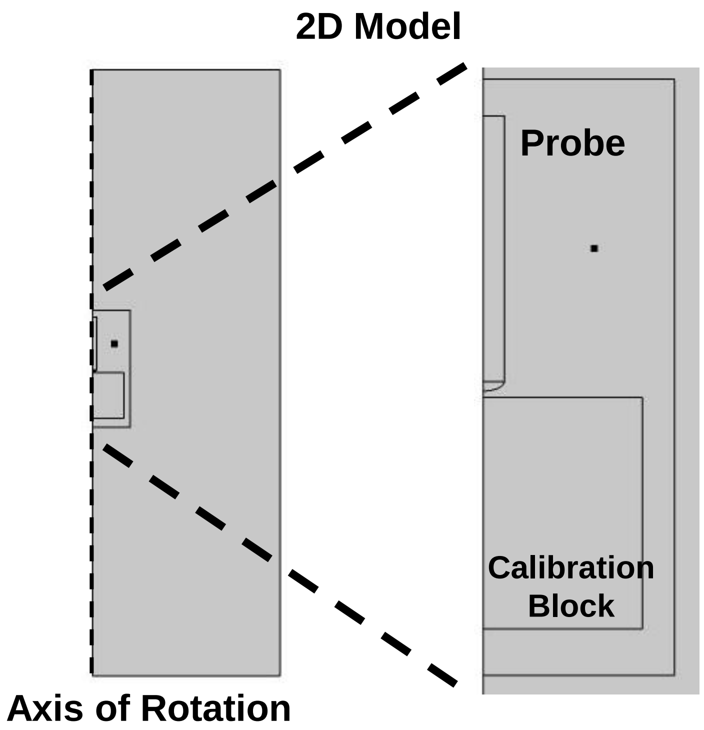
# Magnetoscop 1.070

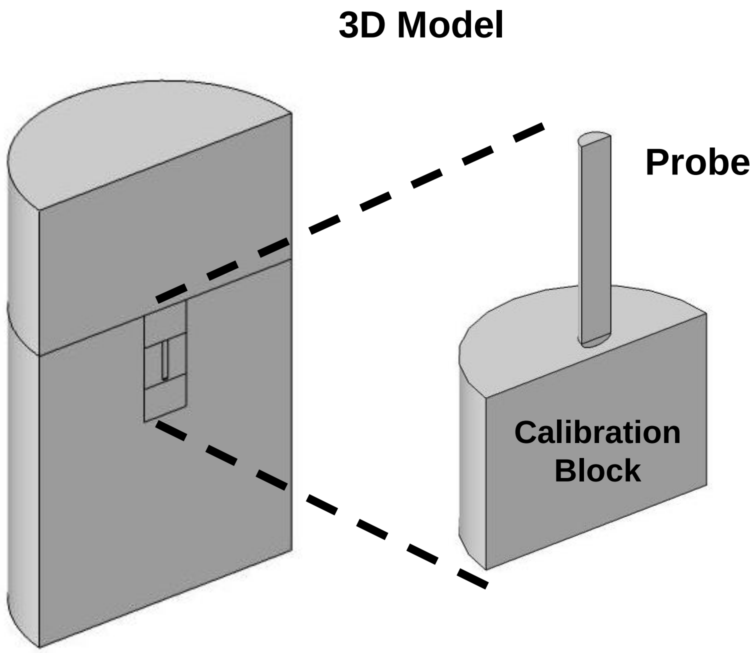
- This permeability probe has a cylindrical magnetic core to generate magnetic fields
- There is a layer of ceramic at the tip of the probe so it never directly touches the surface
- The precise method used by the probe to calculate the relative permeability is not available

