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High Accuracy Extended Range (HAER) CTs in the Real World: Variability, Material Limits, and Why Testing Matters

EEI Spring Transmission, Distribution, and Metering Conference 2026

Measurement Technology Working Group
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Dan Falcone

HAER CTs: WHY SHOULD UTILITIES TEST

- CT accuracy is often assumed not verified
- OEMs certify CTs at standard test points
- Current IEEE C57.13 standards stop at 5% of rating factor
- OEMs now claim accuracy down to 1%
- Low-end accuracy is largely unverified across the industry
- Equipment to test down to 1% is scarce and only recently available

HAER CTs: WHY SHOULD UTILITIES TEST

- Many CTs operate for many hours each week at:
  - <10% loading
  - <1A secondary current

- Especially with
  - Light load periods
  - Commercial / industrial variability
  - Distributed generation impacts

- Low End Accuracy Drives Billing & Analytics Accuracy and represents a loss of billing revenue across all C&I accounts of greater than 5%.

- Given that utilities size the CT's for the potential load of the new customer and then do not review this sizing as the customer changes in the same facility the potential for a site to operate at these levels for most and at times all of the service hours each week increases dramatically.

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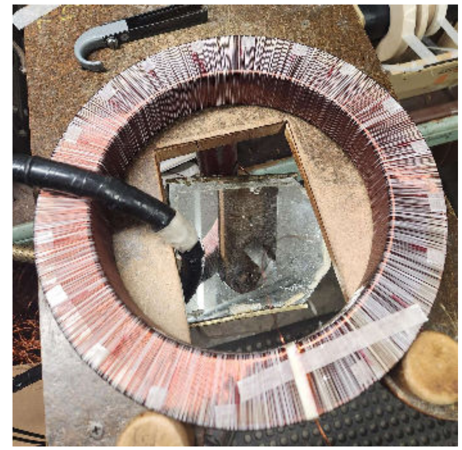
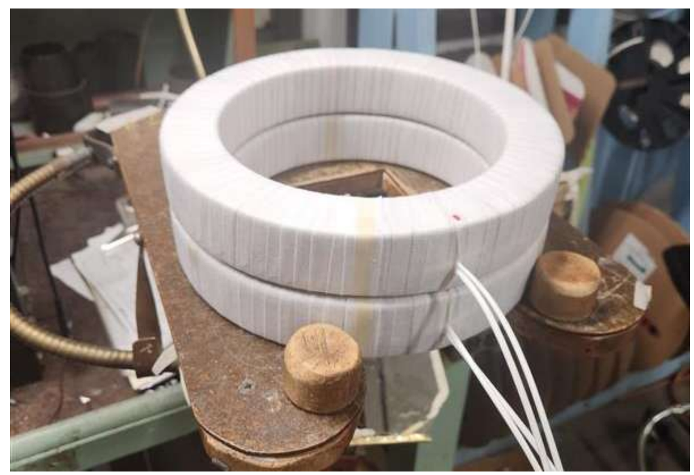
HAER CTs: THE HIDDEN RISK

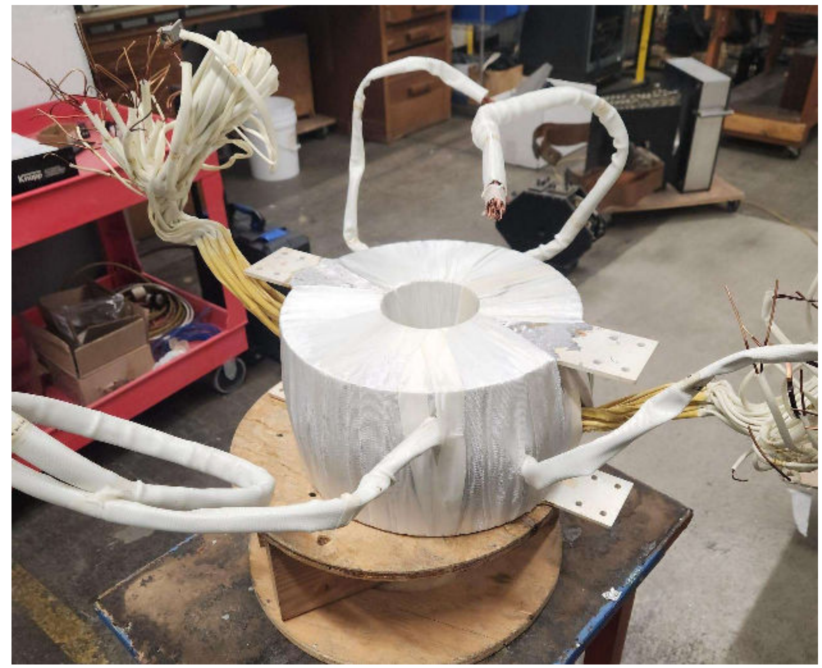
- Utilities may be billing off inaccurate data
- CT passes at 100% = assumed good
- CT then fails / drifts at low current
- Impact to revenue leakage, incorrect modeling, and value for cost of goods acquired
- Several large IOUs have found batches of CTs with variability, low-end failures, yet passed OEM tests on multiple different vintages of equipment
- WHY
    - Core material variability
    - Winding tension
    - Broken or imperfect cores
    - Softer magnetic materials
    - Manufacturing tolerances





HAER CTs & MEASUREMNT

- Testing at 1% is fundamentally different
- 1% of 5A = 50mA
  - Error signals drop to milli amp levels
  - Noise can dominate the measurement
- Most legacy systems were not designed for this
- OEMs historically tested down to 10% and now 5% reliably
- Some have newer equipment that can test down to 1%
- Utilities can not rely solely on OEM certification
- The equipment to test down to 1% did not exist 5+ years ago let alone 10+ years ago when HAER CTs began to enter the industry



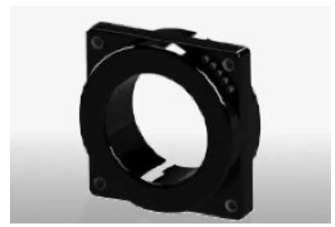
WHY TESTING AT 1%

- Without tight enough core material process control, CT's can have variability at the low end, even with "higher end" Materials

- Shrinking the core can also improve the low end. This can result in the high end starting to come close to saturation on larger burdens

- Softer Cores also can be more sensitive to magnetization due to the reduced B scale

- Reduction of inventory of CT's, more overlap

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https://new.abb.com/medium-voltage/apparatus/instrument-transformers-and-sensors-id/outdoor-application/ansi-outdoor-instrument-transformers

WHY?

- C57.13 does not spec below 5% but many manufactures are beginning to claim measurements down to 1%
  - *These claims need validation*

- Reduced inventory variety
  - *600:5 can go down to 6amps, rendering 100:5 and 50:5 less critical to have*

- Most of the present 1% CT's are 0.15 Accuracy Class, so an upgrade of range is an upgrade in accuracy as well
  - *When compared to 0.3, 0.6, and 1.2 accuracy class CT's*

https://ritzusa.com/wp-content/uploads/2020/11/Low-Voltage-Extended-Range-Current-Transformers.pdf

UNDERSTANDING THE PARALLELOGRAM

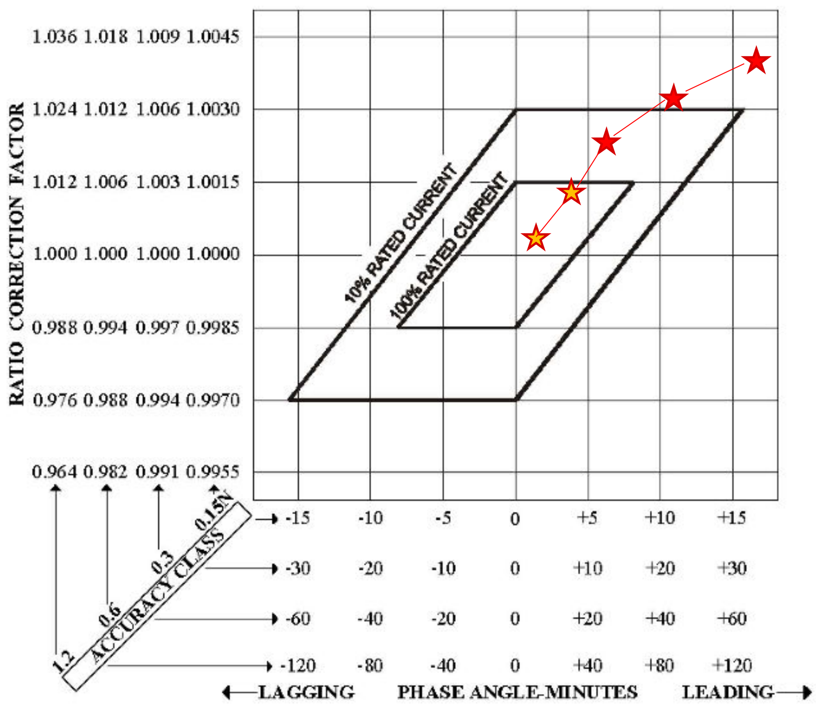

Figure 2, IEEE C57.13-2016

- Transformers when under test must comply within their respective class bounds for phase and ratio
- The class they fit within also depends on the current value, all must match nameplate at 5amps, but some (0.3 in example) can double when below an RF of 1.0

