Measurement Uncertainty and Decision Rules in NDT

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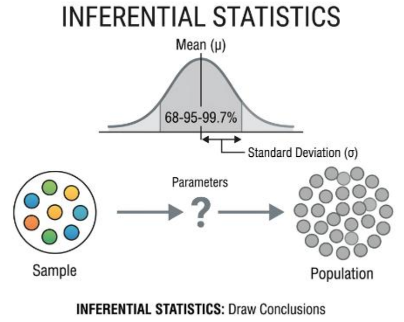
A few notes:

- I'm not a statistician

- Every approach will be different

- Standards / specifications in NDT rarely provide clear requirements for accounting for MU, and applying decision rules

- Everybody's risks and confidence levels will vary



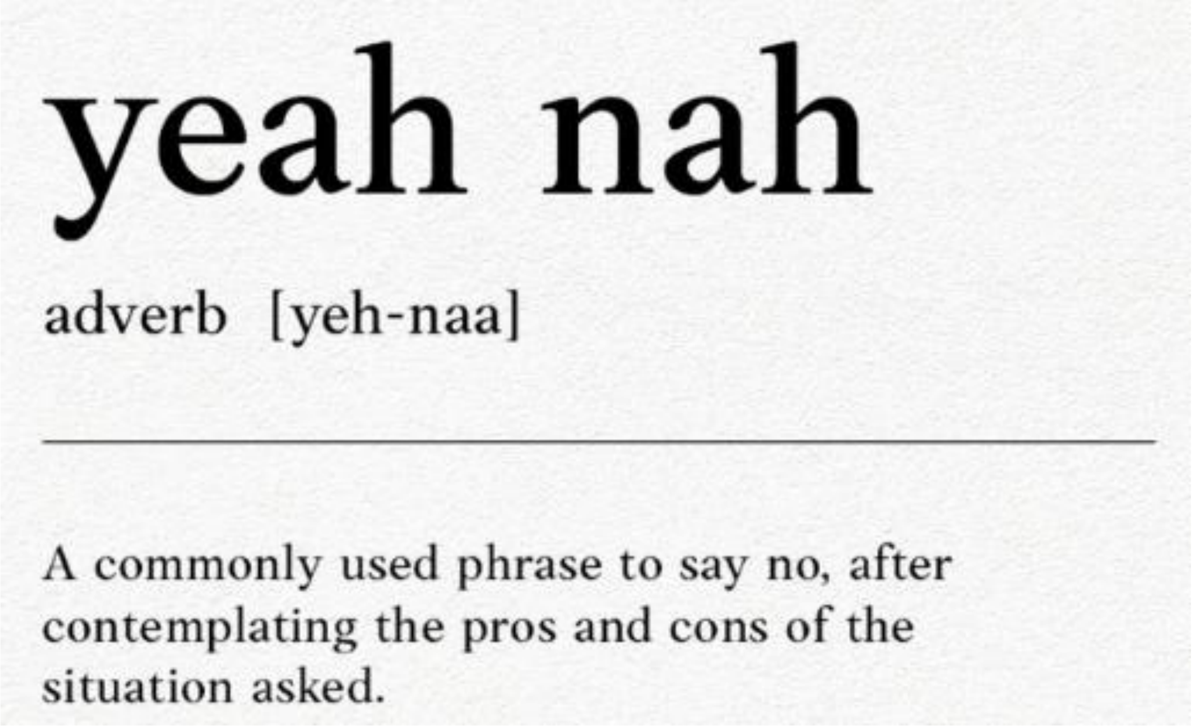
Topics:

- What is Measurement Uncertainty?
- When do we have to factor it in?
- Determining MU Values
- Applying MU Values
- Applying Decision Rules
- Tips
- Resources

What is Measurement Uncertainty?

- In general, no measurement or test is perfect, imperfections give rise to error of measurement in the result.

- Consequently, these errors could change the impact and compliance of a particular measurement.



Why the Uncertainty? - Errors

- Random errors arise from random variations of the observations
  - Random errors cannot be eliminated but the uncertainty due to their effect may be reduced by increasing the number of observations and applying statistical analysis

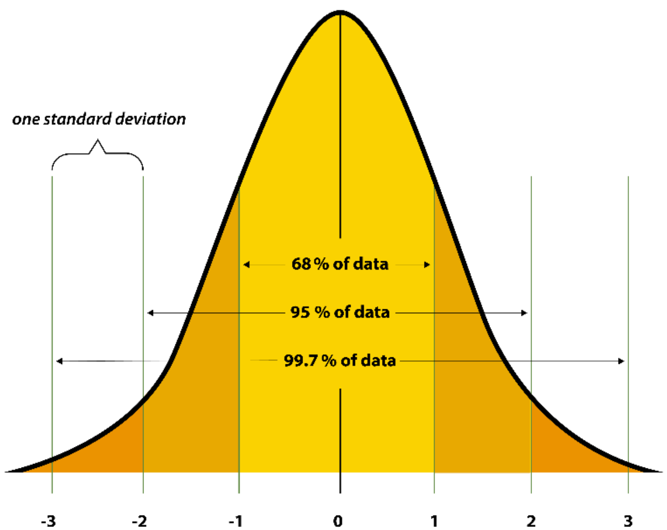
- Systematic errors arise from systematic effects
  - errors remain unchanged when a measurement is repeated under the same conditions
  - cannot be eliminated but may be reduced by correction
  - if no corrections are applied to the measurement, the difference between true value and measured value can be considered as an uncertainty component

A Quick Refresher

In a normal, bell-shaped distribution (a common pattern for measurement distribution), the standard deviation helps define where most values lie:

- Approximately 68% of the data falls within one standard deviation (σ) of the mean.
- Approximately 95% of the data falls within two standard deviations (2σ) of the mean.
- Approximately 99.7% of the data falls within three standard deviations (3σ) of the mean.

