AI/ML for Tubing EC Analysis

Determining Efficacies of ML Tools to Improve Tubing Flaw Depth Sizing

Nuclear

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Motivation

- Eddy current (EC) techniques are commonly used in balance-of-plant (BOP) heat exchanger (HX) tubing inspection
- Current practices are challenged to accurately depth size damage cause by microbiologically influenced corrosion (MIC):
  - Unnecessarily remove tubes from service $\Rightarrow$ impact performance
  - Unexpected leaks $\Rightarrow$ impact safety
- Simplistic sizing: mono-parametric approach based on calibration curves typically built on single, specific defect profile.

Can Machine Learning help improve sizing accuracy?

Approach

Specimen Inventory	Data Acquisition	Benchmark	Machine Learning
• Separate specimen sets for train/test • ID pits • Several defect profiles	• Additional frequencies • Multiple pulls	• Assess performance following current practices • Multiple calibration references	• Develop models • Assess performance

Approach

Specimen Inventory → Data Acquisition → Benchmark → Machine Learning

Develop models for ID pits

Adapt for MIC (see 1013454)

Specimen Inventory

- 19 tubes for train, 4 for test
- 9 flaws per tube
- Flaw profiles:
  - Round pits
    - 5 diameters from 1.59 to 6.35mm
  - Rectangular (axial) pits
    - 5 aspect ratios from 2 to 8
  - Rectangular (circumferential) pits
    - 5 aspect ratios from 1/8 to 1/2
- Training tubes:
  - Aligned defects, all same profile
  - Depths of 10%, 20%, 30%, …, 80%, 100%
- Test tubes:
  - Varied profiles, depths, angular location

Material	304 Stainless Steel
Outside Diameter	1 in. = 25.4 mm
Wall Thickness	0.028 in. = 0.711mm
Length	24 in. = 609.6 mm

Training tube with round pits

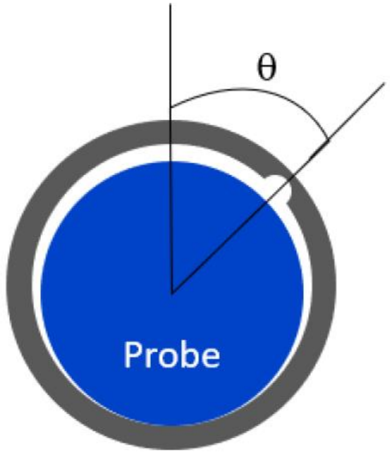
Training tube with axial pits

Training tube with circumferential pits

Test tube

Data Collection

- Absolute and differential modes
- 10 frequencies
  - 4 typically used in EC inspections
  - 6 extras, mainly higher than prime
- 36 pulls at different tube rotations
  - Every 10°



Frequency (kHz)	Prime Frequency Factor
100	0.11
220	0.25
440	0.50
660	0.75
880	**1.00**
990	1.12
1100	1.25
1320	1.50
1540	1.75
1760	2.00

