Control Systems: Design, Performance and Commissioning Issues

Inputs

Instructor:

David Sellers

Senior Engineer

Facility Dynamics Engineering

October 23, 2017

Control Systems: Design, Performance and Commissioning Issues

Inputs

A Bit of History

Instructor:

David Sellers

Senior Engineer

Facility Dynamics Engineering

October 23, 2017

A 1912 Vintage RPM Sensor (Revolutions Per Minute)

A 1912 Vintage RPM Sensor

A 1912 Vintage RPM Sensor

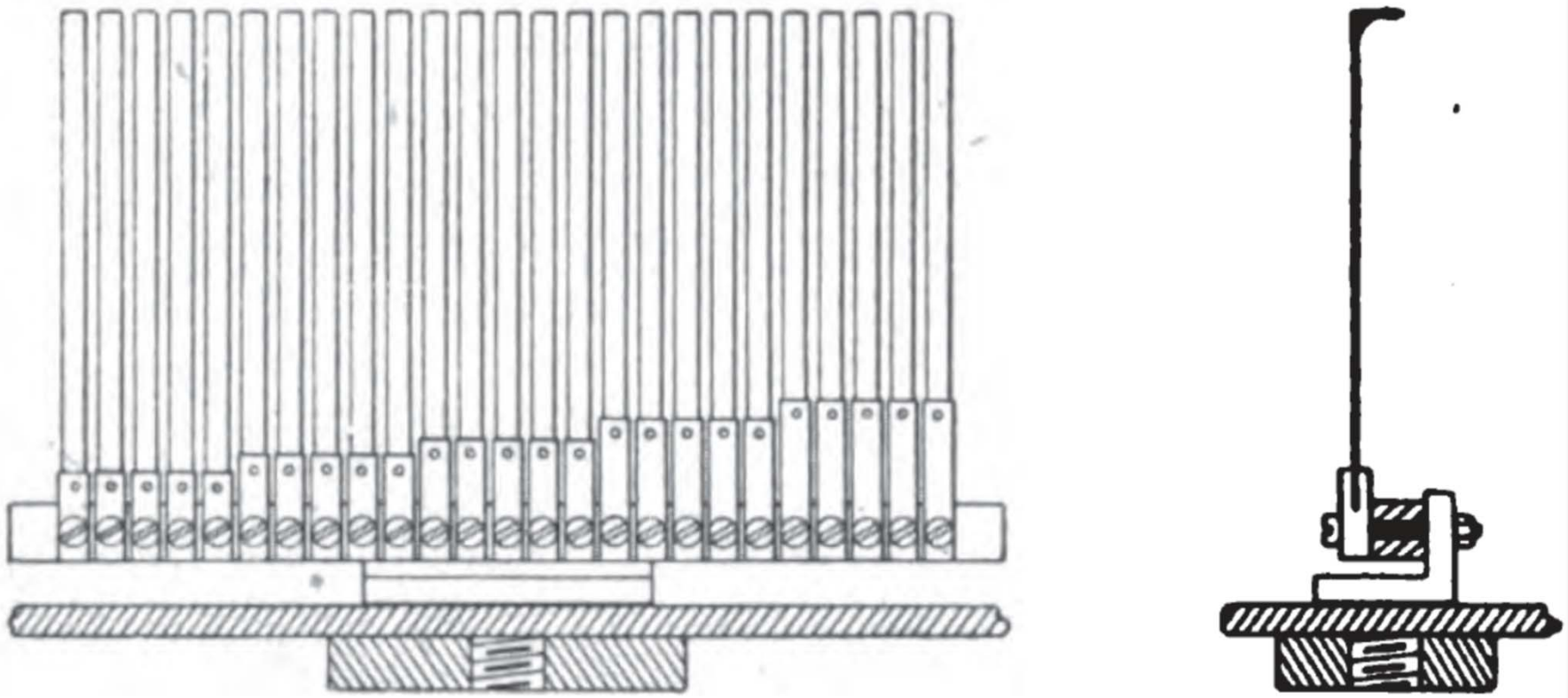


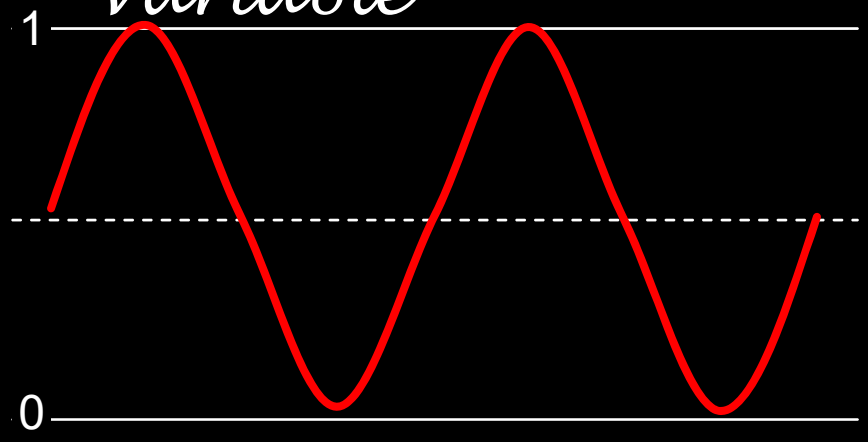
FIG. 2. INDICATING REEDS AS MOUNTED IN FRAHM VIBRATION TACHOMETERS

Image from August 1912 Steam; http://tinyurl.com/August-1912-Steam

Analog vs. Digital

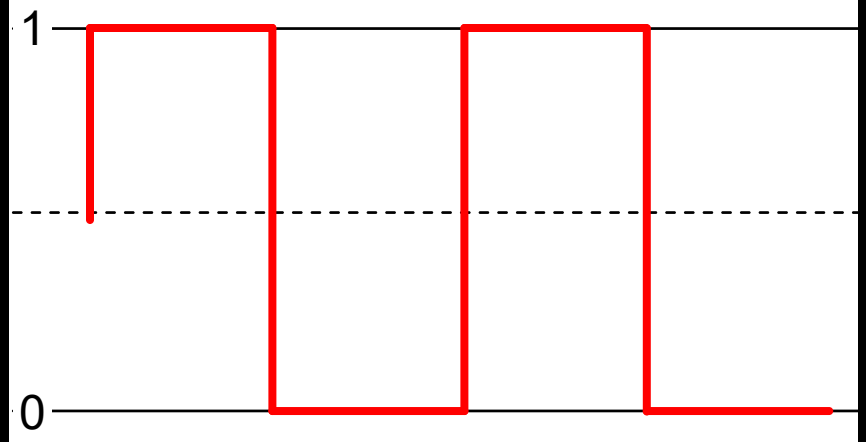
Analog

Continuously Variable



Digital

Discrete units



Control Systems: Design, Performance and Commissioning Issues

Inputs

Sensors and Transmitters

Instructor:

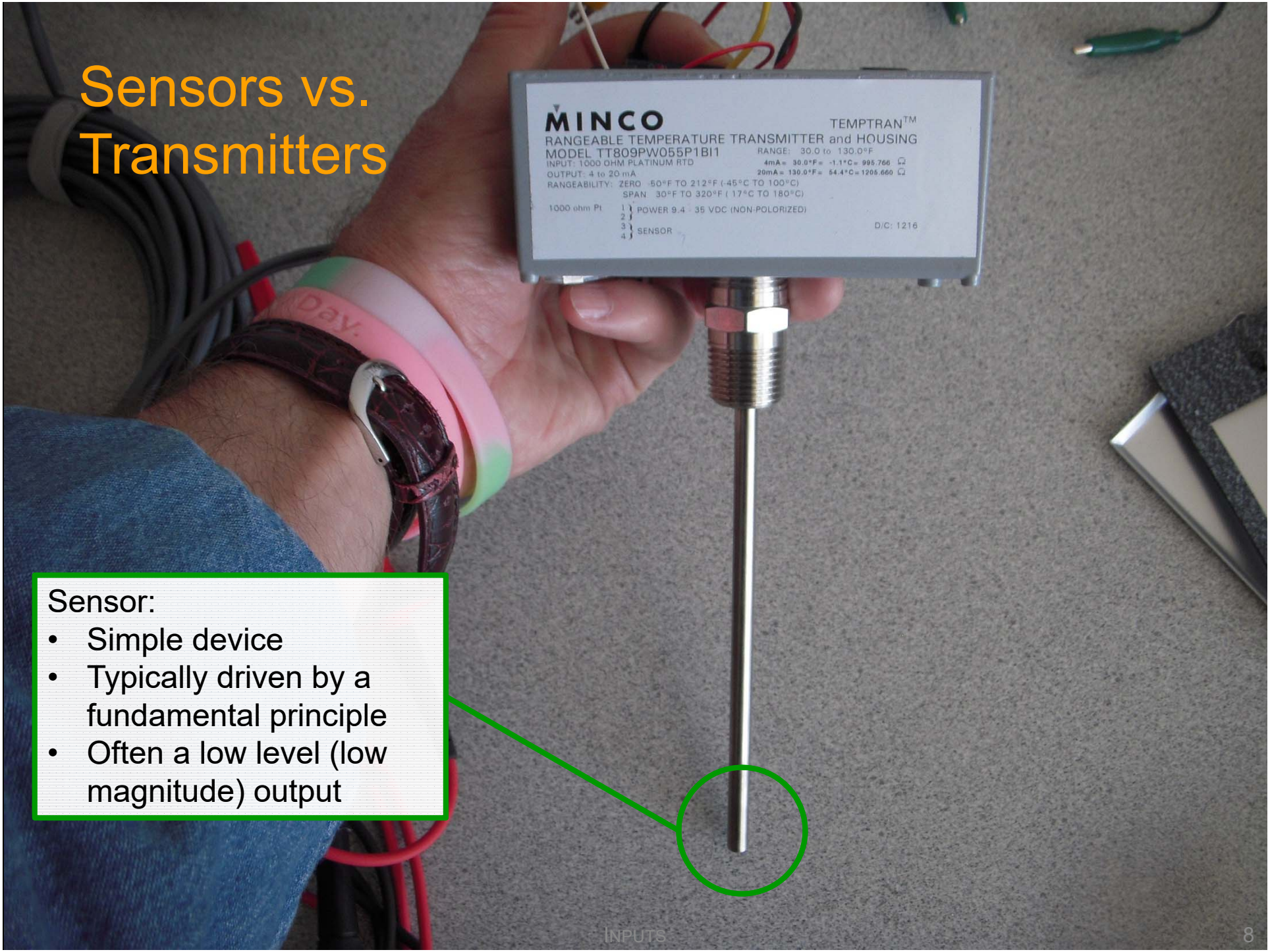
David Sellers

Senior Engineer

Facility Dynamics Engineering

October 23, 2017

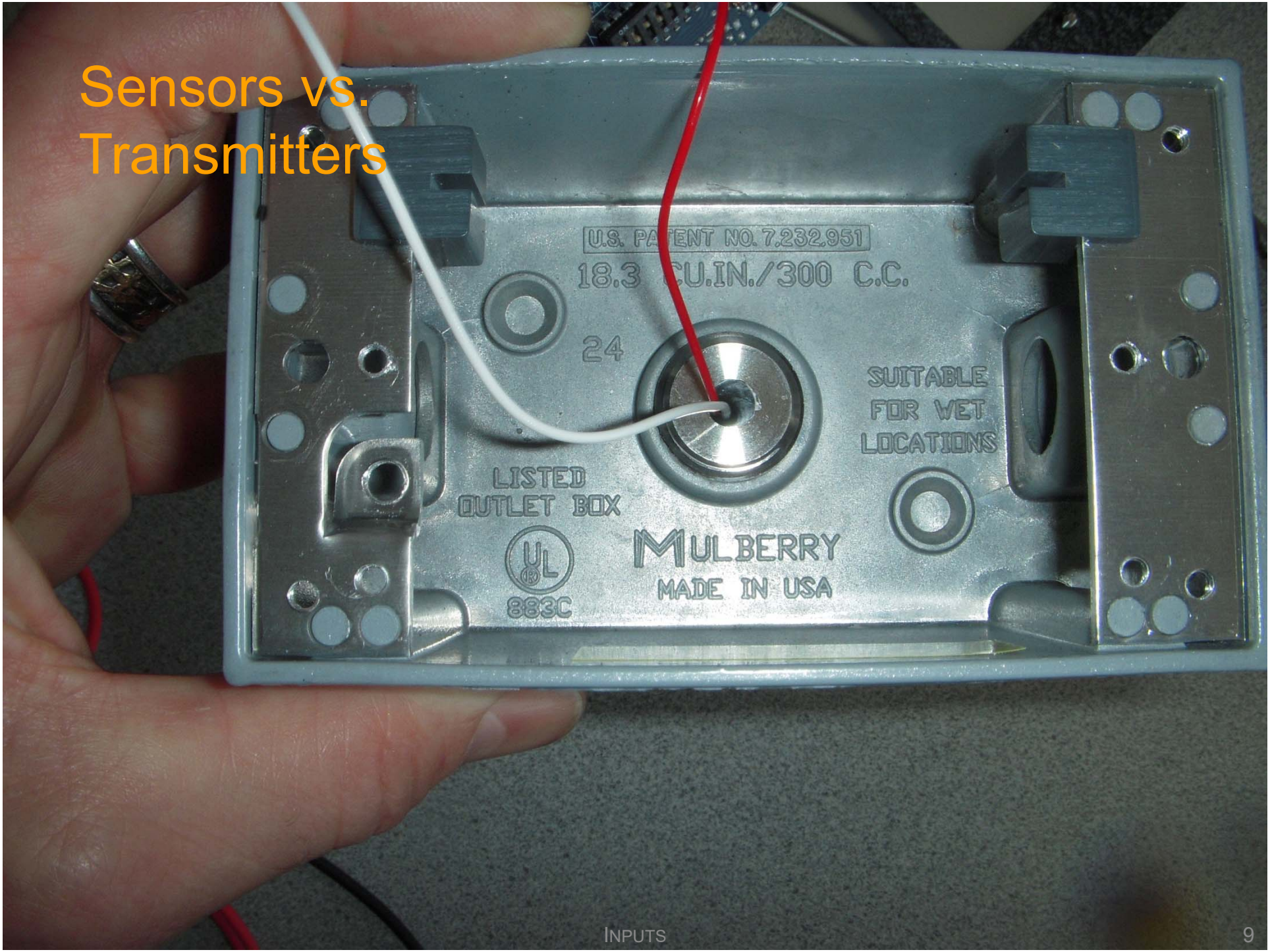
Sensors vs. Transmitters



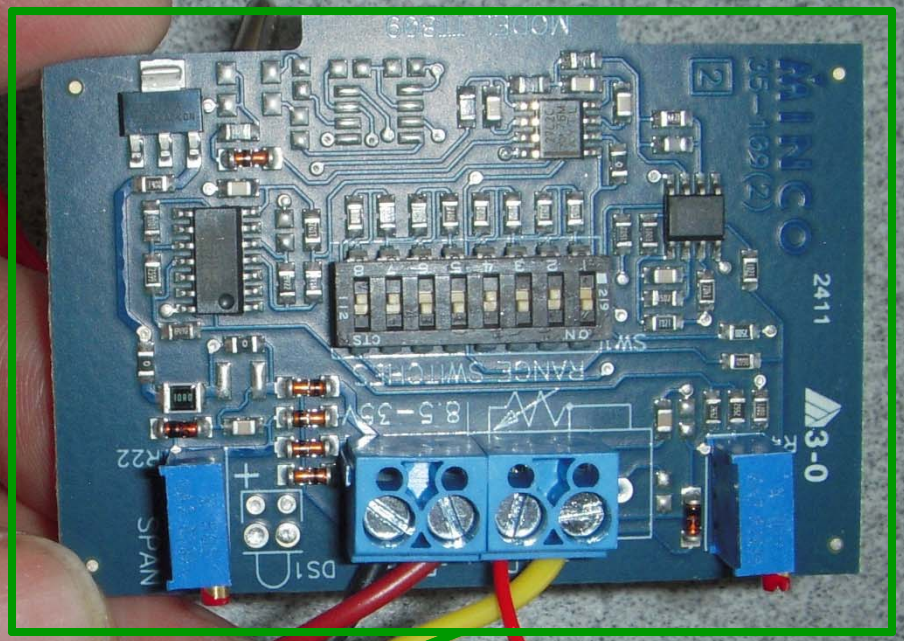
Sensor:

- Simple device
- Typically driven by a fundamental principle
- Often a low level (low magnitude) output

Sensors vs. Transmitters



Sensors vs. Transmitters



Transmitter:

- Complex device
- Scales up the low level signal
- May “condition” it (set a span, linearize it, etc.)
- Typically provides a standard output (4-20 ma, 1-5 vdc, 2-10 vdc, 3-15 psi, etc.)