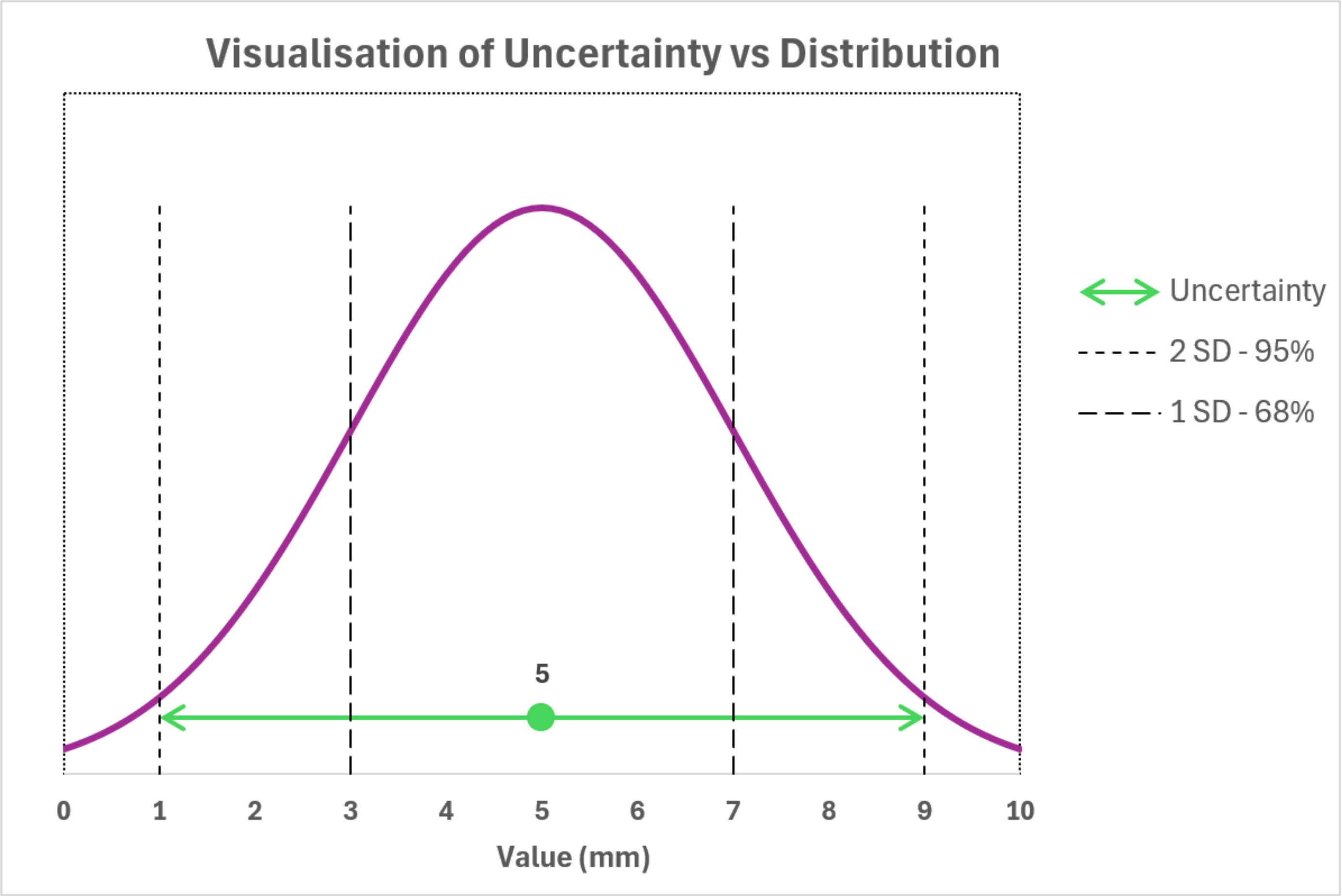
In simple terms, standard deviation measures the typical distance of data points from the average value.



Measurement	Mean	Square of Variation from Mean	Square Root of Mean Variation
2		9.766	
6		0.766	
5		0.016	
5	5.125	0.016	1.615
4		1.266	
5		0.016	
6		0.766	
8		8.266	

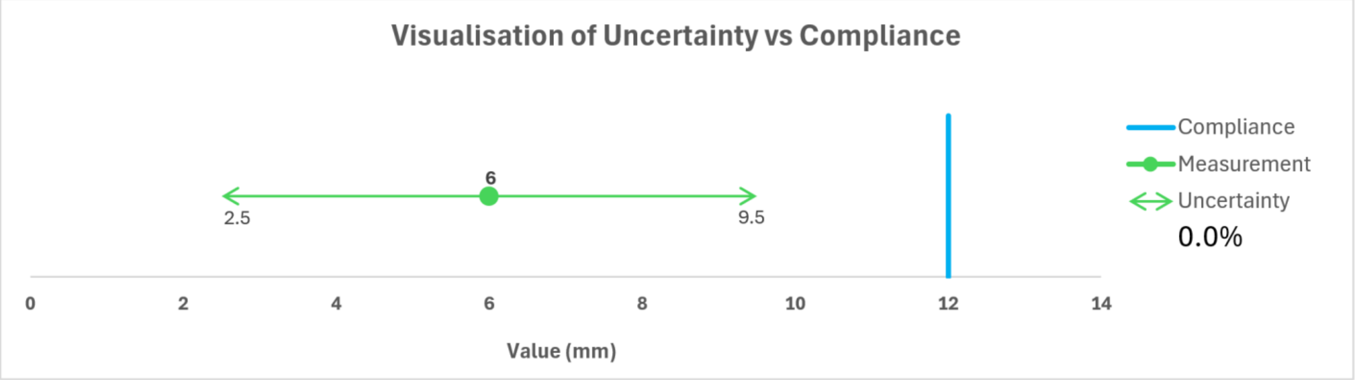
What is Measurement Uncertainty?