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UNDERSTANDING ACCURACY CLASS

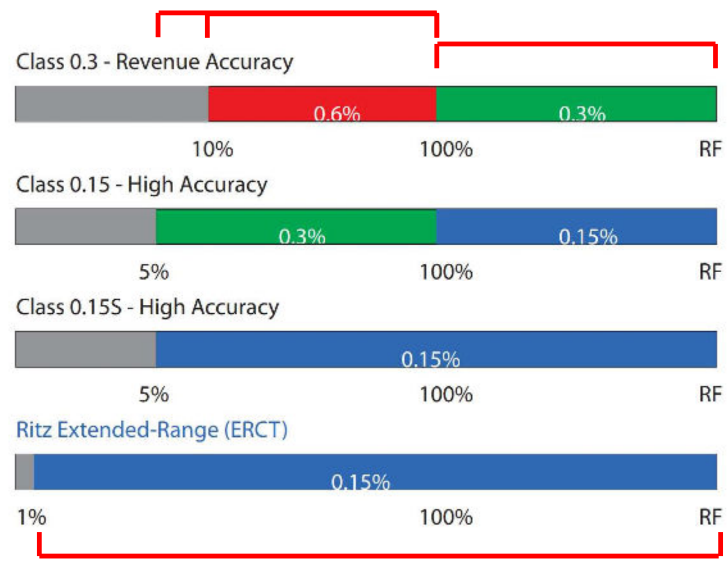
IEEE Std C57.13-2016
IEEE Standard for Requirements for Instrument Transformers

Table 8—Standard accuracy class for metering service and corresponding limits of transformer correction factor and ratio correction factor [0.6 to 1.0 power factor (lagging) of metered load][c]

Metering accuracy class	Voltage transformers (at 90% to 110% rated voltage)		Current transformers					
			At 100% rated current[a]		At 10% rated current		At 5% rated current	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
0.15S[b]	—	—	0.9985	1.0015	—	—	0.9985	1.0015
0.15[b]	0.9985	1.0015	0.9985	1.0015	—	—	0.9970	1.0030
0.15N	—	—	0.9985	1.0015	0.9970	1.0030	—	—
0.3S	—	—	0.9970	1.0030	—	—	0.9970	1.0030
0.3	0.9970	1.0030	0.9970	1.0030	0.9940	1.0060	—	—
0.6	0.9940	1.0060	0.9940	1.0060	0.9880	1.0120	—	—
1.2	0.9880	1.0120	0.9880	1.0120	0.9760	1.0240	—	—

[a] For current transformers, the 100% rated current limit also applies to the current corresponding to the continuous thermal current rating factor.
[b] Previously defined in IEEE Std C57.13.6.
[c] Other accuracy requirements may be specified and should be included on the nameplate.

Table 8, IEEE C57.13-2016



https://ritzusa.com/wp-content/uploads/2020/11/Low-Voltage-Extended-Range-Current-Transformers.pdf

ACCURACY CLASS EXAMPLES

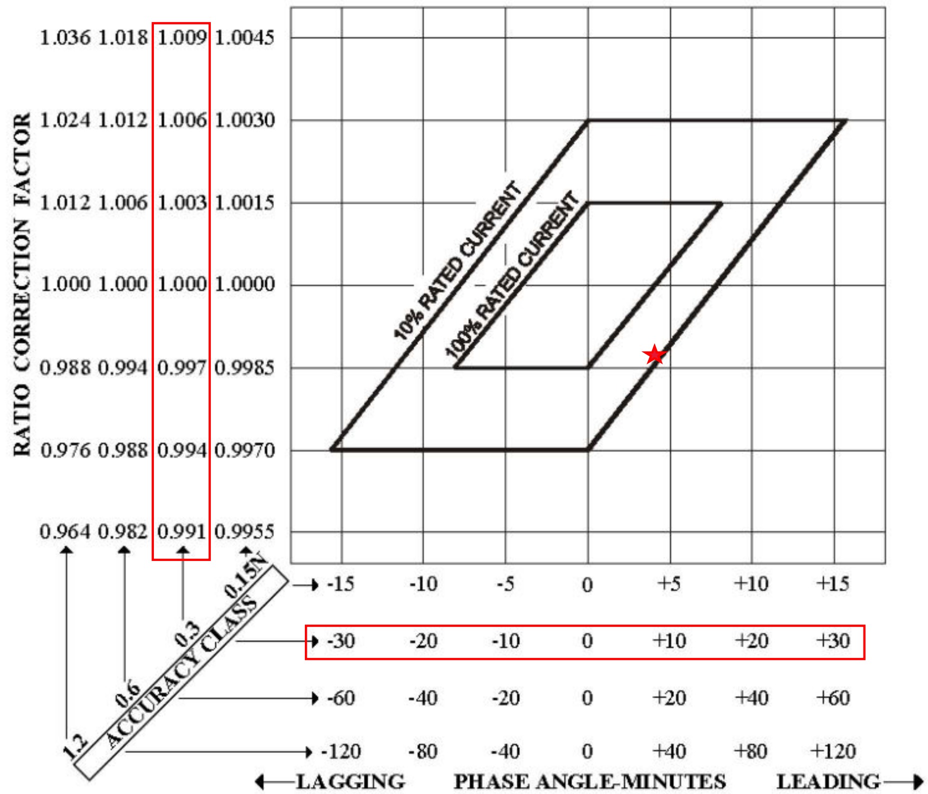
Acc = Greater of Acc1 vs Acc2

$$Acc1 = |RCF - 1| \times 100$$

$$Acc2 = \left| RCF - 1 - \frac{\beta}{2600} \right| \times 100$$

$$\beta = Phase\ Difference\ in\ Minutes$$

- ***Given***: RCF 0.9975, Mins +8, Nameplate 0.3Acc
- Acc1 = 0.25 *Pass or Fail?*
- Acc2 = 0.558
- Accuracy Class = 0.558, *Pass or Fail?*
- *Fail @ 100%, Pass at 10%*



CT TESTING METHODS

Secondary Injection

- Mobile, can be done in field
- Can determine other CT parameters for use diagnosing site issues
- Medium Accuracy

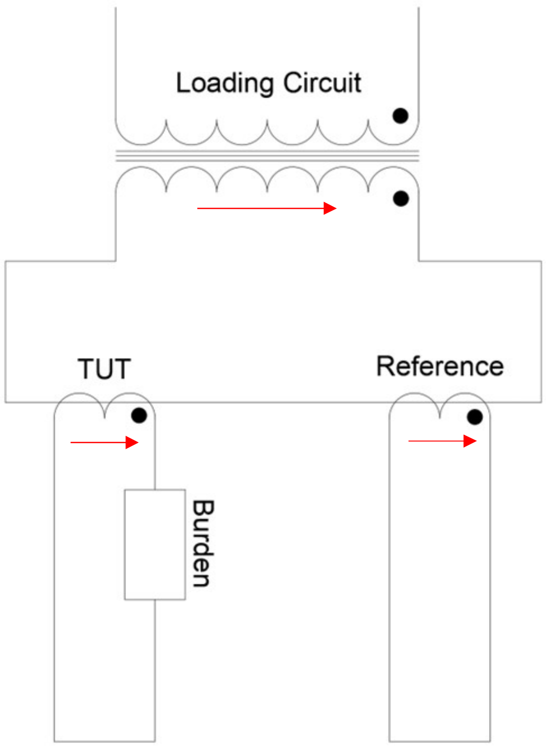
Direct Primary Measurement

- Mobile, can be done in field
- Testing can be done in conjunction with metering
- Medium-Low Accuracy