Why Transmitters?

Effect of length of lead wire on RTD measurements

- Distance to the sensor - 100 ft
- Wire size - 22 AWG
- Specific resistance - 0.0165ohms per foot at 25°C
- Total lead length in series with the RTD – 200 ft

The added resistance from the length of wire is 3.3 ohms.

With an average RTF sensitivity of 4.7880 ohms per°C, the equivalent temperature associated with lead resistance is 1.24 °F

Why Transmitters?

Effect of temperature change on RTD measurements on a rooftop unit where the conduit is run outdoors in the Midwest

- Minimum temperature - minus 20°F
- Maximum temperature - 105°F (assuming no solar effects)
- Temperature change - 125°F or 69°C
- Resistance temperature coefficient for copper - 0.0043 ohms per ohm per °C

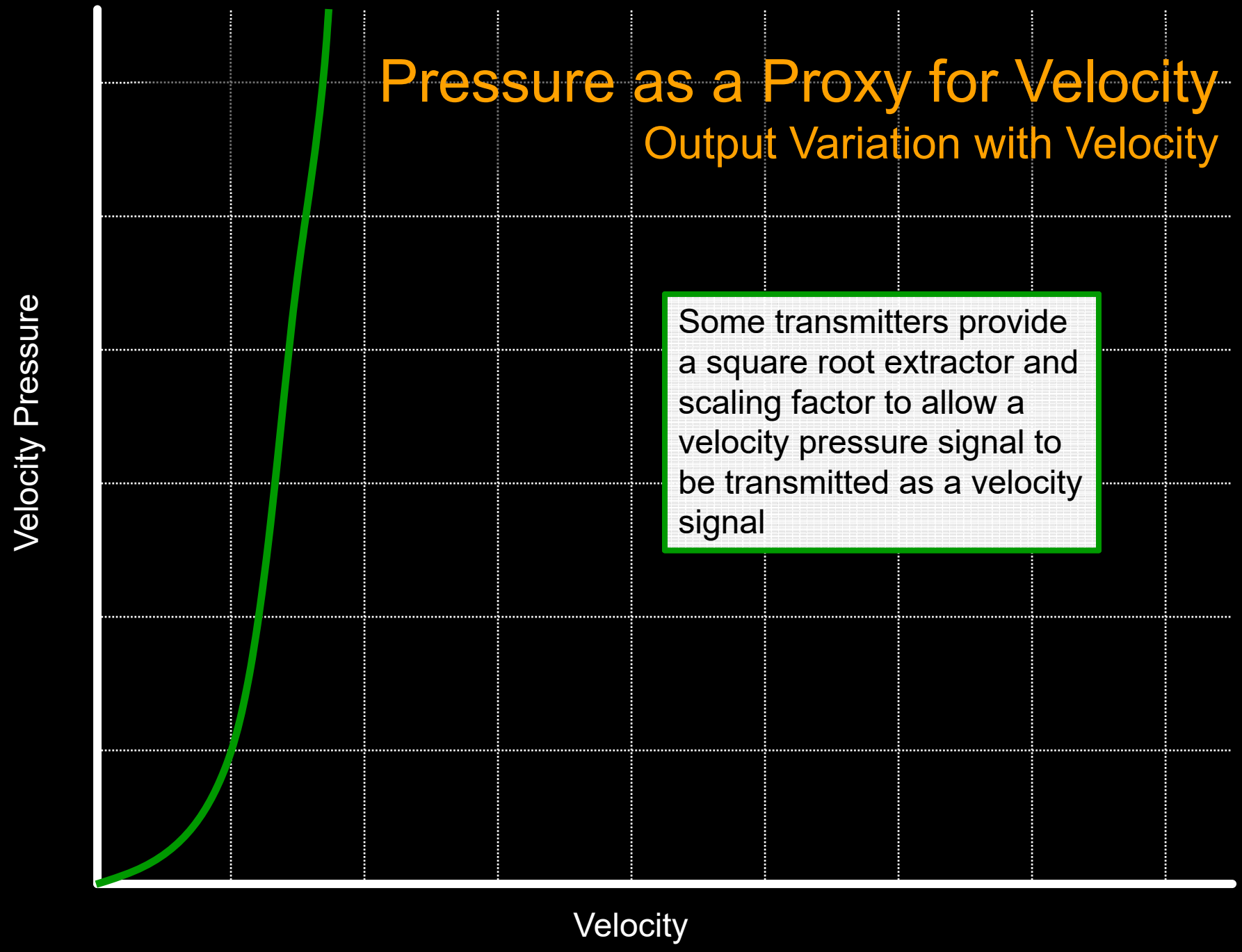
For the temperature variability stated, the corresponding change in RTD resistance is 0.98 ohms.

This change in resistance translates to a 0.37°F change in indicated temperature due to the outdoor temperature change

A High End RTD with Transmitter

Pressure as a Proxy for Velocity

Output Variation with Velocity



Some transmitters provide a square root extractor and scaling factor to allow a velocity pressure signal to be transmitted as a velocity signal

Control Systems: Design, Performance and Commissioning Issues

Inputs

Sensing What is Really Going On

Instructor:

David Sellers

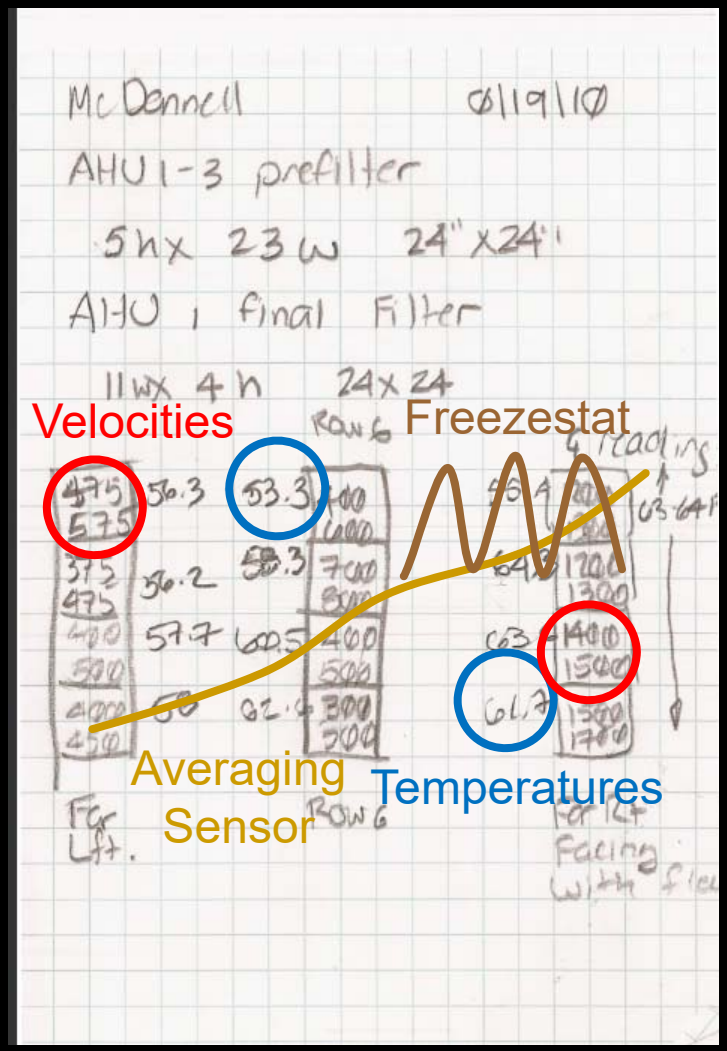
Senior Engineer

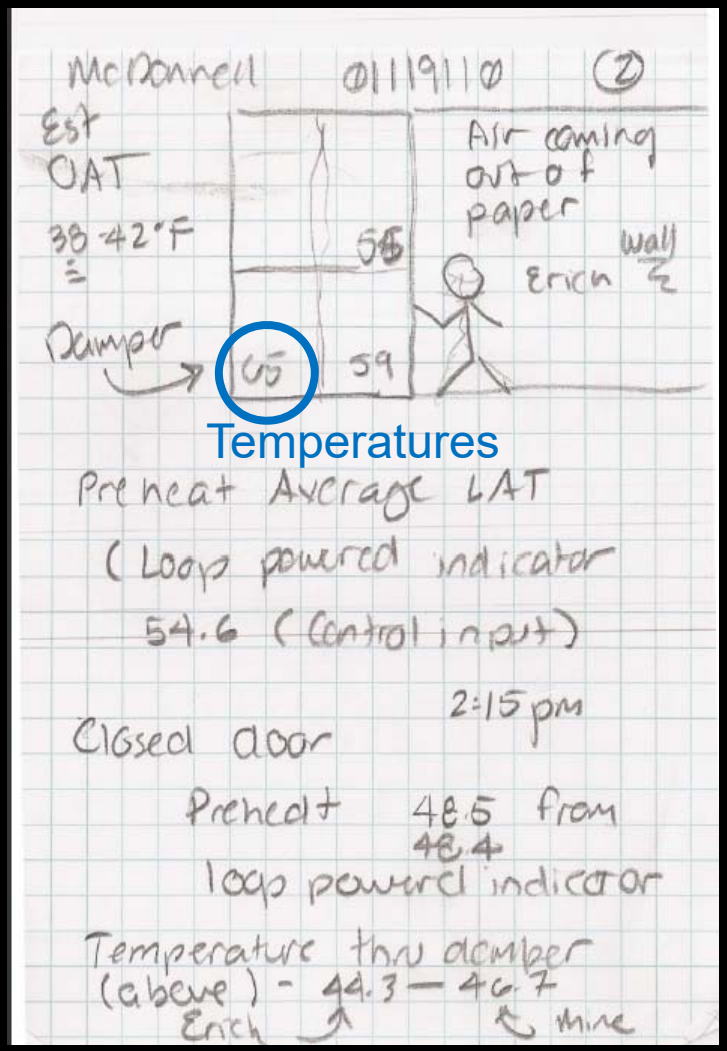
Facility Dynamics Engineering

October 23, 2017

Sensing What is Really Going On

Sensing What is Really Going On





Sensing What is Really Going On

Another Thing:

If you mix 1 gallon of 50°F water with 99 gallons of 100°F water, do you get 75°F water?

Sensing What is Really Going On

Another Thing:

If you mix 1 gallon of 50°F water with 99 gallons of 100°F water, do you get 75°F water?

The Answer:

No, you get 100 gallons of water at about 99.5°F (even though the average of the temperatures is 75°F) because the mass of the water comes into play

Averaging sensors assume a uniform distribution of flow across the sensing element

- *This is generally not the case due to the "bullet" shape of the fully developed velocity profile for the air and water flowing in our systems.*
- *This s hardly ever the case in mixed air plenums or other locations where two fluid streams are mixing.*

Sensing What is Really Going On

For more about mixing and temperature stratification in a mixed air plenum, see *Economizers–The Physics of a Mixed Air Plenum* and *Retrocommissioning Findings: Economizer Mixed Air Plenum Stratification–Overview*, *both at www.Av8rDAS.Wordpress.com*

Control Systems: Design, Performance and Commissioning Issues

Inputs

Thermal Effects and Position Effects

Instructor:

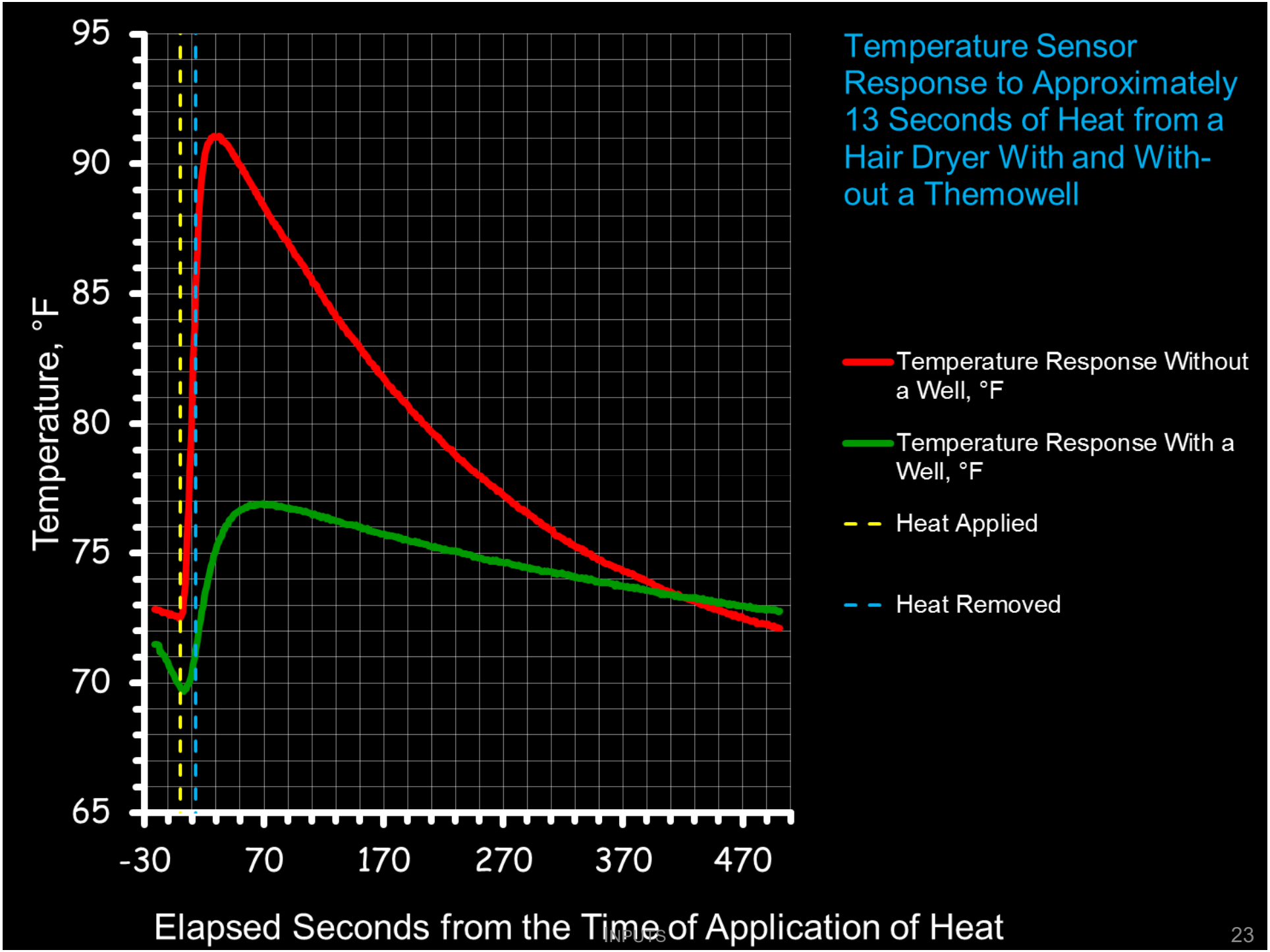
David Sellers

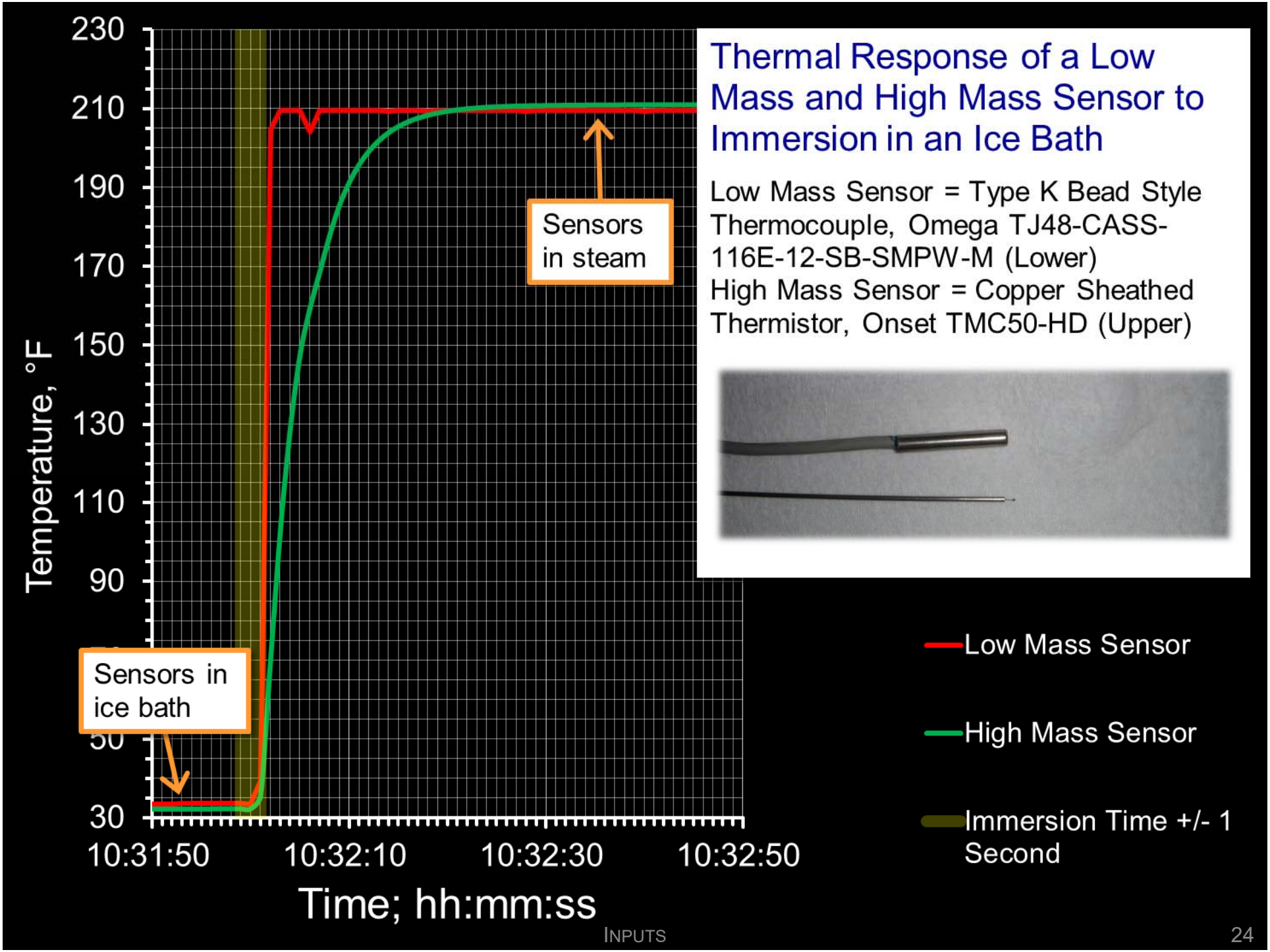
Senior Engineer

Facility Dynamics Engineering

October 23, 2017

Well, Well, Well; What Have We Here?


Temperature Sensor Response to Approximately 13 Seconds of Heat from a Hair Dryer With and Without a Themowell
Temperature, °F
95
90
85
80
75
70
65
-30
70
170
270
370
470
Elapsed Seconds from the Time of Application of Heat
Temperature Response Without a Well, °F
Temperature Response With a Well, °F
Heat Applied
Heat Removed


Thermal Response of a Low Mass and High Mass Sensor to Immersion in an Ice Bath
Low Mass Sensor = Type K Bead Style Thermocouple, Omega TJ48-CASS-116E-12-SB-SMPW-M (Lower)
High Mass Sensor = Copper Sheathed Thermistor, Onset TMC50-HD (Upper)
Temperature, °F
230
210
190
170
150
130
110
90
30
10:31:50
10:32:10
10:32:30
10:32:50
Time; hh:mm:ss
Sensors in steam
Sensors in ice bath
Low Mass Sensor
High Mass Sensor
Immersion Time +/- 1 Second

Visit http://av8rdas.wordpress.com/2014/03/28/4-20-ma-current-loop-experiments-thermal-mass-effects/ for video clips and details

For More on Thermal Lags

More details and examples of thermal lags can be found in the blog post titled *4-20 ma Current Loop Experiments – Thermal Mass Effects* on my blog at www.Av8rDAS.Wordpress.com

More than One Well is a Good Thing

Providing a second well next to a pipe mounted sensor allows you to insert a calibration standard that sees the same conditions

The same is true for other sensors like pressure sensors (provide a second service valve for calibration)

Mounting Position Can Be Important

Mounting Position Can Be Important

Mounting Position Can Be Important

Mounting Position Can Be Important

Visit http://tinyurl.com/ngwb3zj for video clips and details

For More on Position Effects

More details and examples of position effect can be found in the blog posts titled *Mounting Position Effects: +30/-90° from vertical = +8/-3% Accuracy* and *4-20 ma Current Loop Experiments – Position Sensitivity* on my blog at www.Av8rDAS.Wordpress.com

Control Systems: Design, Performance and Commissioning Issues

Inputs

Calibration and Accuracy

Instructor:

David Sellers

Senior Engineer

Facility Dynamics Engineering

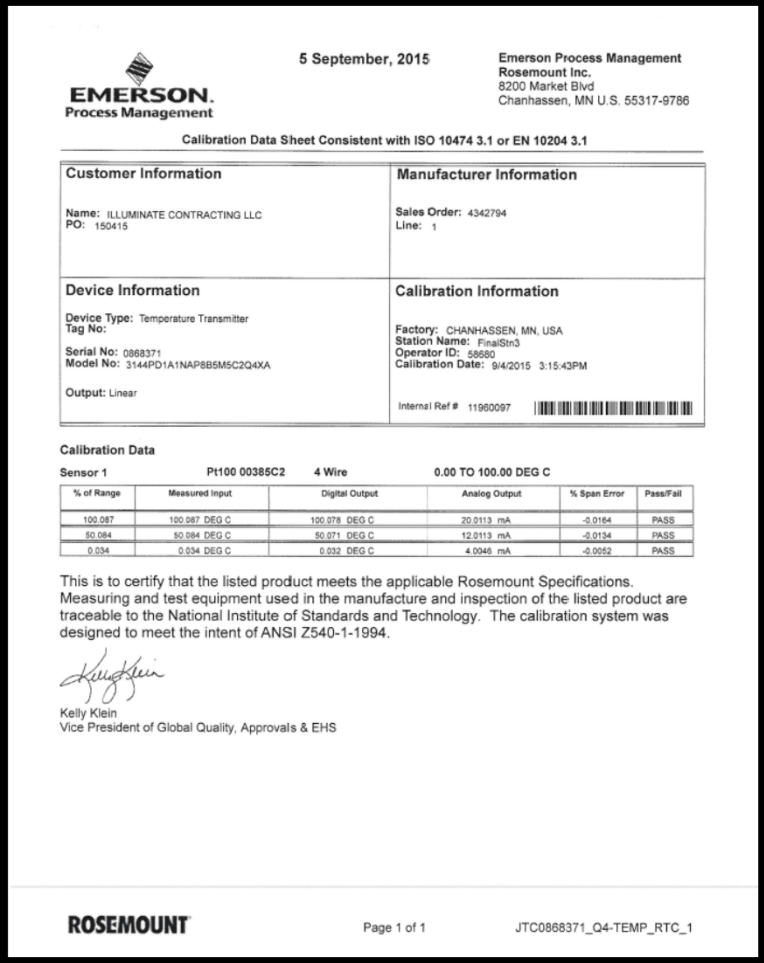
October 23, 2017

Verify Input/Output Details

Calibration

Factory Calibration

- A good start
  - Addresses the factory provided components
  - Does not address the potential field impacts
    - Position effect
    - Lags
    - Lead resistance
    - A to D conversion
    - D to A conversion
    - COV limits
    - Bifocals



EMERSON. Process Management

5 September, 2015

Emerson Process Management
Rosemount Inc.
8200 Market Blvd
Chanhassen, MN U.S. 55317-9786

Calibration Data Sheet Consistent with ISO 10474 3.1 or EN 10204 3.1

Customer Information

Name: ILLUMINATE CONTRACTING LLC
PO: 150415

Manufacturer Information

Sales Order: 4342794
Line: 1

Device Information

Device Type: Temperature Transmitter
Tag No:
Serial No: 0868371
Model No: 3144PD1A1NAP8B5M5C2Q4XA
Output: Linear

Calibration Information

Factory: CHANHASSEN, MN, USA
Station Name: FinalStn3
Operator ID: 58680
Calibration Date: 9/4/2015 3:15:43PM
Internal Ref # 11960097

Calibration Data

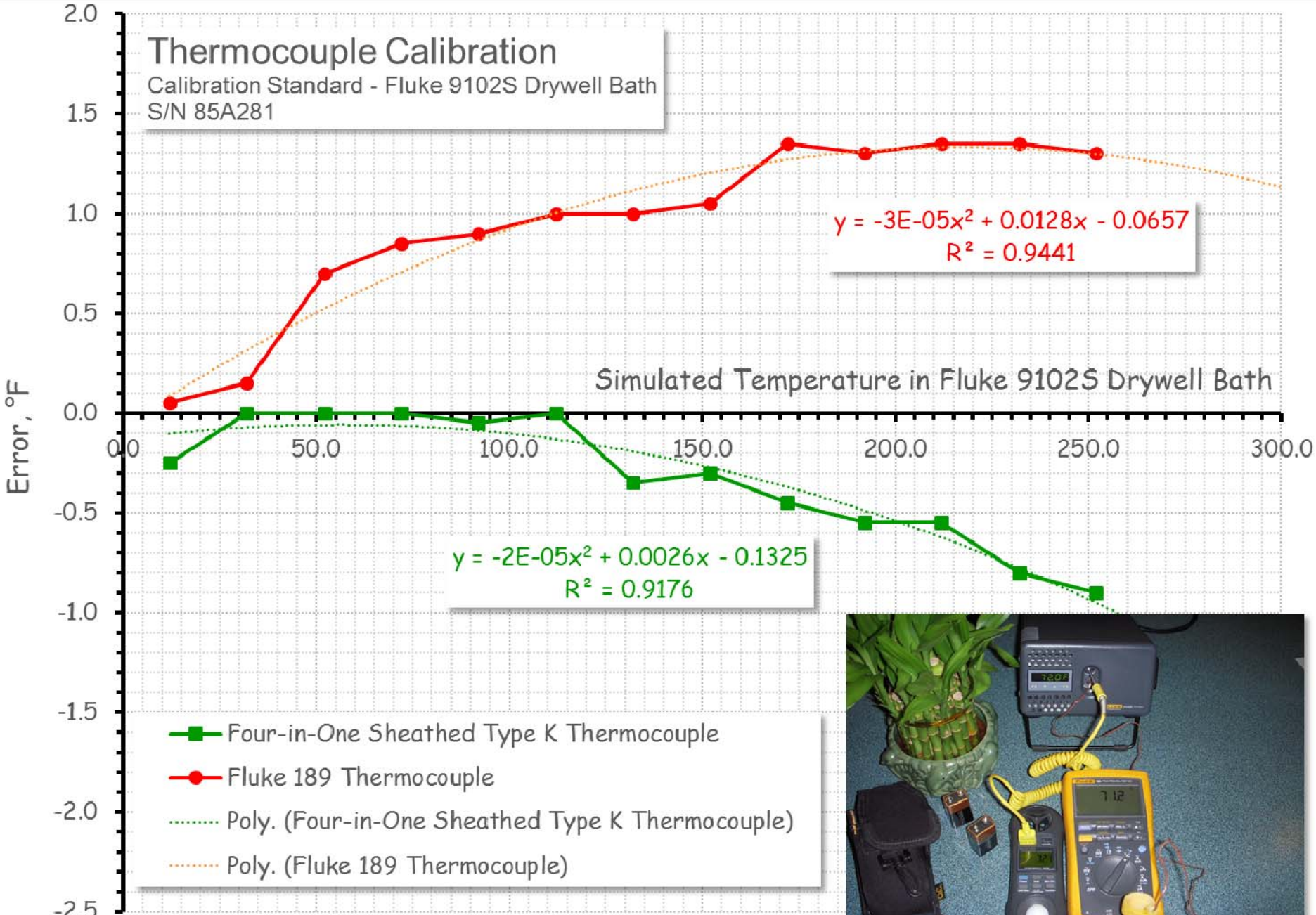
Sensor 1 Pt100 00385C2 4 Wire 0.00 TO 100.00 DEG C

% of Range	Measured Input	Digital Output	Analog Output	% Span Error	Pass/Fail
100.087	100.087 DEG C	100.078 DEG C	20.0113 mA	-0.0164	PASS
50.084	50.084 DEG C	50.071 DEG C	12.0113 mA	-0.0134	PASS
0.034	0.034 DEG C	0.032 DEG C	4.0046 mA	-0.0052	PASS

This is to certify that the listed product meets the applicable Rosemount Specifications. Measuring and test equipment used in the manufacture and inspection of the listed product are traceable to the National Institute of Standards and Technology. The calibration system was designed to meet the intent of ANSI Z540-1-1994.