Method	Technique	Dimension	Measure	UM 95%	Measured	Upper	Lower
MT	CC / AC Yoke	Length	mm	4	5	9	1

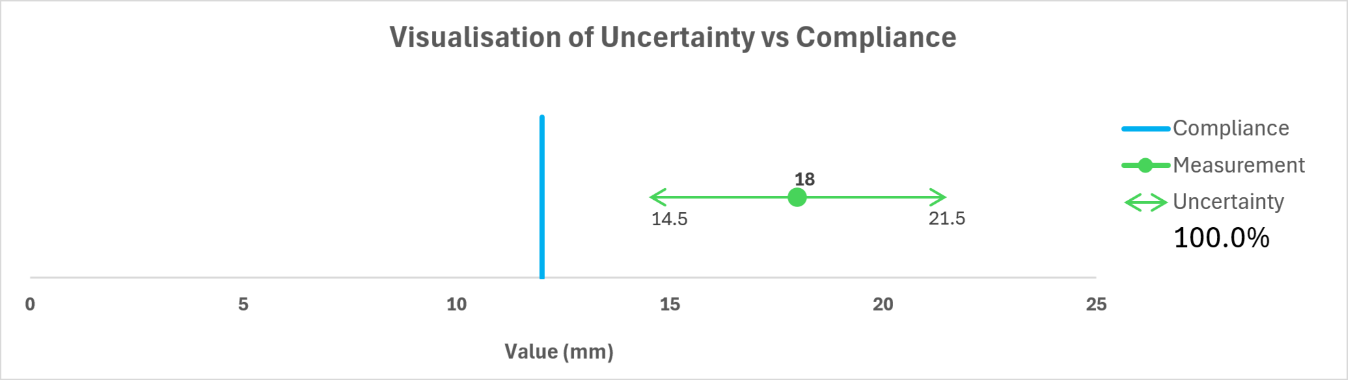


When Are We Certain?

Method	Technique	Dimension	Measure	UM 95%	Measured	Upper	Lower	Compliance Value	Likelihood Accept	Likelihood Reject
MT	CC / AC Yoke	Length	mm	3.5	6	9.5	2.5	12	100.0%	0.0%



Method	Technique	Dimension	Measure	UM 95%	Measured	Upper	Lower	Compliance Value	Likelihood Accept	Likelihood Reject
MT	CC / AC Yoke	Length	mm	3.5	18	21.5	14.5	12	0.0%	100.0%



When do we have to factor it in?

From ISO 17025:2017 - General Requirements For The Competence Of Testing And Calibration Laboratories

- 7.6.3 A laboratory performing testing **shall** evaluate measurement uncertainty.

- 7.8.3.1 c) when:
  - — it is relevant to the validity or application of the test results;
  - — a customer's instruction so requires, or
  - — the measurement uncertainty affects conformity to a specification limit;

- 7.8.6.2 The laboratory shall report on the statement of conformity, such that the statement clearly identifies:
  - a) to which results the statement of conformity applies;
  - b) which specifications, standards or parts thereof are met or not met;
  - c) the **decision rule** applied

The first edition of ISO 17025:1999 made clear reference to the requirement for measurement uncertainty and decision rules. **This is not a new requirement.**

Typical Application

Measurement Uncertainty is typically **not required to be addressed** in the following cases.

- Inspections that are to determine the presence of discontinuities only, or where any recorded measurements are <u>**not used**</u> to determine compliance with a code or specification.

  Typical examples are:

  - In-service Inspections, i.e.: report the presence of discontinuities
  - Thickness Testing

- Measurement Uncertainty is required to be addressed in the following cases.
  - As specified by the client, code or specification.
  - Where measurements will be used in determining levels of quality or compliance.

  Typical examples are:

  - Standards and Codes: AS 1554, AS 4037, B31.3 etc
  - Client specific codes and specifications.

Typical Measurements Taken With NDT

Magnetic Particle
- Length

Liquid Penetrant
- Length
- Area / Diameter

Ultrasonic Thickness Testing
- Thickness

Ultrasonic Corrosion Mapping
- Thickness
- Area

Ultrasonic Weld Inspection
- Length
- Height
- Depth

Eddy Current
- Coating Thickness
- Length

Radiography
- Length
- Diameter
- Area

Visual Inspection
- Length
- Depth
- Area

Determining MU Values – Empirical Estimation

- Based on actual inspection values, for a specific method and technique.
- For facilities which have the luxury of repeatedly testing similar items under a wide range of representative conditions.
- Where records for inter-laboratory comparisons are available, an empirical approach to uncertainty is possible, and in some circumstances can lead to a more reliable estimate of uncertainty.
- Provided that the sample size is large enough, twice the standard deviation of all measurements of a given item, ideally over an extended time period, would be expected to approximate to an estimate of uncertainty for the 95% range.

Determining MU Values – Error Range Conversions

It is necessary to list each aspect of the testing activity which contributes uncertainty to the final measurement and to make an estimate of the maximum reasonable contribution that each could make to the final test result – that is, the maximum amount by which the true value could be missed due to the particular source of error.

Steps:

- List all possible sources of uncertainty
- Evaluate each source of uncertainty
- Characterize uncertainties by type & distribution
- Convert uncertainties to standard deviations (σ)
- Combine uncertainty using the root-sum-of-squares method
- Expand uncertainty to 95 % confidence with a coverage factor (2σ)

Determining MU Values – Error Range Conversions

Examples of distribution types include:

Normal: For sampling (type A) assessment.

Triangular: Where hard limits can be estimated.

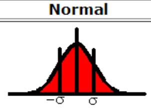
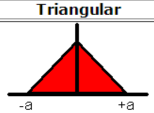
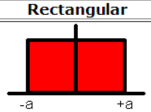
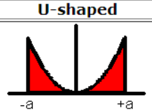
- Noise
- Vibration

Rectangular: Where only variation limits are known.