Frequencies typically used in EC
Additional frequencies

Benchmarking: Manual Sizing

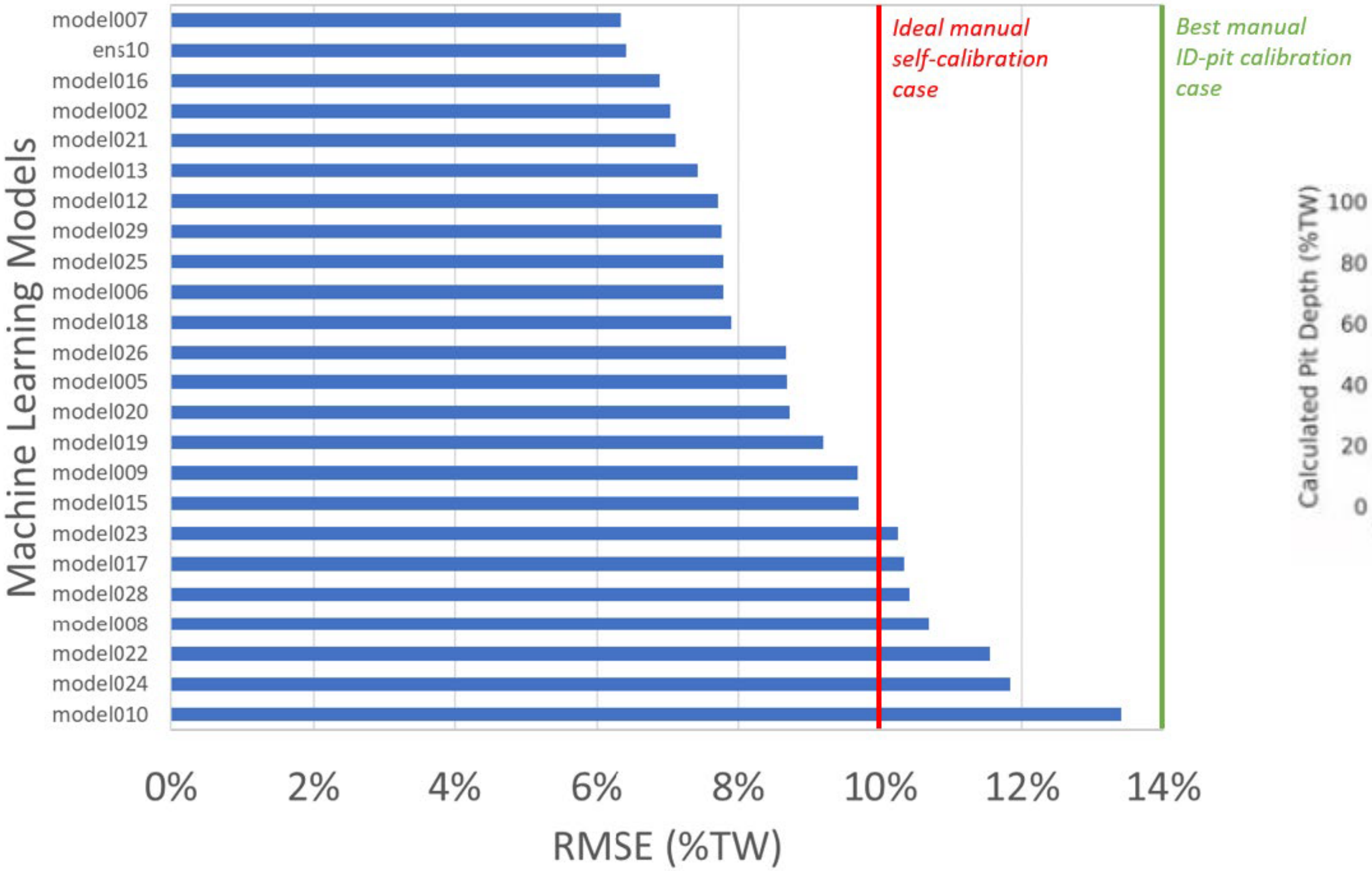
Case	Reference	Target	What It Represents	RMSE (%TW)
Self-Calibration	Same as target	All training tubes	Utopic best-case scenario where reference and target defects match perfectly. Used as a reference for upper limit for performance of manual analysis. Not expected to be achieved in the field.	10%
ASME Calibration	ASME	All test tubes	Performance based on available ASME standard (OD defects), without using any custom reference standards.	24%
ID Pit Calibration	Each of the seamless training tubes	All test tubes	Typical field scenario, where reference defect profiles are not expected to match the unknown target defect. Provides an assessment of variance in performance based on choice of reference standard.	14 – 29%