# Model Setup

# Geometry

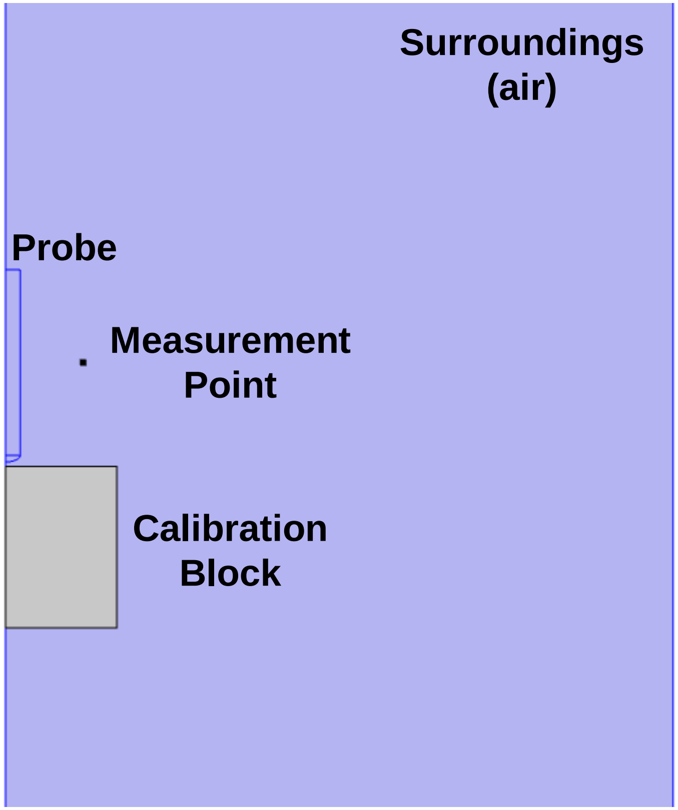
- We used a 2D axisymmetric model when the probe remained at the cylindrical axis of the calibration block and moved only in the vertical direction
- We used a 3D model when the calibration block moved perpendicular to the cylindrical axis and modeled only half of the set up due to symmetry



# Materials

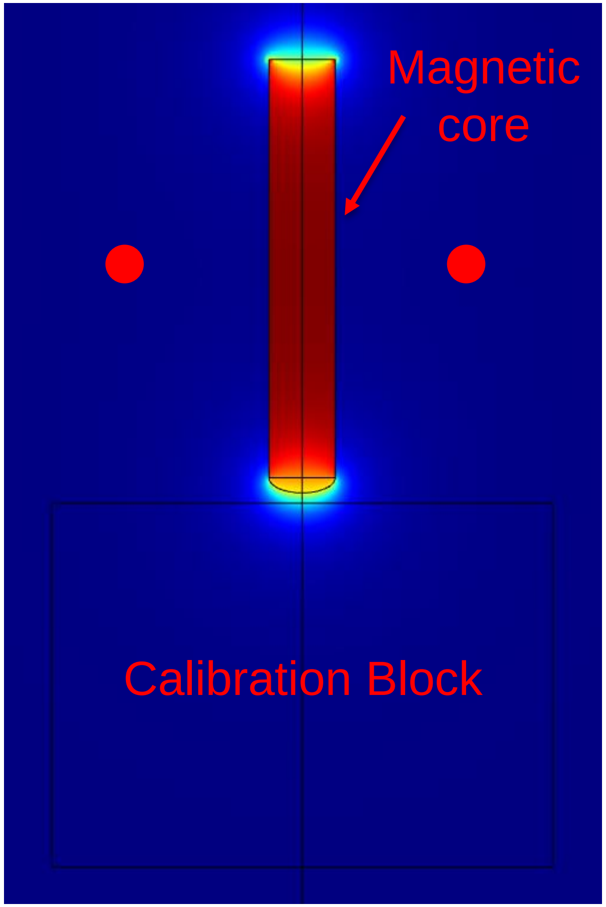
- All objects aside from the calibration block, or hot corrosion zone, have a relative permeability of 1, shown in blue on the figure to the right
- The calibration block, or if applicable, the hot corrosion zone, has a relative permeability > 1, shown in grey




2D Model for Calibration

# Physics Setup

- The validation model included the central magnet, the calibration block of high permeability, and the surrounding air
- We assumed a magnetostatic problem with no electric field or high frequency effects on the probe or its surroundings
- Magnetic core was prescribed with a magnetic field strength
- Red circles show the horizontal magnetic flux density measurement points
  - Location of these two points were validated from model calibration