- Calibration Certificates
- Manufactures specifications

Step: When resolution is limited.

- Verniers
- Digital Readout

Type	Normal	Triangular	Rectangular	U-shaped	Step
Graphical Representation					
Equivalent Standard Deviation	$s = \sigma$	$s = \frac{a}{\sqrt{6}} \approx 0.4a$	$s = \frac{a}{\sqrt{3}} \approx 0.6a$	$s = \frac{a}{\sqrt{2}} \approx 0.7a$	$s = \frac{a}{2\sqrt{3}} \approx 0.3a$

Determining MU Values (NATA provided example)

1. Magnetic particle (magnetic flow) MU estimate

Error source component	Include? Y/N	Estimated 99% confidence range (mm) [note a]	Assumed distribution	Component standard Uncertainty	Squared Standard uncertainty	See notes
Contrast coating too thin	N					b
Contrast coating too thick	Y	+/- 1.0	Normal	0.3	0.09	
Poles of magnet too far apart	Y	+/- 1.0	Normal	0.3	0.09	
Edge only of magnet poles applied to test area	Y	+/- 2.0	Normal	0.7	0.49	
Insufficient particle concentration	N	Not considered (note b)				c
Excessive particle concentration – masks indication	N					c
Ruler – 1 mm graduations	Y	+/- 1.0	Normal	0.3	0.09	
Ruler- parallax error	Y	+/- 0.5	Normal	0.15	0.0225	
Level of experience of technician	N					d
Very/fine/tight/short crack	Y	+/- 2.0	Normal	0.7	0.49	
Defect not at 90° to magnetic field	Y	+/- 1.0	Normal	0.3	0.09	
Magnetization time too short/too long	N					e
Location/geometry of defect e.g., crack along weld toe (difficult to see location)	Y	+/- 2.0	Normal	0.7	0.49	f
Confined space/hard to access test area	N					f
Surface contamination	N					g
Inadequate lighting	Y	+/- 2.0	Normal	0.7	0.49	
A. Sum of squares of component values					2.3425	
B. Estimated combined std uncertainty (i.e. take square root after step 'A')					1.5305	
C. Estimated expanded uncertainty 95% range (i.e. 'B' multiplied by 2) **Or, expressed as MU at 95%confidence:**					3.061 i.e., **+/- 3.1mm**	

Determining MU Values (ISO 16809 example)

Parameter	Group	Factors	Measuring conditions	Estimated accuracy mm	
				Method a)	Method b)
Test object	Material	Composition	Ferritic steel	0	0
		Structure	Fine grained	0	0
		Anisotropy		0	0
	Surface condition	Cleanliness		0	0
		Roughness	Surface *Ra* = 6,3 µm	0,006 3	0,003 2
		Surface profile	Flat	0	0
	Coating	Coating	Not coated	0	0
		Paint	Not painted	0	0
		Surface treatment	Un-treated	0	0
	Geometry	Non-parallelism	Parallel faces	0	0
		Curve radius	No curvature	0	0
		Range	Negligible attenuation	0	0
Reference	Calibration method	Uncertainty of calibration method	Reference block Same material/5 step calibration	0	0
	Reference block	Thickness and velocity uncertainty	Thickness uncertainty: 0,01 mm Velocity uncertainty: ±30 m/s	0,05	0,025
Measuring	Equipment	Resolution	Digital instrument resolution: 0,01 mm	0,01	0,006
		Cable length	Fixed length	0	0
		Drift of instrument	Stable instrument	0	0
		Time of flight	Accuracy of time measurement: 10 ns	0,03	0,018
		Linearity	1 % of the maximum range (manufacturer's data)	0,1	0,05
Measuring	Operation	Trigger point	Constant amplitude	0	0
		V-path	Single-element probe	0	0
		Phase shift	No phase shift	0	0
Repeatability	Operation	Coupling	Coupling error included in method	0	0
		User training	Qualified operator	0,1	0,05
Miscellaneous	Temperature	Variation of sound velocity	Measurement at room temperature, negligible variation	0	0
			Global error	**0,296**	**0,135**

Multiple Discontinuities

- When applying MU against multiple discontinuities (e.g. AS 1554.1), the overall MU is not the sum of all MU's.

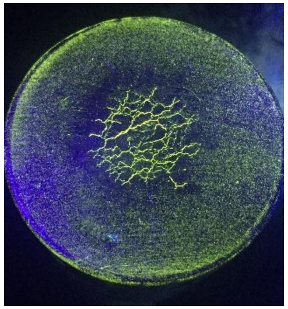
- Simply adding the standard uncertainties would inflate the estimate since, statistically, it would be expected that some of the contributing errors would cancel themselves out.

Example:

- Three discontinuities each with a MU of 4 mm, would have an overall MU of 6.93 mm when added.

- Six discontinuities each with a MU of 4 mm, would have an overall MU of 9.8 mm when added.

Note: Normal distribution used for calculation.



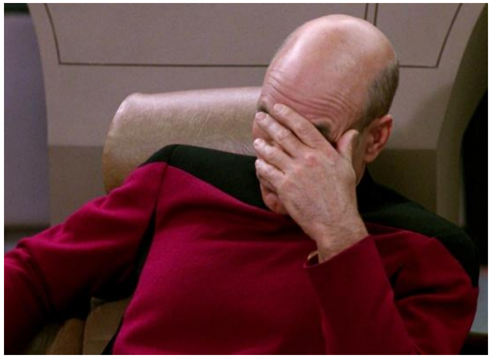
Really?

Surely this only applies to controlled Lab Conditions!

What about human factors?

What about productivity and client pressure?

How are these factored in?

