Probabilistic Evaluation of the Impact of Inspection Uncertainties On the Estimation of Flaw Growth Rate

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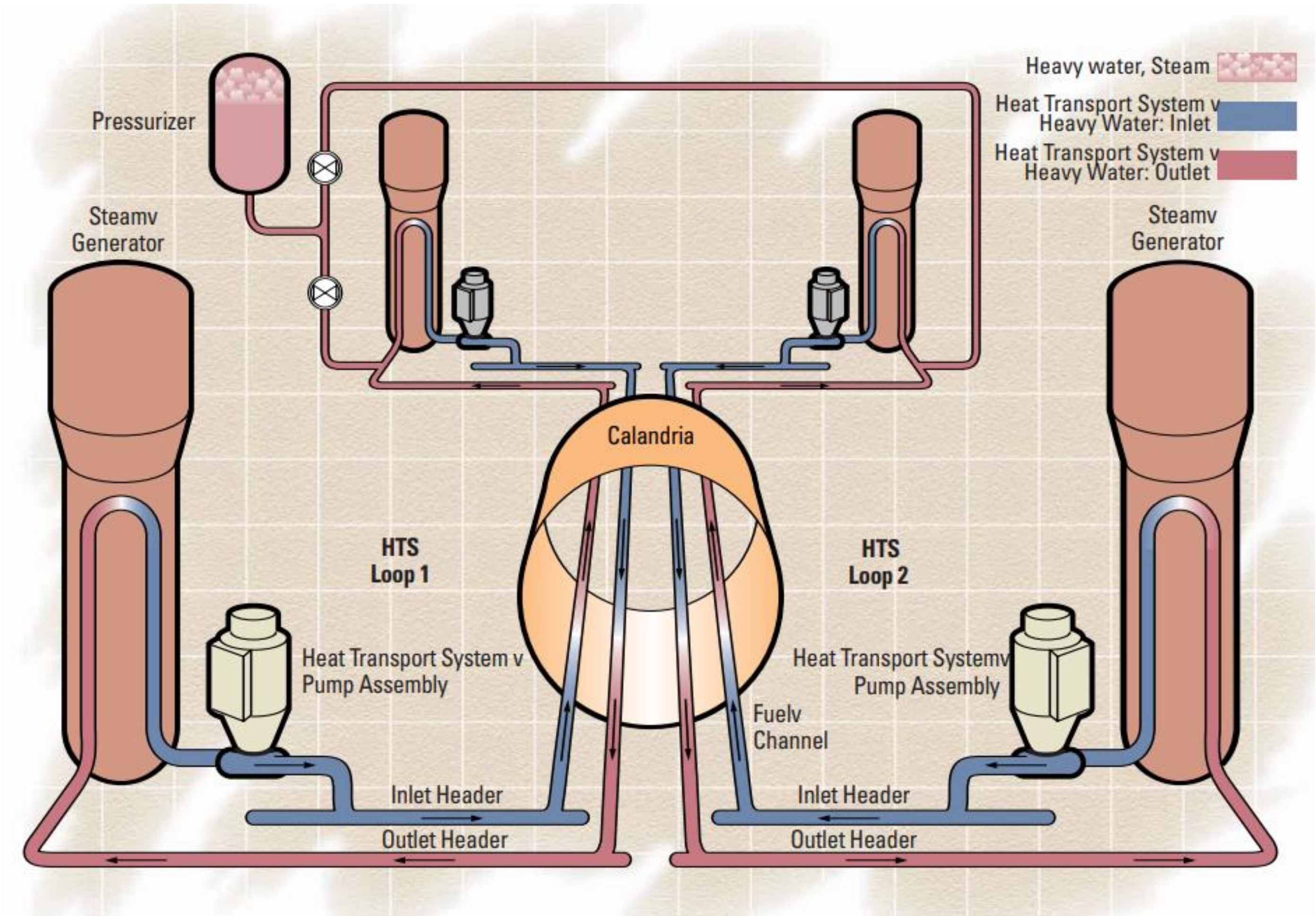
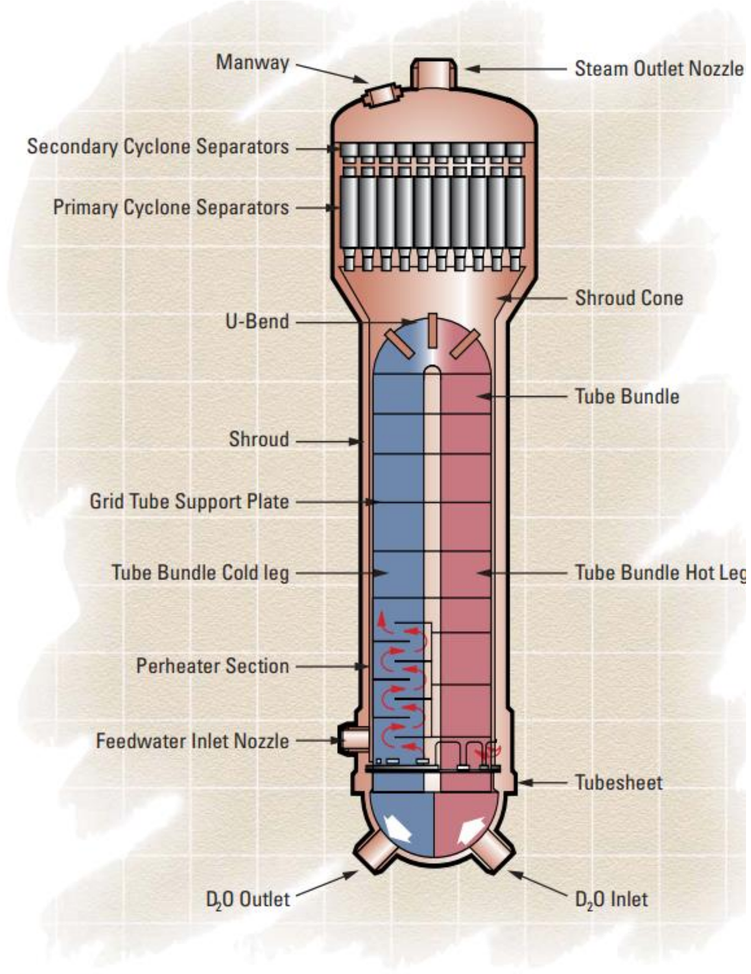
Outline