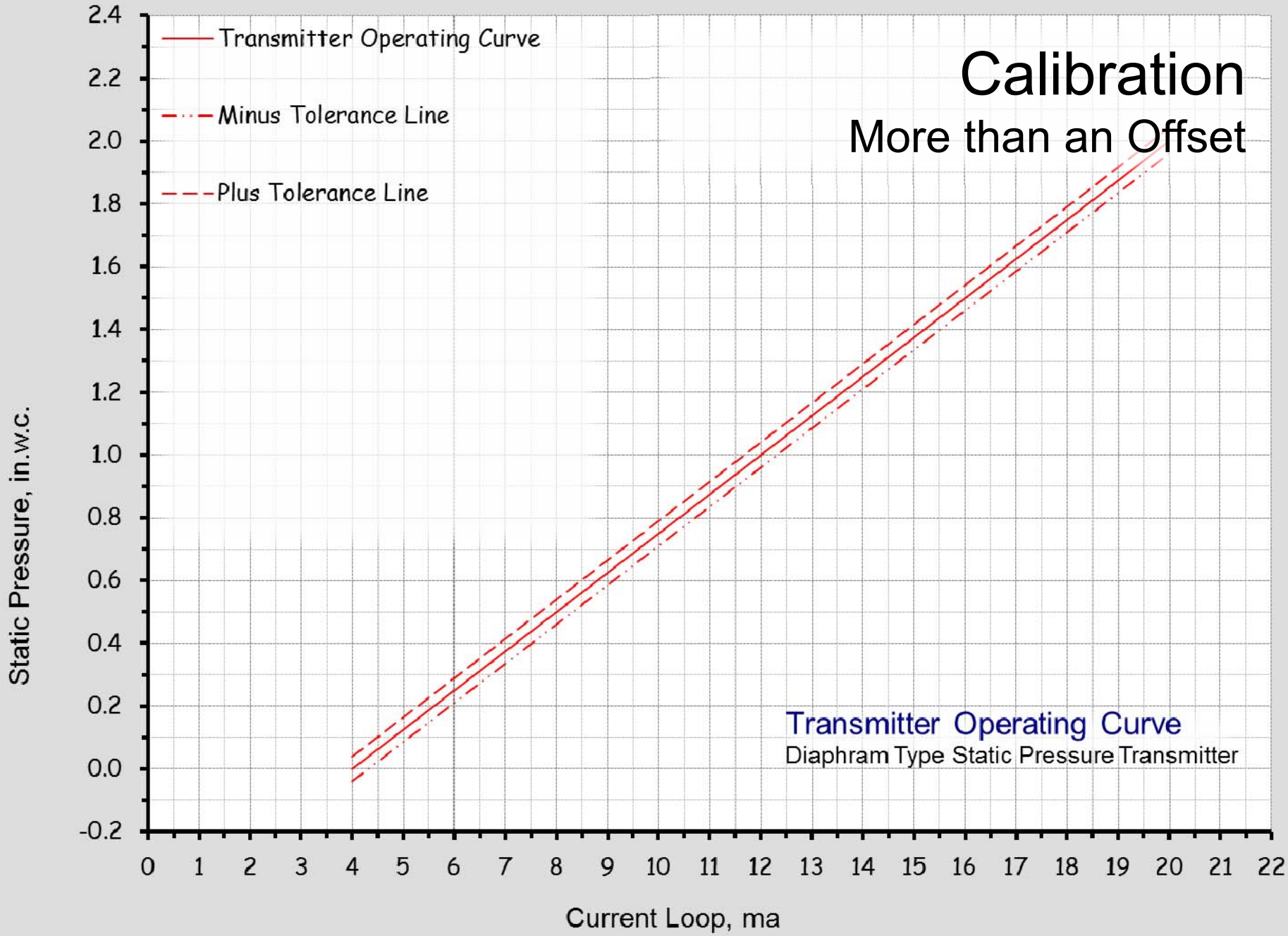
Kelly Klein
Vice President of Global Quality, Approvals & EHS

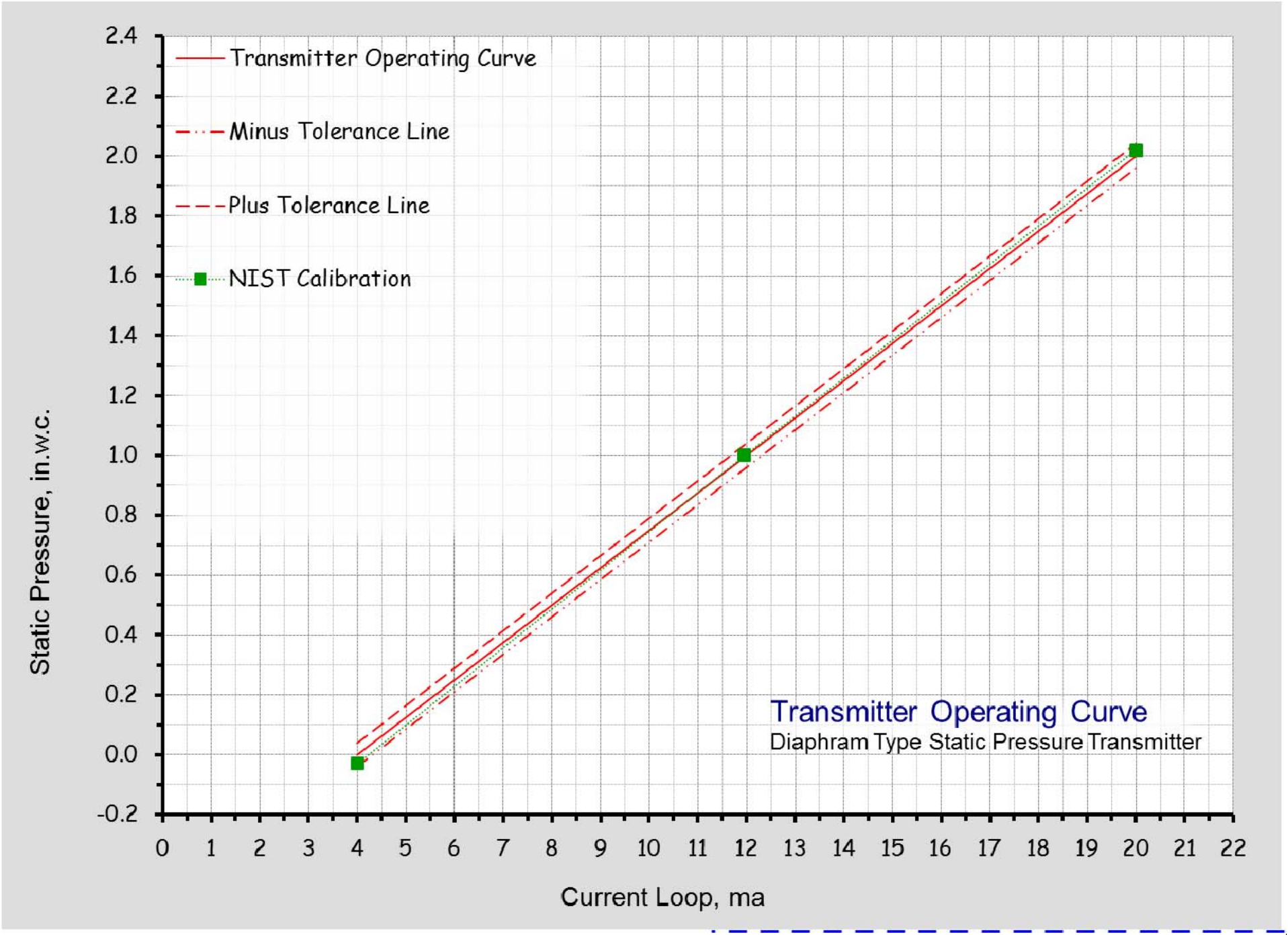
ROSEMOUNT Page 1 of 1 JTC0868371_Q4-TEMP_RTC_1


Thermocouple Calibration
Calibration Standard - Fluke 9102S Drywell Bath
S/N 85A281
y = -3E-05x² + 0.0128x - 0.0657
R² = 0.9441
Simulated Temperature in Fluke 9102S Drywell Bath
Error, °F
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
0.0
50.0
100.0
150.0
200.0
250.0
300.0
y = -2E-05x² + 0.0026x - 0.1325
R² = 0.9176
Four-in-One Sheathed Type K Thermocouple
Fluke 189 Thermocouple
Poly. (Four-in-One Sheathed Type K Thermocouple)
Poly. (Fluke 189 Thermocouple)

Calibration

More than an Offset



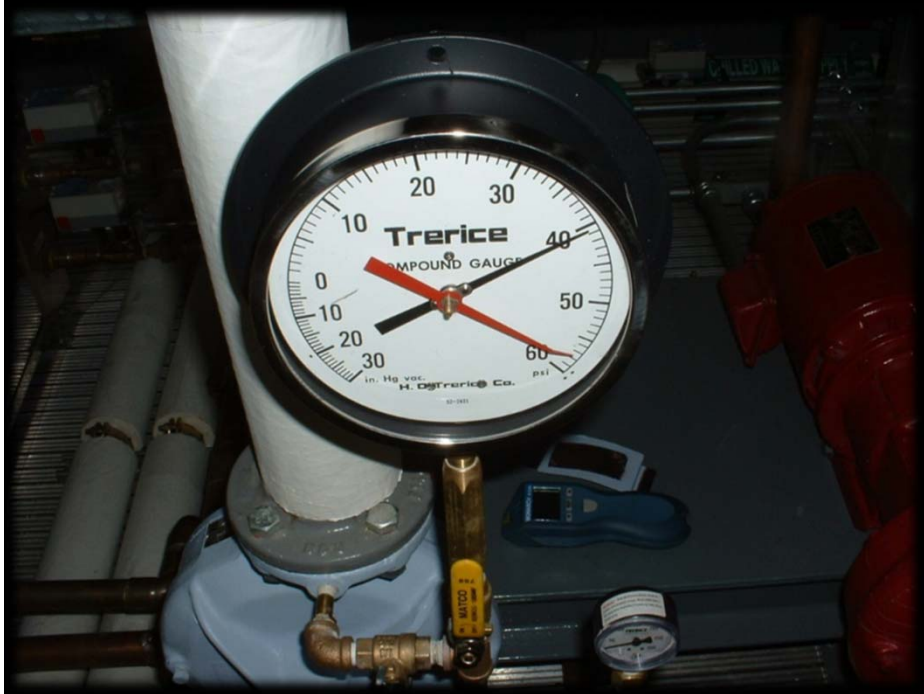

Transmitter Operating Curve
Minus Tolerance Line
Plus Tolerance Line
NIST Calibration
Static Pressure, in.w.c.
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
Current Loop, ma
Transmitter Operating Curve
Diaphram Type Static Pressure Transmitter