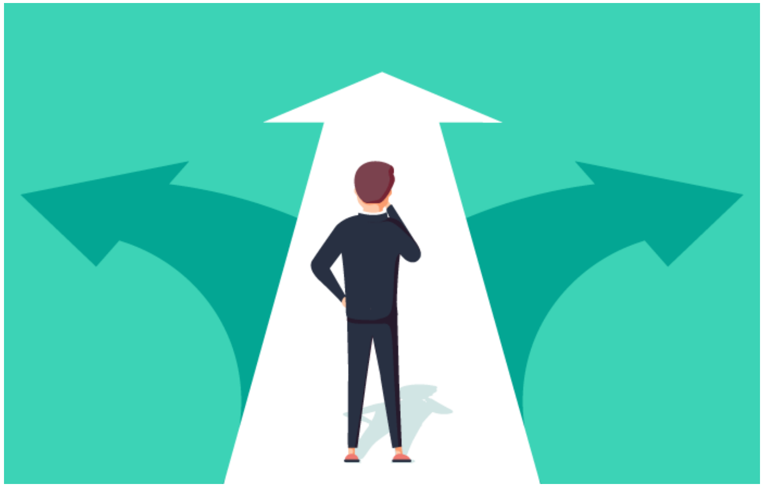


Decision Rules

From ISO 17025:2017 - General Requirements For The Competence Of Testing And Calibration Laboratories

decision rule

rule that describes how measurement uncertainty is accounted for when stating conformity with a specified requirement



In NDT, the specification rarely specifies tolerances.

Decision Rules

- Laboratories should determine boundaries for the application of MU.
  - NDT is unique in that the boundaries are usually expected to developed by the testing body (laboratory)

- These boundaries will determine how MU will be accounted for.

- Boundaries will vary based on risk/confidence.

- A common approach is to calculate % likelihood of Reject/Fail
  - Formula based on the 95% confidence level nominally given to MU

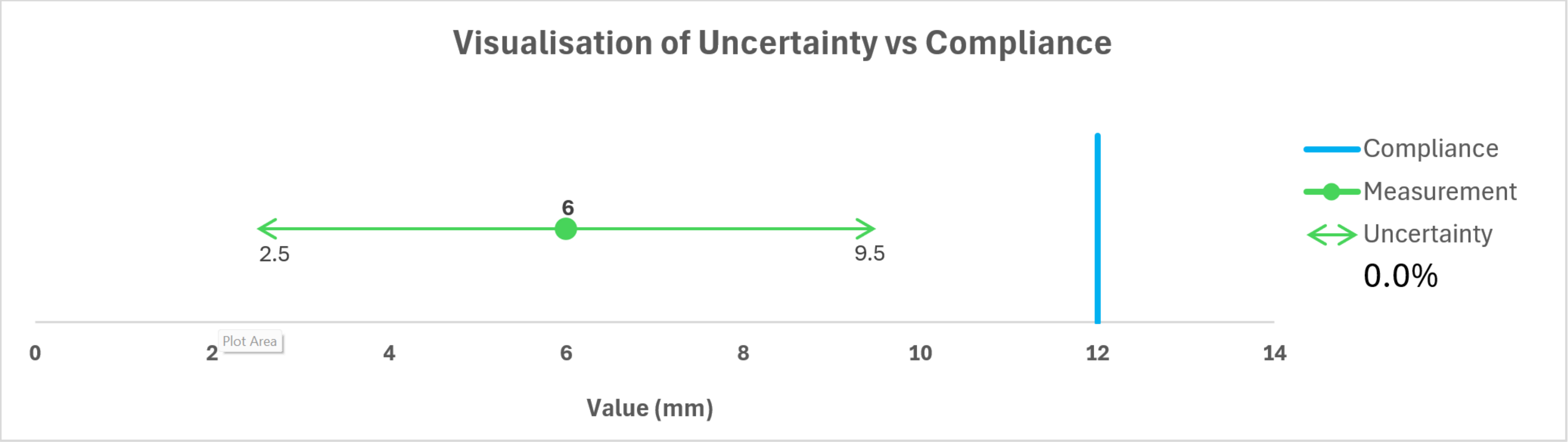
- Example Only:
  - If Likelihood of Reject < 10% - Pass
  - If Likelihood of Reject Between 10% and 50% - Review
  - If Likelihood of Reject > 50% - Reject

- **Boundaries will vary based on risk and confidence in the measurement.**

Scenarios

- UM not a factor in compliance
- Decision rule not required

Method	Technique	Dimension	Measure	UM 95%	Measured	Upper	Lower	Compliance Value	Likelihood Accept	Likelihood Reject
MT	CC / AC Yoke	Length	mm	3.5	6	9.5	2.5	12	100.0%	0.0%