- Introduction
- Flaw growth model
- Uncertainties in eddy current probes
  - Probability of detection (POD)
  - Sizing error (SE)
- Considerations for sizing error
- Development of probabilistic modelling approach
  - Account for the effect of sizing error on measured flaw sizes
- Closing remarks
- Acknowledgements

CANDU 6 heat transport system and steam generator





Steam Generator

Pictures from CANDU 6 Technical Summary, Atomic Energy of Canada (AECL), 2005

Periodic inspections of SG tubes

Periodic inspections have played a major role in demonstrating fitness for service of SG tubes

purpose: detect and size existing flaws in SG tubes

discover development of any new degradation

Non-destructive examination (NDE) methods and probes for SG tubes

eddy current (EC) probes (bobbin, X-probe) – principal inspection methods

ultrasonic (UT) probe – used for more detailed sizing of already detected flaws

The Canadian nuclear industry has predominantly maintained the required structural integrity and reliability of SG tubes

Fitness-for-service evaluations of SG tubes

Operational assessment (OA)

forward look and predicted progression of known degradations over the next evaluation interval or next inspections

predicted flaw sizes at the end of evaluation period and demonstrated satisfaction of fitness-for-service criteria

plug SG tube if predicted flaw size exceeds the plugging criteria

Condition monitoring assessment (CMA)

comparison of present periodic inspection (PI) or in-service inspection (ISI) results to predictions

backward look at the change in degradation process and degradation rates

flaw growth observed at present examination should not be unexpected while degradation progresses