Machine Learning Models

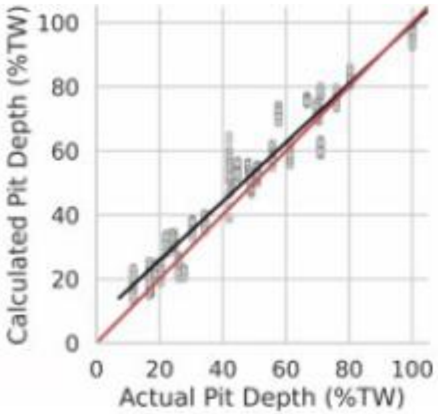
- 10 frequencies × 2 modes × 2 signals = 40 waveforms
- Trained on data from several pit profiles, at several angular locations
- 300 total features
  - Amplitude, phase, correlations, frequency analysis components, etc…
- 24 different models
  - Linear, **random forest**, MLP, KNN, SVM
  - Feature selection (statistical, lasso, etc)
  - Multiple strategies
    - **Regression models**
    - Classification for TW holes + regression for others
    - Multi-label classifiers (binned depths)
  - **Absolute** (mm) and relative (%TW) scales
  - Ensemble of top 10 models (mean)

Performance Comparison

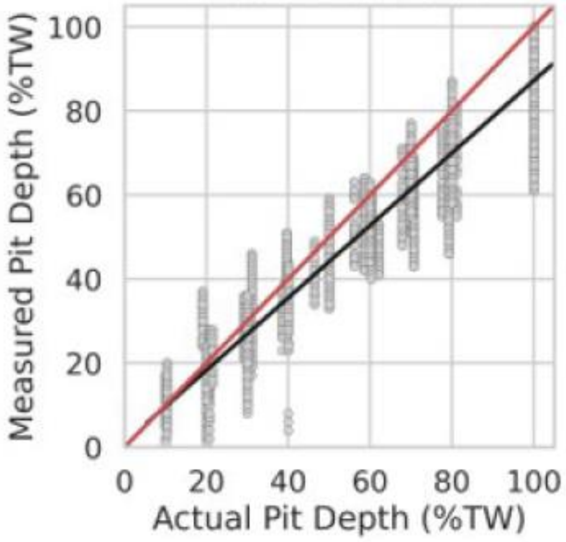
- Machine learning out-performs self-calibration case by 40%