Magnetic flux density

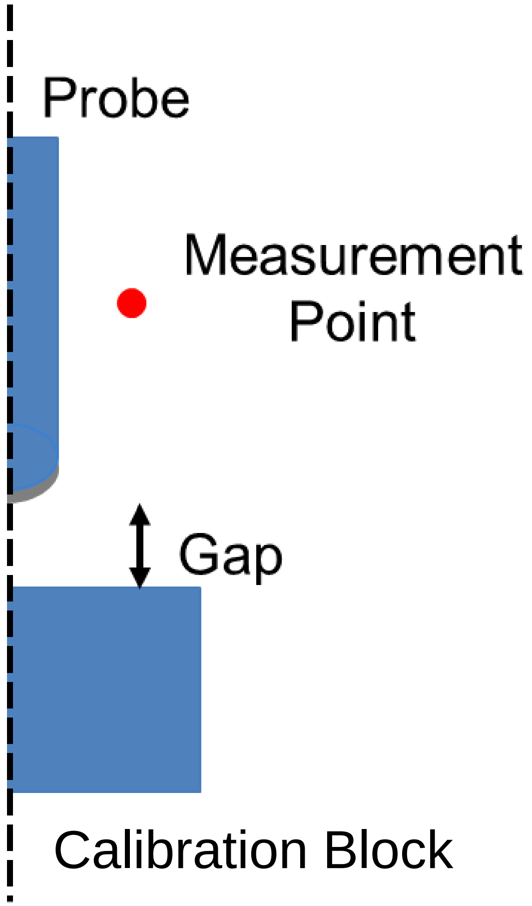
# Model Calibration

# Model Calibration

- Experimental data of probe reading for calibration blocks were gathered for comparison with simulation
- Calibration was performed to verify that measurement procedure is accurate
- A table that relates the relative permeability (probe reading) and the horizontal component of the magnetic flux density recorded at the measurement point(s) was developed and verified from the simulations
  - Measurement point remained at middle of probe vertically
  - Point’s radial distance from magnetic core was based on measurement from an X-ray image
  - This location was verified by comparing the simulated and experimental data

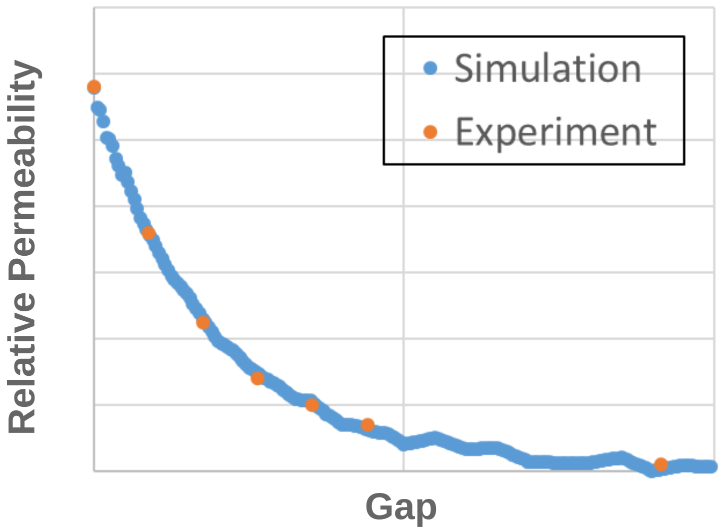
# Simulation #1

- Used the 2D model to derive a conversion table from magnetic field to permeability
- Gap refers to the distance between the ceramic layer of the probe and the calibration block
- Three studies using the model were performed
  - For study 1, the gap was kept at zero while the relative permeability of the block increased
  - For study 2, we kept the relative permeability of the block at $\mu_1$ while the gap increased
  - For study 3, we kept the relative permeability of the block at $\mu_2$ ($\mu_2 > \mu_1$) while the gap increased
- Experimental tests identical to studies 2 and 3 were performed for comparison