Considerations for developing probabilistic approach

Estimation of flaw growth rate is considered one of the key influential factors in operational assessments of SG tubes

Adopting generic probabilistic approach features

- uncertainties associated with NDE probes are recognized and included
- probabilistic methods explicitly account for distributed uncertainties

Investigation objective

- assess conservatism in estimates of flaw growth rates, recognizing inspection uncertainties within a developed probabilistic framework
- quantify embedded conservatism in OAs of SG tubes

Flaw growth model

- Flaw growth model is needed for prediction of flaw size at next inspection interval
- Flaw growth rate (R) is considered an uncertain variable
- Linear flaw growth model is implicit in present evaluation methodologies
  - $x(\mathrm{t}) = x_0 + \Delta x(t) = x_0 + R \times t$

- Measured flaw growth rate: $= \frac{Y_2 - Y_1}{t_2 - t_1}$
- Actual flaw growth rate: $= \frac{X_2 - X_1}{t_2 - t_1}$
- Measured flaw sizes are contaminated by probe sizing error

Effect of sizing error on flaw growth rate estimates

- Flaw growth rate estimation from flaw distribution, inspected at two different outages (at the times t_1 and t_2)
- Consider inspected flaw of size $x(t_1)$ at previous outage (t_1)
  - flaw measurement is contaminated with sizing error (Z_1)
    - $\mathrm{Y}(t_1) = x_i(t_1) + Z_1$
- Consider the 2nd inspection of this flaw at present outage (t_2)
  - $Y(t_2) = [x(t_1) + R\Delta t] + Z_2, \quad R\Delta t$ = actual flaw growth
- Measured flaw growth
  - $[Y(t_2) - Y(t_1)] = R\Delta t + [Z_2 - Z_1]$
  - Equivalently: Measured growth = Actual growth + Sizing error component

Uncertainties of inspection probes

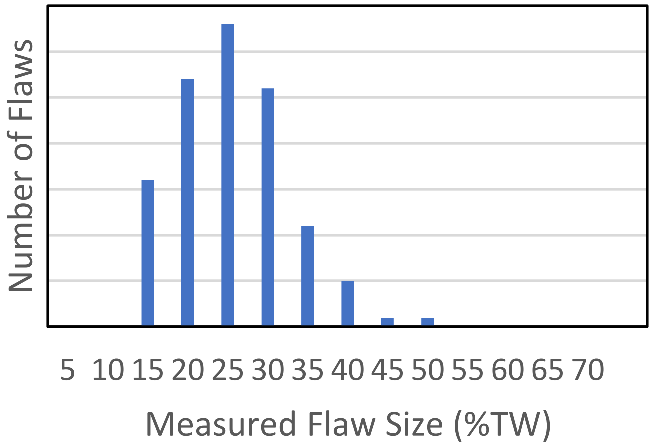
- Limitations of eddy current probes due to noise and other interference
  - flaw detection and flaw sizing are subject to variability
- NDE probe and inspection capability is quantified
  - probability of detection (POD)
  - sizing error (SE)
- POD and SE are characterized during qualification process of the inspection probe
- Investigation focused on accurately accounting for flaw sizing error