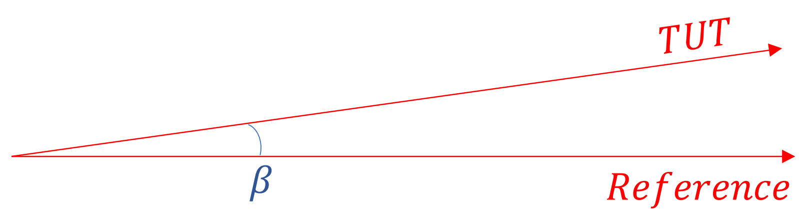
True Primary Reference Comparison

- Static, lab based
- Testing with variety of parameters (purchasing/Eng.)
- High to Very High Accuracy

UNDERSTANDING A TRUE PRIMARY TEST



- A True Primary test, pushes the entire primary current through the CT to be tested, and a reference transformer.
- Both of these output their secondary current which are each read. The TUT must push its secondary Current through a Burden which will affect its output



UNDERSTANDING A TRUE PRIMARY TEST

TUT

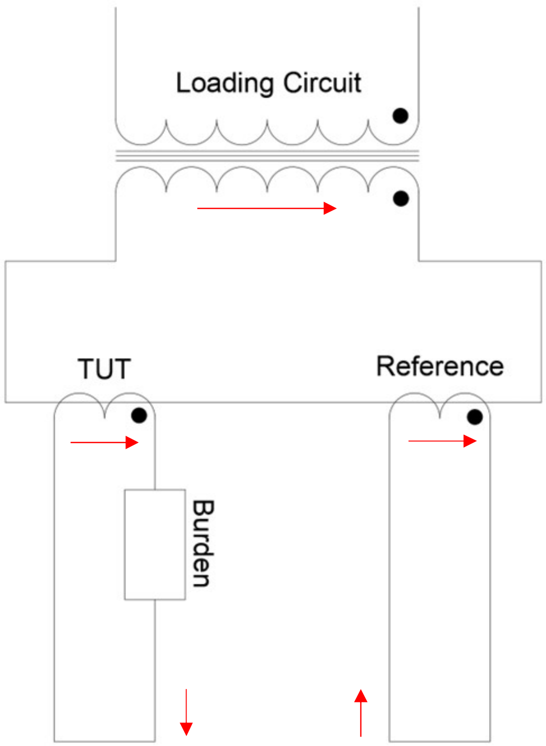
$Reference$

The difficulty without a trick…

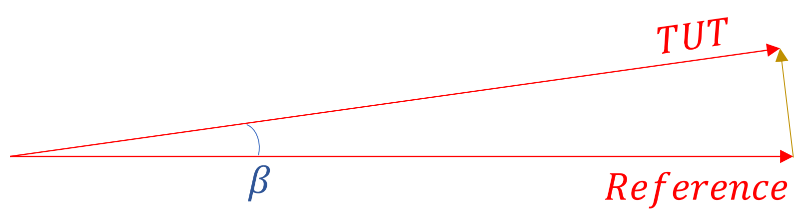
5.0000A vs 5.0200A

0.38Acc

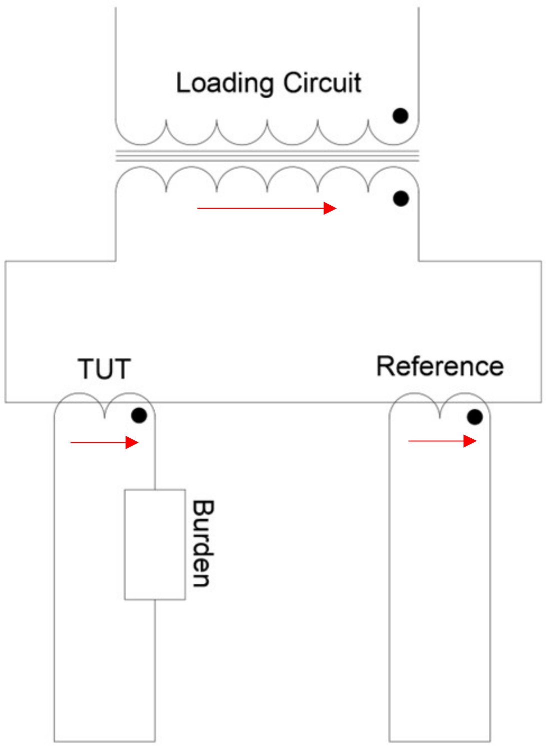
UNDERSTANDING A TRUE PRIMARY TEST



- Notice the Reference and TUT are opposing one another in the center…
- What happens to opposing currents in a branch?
- Summed Vector (opposite direction is subtractive)
  - *At Knopp, we call this the "Error" Vector*

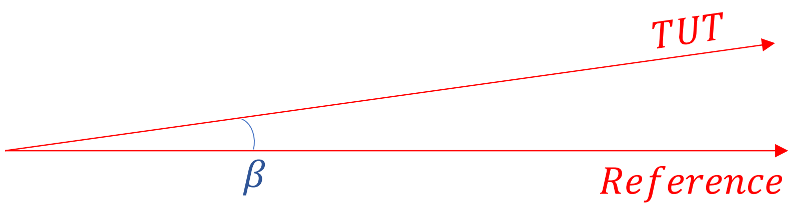


UNDERSTANDING A TRUE PRIMARY TEST



- So, we have devised a test that tests a CT in the way that it will be used rather than secondary injection

- And, we have used “Electrical Trig” to increase the accuracy of the measurement vs measuring primary to secondary



UNDERSTANDING RCF: AN EXAMPLE

$$RCF = \frac{Reference\ Current}{TUT\ Current}$$

$$RCF = \frac{Measured\ Ratio}{Marked\ Ratio}$$

Take a 600:5 for example:

- Marked ratio: $\frac{600A}{5A} = 120$
- Primary Current = 600A
  - Ref Current = 5.00A
  - TUT Current = 4.99A

Calculate RCF by Current, and by Ratio

RCF by Current: $\frac{5.00A}{4.99A} = \mathbf{1.002}$

Ref Measured Ratio: $\frac{600A}{5A} = 120$

TUT Measured Ratio: $\frac{600A}{4.99A} = 120.24$

RCF by Ratio: $\frac{120.24}{120} = \mathbf{1.002}$

UNDERSTANDING TCF: AN EXAMPLE

$$TCF = RCF - \frac{\beta}{2600}$$

From before, RCF = 0.9975, and phase = +8mins:

$$TCF = 0.9975 - \frac{8}{2600}$$

$$TCF = 0.9944$$

This is similar to RCF, but accounts for phase error as well and is what is typically used to correct for a CT's error if only one number can be given

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1% CT CONSTRUCTION AND DESIGN