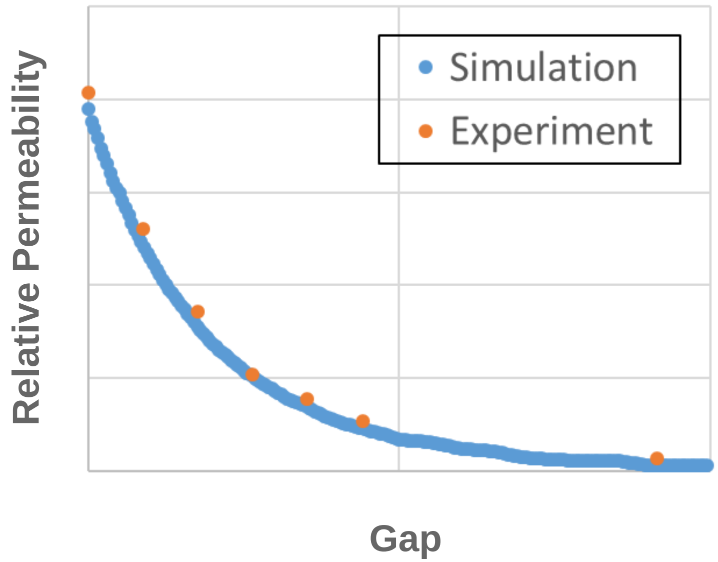


# Results

- We interpolated the magnetic flux density from study 2 with the flux density from study 1 to get the corresponding theoretical relative permeability (left)
- This was repeated for the magnetic flux density recorded from study 3 (right)
- Radial distance of measurement point was adjusted until the simulated and experimental data matched as seen below