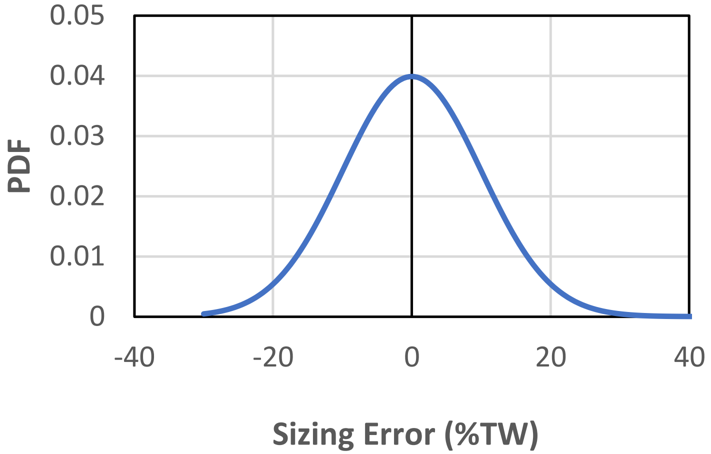
Flaw sizing error

- Measured flaw size is affected by sizing error
- Sizing error (SE) could be estimated through laboratory experiments
  - bobbin probe: sizing error is 10% through-wall (TW)
  - flaw sizes measured during inspection are different from actual flaw sizes
  - sizing error affects accuracy of reported flaw size used in fitness-for-service evaluations
- Probabilistic inversion approach has been adopted
  - using measured flaw size data distribution of actual flaw size is determined
  - selected approach: maximum likelihood (MLE) method

Example inspection data

- SG tubing inspection provides sample of flaw size data
    - it is interpreted as a random sample of measured sizes (Y)
- Sizing error
    - assumed as a normally distributed random variable
    - mean = 0, standard deviation $\sigma_Z = 10\%$ TW





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Sizing error modelling

- Distribution of measured flaw size (Y)
  - sum of actual flaw size distribution (X) and sizing error distribution (Z)

$$Y = \text{actual flaw size } (X) + \text{random sizing error } (Z)$$

- How does the sizing error distribution mask actual flaw size distribution?
- Example
  - X follows lognormal distribution, mean 23% or 0.23 TW and COV = 0.3
  - Z follows normal distribution, mean = 0, SD = 10% or 0.10 TW
- The distribution of measured flaw size is computed by convolution relation

$$f_Y(y) = \int f_X(y - z) f_Z(z) dz$$

Effects of sizing error

The sizing error alters the distribution of actual flaw size

The measured flaw size distribution has higher spread (or uncertainty)

- The difference between the actual and measured distributions involves the effect of sizing error

Illustration of effect of sizing error, three category cases:

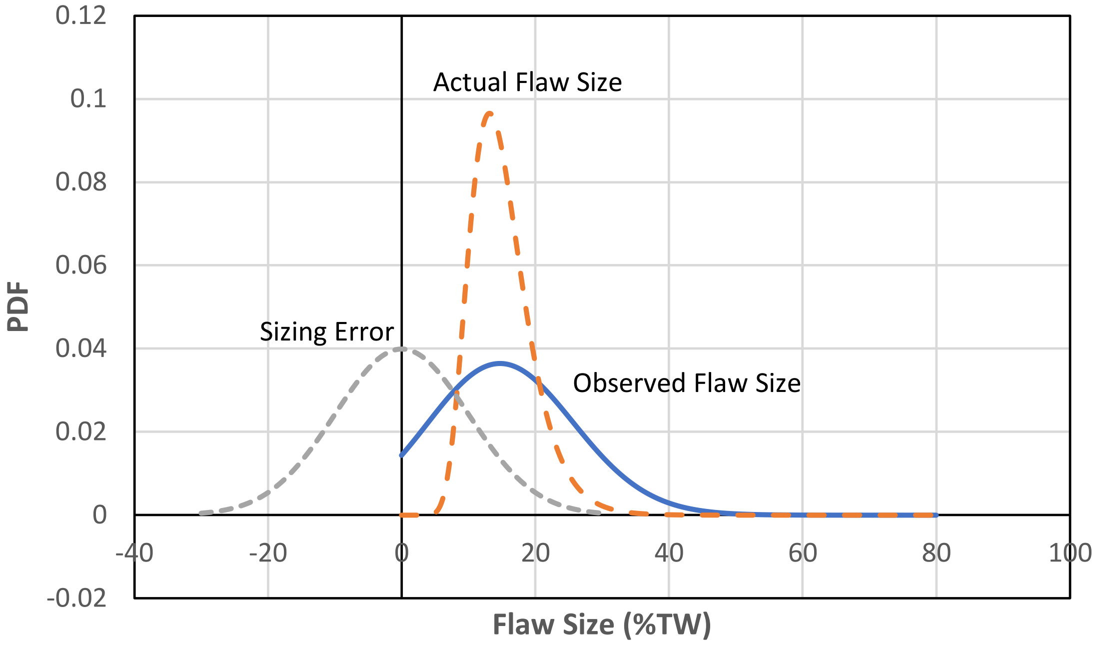
Case 1: Shallow flaw size (depth) distribution