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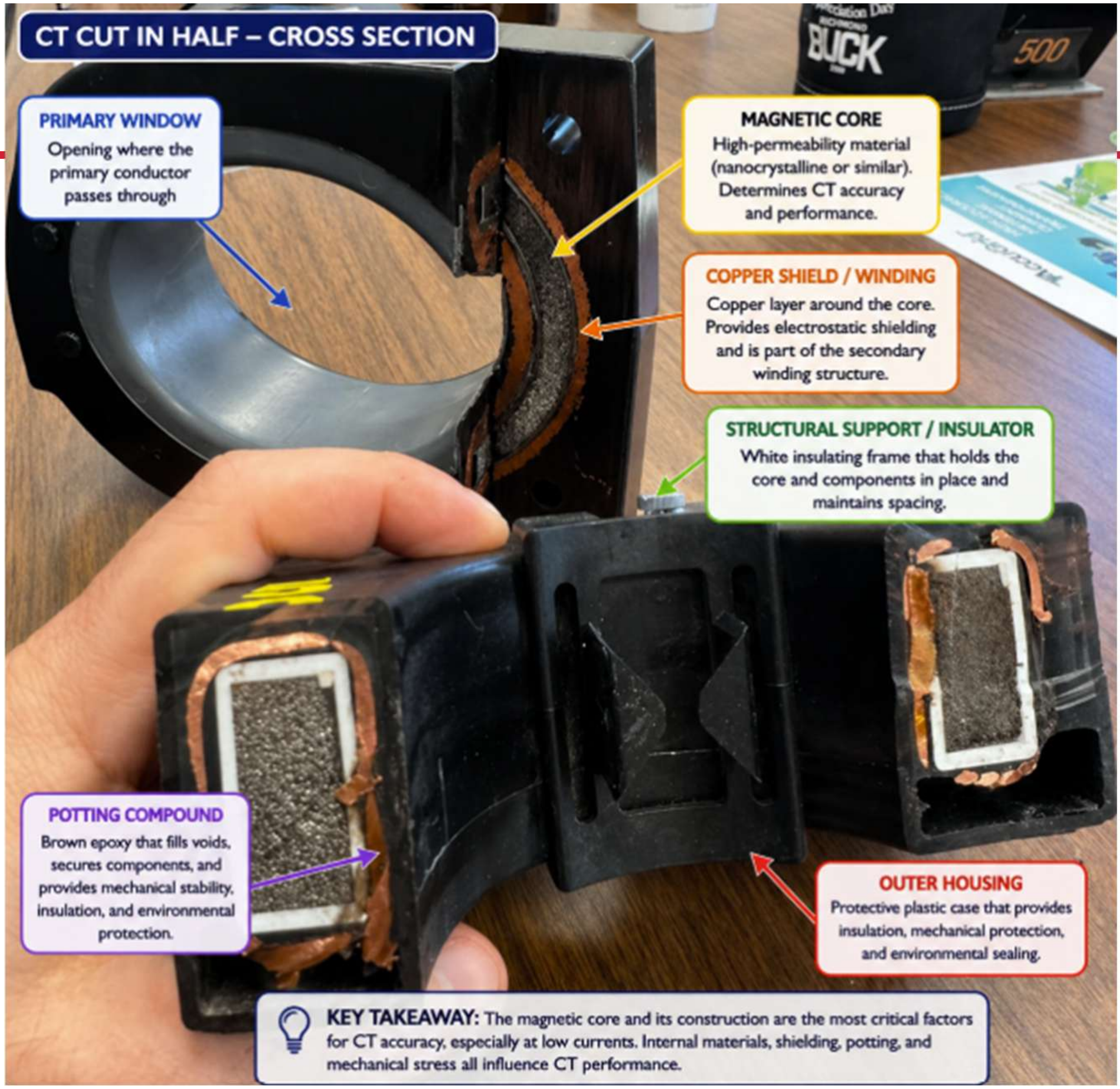
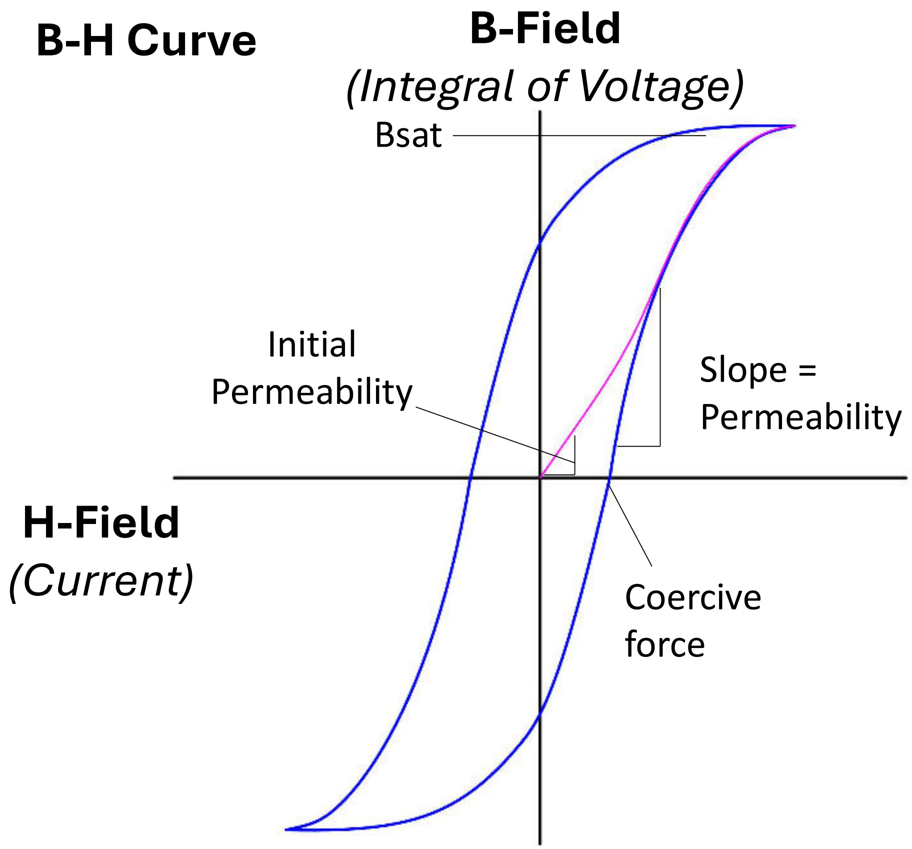
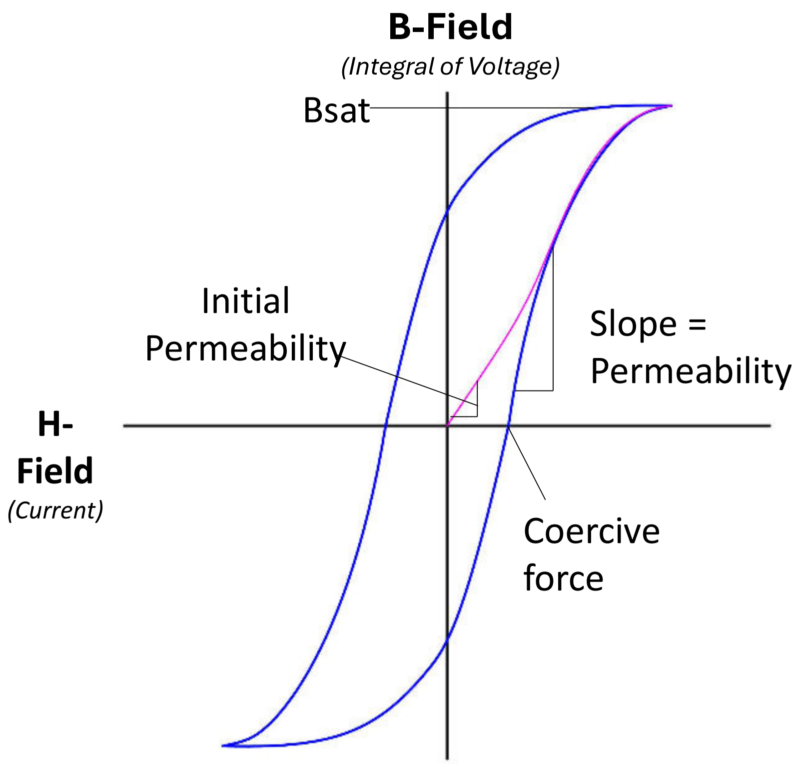


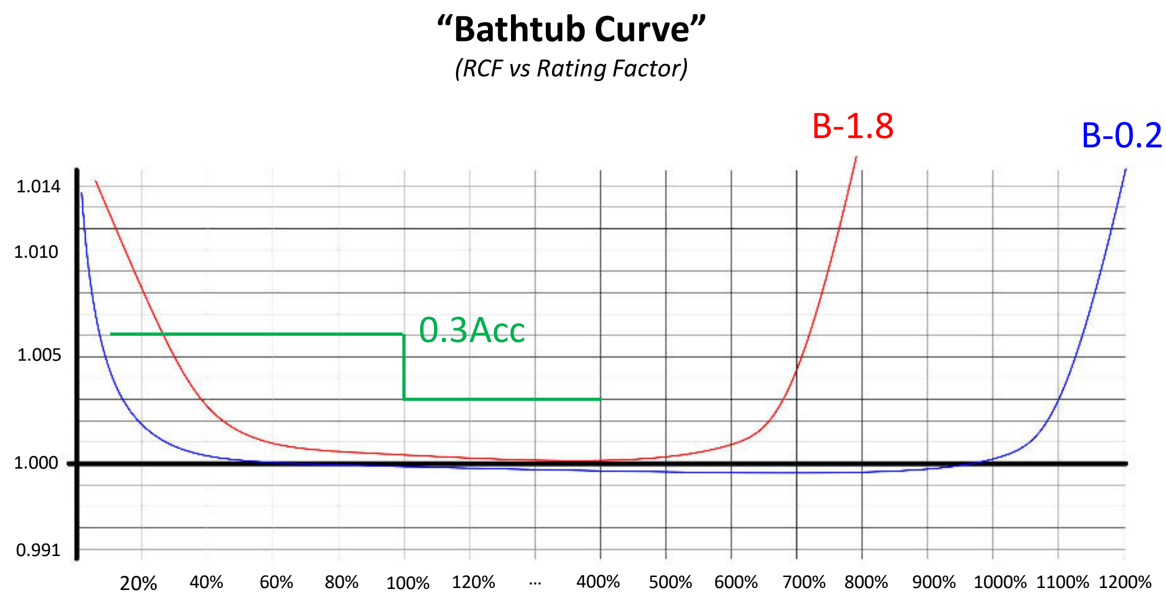
TRANFORMER MAGNETIC OPERATION



- A Transformer is a magnetic device that reacts to current passing through a core
- The Core builds up a magnetic field
- In turn, the magnetic field creates a secondary current
- The Core can only contain so much field until it is saturated
- The area in graph is the CT core losses
- The consistency of the permeability slope yields a more linear transformer