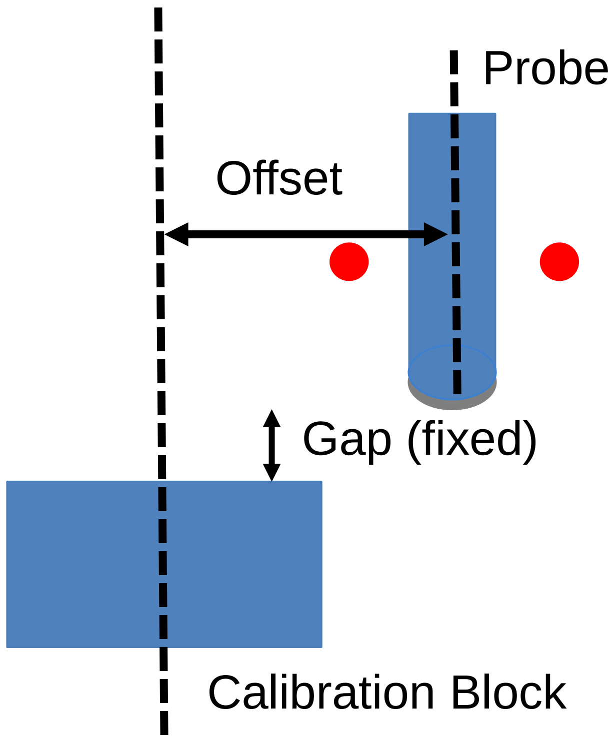

Calibration Block: $\mu_1$




Calibration Block: $\mu_2$

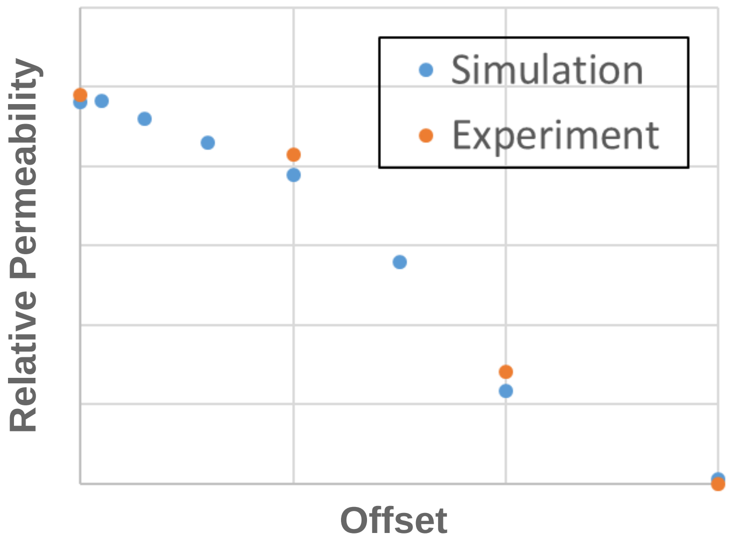
# Simulation #2

- To check the probe calibration based on Simulation #1, additional experiments where the probed was moved parallel to the calibration block and the effective permeability measured were performed
- The same test using the 3D finite element model shown on the right was simulated
  - The horizontal magnetic flux density as the block moved parallel to the probe was recorded
- Offset refers to the distance between the center of the probe and the cylindrical axis

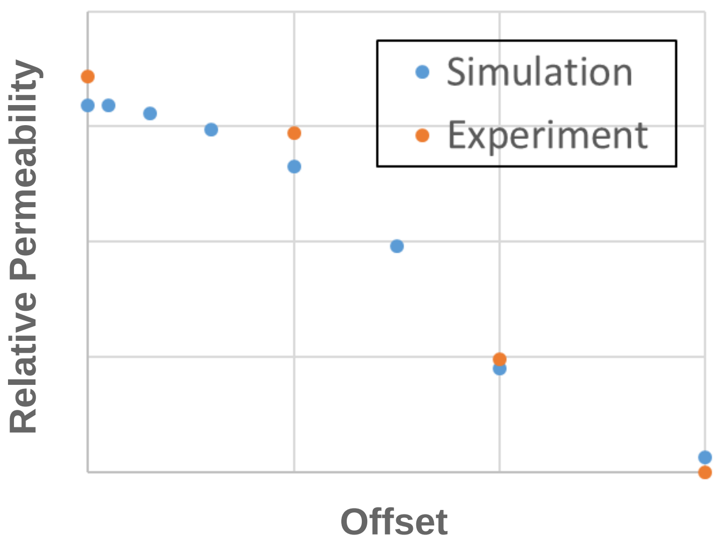


# Results

- The figures below compare the probe readings from experiments and simulation for the two calibration blocks
- The results show good agreement