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Method	Technique	Dimension	Measure	UM 95%	Measured	Upper	Lower	Compliance Value	Likelihood Accept	Likelihood Reject
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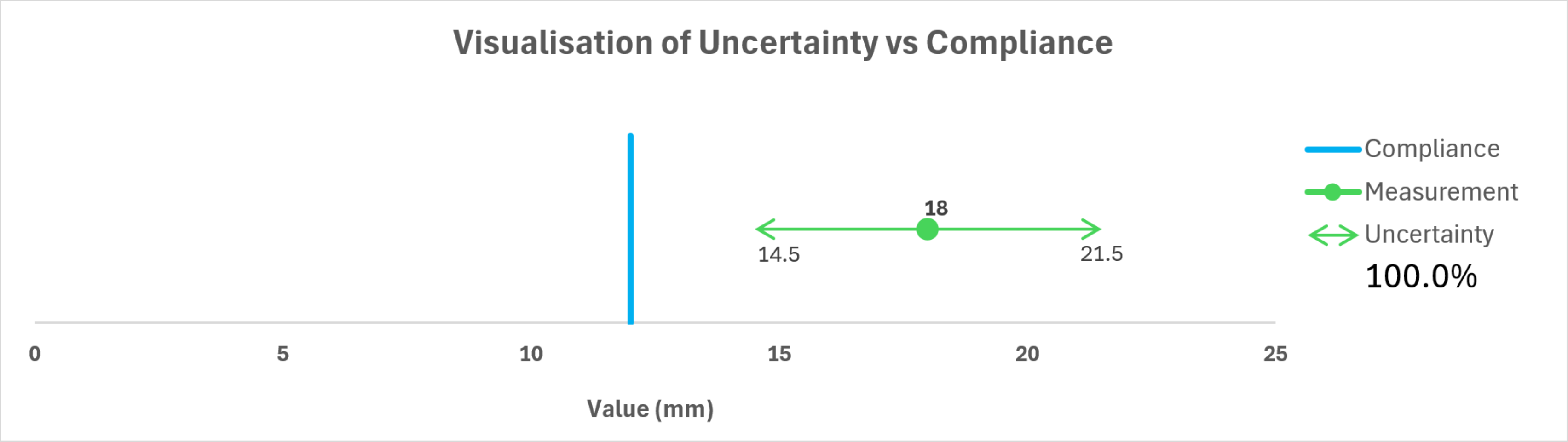
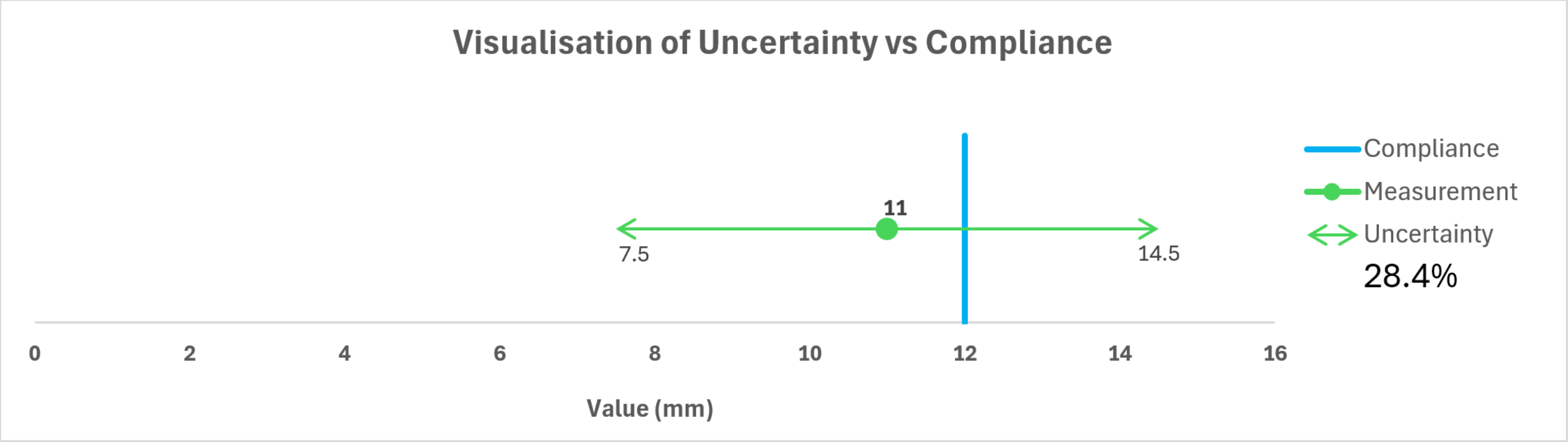


Scenarios

- UM a factor in compliance
- Decision rule required

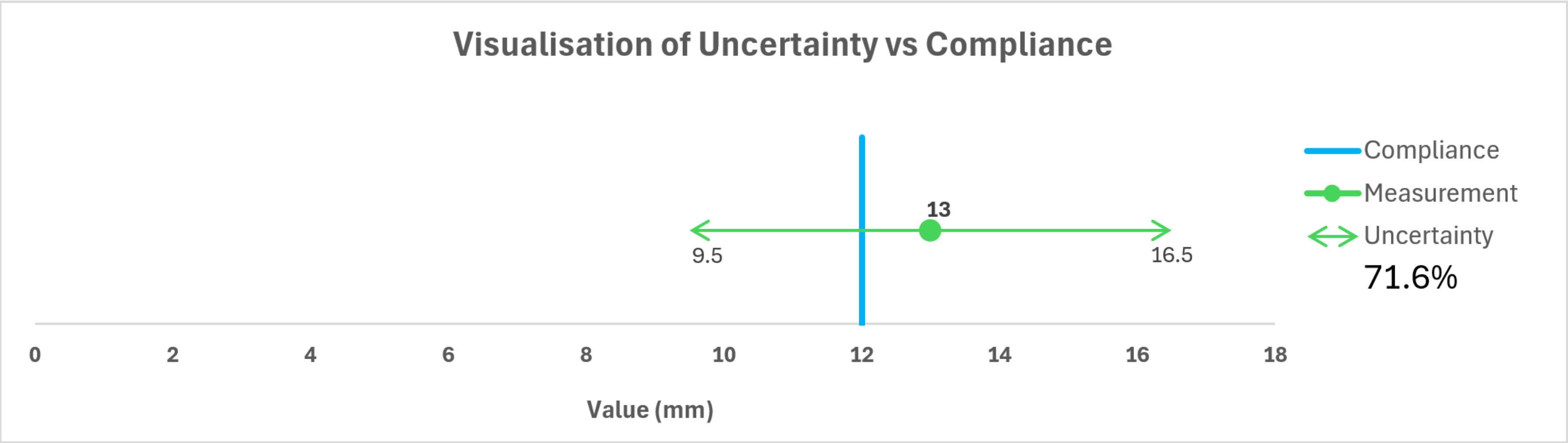
Method	Technique	Dimension	Measure	UM 95%	Measured	Upper	Lower	Compliance Value	Likelihood Accept	Likelihood Reject
MT	CC / AC Yoke	Length	mm	3.5	11	14.5	7.5	12	71.6%	28.4%



Scenarios

- UM a factor in compliance
- Decision rule required

Method	Technique	Dimension	Measure	UM 95%	Measured	Upper	Lower	Compliance Value	Likelihood Accept	Likelihood Reject
MT	CC / AC Yoke	Length	mm	3.5	13	16.5	9.5	12	28.4%	71.6%



Applying Decision Rules

- NDT is unique in that decision rules are expected to be defined by the testing body (laboratory).
  - Is this a conflict of interest?
  - Does this promote consistency across industry?
  - Does it encourage the client to shop around, pay to pass?