- Actual flaw size distribution with the mean of 15% TW and COV = 0.3, follows lognormal distribution
- Sizing error, mean = 0, SD = 10% TW, follows normal distribution

Case 2: Medium flaw size (depth) distribution, mean = 30% TW and COV = 0.3

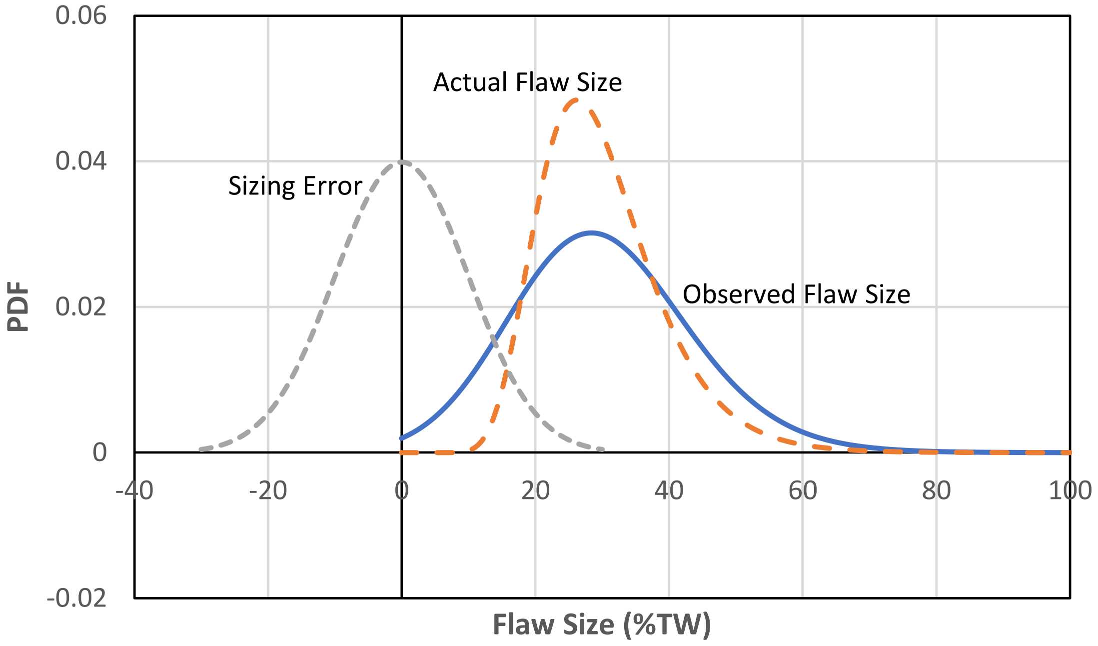
Case 3: Deeper flaw size (depth) distribution, mean = 50% TW and COV = 0.3