Un-Calibration

Use an Un-calibrated Standard

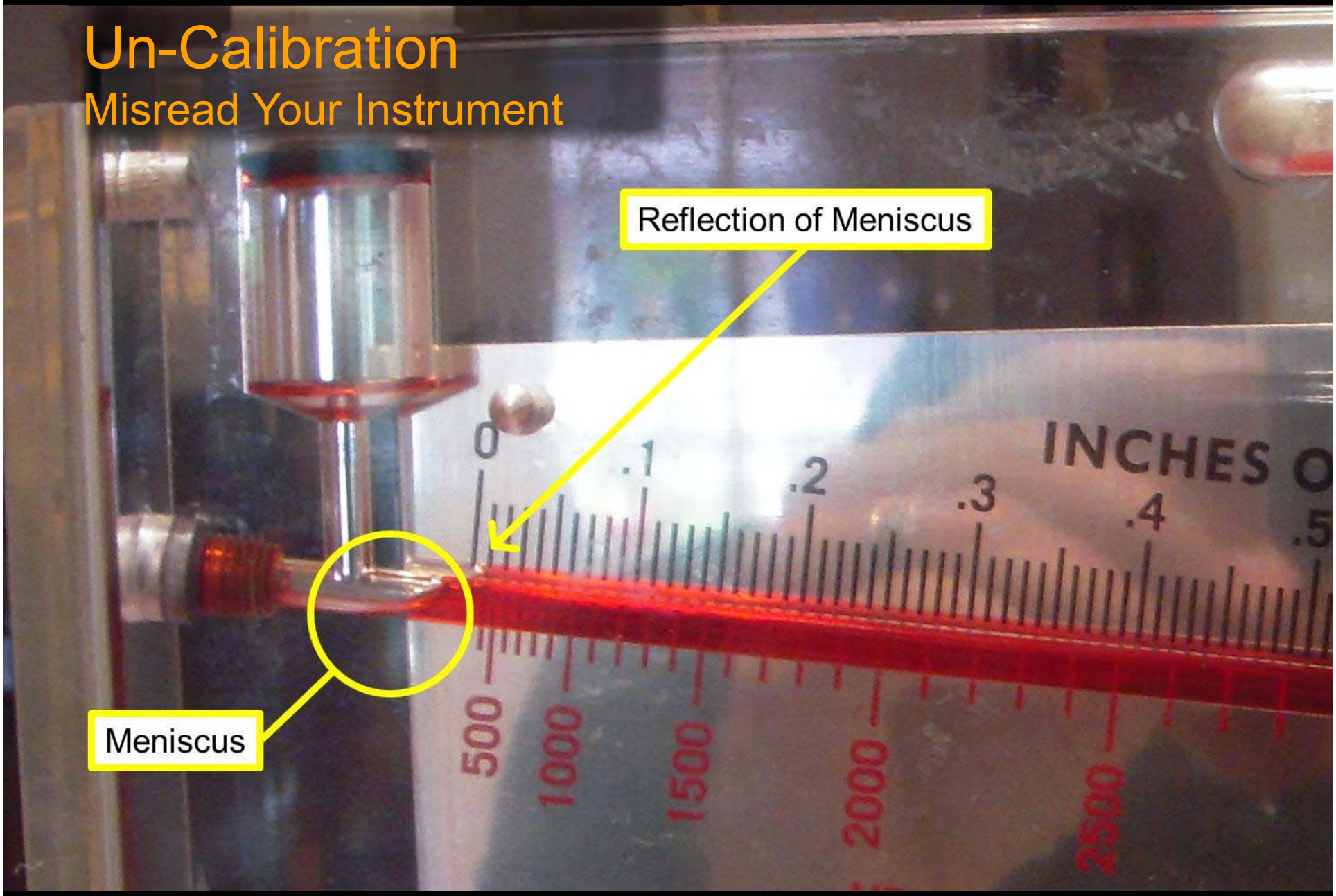
Un-Calibration

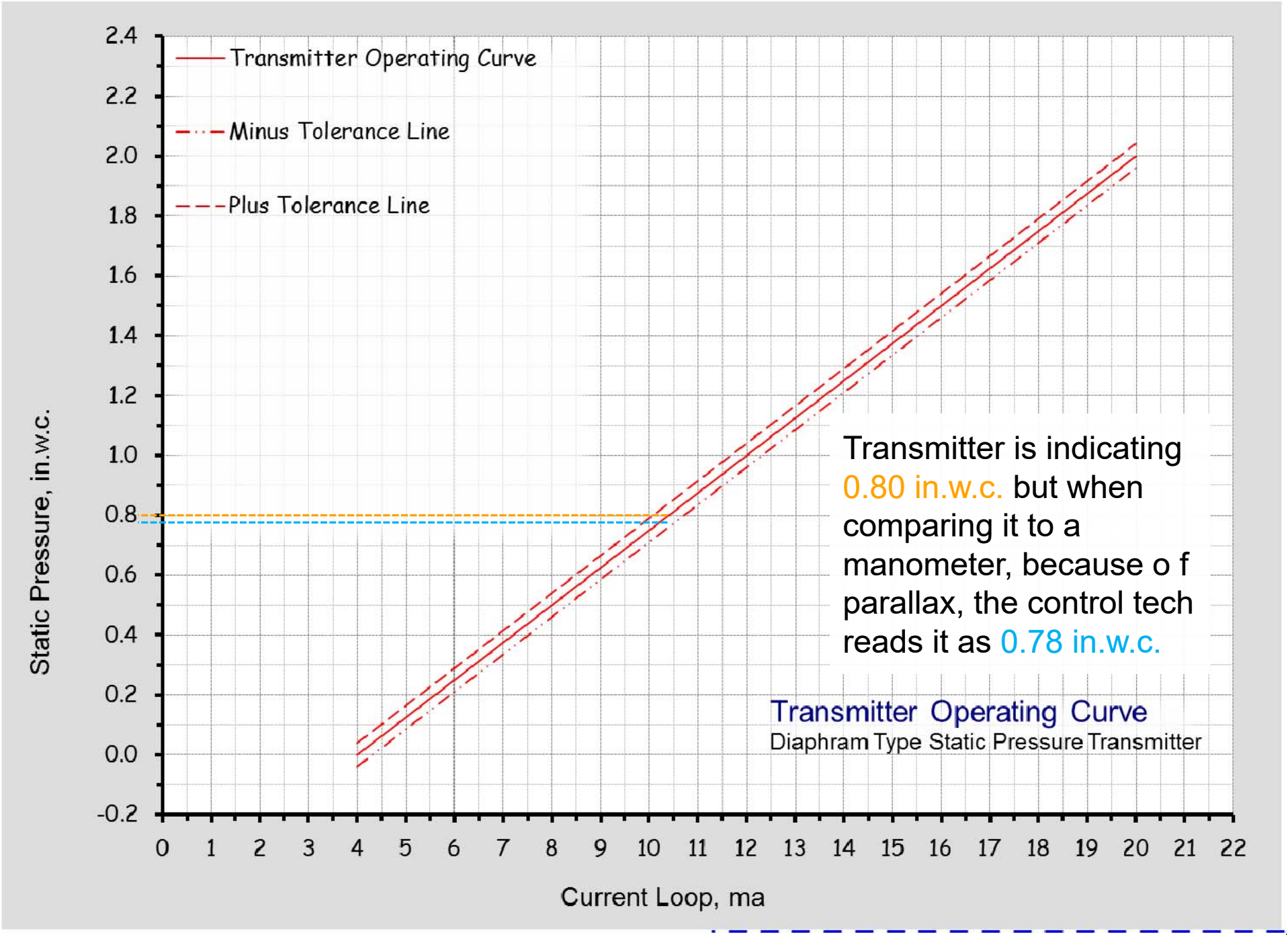
Misread Your Instrument

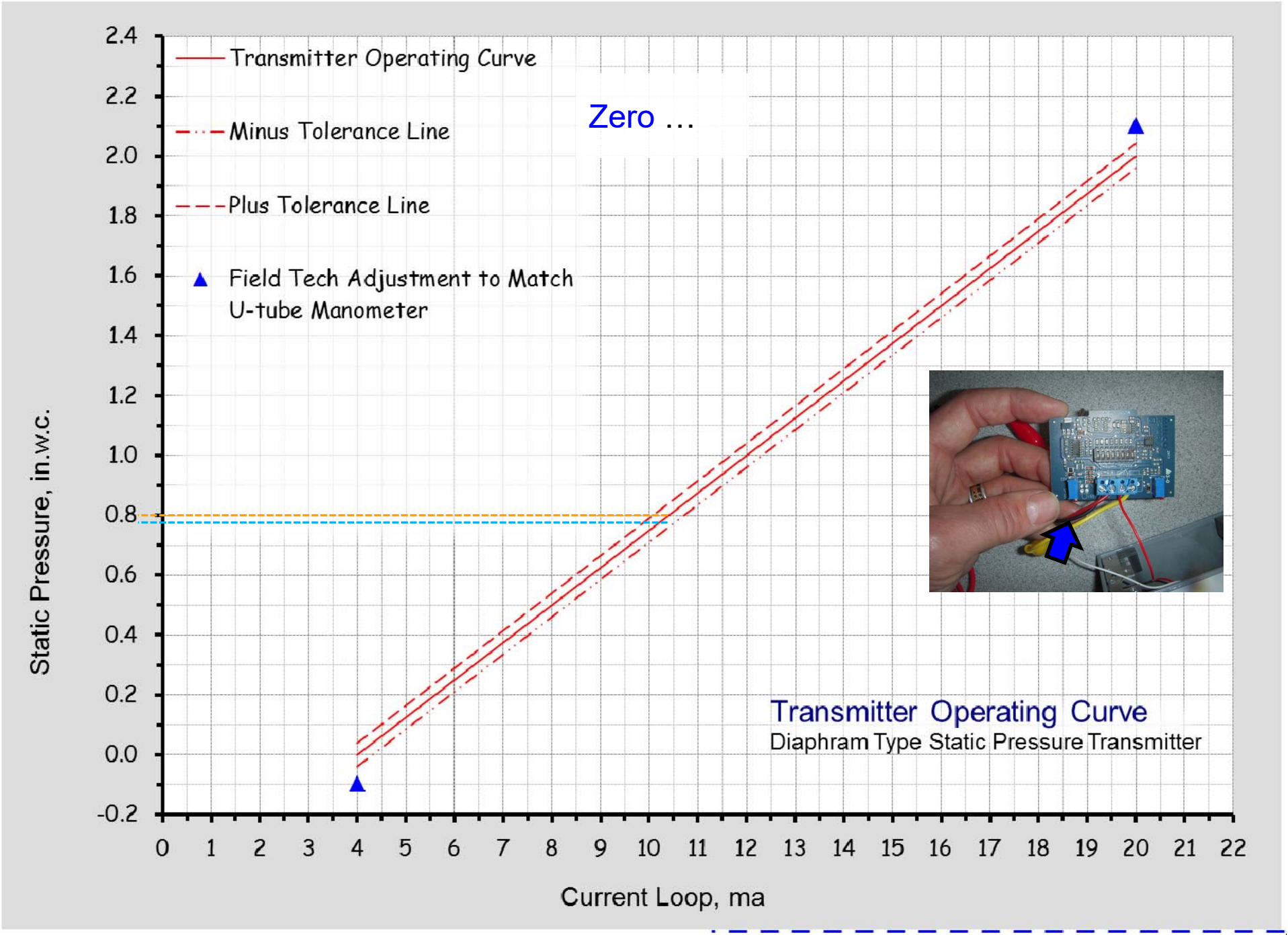


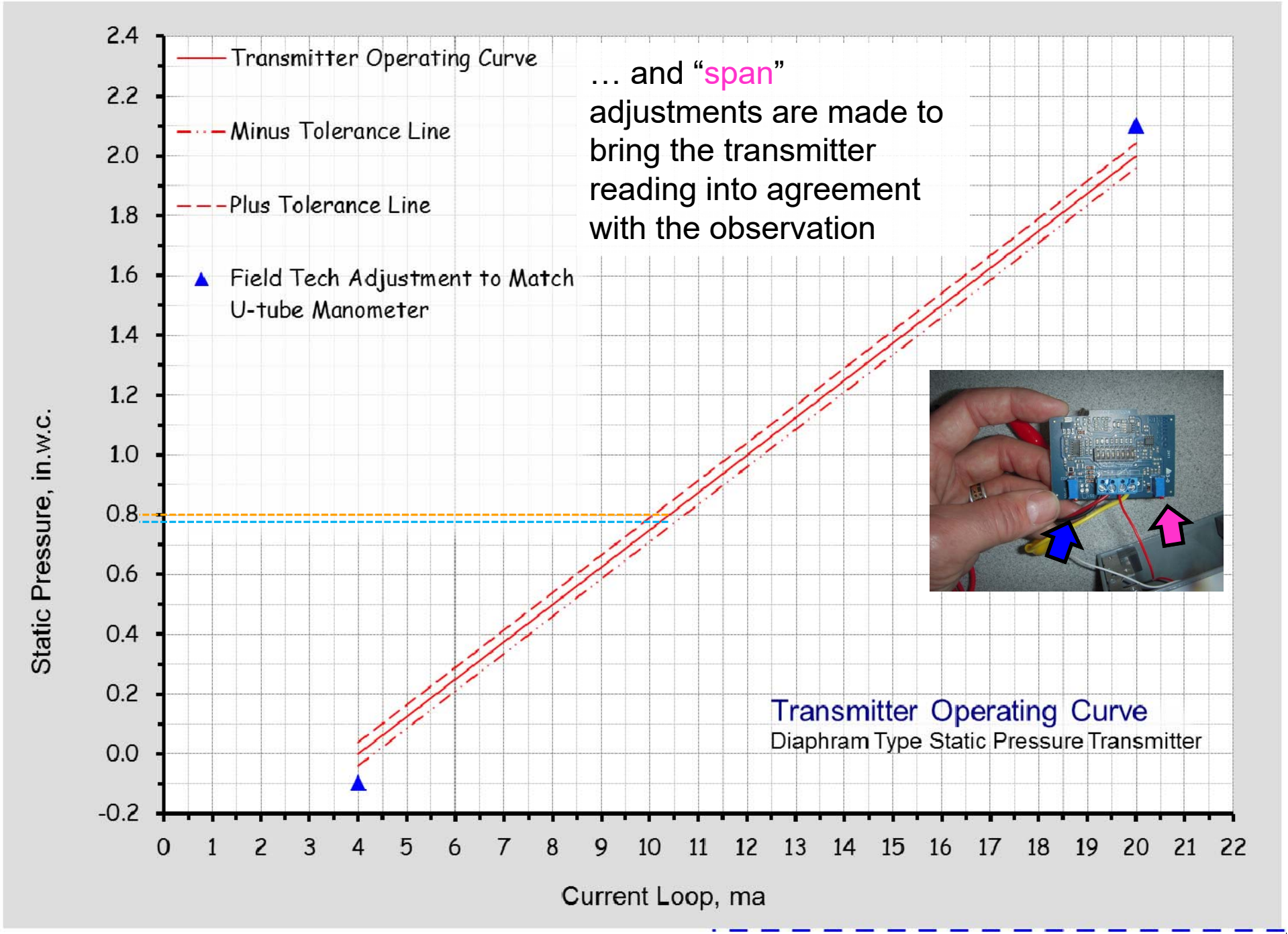
Un-Calibration

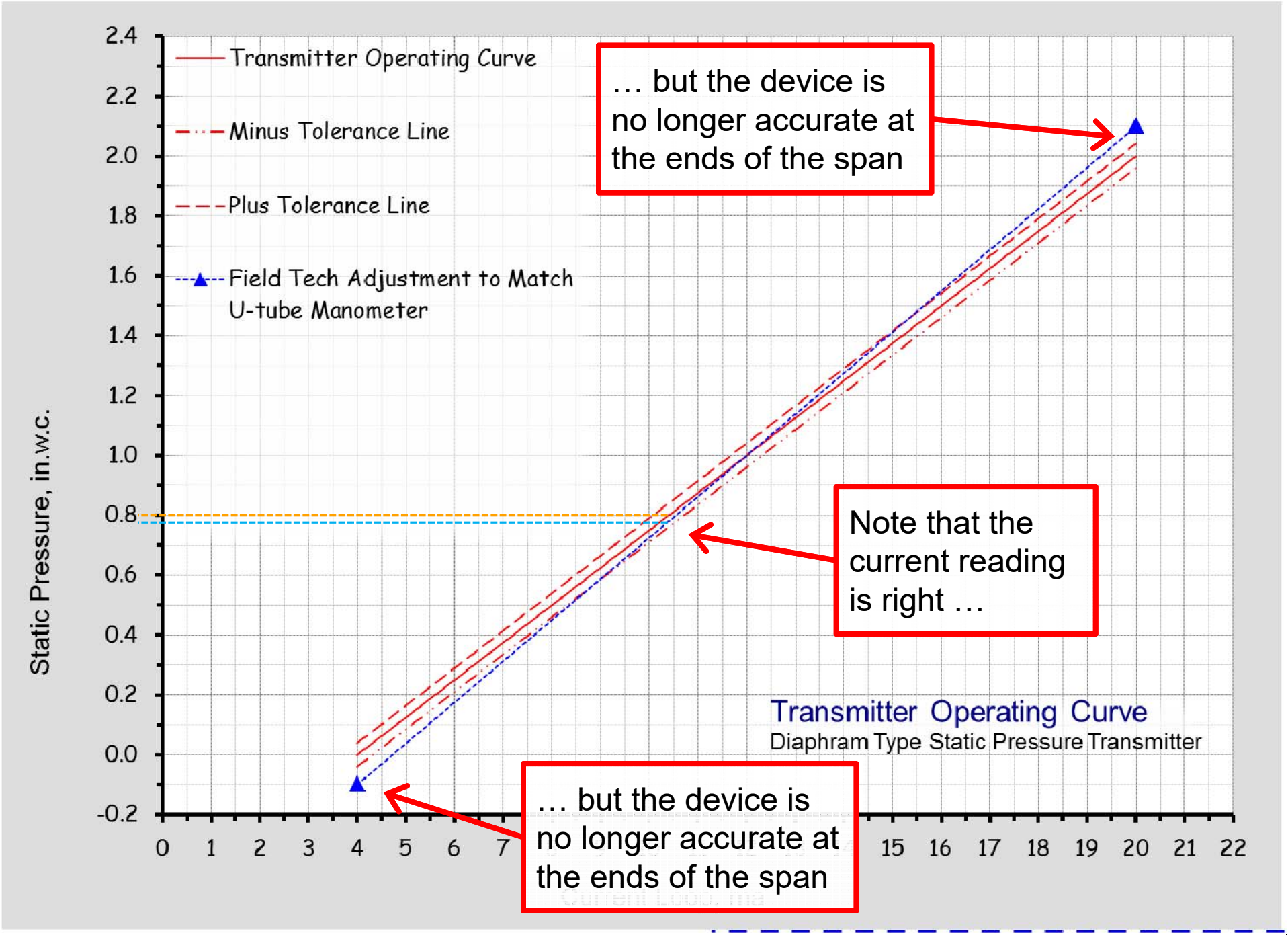
Misread Your Instrument

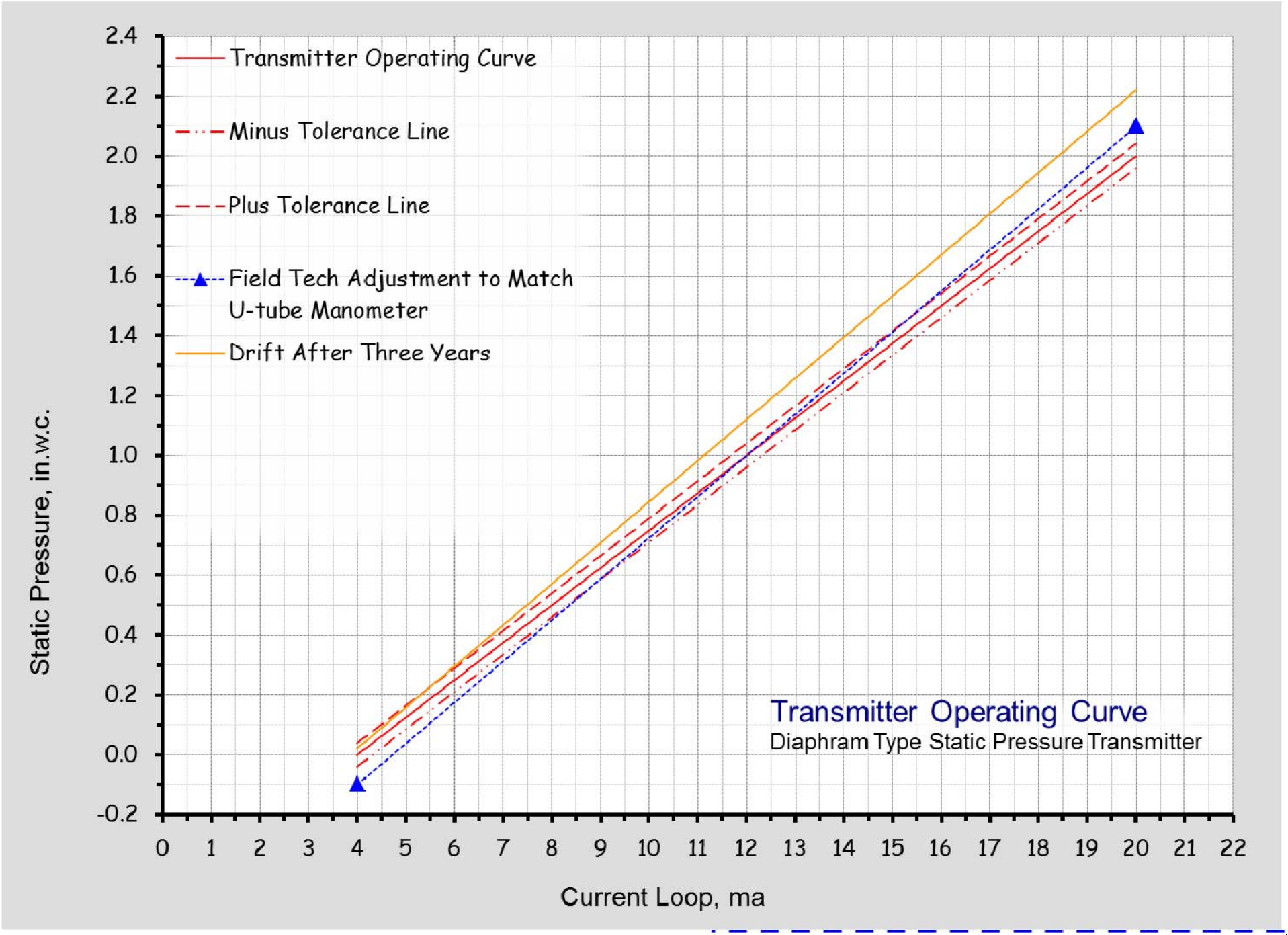


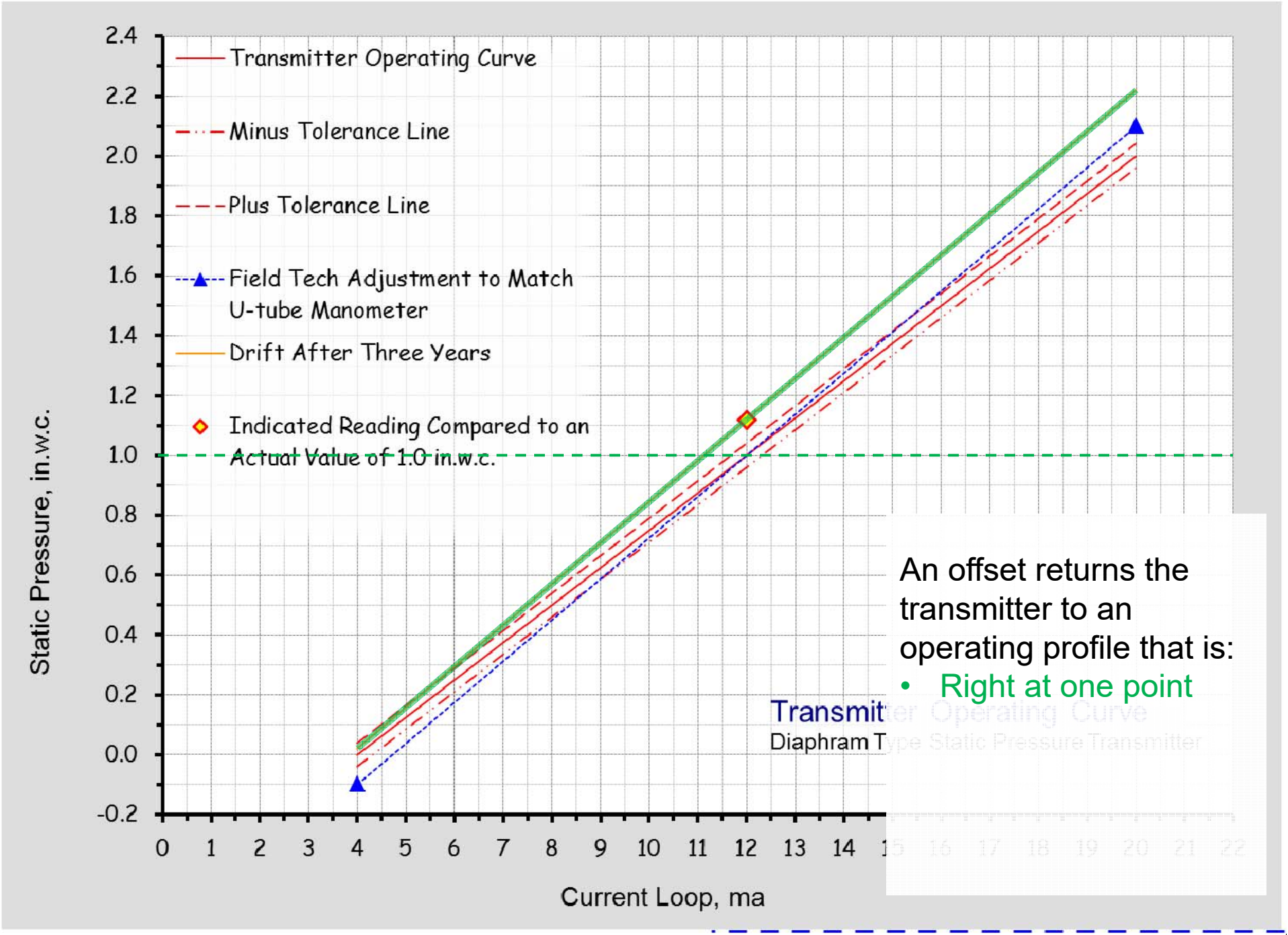

Transmitter Operating Curve
Minus Tolerance Line
Plus Tolerance Line
Static Pressure, in.w.c.
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
Current Loop, ma
Transmitter is indicating 0.80 in.w.c. but when comparing it to a manometer, because o f parallax, the control tech reads it as 0.78 in.w.c.
Transmitter Operating Curve
Diaphram Type Static Pressure Transmitter


Transmitter Operating Curve
Minus Tolerance Line
Plus Tolerance Line
Field Tech Adjustment to Match U-tube Manometer
Zero …
Transmitter Operating Curve
Diaphram Type Static Pressure Transmitter
Static Pressure, in.w.c.
Current Loop, ma
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22


Transmitter Operating Curve
Minus Tolerance Line
Plus Tolerance Line
Field Tech Adjustment to Match U-tube Manometer