- Decision rule boundaries will determine how MU will be accounted for.

- The likelihood that MU could affect overall compliance must be considered.

- The use of defined boundaries will assist in clarifying when a decision rule is required.

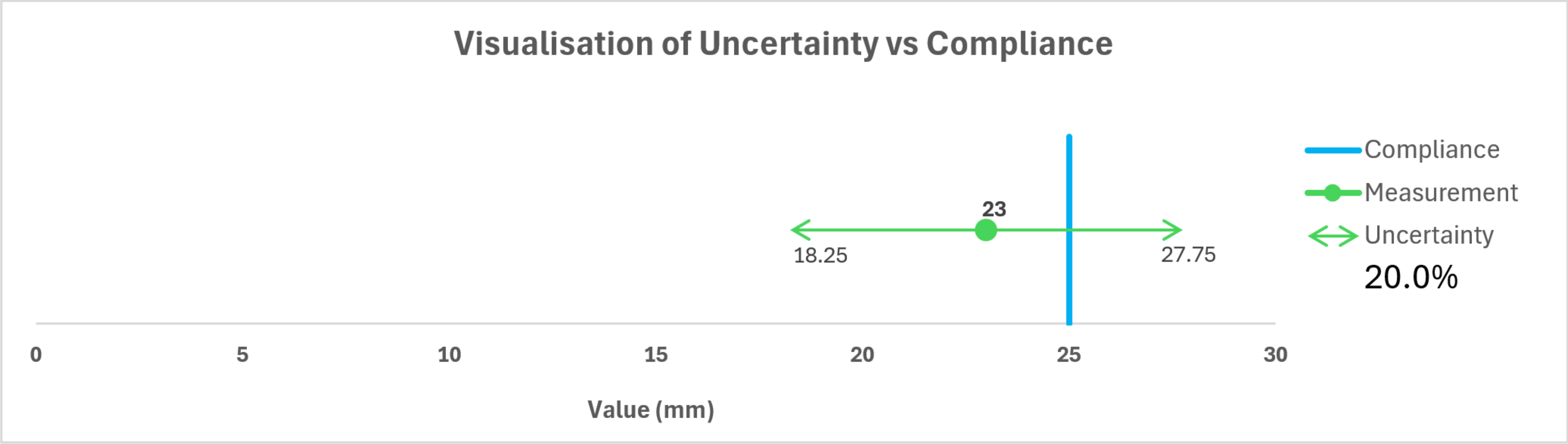
- In the case of review, a risk assessment approach can be used.

Applying Decision Rules – Example Accept

Technician measures inclusion in weld @ 23 mm long. MU is 4.75 mm.
Compliance value is 25 mm long.

Does MU factor in compliance? Yes

Method	Technique	Dimension	Measure	UM 95%	Measured	Upper	Lower	Compliance Value	Likelihood Accept	Likelihood Reject
UT	Welds / AS & ISO	Length	mm	4.75	23	27.75	18.25	25	80.0%	20.0%



Applying Decision Rules – Example Accept

Job #:	12345-1	**Date of Review:**	1-Jan-25	**Likelihood Reject Initial %:**	20
Details:	UT weld, where MU may affect decision ruling on slag inclusion length				
Reviewed By:	Bill Bob (Level 3) and Jim Smith (Level 2)				
Initial Result before applying MU:				**Accept**	
Decision Rule after applying MU:				Accept	

Review Item:	**Comments:**	**Likelihood / Risk**
Risk / consequence of failure?	Wind Turbine Circ Weld	No Change
Previous history?	Very low repair rate	Low, Decreased
Is re-testing/sampling viable?	Not viable, job remote.	No Change
Were there any specific conditions that may affect results? Confined space, elevated temperatures, etc	No	No Change
Technician confidence/experience level?	Senior Technician, Very Experienced, recalibrated and re-measured (similar measurement each time)	Low, Decreased
Sample configuration?	Double V, Good Access	Low, Decreased
Sample Material?	Carbon Steel	No Change
Sizing technique?	LSE	No Change
Other?	Nil	No Change
Likelihood MU is overstated for this specific task:	Yes, Low risk of MU affecting outcome.	