Case 1: Shallow flaw size distribution



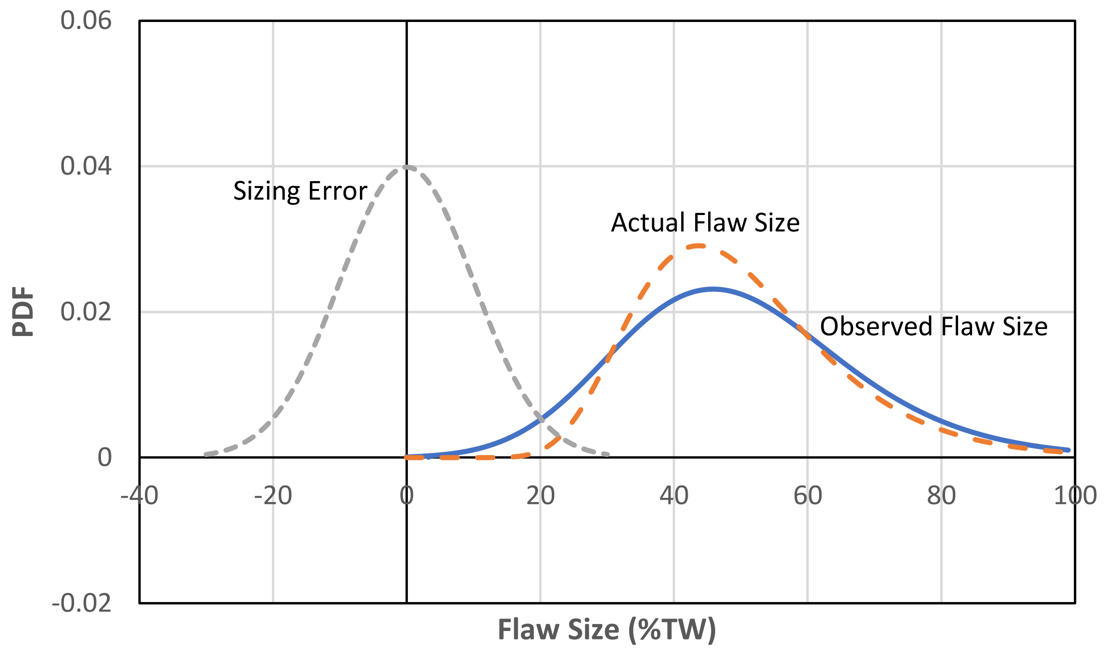
- Flaw sizing error shows significant effect on observed (measured) flaw size (depth) distribution
- Potential for both over- and underestimation of actual flaw size distribution
- Less significant from a fitness-for-service demonstration perspective

Case 2: Medium flaw size distribution



- Flaw sizing error has higher potential for underestimating actual flaw size (depth) distribution