Calibration Block: $\mu_1$

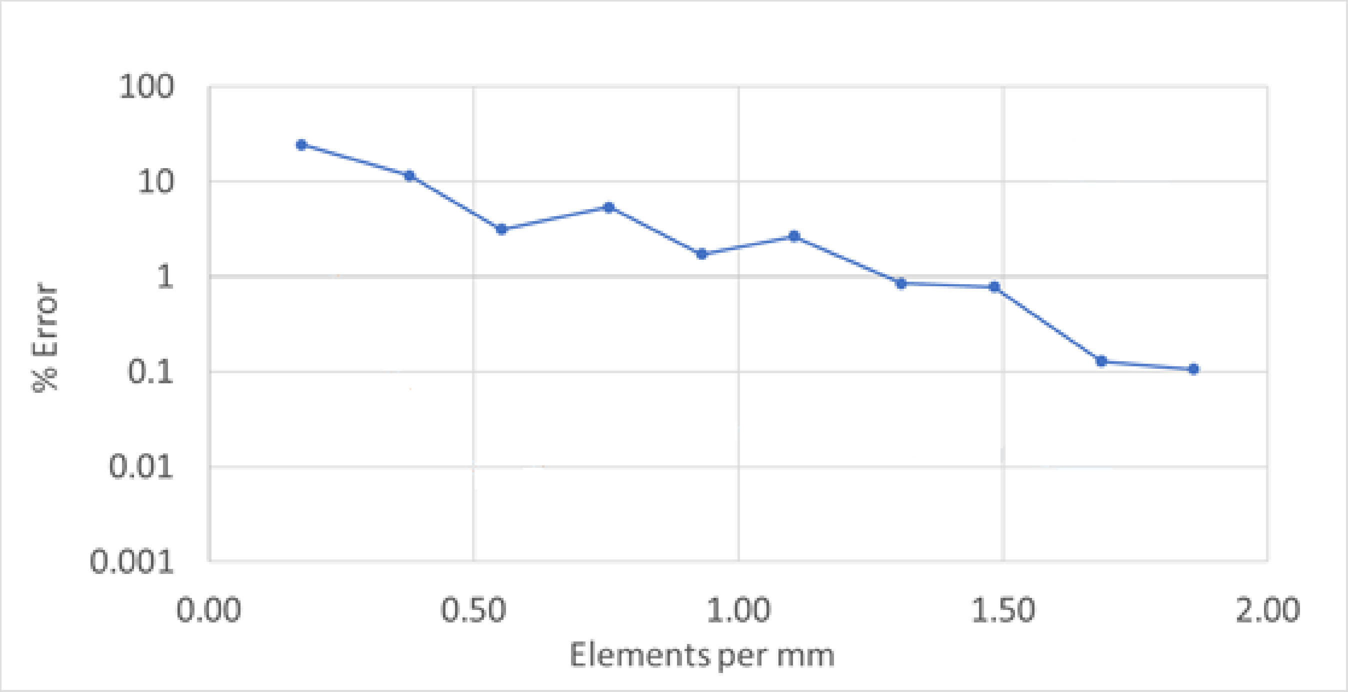



Calibration Block: $\mu_2$

# Model Improvements

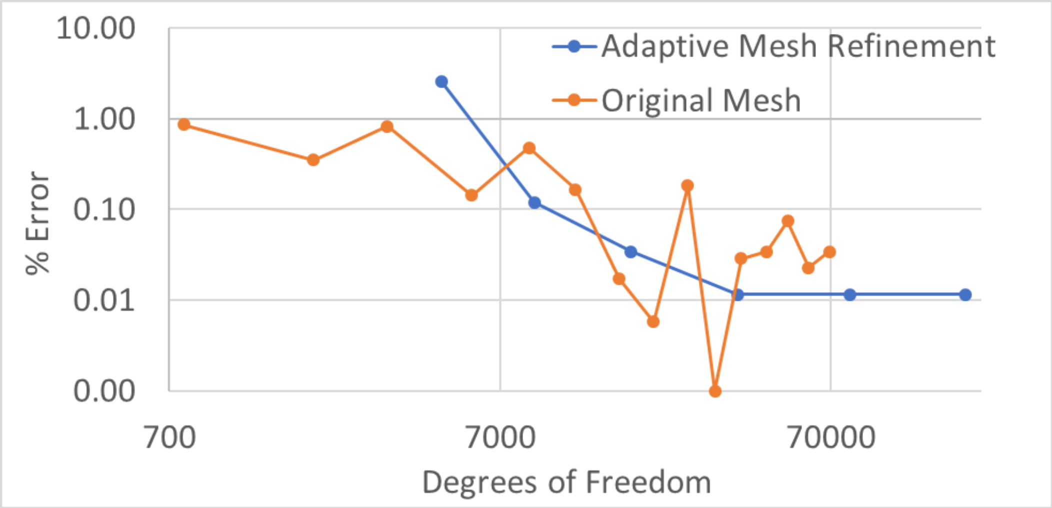
# Mesh Convergence Study

- Percent error calculated as the difference between the predicted horizontal component of the magnetic field and its exact value, divided by the exact value, multiplied by 100



# Adaptive Mesh Refinement

- Used COMSOL's adaptive mesh refinement to get more accurate results with less meshing effort
- Start with a very coarse mesh and let COMSOL do the refinement!
- The figure below shows that in general, for the same total number of elements, the error was lower for the adaptive meshing compared to the manual meshing

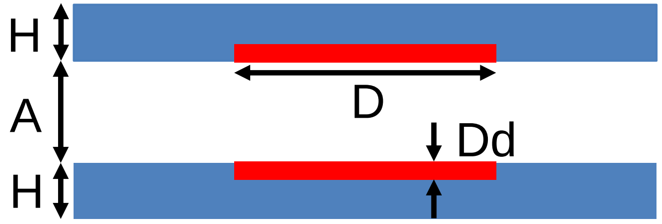


# Probe Reading of Idealized Component

# Blade Geometry

- Developed computational models used to predict reading of Magnetoscop 1.070 when there are hot corrosion zones within a section of a component
- The figure below shows a cross section of an idealized geometry double walled component