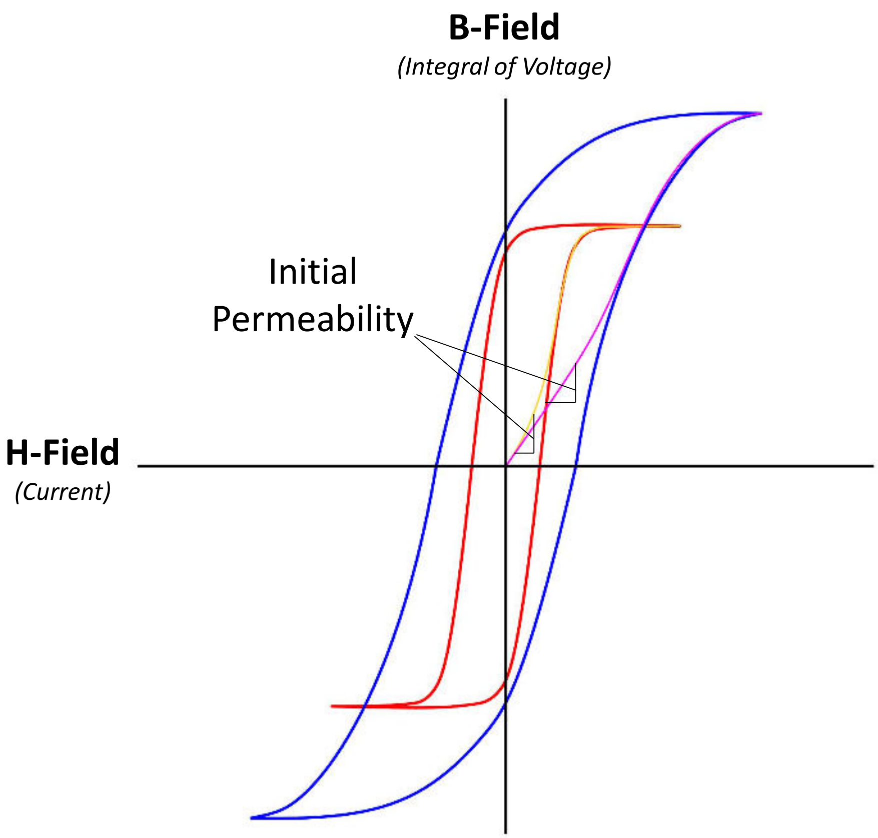
TRANFORMER MAGNETIC OPERATION



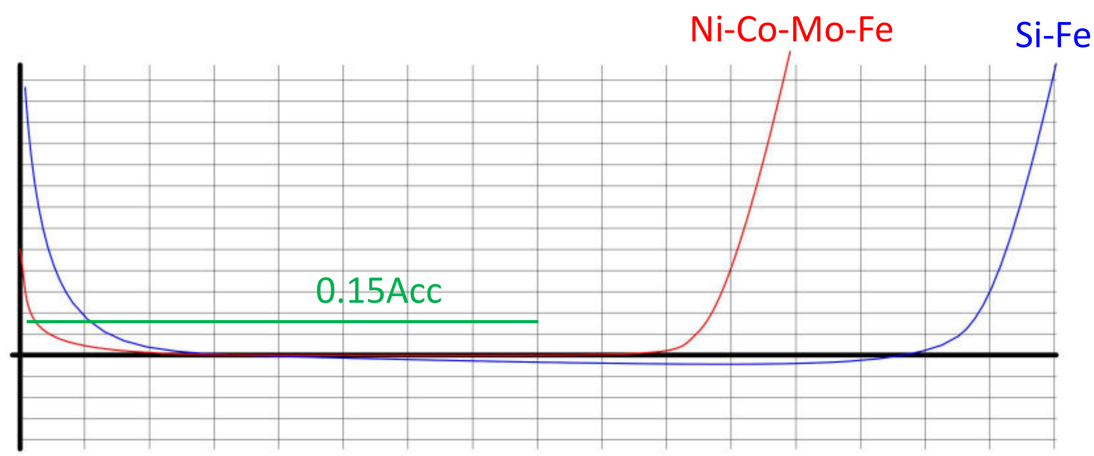


- Take note of initial perm and saturation
- Increased burden increases secondary voltage, hence Bsat is hit faster

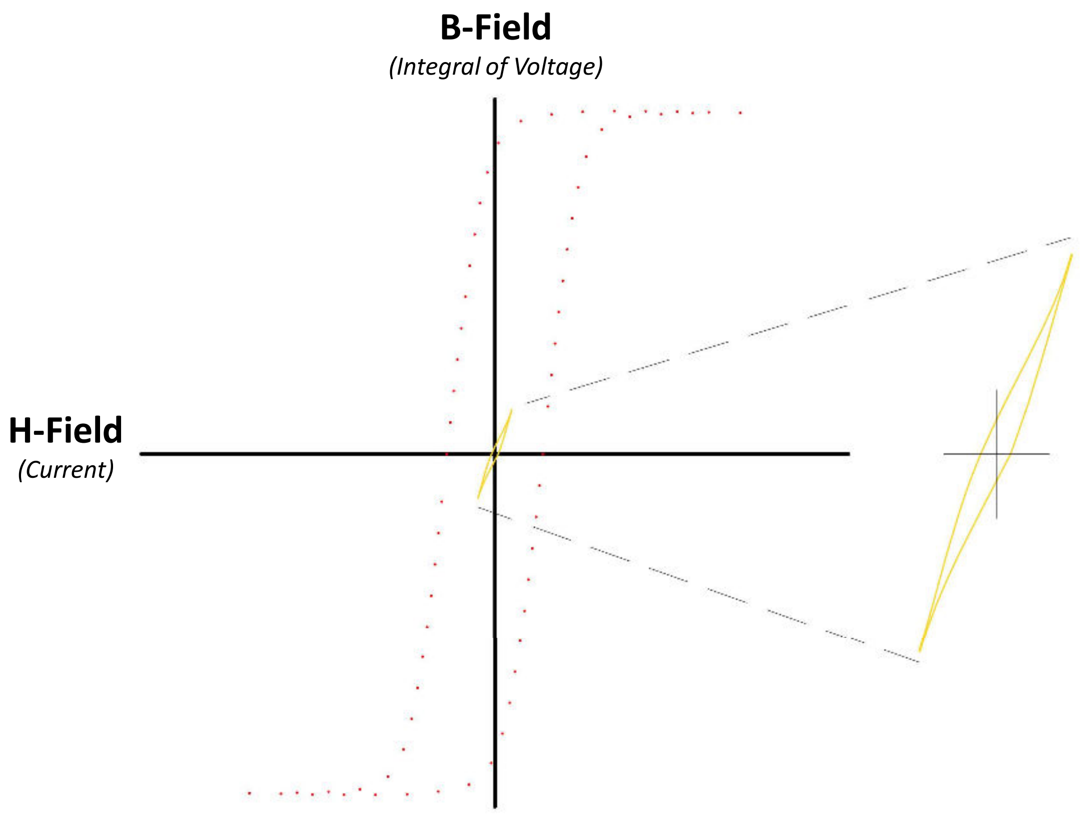
MATERIAL SELECTION



- In order to go lower, and be more accurate, more exotic materials were chosen.
    - Blue represents normal silicon steel, found in power transformers.
    - Red represents nickel and amorphous alloys
- Softer new materials have a lower saturation, but tend to be more linear and better low end
- Note the initial permeability slopes…



HOW CTS OPERATE



- CTs should never be run near saturation, they are a near zero flux device
- If there was a true zero burden (including windings), no core losses, CTs would have almost no B-H curve as the ratio would be perfectly cancelled out
- This is why initial perm plays such a large role in material selection
- Initial perm can be a bit erratic as its almost entirely material and material processing, so CT to CT can differ depending on process control