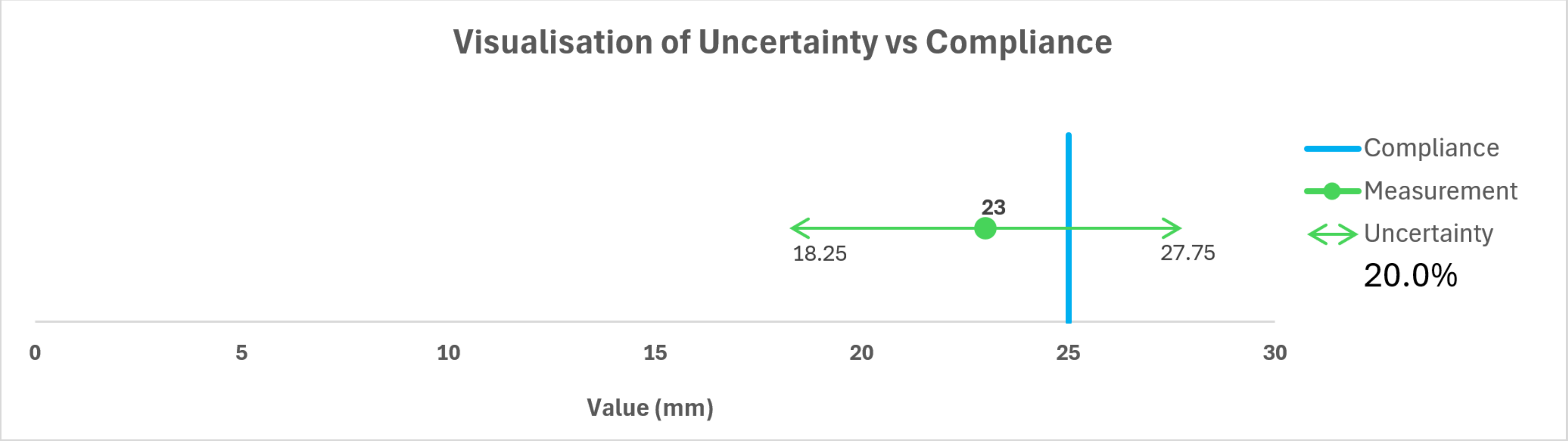
Comments:	Nil

Applying Decision Rules – Example Reject

Technician measures inclusion in weld @ 23 mm long. MU is 4.75 mm. Compliance value is 25 mm long.

Does MU factor in compliance? Yes

Method	Technique	Dimension	Measure	UM 95%	Measured	Upper	Lower	Compliance Value	Likelihood Accept	Likelihood Reject
UT	Welds / AS & ISO	Length	mm	4.75	23	27.75	18.25	25	80.0%	20.0%



Applying Decision Rules – Example Reject

Job #:	12345-1	**Date of Review:**	1-Jan-25	**Likelihood Reject Initial %:**	20
Details:	UT weld, where MU may affect decision ruling on slag inclusion length				
Reviewed By:	Bill Bob (Level 3) and Jim Smith (Level 2)				
Initial Result before applying MU:				**Accept**	
Decision Rule after applying MU:				**Reject**	

Review Item:	**Comments:**	**Likelihood / Risk**
Risk / consequence of failure?	Pressure Vessel, lethal contents	Increased
Previous history?	Current project has a high repair rate	Increased
Is re-testing/sampling viable?	Not viable, job remote.	No Change
Were there any specific conditions that may affect results? Confined space, elevated temperatures, etc	Yes, Confined space, cramped compartment	Increased
Technician confidence/experience level?	Moderate , not considered a factor	No Change
Sample configuration?	Simple Double V	No Change
Sample Material?	Carbon Steel	No Change
Sizing technique?	6 dB drop, not considered a factor	No Change
Other?	Nil	No Change
Likelihood MU is overstated for this specific task:	No, MU likely, consequences high	

Comments:	Consult with client, suggest retest alternative inspection method (PAUT/ToFD)

Reporting Decision Rules

Example: Accept

- For the specific inspection covered in this report, measurement uncertainty was taken into account when assessing the conformity of the weld.

- The assessment found that the measurement uncertainty would have a low impact on the decision rule, and the initial finding as a compliant weld was upheld.

- Details of the assessment and decision rule are retained in the job pack.

Example: Reject

- For the specific inspection covered in this report, measurement uncertainty was taken into account when assessing the conformity.

- The assessment found that the measurement uncertainty could have an impact on the decision rule, and the finding is non-compliant.

- Details of the assessment and decision rule is retained are the job pack.

Tips:

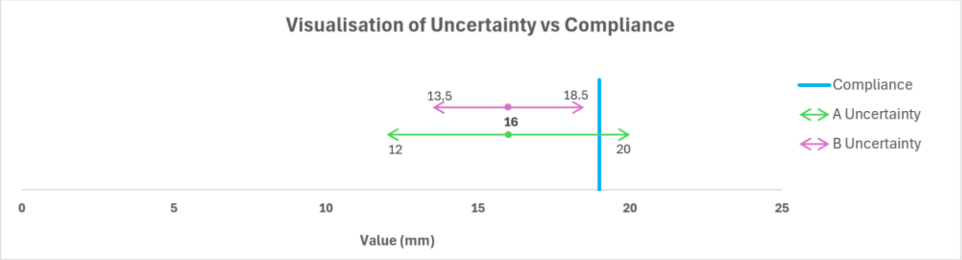
- If a significant decision rule must be made, effective communication with client is vital.

- Ensure technicians understand decision rules
  - Try to minimise as many factors as possible **before** leaving the job site.

- Wherever possible use sampling:
  - Have multiple technicians confirm result
  - Have the same technician, re-calibrate and re-test

- Try another technique with lower MU
  - Fluro vs Visible
  - 10 MHz vs 5 MHz
  - X-Ray vs Gamma
  - Type 1 vs Type 2 Film
  - Calibrated Ruler vs Tape Measure
  - Vernier vs Ruler

	Method	Technique	Dimension	Measure Unit	UM 95%	Measured Value	Upper	Lower	Compliance Value	Likelihood Accept	Likelihood Reject
A	MT	CC / AC Yoke	Length	mm	4	16	20	12	19	93.3%	6.7%
B	MT	Fluro / AC Yoke	Length	mm	2.5	16	18.5	13.5	19	99.2%	0.8%



Resources:

JCGM - Joint Committee for Guides in Metrology Guidelines (GUM)

UKAS - M3003 The expression of uncertainty and confidence in measurement, March 2024

UKAS - LAB 48 Decision rules and statements of conformity, July 2024

SAC - Guidance note NDT 001 estimation of measurement uncertainty in non-destructive testing, March 2019

NPL - MAT105 Uncertainty of measurement for non-destructive testing (NDT), March 2022

~~NATA - Uncertainty in NDT, January 2018~~

ISO 14253 Series*

ASME PTC 19.1*

Most are accessible online*