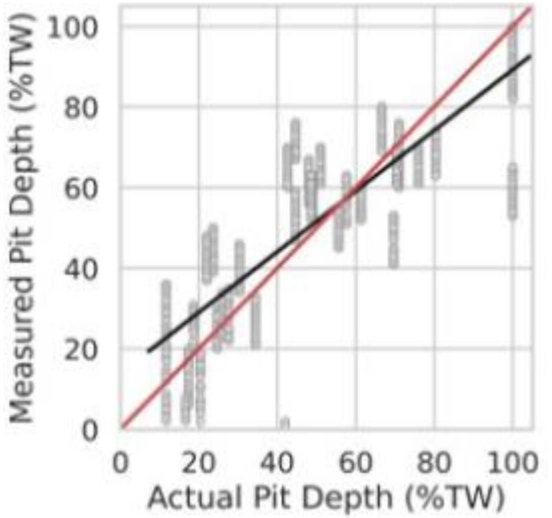
Ensemble ML model
RMSE: 6%TW



Self-Calibration
RMSE: 10%TW

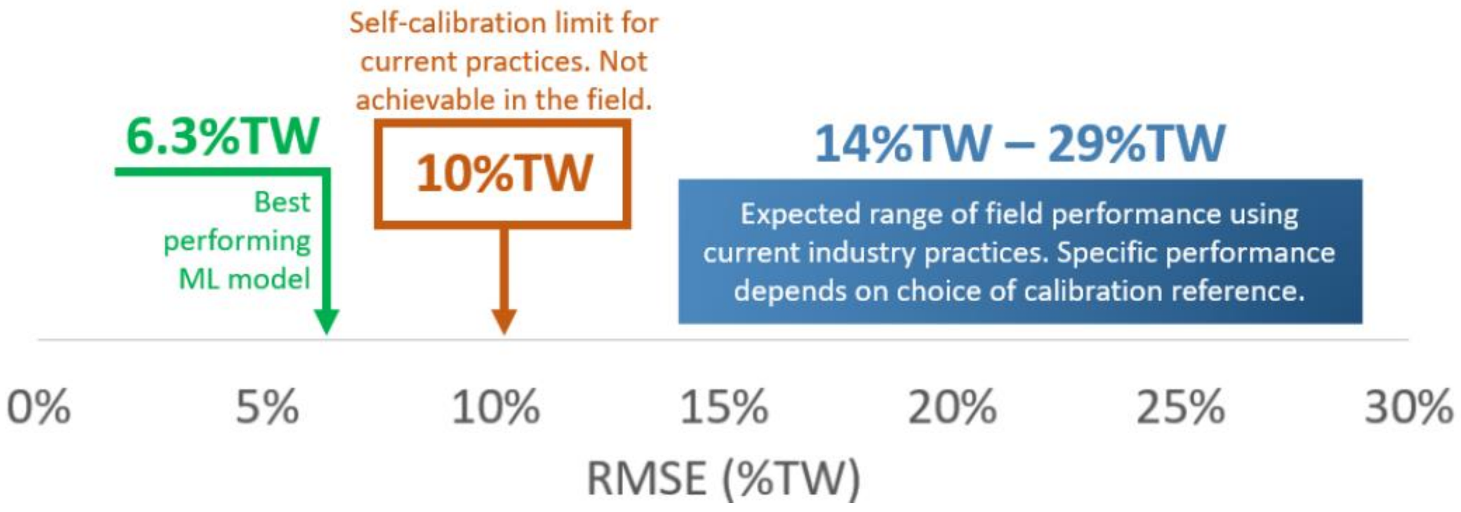


Best ID pit reference
RMSE: 14%TW



Remarks on ID Pit Sizing

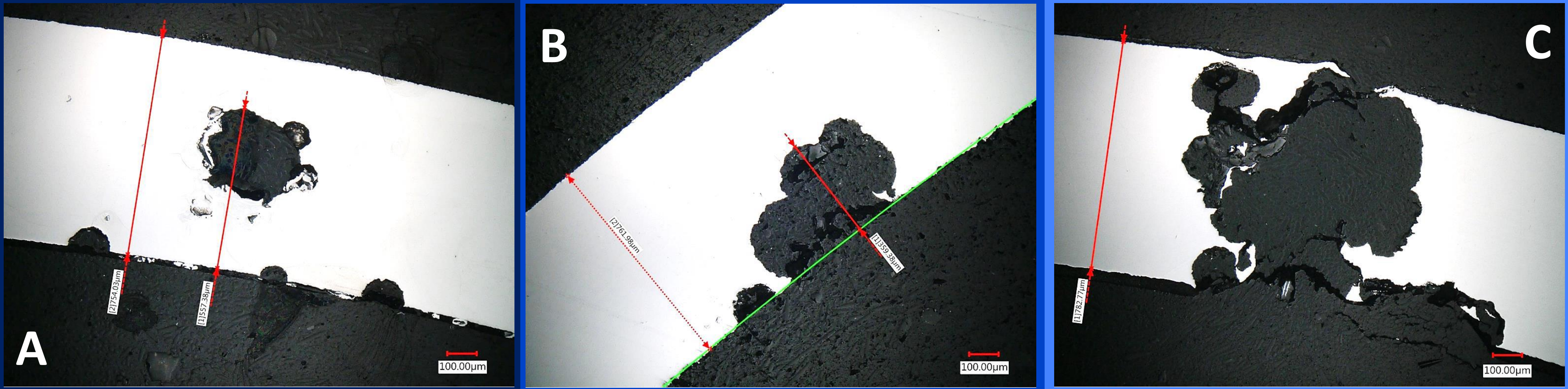
- Performance of current practices vary significantly depending on choice of calibration reference
  - Biased measures observed in some cases
- Results show ML methods to be at least 2× more accurate than expected performance following current practices
  - 40% better than limiting self-calibration case
  - No need to choose calibration reference