… and "span" adjustments are made to bring the transmitter reading into agreement with the observation
Transmitter Operating Curve
Diaphram Type Static Pressure Transmitter
Static Pressure, in.w.c.
Current Loop, ma
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22

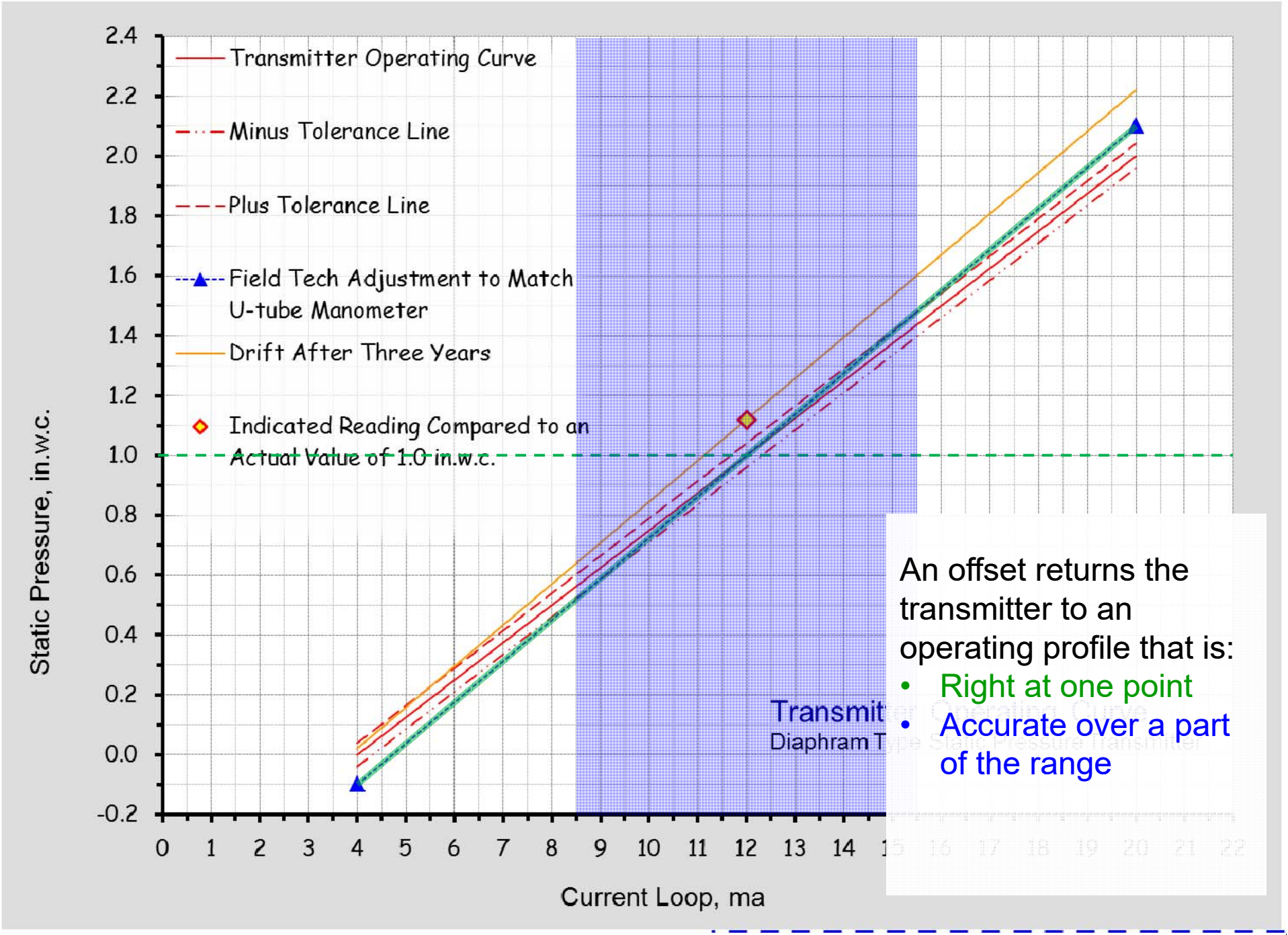

Transmitter Operating Curve
Minus Tolerance Line
Plus Tolerance Line
Field Tech Adjustment to Match U-tube Manometer
… but the device is no longer accurate at the ends of the span
Note that the current reading is right …
… but the device is no longer accurate at the ends of the span
Transmitter Operating Curve
Diaphram Type Static Pressure Transmitter
Static Pressure, in.w.c.
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
0 1 2 3 4 5 6 7 15 16 17 18 19 20 21 22


Transmitter Operating Curve
Minus Tolerance Line
Plus Tolerance Line
Field Tech Adjustment to Match U-tube Manometer
Drift After Three Years
Transmitter Operating Curve
Diaphram Type Static Pressure Transmitter
Static Pressure, in.w.c.
Current Loop, ma
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22



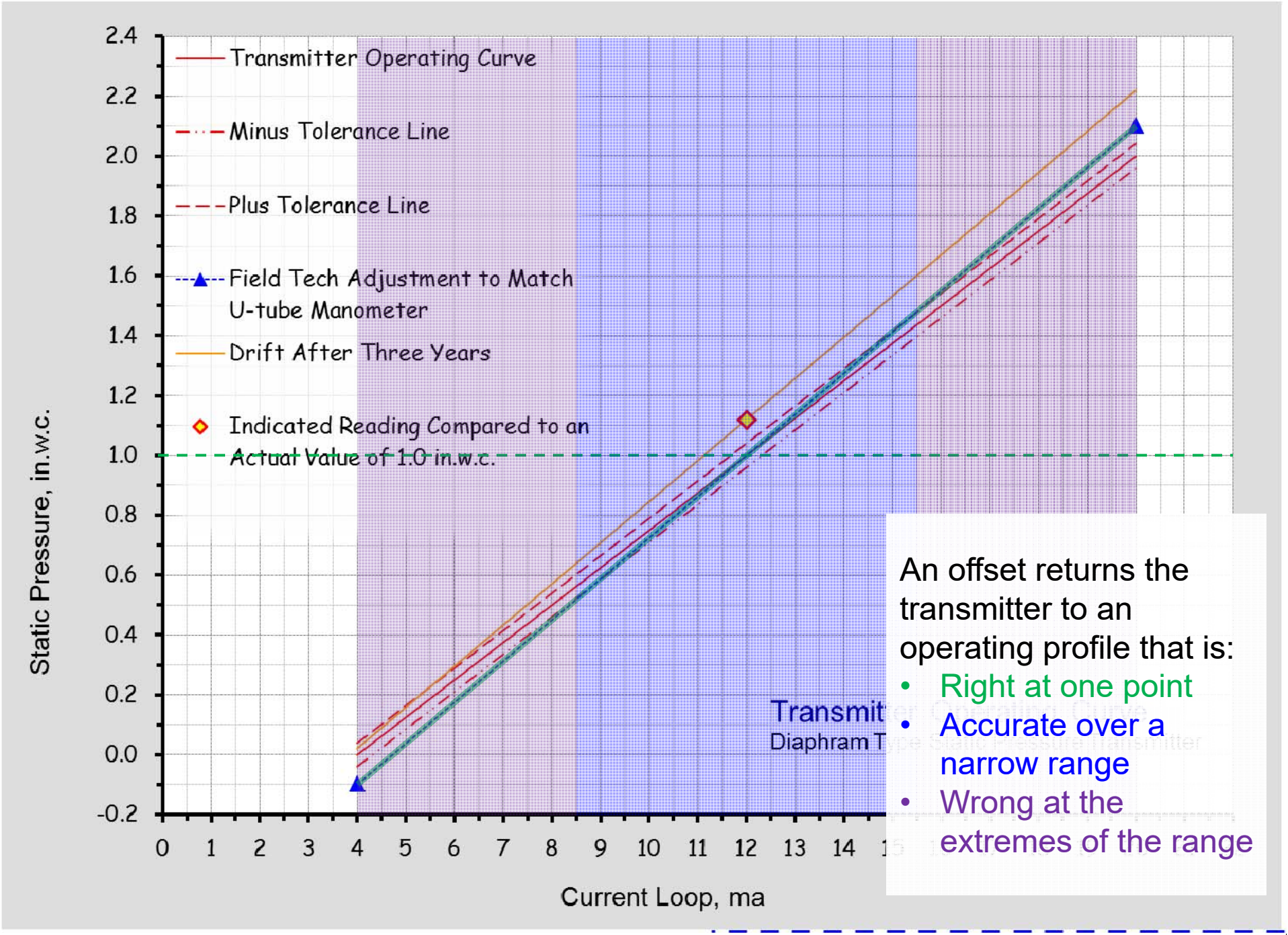
An offset returns the transmitter to an operating profile that is:

- Right at one point



An offset returns the transmitter to an operating profile that is:

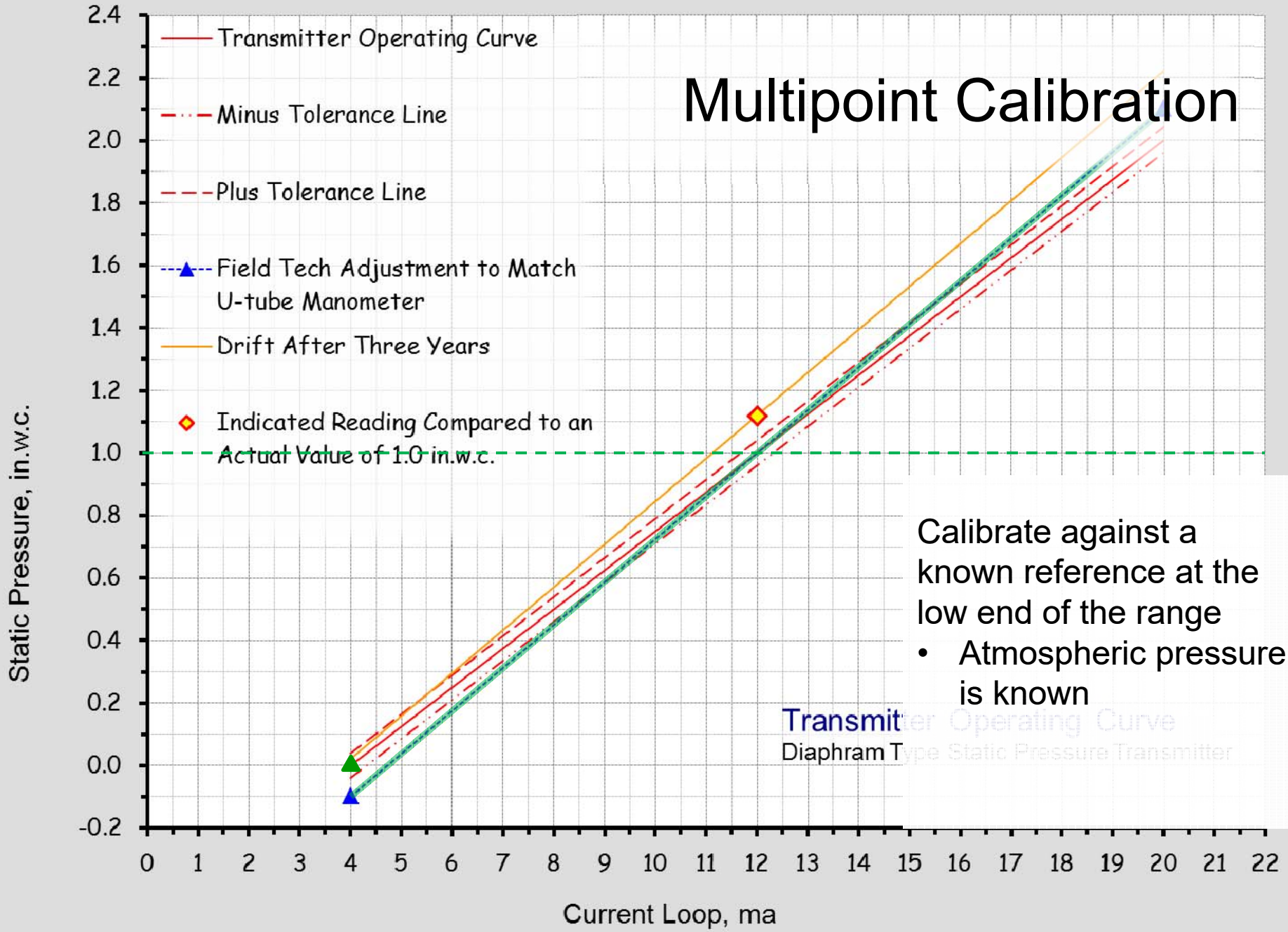
- Right at one point
- Accurate over a part of the range



An offset returns the transmitter to an operating profile that is:

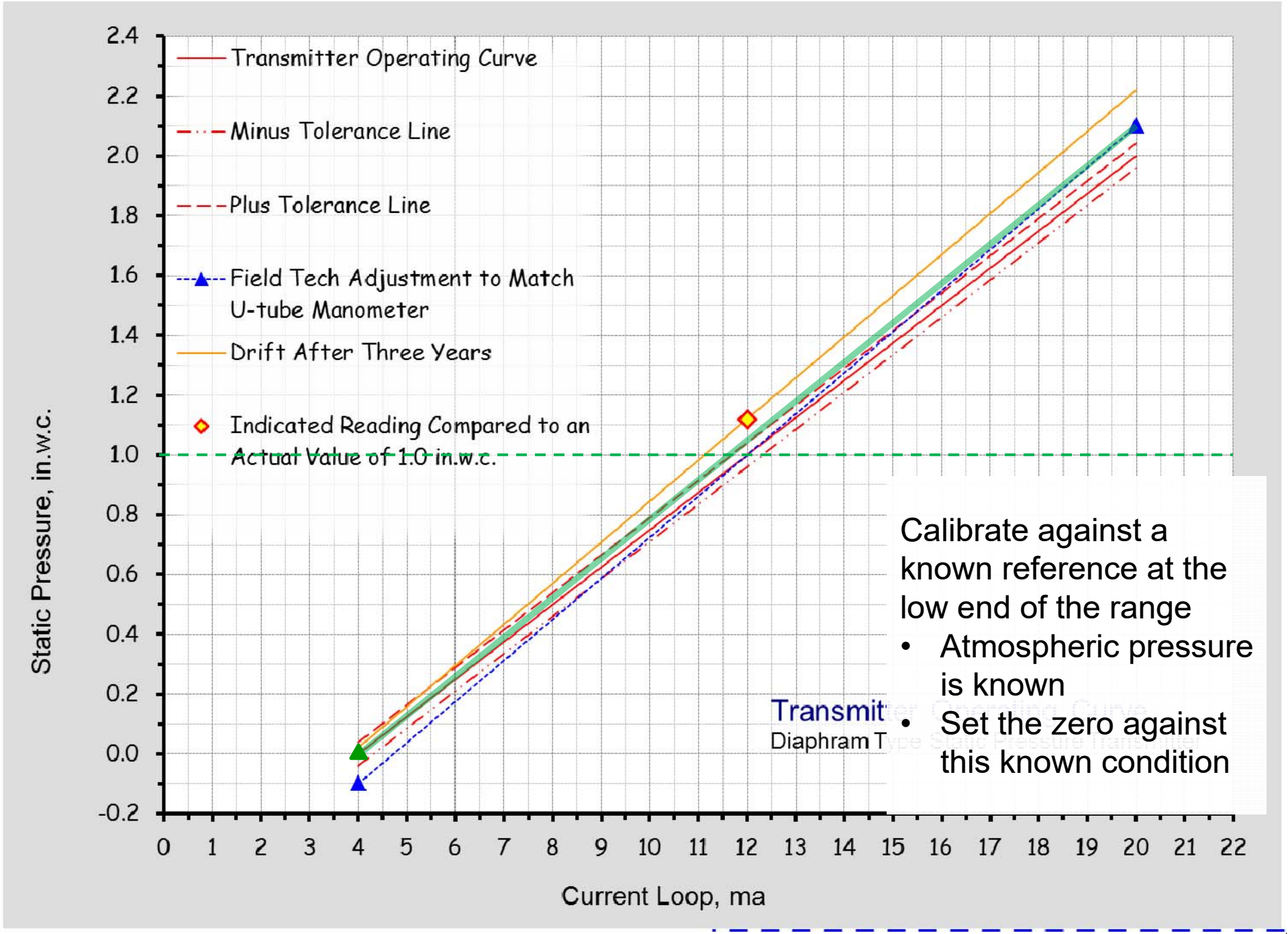
- Right at one point
- Accurate over a narrow range
- Wrong at the extremes of the range

Multipoint Calibration



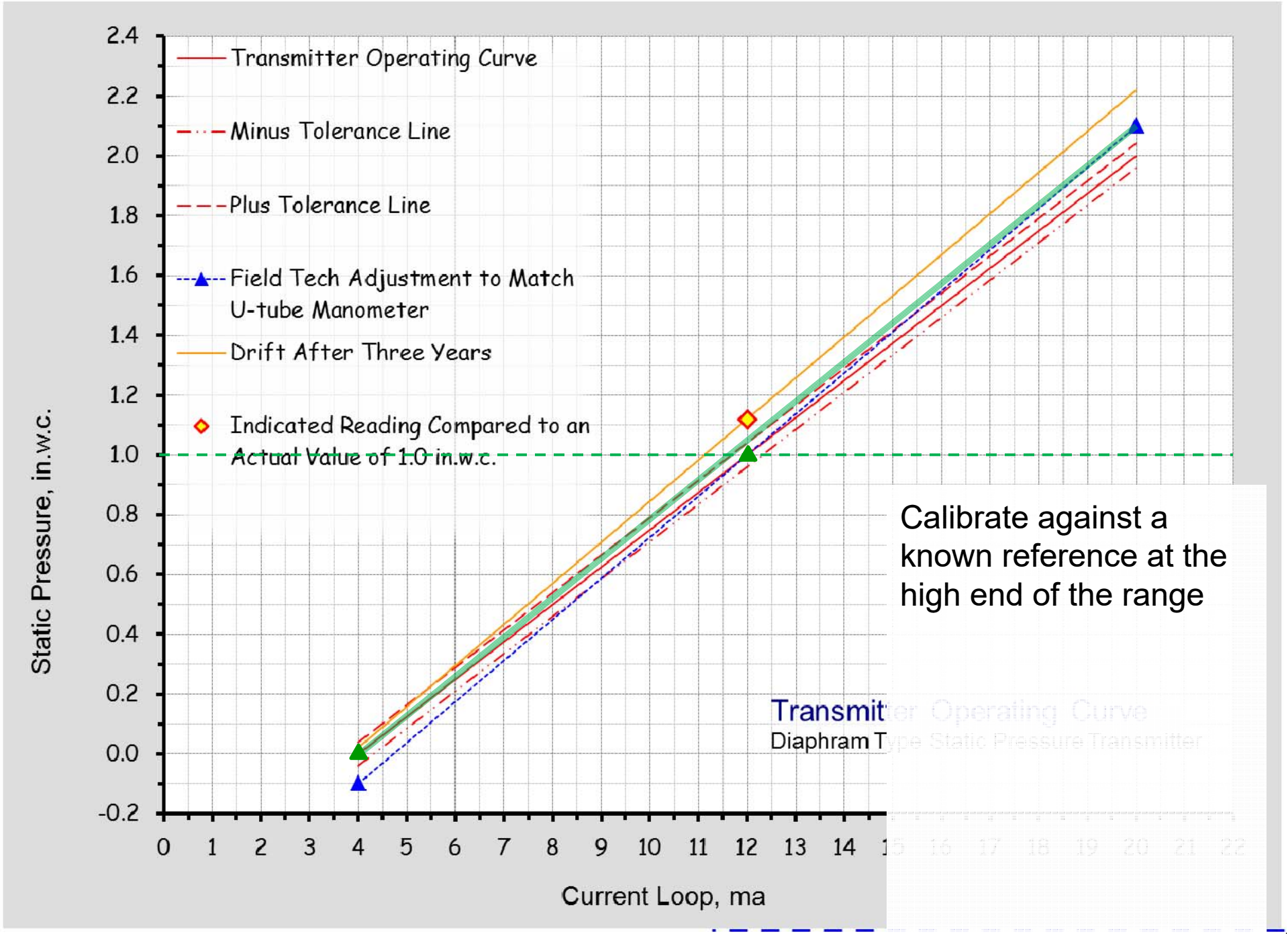
Calibrate against a known reference at the low end of the range