Case 3: Deeper flaw size distribution

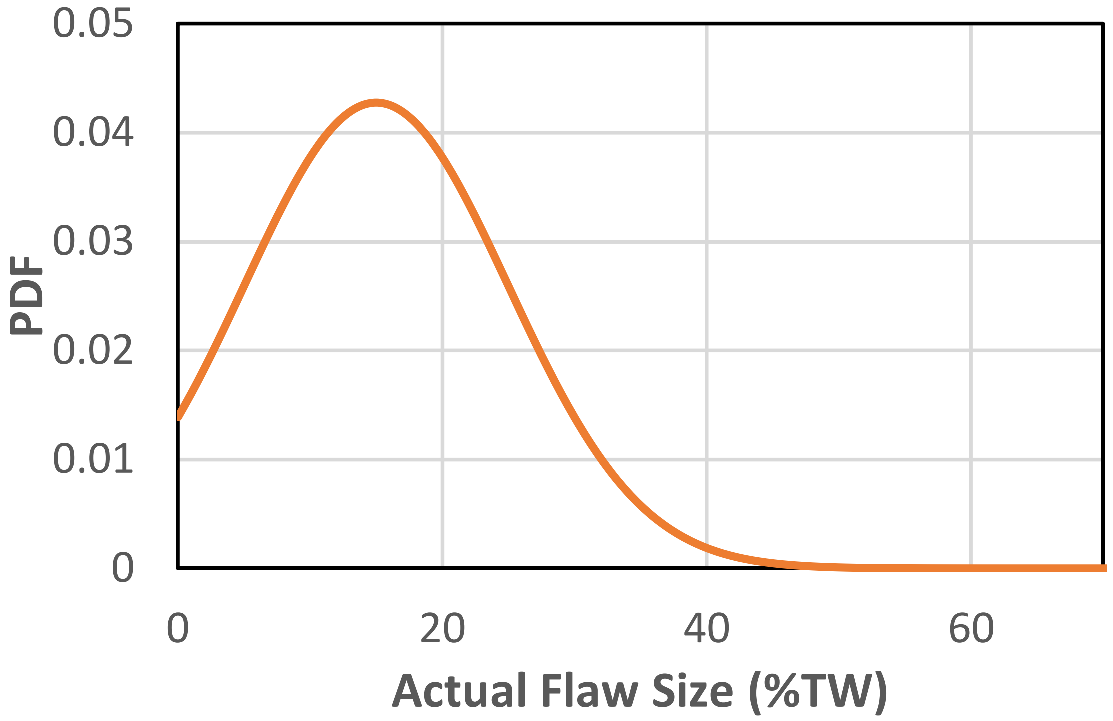


- Sizing error reflected with relatively less influence compared with small and medium flaws
- Deeper flaws are of more limiting from a fitness-for-service demonstration perspective

Flaw evaluation approach

- **Flaw evaluation approach is divided into two parts**
  - Assessment of inspected SG tube population
  - Assessment of un-inspected SG tube population
- **Inspected SG tube population**
  - Requires evaluation of detected flaws in inspected SG tubes
- **Uninspected SG tube population**
  - Actual flaw size (depth) distribution needed to predict condition of SG tubing
  - Estimated from reported flaw data obtained via inspections
- **Probabilistic analysis explored for both cases**

Case 1: Inspected SG tubes – measured flaw size data



- Actual size of each detected flaw has a distribution due to sizing error
  - Actual flaw size is unknown, since the impact of sizing error with the measurement is not known
  - Thus, the actual flaw size has its own distribution
- Example case:
  - Suppose flaw size, $Y = 25\%\,TW$, is measured by the EC probe
  - Measured flaw size distribution, $Y = X + Z$
- Evaluation of each detected flaw
  - Based on average of upper percentile of flaw size

Case 2: Uninspected tubing – flaw size distribution (1)

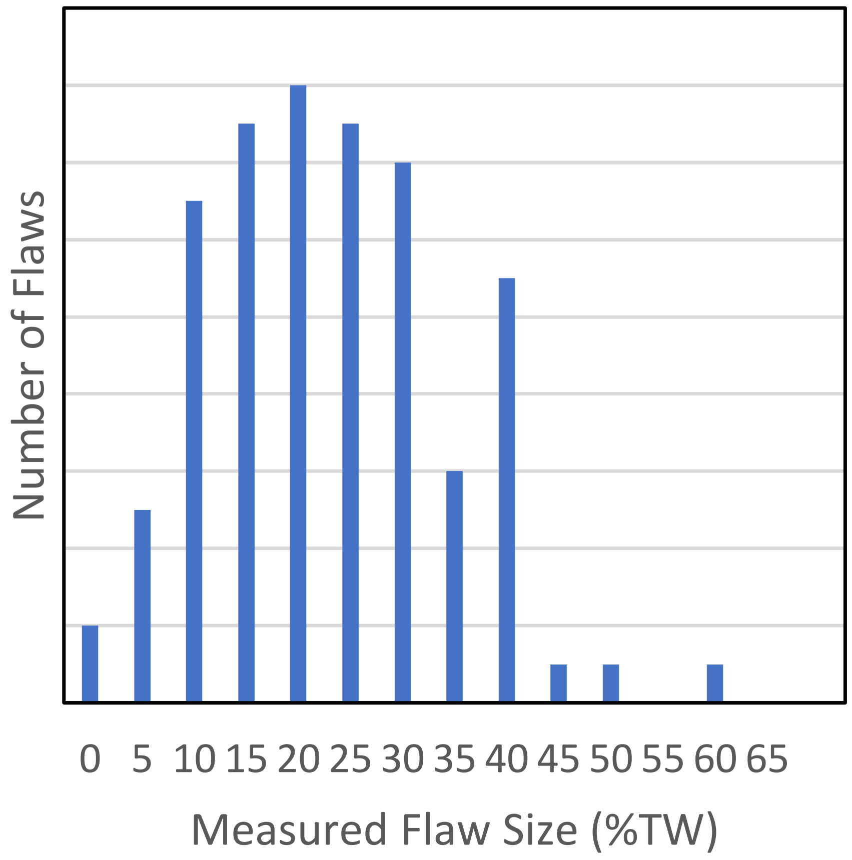
A key problem is to estimate the distribution of actual flaw sizes from the measured flaw sizes