Machine Learning to Improve ID Pit Sizing in Balance-of-Plant (BOP) Heat Exchanger Tubes: Target—Type 304 Stainless Steel Tubing (3002021048)

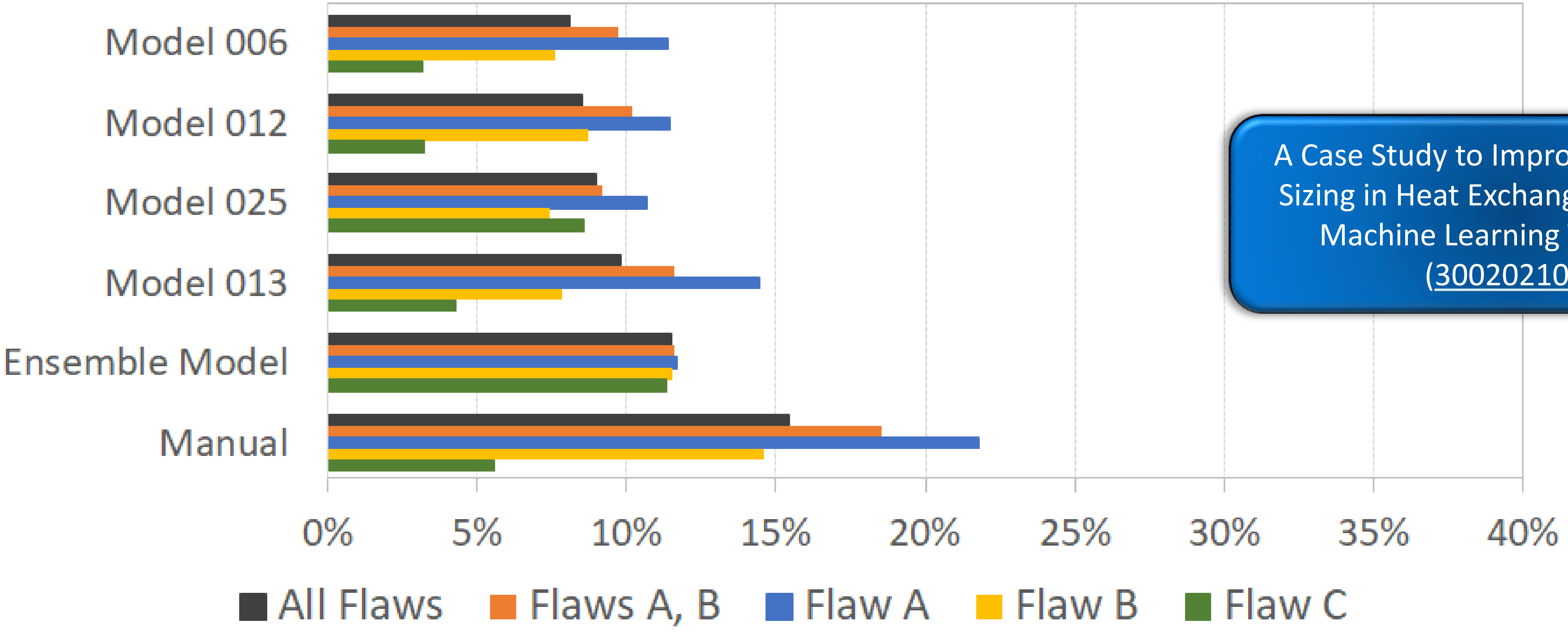
Field MIC Damage

Field-removed tube supplied by member utility



What happens when we apply the models directly to this?