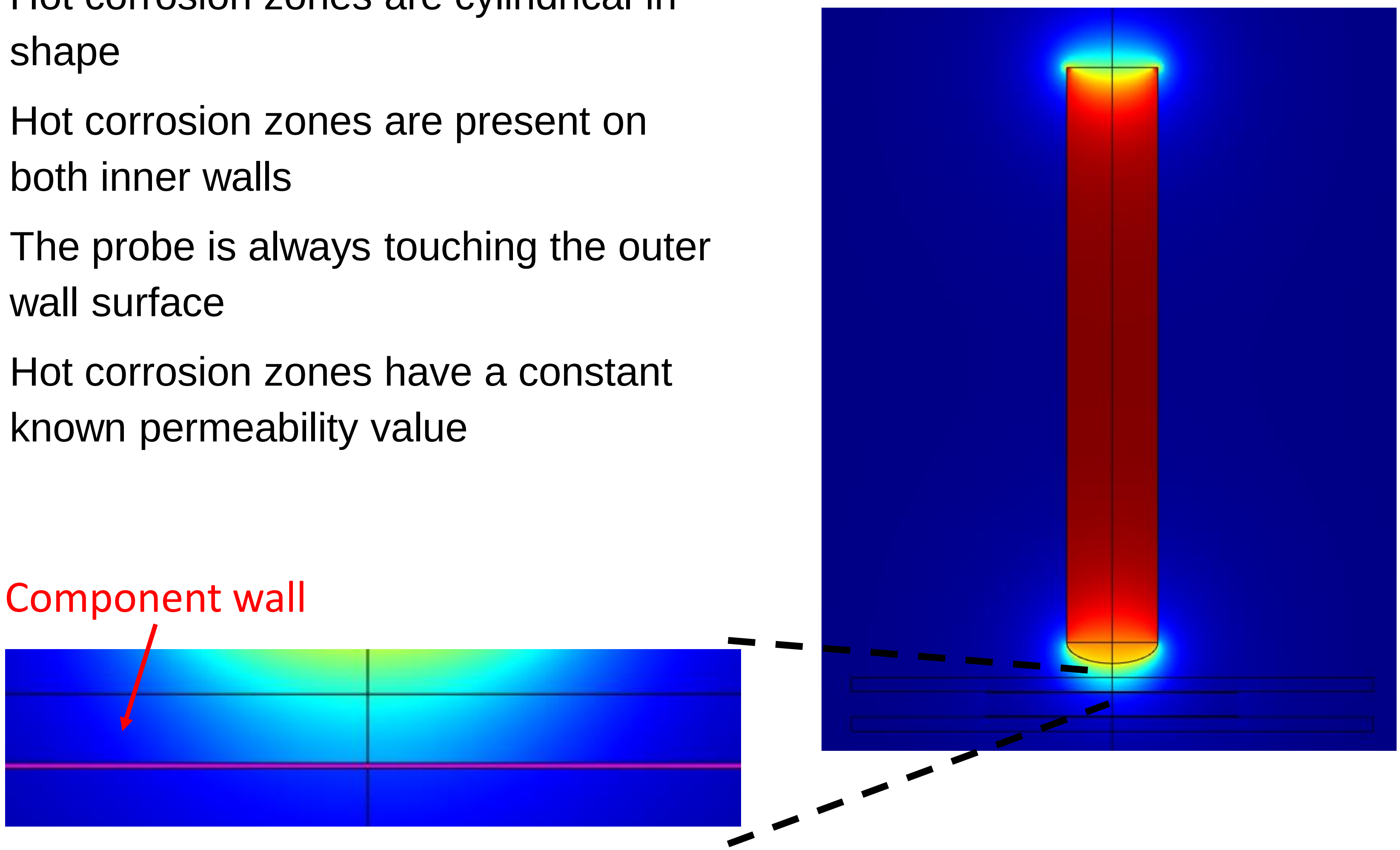
| Variables | Description |
|---|---|
| H | Thickness of component wall |
| A | Distance between component walls |
| D | Diameter of hot corrosion zone |
| Dd | Depth of hot corrosion zone |