BE SURE TO TEST UPPER AND LOWER LIMITS

- The upper end is important to test for many obvious and less obvious reasons
  - This is where the largest billing revenue will occur and we want to know everything about the instrument transformers being used
  - We want to make sure that the transformer does not saturate at these levels
- At the low end
  - We need to understand where the measurement can go down to. 1.0%? 1.2%? 0.8%
- Testing before releasing to the field
  - Ensure the core has not been wound too tightly and cracked or broken during transport
  - Ensure the transformer is not magnetized before release to the field as this is more likely than ever with HAER CTs

THE NEXT GENERATION OF CT TESTING EQUIPMENT

- Key features
  - The KCTS-8000X is a piece of lab equipment that is perfect for type testing new HAER Current Transformer offerings as well as more traditional instrument transformers.
  - Traditional Knopp transformer test equipment less than ten years old can be upgraded to an X
  - The KCTS-8000XA can test multiple transformers at one time to the same level of accuracy

KCTS-8000XA

KCTS-8000X

THE NEXT GENERATION OF COMPARATORS

- Key features
  - The C2 and the V2 can be retrofit onto any Knopp Transformer testing equipment CT or PT manufactured in the past forty years
  - These new units allow for an enhanced User Interface (UI) and streamlined connection for the data to be sent to the system of record for reporting and analysis purposes
- Other important notes
  - When looking for technical specifications and traceability - the comparator is only one of the elements in the system
  - When looking at your transformer test system and reporting on the accuracy and traceability always make sure to check with the manufacturer to ensure you are reporting traceability, uncertainties and accuracies as they pertain to entire system and not just the comparator
    - If you do not your claims will be "too good to be true"

C2, C2X, V2

C3

QUESTIONS AND DISCUSSION

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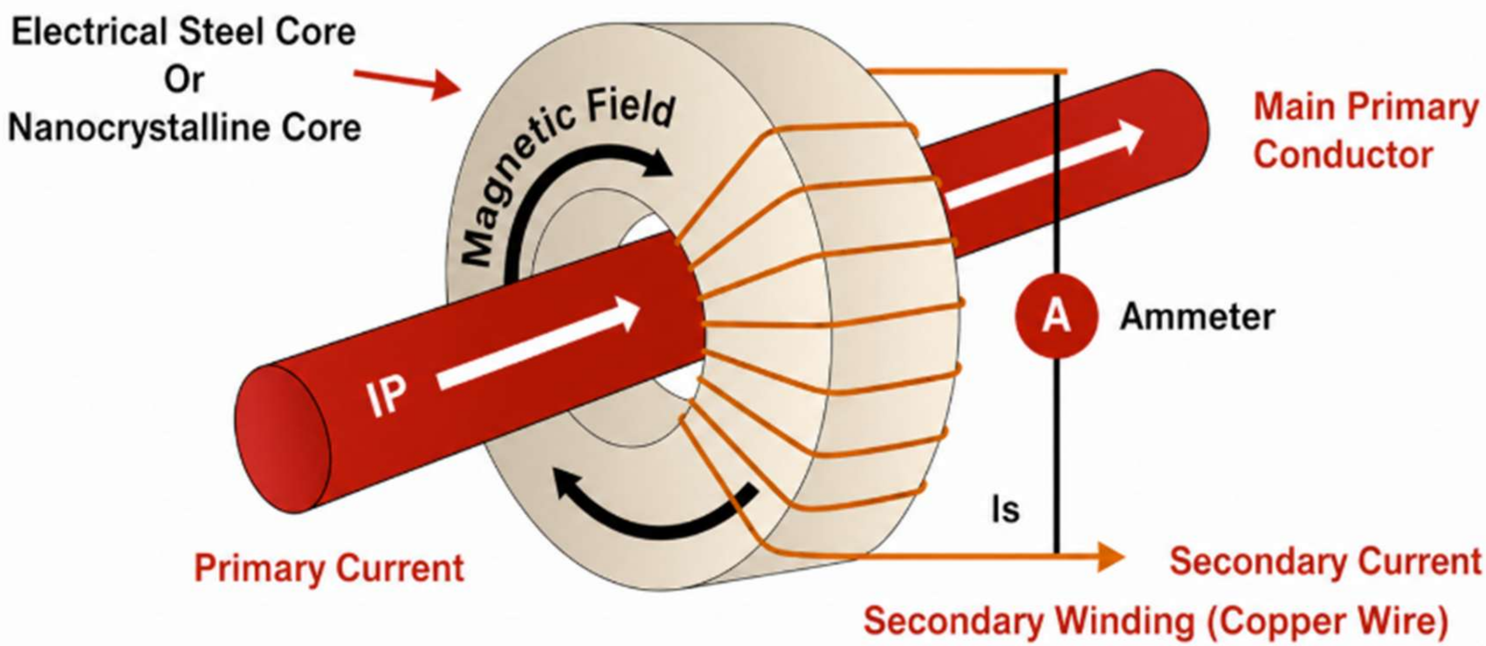
APPENDIX

COMMON ACRONYMS AND TERMS



The relationship of the primary current to the secondary current is known as the ratio; example 500:5

COMMON ACRONYMS AND TERMS

- **Ref**: Reference Transformer
- **TUT**: Transformer Under Test
- **RCF**: Ratio Correction Factor
- **TCF**: Transformer Correction Factor
- **Minutes**: 1 degree = 60 minutes
- **RF**: Rating factor, sometimes expressed as a % (100% = 5A) or a number (4 = 20A), can be based on thermal rating
- **Accuracy Class (Acc)**: Percentage of allowed error, ex. 0.3Acc means +/-0.3% accuracy
  - Knopp gives a measured accuracy class during test, this should be below the nameplate of CT. Ex. 0.21 shown, <0.3 so within spec

COMMON ACRONYMS AND TERMS

Accuracy

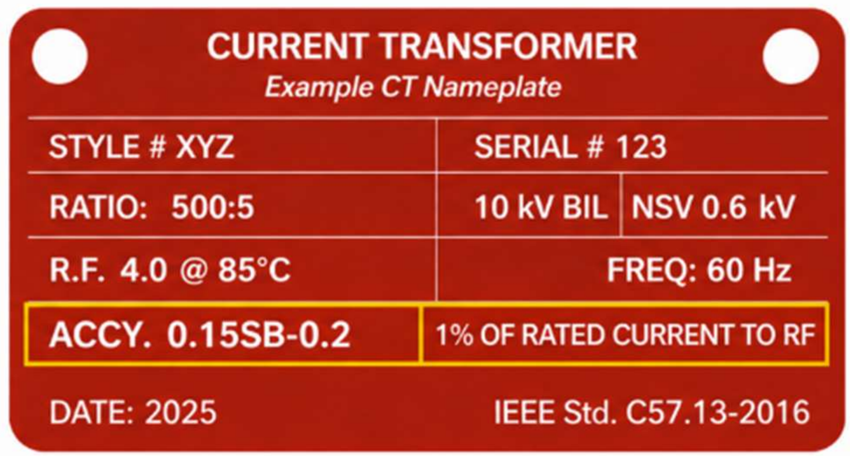
IEEE Std. C57.13-2016

Class	Description
0.6	Indicating Instrument
0.3	Revenue Grade
0.15	High Accuracy
0.15S	Special High Accuracy