Applying Models to MIC Damage



A Case Study to Improve Flaw Depth Sizing in Heat Exchanger Tubes with Machine Learning Techniques (3002021042)

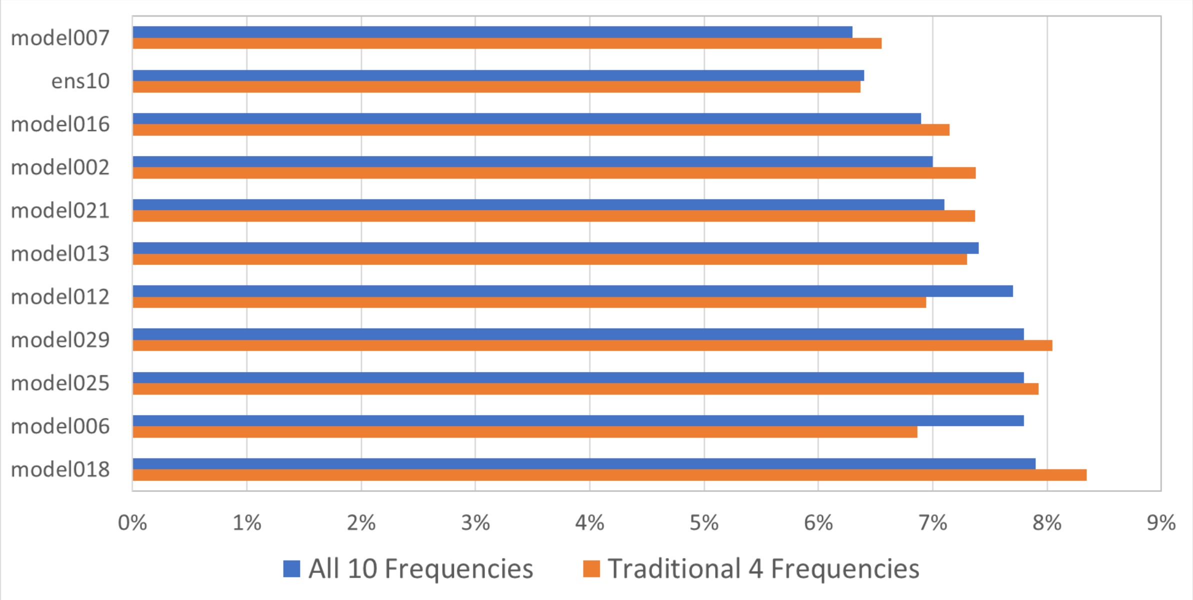
Top models still out-perform manual by approximately 2×

What If We Only Have the Fab-Four?

- Top-10 models re-trained to use only traditional 4 frequencies
  - 1×, 0.5×, 0.25×, 0.125× prime
- No significant performance degradation observed

Models can be leveraged with current industry data collection practices

Frequency (kHz)
100
220
440
660
880
990
1100
1320
1540
1760



Future Efforts

2025-2027

- Staring New Project in 2025 titled: Harnessing Machine Learning (ML) Tools to Depth Sizing Tubing Flaws.
- Target: 90/10 CuNi, 1.0” OD x 0.035” wall thickness (25.4mm x 0.889mm).

2025 – Tasks, Eddy Current (EC) Inspection

- Prepare draft inspection technique sheet with required parameters to enable EC and ML
- Perform bobbin coil eddy current inspection to identify tubes with and without indications.
- Extract some tubes for destructive analysis to determine types of defects seen.
- Fabricate the known defects in calibration standards.
- Update inspection technique sheet.
- Perform eddy current inspection on all accessible tubes in the heat exchanger.
- Evaluate and report all conditions (relevant and non-relevant indications).
- Extract some tubes with indications for detail destructive analysis to obtain ground truth.
- Compare eddy current results with ground truth measurements and if necessary, tweak analysis technique to improve eddy current measurements.
- Finalize examination technique specification sheet (ETSS), results, and prepare white paper.
- Include results in BOP tubing inspection best practice database during next update, ~2026