Idealized Double Wall Component

# Model Assumptions

- Hot corrosion zones are cylindrical in shape
- Hot corrosion zones are present on both inner walls
- The probe is always touching the outer wall surface
- Hot corrosion zones have a constant known permeability value

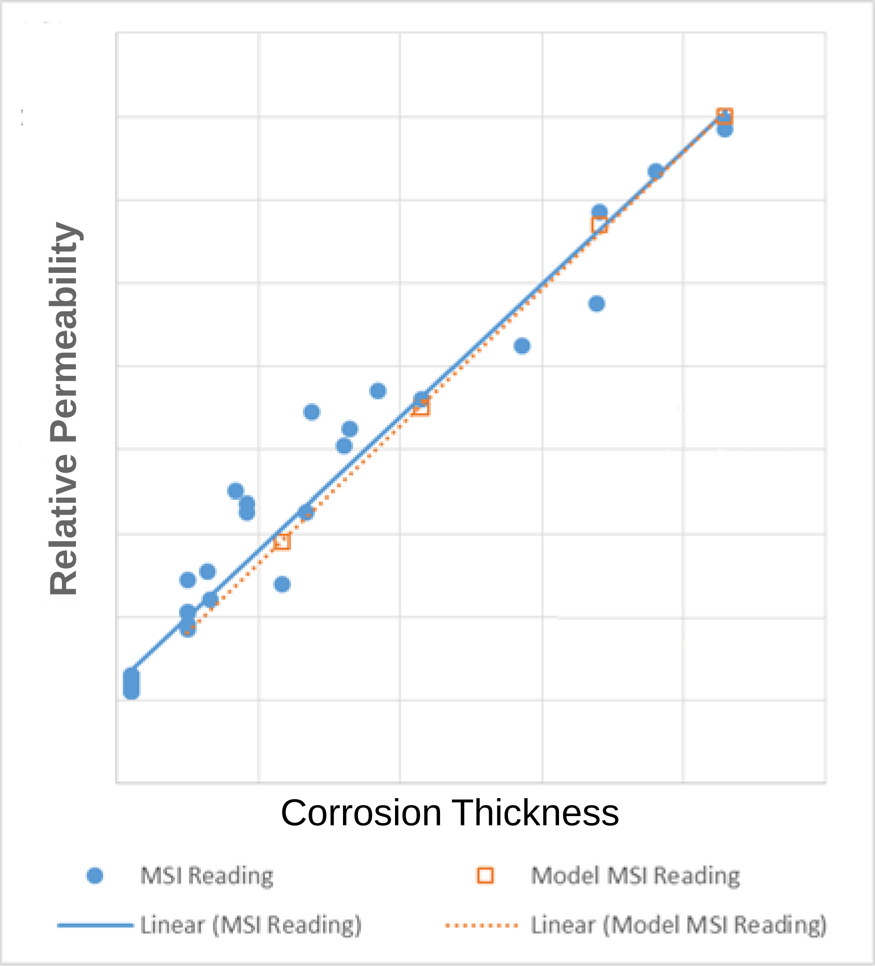


# Simulation

- We defined the H (wall thickness) and A (gap between walls) based on the dimensions at specific component locations
- Simulations ran with hot corrosion zones for all combinations of a range of diameters and depths
- For each case, the horizontal magnetic flux density evaluated at the measurement point was converted to a relative permeability, as detected by the probe, using the verified calibration table
- We determined the combinations of the minimum/maximum detectable diameters and depths of hot corrosion zones that output probe readings
  - Were able to relate the recorded probe reading to the min/max dimensions of a hot corrosion zone

# Results Comparison

- This figure shows a plot of permeability results from simulation and measurements on actual component
- Excellent agreement between modeling and measurements



# Summary and Findings

# Summary

- Magnetic permeability probes can detect hot corrosion zones caused by sulfidation corrosion in nickel super-alloy components
- Computational models that predict the magnetic permeability measured by the Magnetoscop 1.070 probe were developed
- Models validated with experimental data
- Models used to predict reading on Pratt & Whitney components to determine the minimum dimensions of the hot corrosion zone for detection by the probe