> 0.15S Accuracy Class
High Accuracy, Extended Range

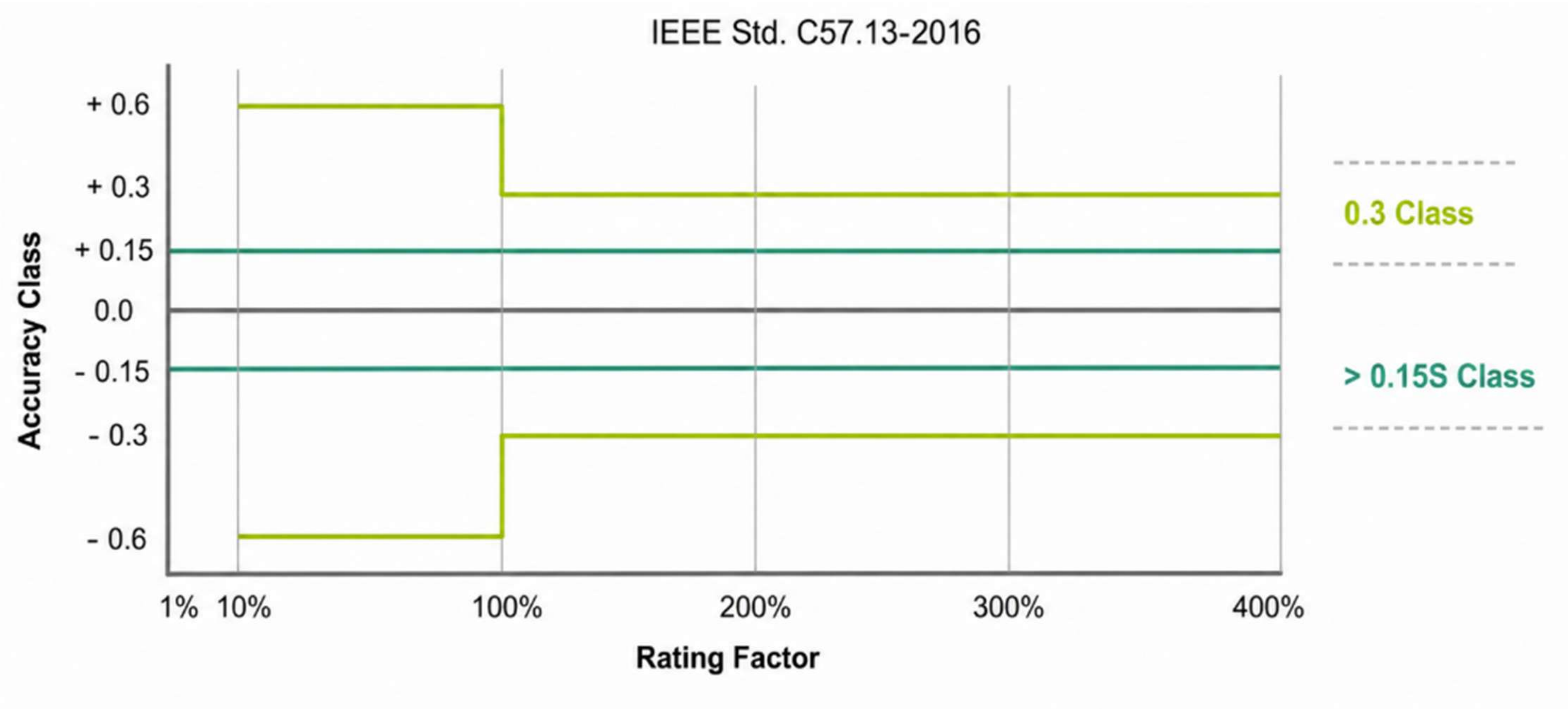
Accuracy is written as:
0.3B-0.5 or **0.15SB-0.2**

Where “B” is for burden*

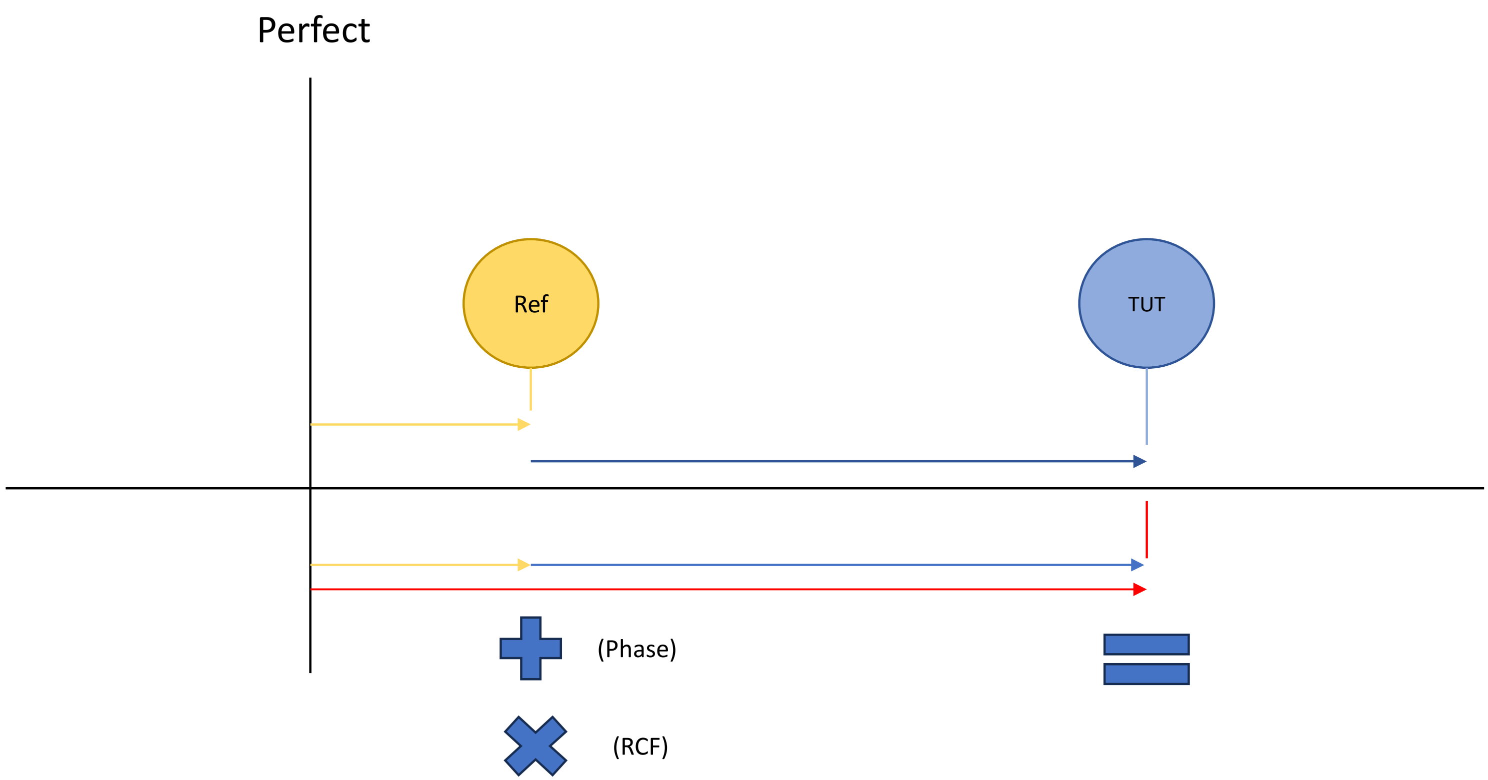


* Burden indicates the amount of <u>resistance</u> (in ohms) that may be connected to the secondary without causing a metering error greater than specified by its accuracy classification.