Future Efforts

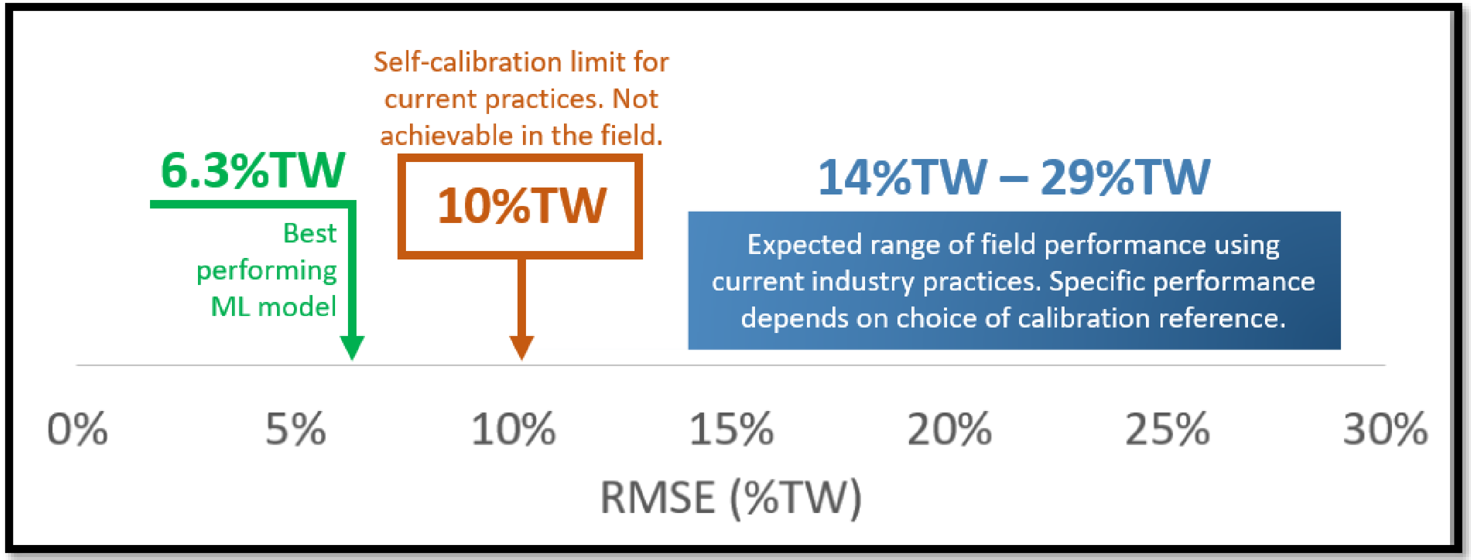
2026-2027

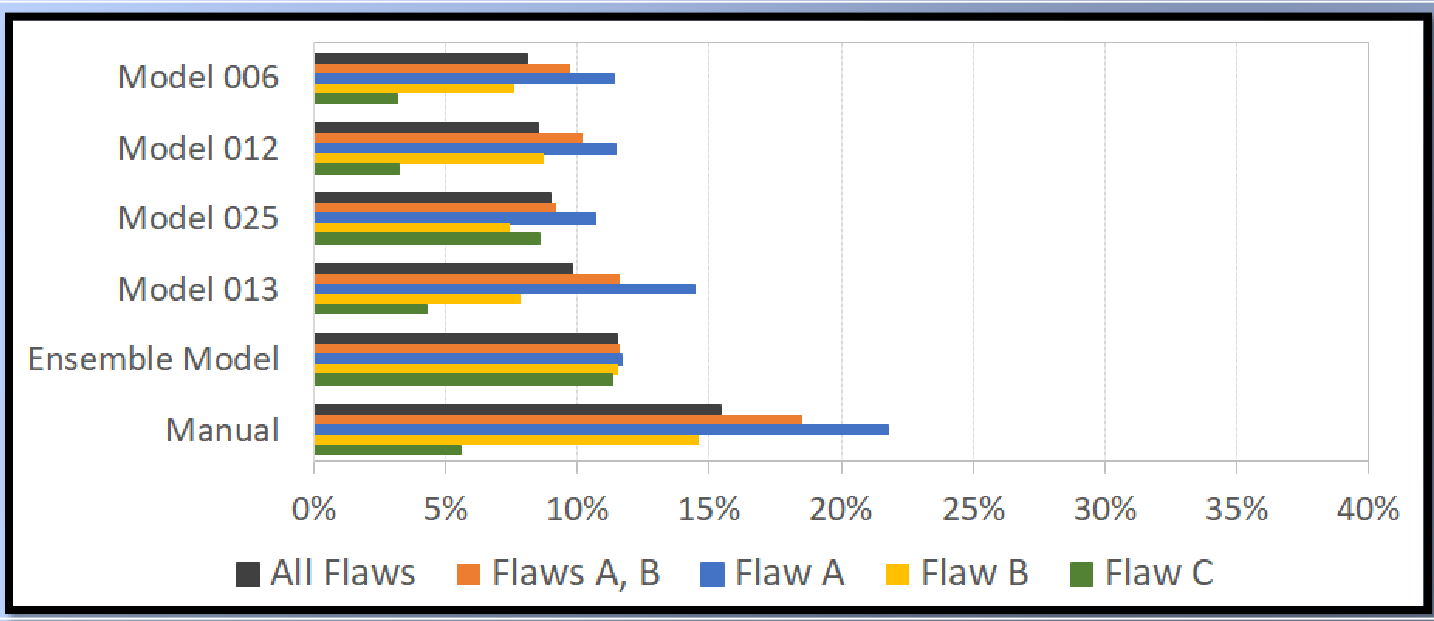
- **Tasks, Machine Learning (ML) Investigation**
  - Use the acquired raw eddy current data and run previously developed sizing models for initial assessment.
    - Gain insights into model generalization capabilities
  - Develop detection, characterization and (potentially new) sizing models for a full solution for both applications (SS304 and 90/10 CuNi)
    - *Detection & characterization*: new for both applications
    - *Sizing*: SS304 models may be updated; new for 90/10 CuNi
  - Compare ML results with Eddy Current and ground truth results.