- Maximum likelihood estimation (MLE) method for estimating parameters of actual flaw size distribution
- Parameters of the sizing error distribution can also be estimated

Example application

- Data required: measured flaw size data
- Sizing error is normally distributed
- MLE applied to estimate actual flaw size distribution

Case 2: Uninspected tubing – flaw size distribution (2)



- **Simulation-based illustration of MLE method**
  - Synthetic inspection data generated
  - Actual flaw size (X) assumed as mean = 20% TW and COV = 0.3, Lognormal distribution
  - Sizing error (Y): mean = 0, SD = 10% TW, Normal distribution
  - Simulate measured flaw size, Y = X+Z
- **Results**
  - Actual flaw size distribution
  - Parameters: $\mu_{LN} = 2.97$, $\sigma_{LN} = 0.36$
    - Mean size = 21% TW, COV = 0.36
  - Sizing error distribution
    - Mean = 0, SD = 8.6% TW

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Case 2: Uninspected tubing – flaw size distribution (3)

- Assessment of MLE results for actual flaw size distribution

Applied results (used in simulating the data)	**MLE results**
Actual flaw size: parameters $\mu_{LN} = 2.95, \sigma_{LN} = 0.29$	Estimated parameters $\mu_{LN} = 2.97, \sigma_{LN} = 0.36$
Flaw size distribution Mean = **20%** TW, COV = **0.3**	Estimated flaw size distribution Mean = **21%** TW, COV = **0.36**
Sizing error distribution – Normal Mean = 0, SD = **10%** TW	Estimated sizing error Mean = 0, SD = **8.6%** TW

- MLE estimates reasonably close to applied parameters

Remarks: MLE method for sizing error analysis

MLE in principle can be used for analyzing the sizing error problem

However, computational limitations are restrictive

Limitations

- Statistical separation of components of a “sum” is an ill-defined problem
- MLE method lacks monotonic convergence
- Results are sensitive to initial starting points
- The stability of MLE must be tested using “real” inspection data (synthetic data may not be representative of real situation)

Sizing error consideration: Canadian industry's approach

- In industrial setting, formal probabilistic analysis (such as MLE) is not performed
  - The distribution of sizing error and its random application to each detected flaw is not explicitly considered
- A simplified engineering approach has been adopted
- A fixed allowance is made for the sizing error, such as $SE = 10\%$ TW
  - This allowance is applied to each prediction of future flaw size over time
- Predicted flaw size, $x(t)$, at the end of the evaluation period (t)
  - $x(t) = [y_0 + SE] + \Delta x(t)$
    - where y_0 - currently measured flaw size by inspections
    - $\Delta x(t)$ – flaw growth over evaluation period, SE = sizing error allowance

Closing remarks

- A probabilistic approach has been explored to analyze the sizing error
- The influence of sizing error on measured flaw size distributions has been investigated
  - small- and medium-sized flaw distributions are more impacted by the sizing error
- The maximum likelihood method is investigated for estimating parameters of the underlying actual flaw size distribution
  - complexities and limitations of MLE have been highlighted
- A practical case application study is planned to further examine practical applications of selected modelling approach

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