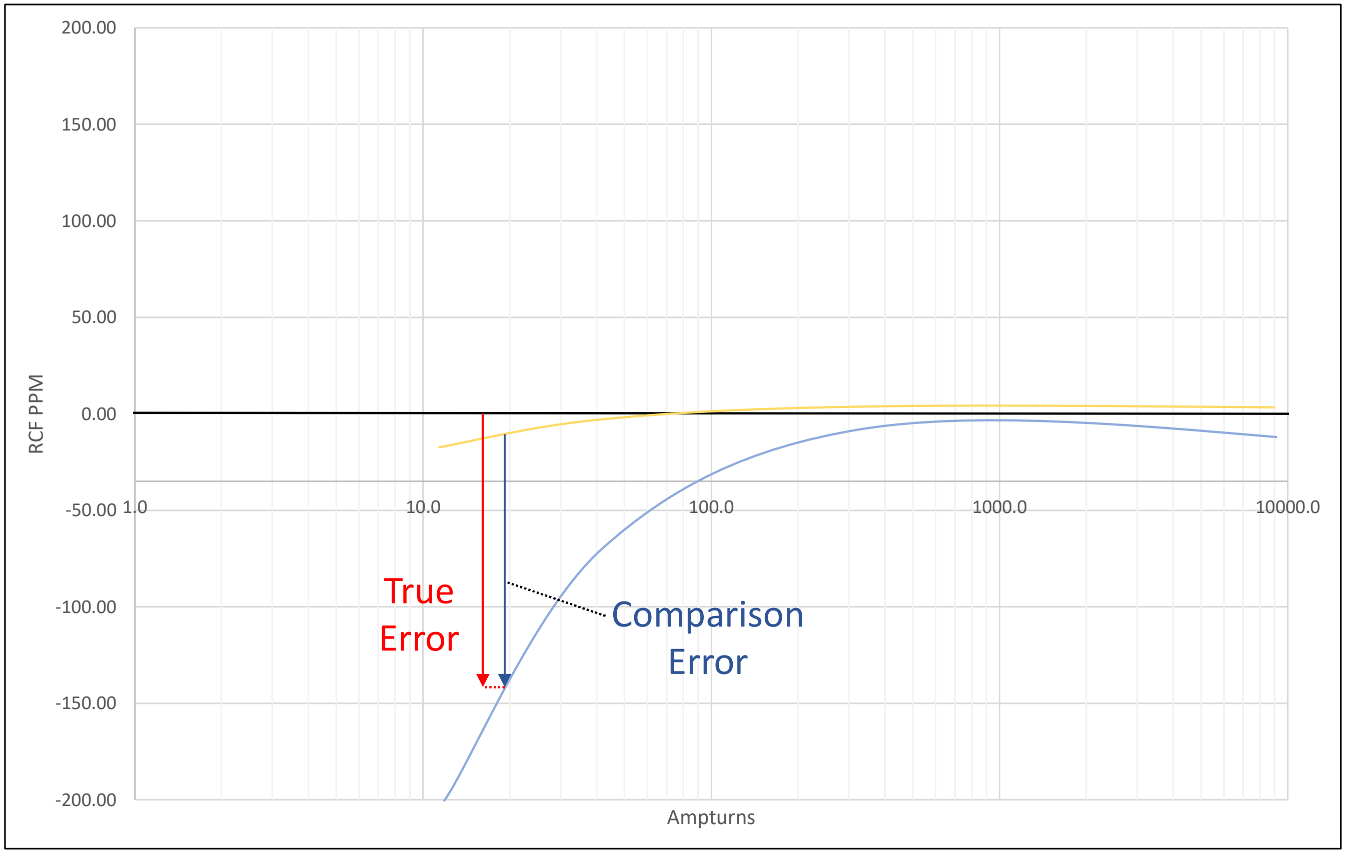
COMMON ACRONYMS AND TERMS



TRUE ERROR



TRUE ERROR


200.00
150.00
100.00
50.00
0.00
-50.00
-100.00
-150.00
-200.00
RCF PPM
1.0
10.0
100.0
1000.0
10000.0
Ampturns
True
Error
Comparison
Error

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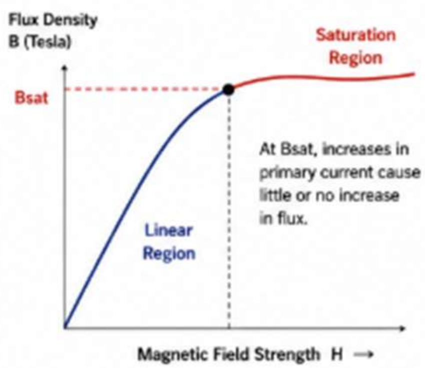
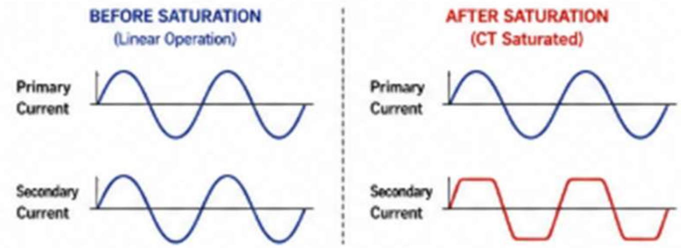
CT SATURATION: WHAT HAPPENS AND WHY IT MATTERS

As core flux approaches Bsat, the CT leaves the linear region and accuracy collapses

B–H CURVE AND SATURATION



WAVEFORM DISTORTION



EFFECTS OF SATURATION

- Secondary current is under-reported (meter reads low)
- Waveform is clipped and distorted
- Phase angle error increases
- High harmonic content
- Accuracy class is no longer valid
- Protection devices may misoperate

WHAT DRIVES SATURATION?

High Primary Current
Faults or overload conditions

High Burden (Secondary Impedance)
Long leads, multiple devices increase voltage and drive core toward Bsat

Core Material Limitations
Each material has a finite Bsat

Improper CT Sizing
CT ratio too small for the application

Once saturated, the CT no longer faithfully reproduces primary current. You no longer know the true current.

TEST BOTH ENDS OF THE CURVE: ACCURACY MATTERS AT LOW AND HIGH CURRENT

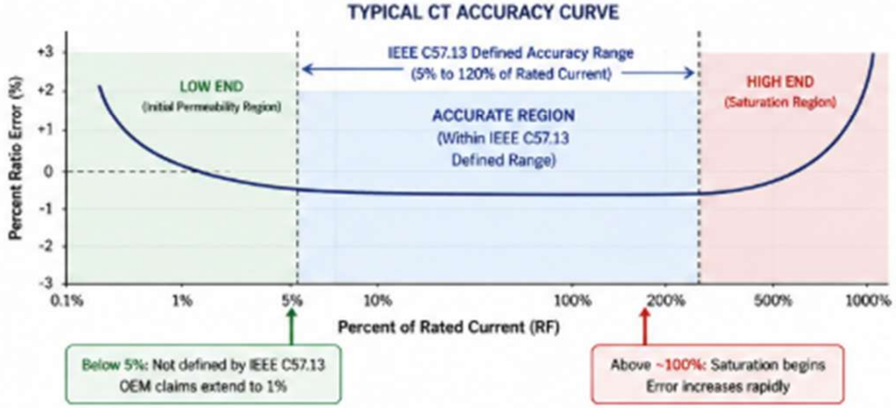
CTs have two accuracy challenges—low end (material/linearity) and high end (saturation). You must test across the entire operating range.

LOW END CHALLENGE (<5% of Rated Current)

- Initial permeability dominates
- Small signals (mA range)
- Noise and material variability cause error to increase
- Standards do not define accuracy below 5%

RISK:
Billing and analytics errors during normal light load operation

TYPICAL CT ACCURACY CURVE



HIGH END CHALLENGE (>100% of Rated Current)

- Core approaches Bsat
- Secondary current no longer increases proportionally
- Waveform distortion and large errors occur

RISK:
Protection misoperation and under-recorded high-current events

KEY TAKEAWAY

Accuracy is not constant.
It depends on current level.

Standards stop at 5%.
But you operate below 5% and above 100%.

You must test both ends of the curve
to ensure truen the high-:cnance real world.

You can't manage what you don't measure. | Test across the full range. Verify accuracy where you operate.

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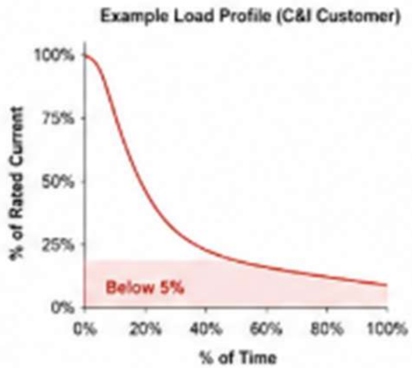
1. Why Low Current Accuracy Matters

Many systems operate in the low end of the CT range.

5–30% of time

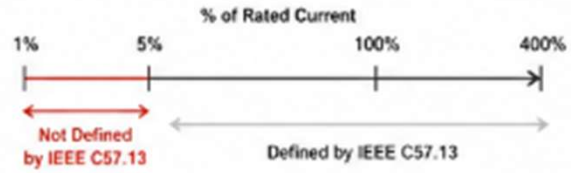
Typical for C&I and lightly loaded circuits



If you don't test here, you don't know.

2. Where Standards Stop

IEEE C57.13 defines accuracy down to 5% of rated current. Below that, accuracy is not required to meet the class.



Operating below 5%?
You're outside the standard.

3. Sources of CT Inaccuracy at Low Current

- Core non-linearity and saturation
- Hysteresis and remanence
- Burden impedance
- Temperature effects
- Manufacturing variability

These effects are amplified at low current.

4. CT Error Impact

Accuracy Error		Metering Impact
1% error	→	$10,000 / year per 100 meters
2% error	→	$20,000 / year per 100 meters
3% error	→	$30,000 / year per 100 meters
5% error	→	$50,000 / year per 100 meters

Small errors at low current create big financial impact across a fleet.

* Example based on 5 MW average load, $0.10/kWh, 80% load factor.

5. The Testing Gap

What Standards Require	What OEMs Typically Test	What Utilities Need
Accuracy validated from 5% to 400% of rated current.	Most testing focuses on 100% of rated current.	Accuracy validated below 5%, down to 1% of rated current.

The gap is where the risk is.

6. Key Takeaways

- CT accuracy is range-dependent.
- Standards only require accuracy down to 5%.
- CTs can pass at 100% and fail at low current.
- Manufacturing variability is real.
- Testing below 5% is essential.
- You can't manage what you don't measure.

Test below 5%. Know your accuracy.