  - If required, acquire EC data with additional frequencies and evaluate EC models.
  - If required, extract additional tubes for destructive analysis to obtain ground truth and compare results.
  - Work with industry to identify preferred implementation method

Summary

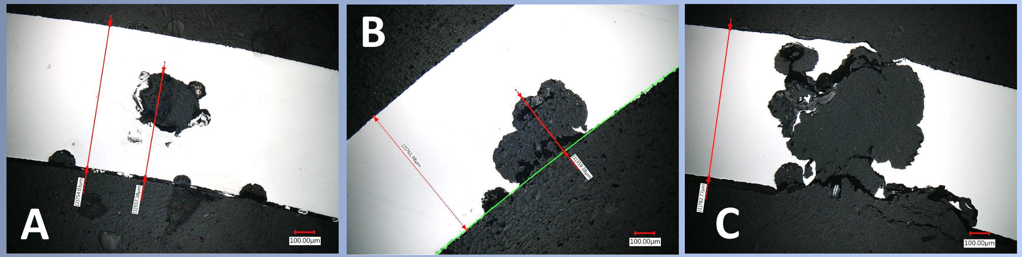
ML approaches offer improvement in ID-pit sizing accuracy when compared to industry practices
(see 3002021048)

Note: ML does not require a choice of reference standard





Direct applications of the models improve MIC depth-sizing as well
(see 3002021042)



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