- Atmospheric pressure is known

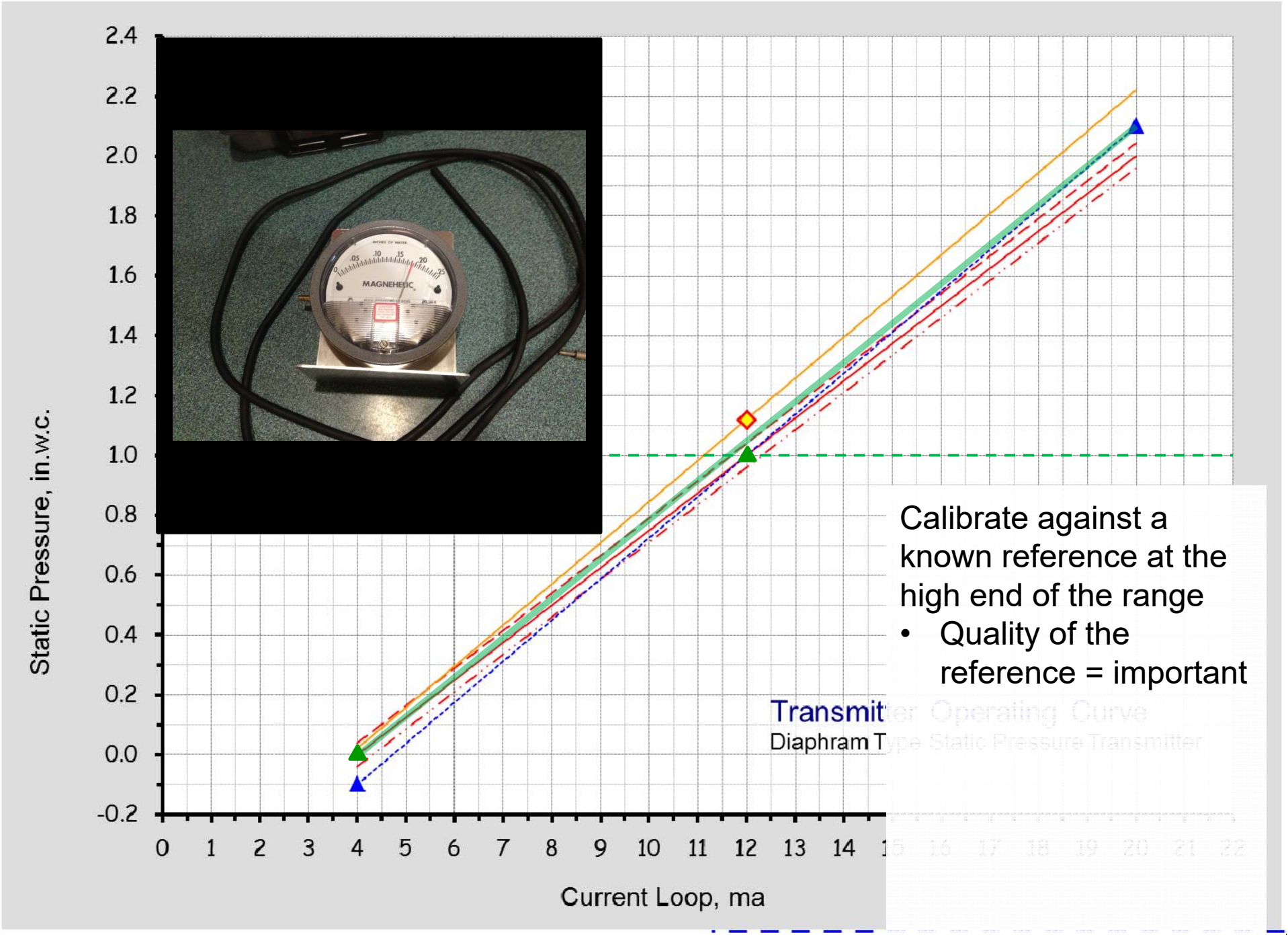


Calibrate against a known reference at the low end of the range

- Atmospheric pressure is known
- Set the zero against this known condition

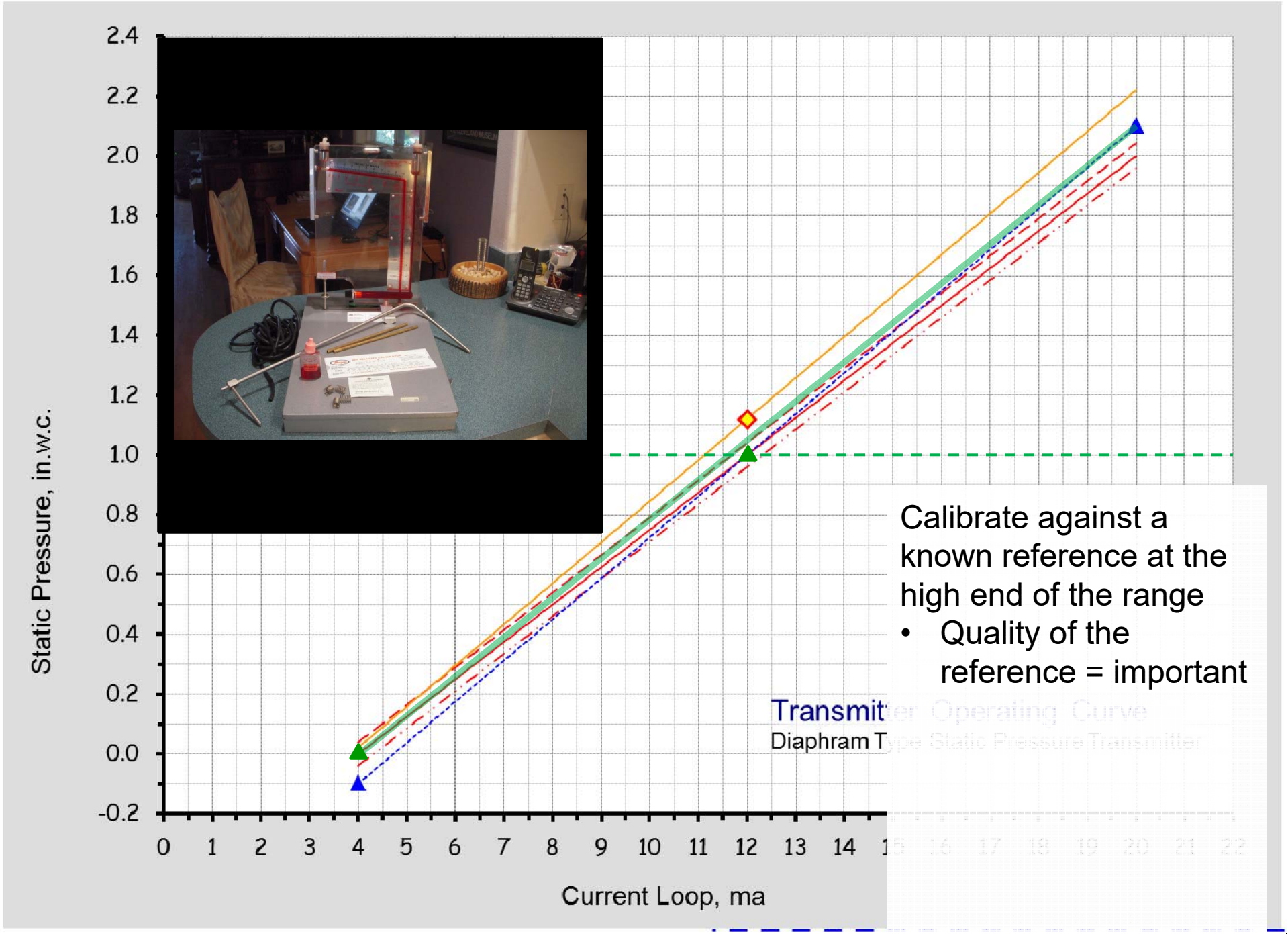


Calibrate against a known reference at the high end of the range



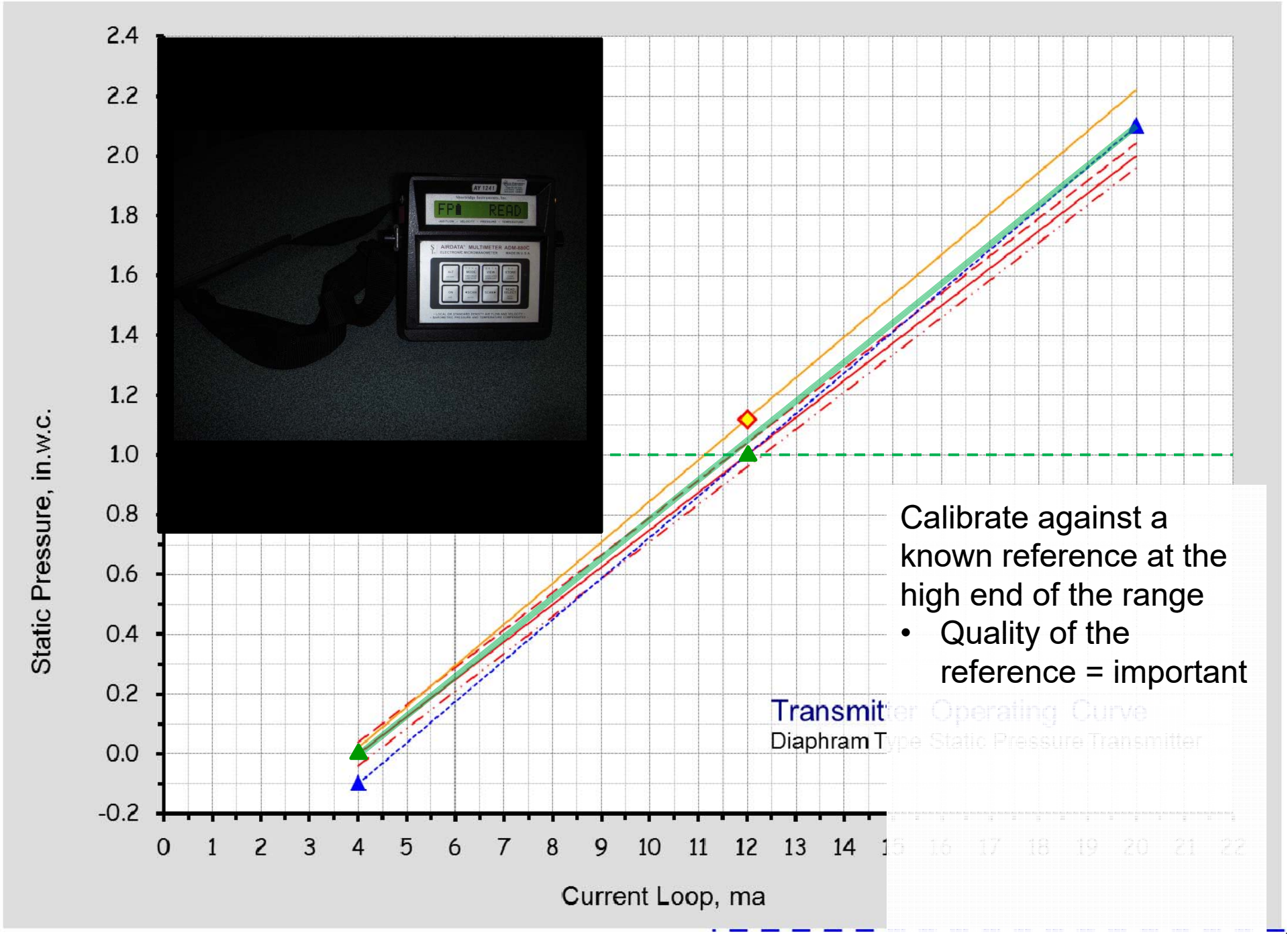
Calibrate against a known reference at the high end of the range

- Quality of the reference = important



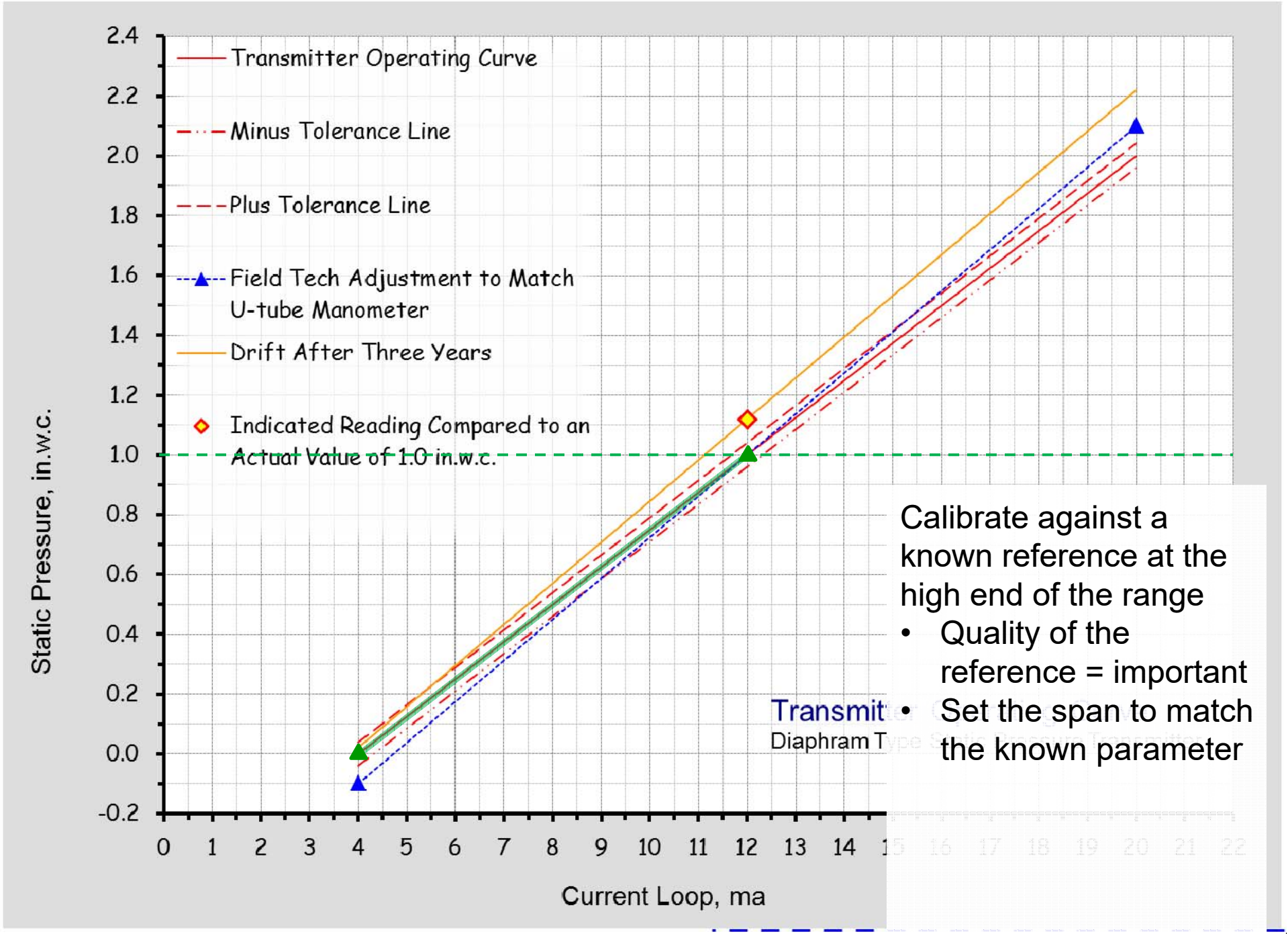
Calibrate against a known reference at the high end of the range

- Quality of the reference = important



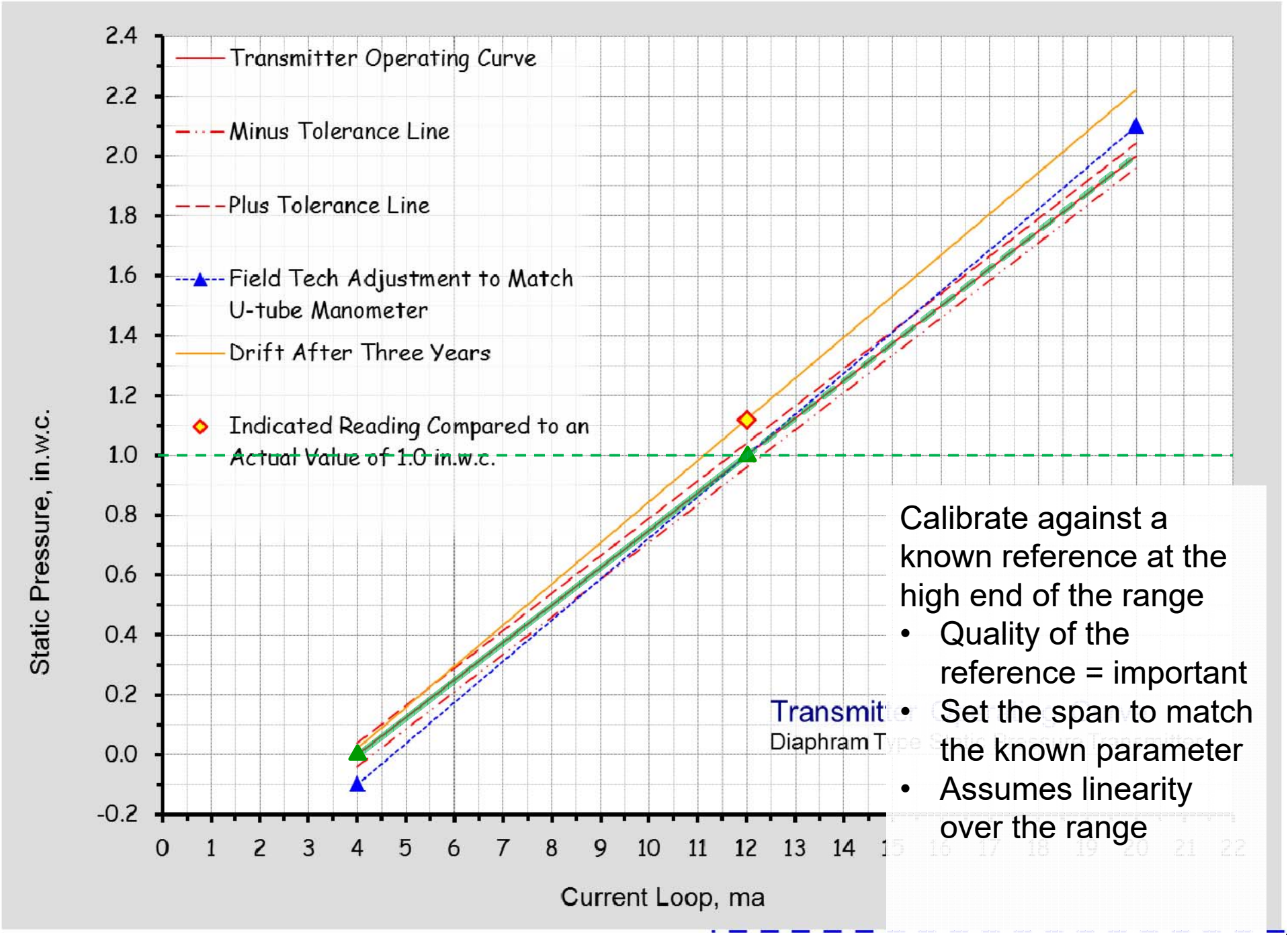
Calibrate against a known reference at the high end of the range

- Quality of the reference = important



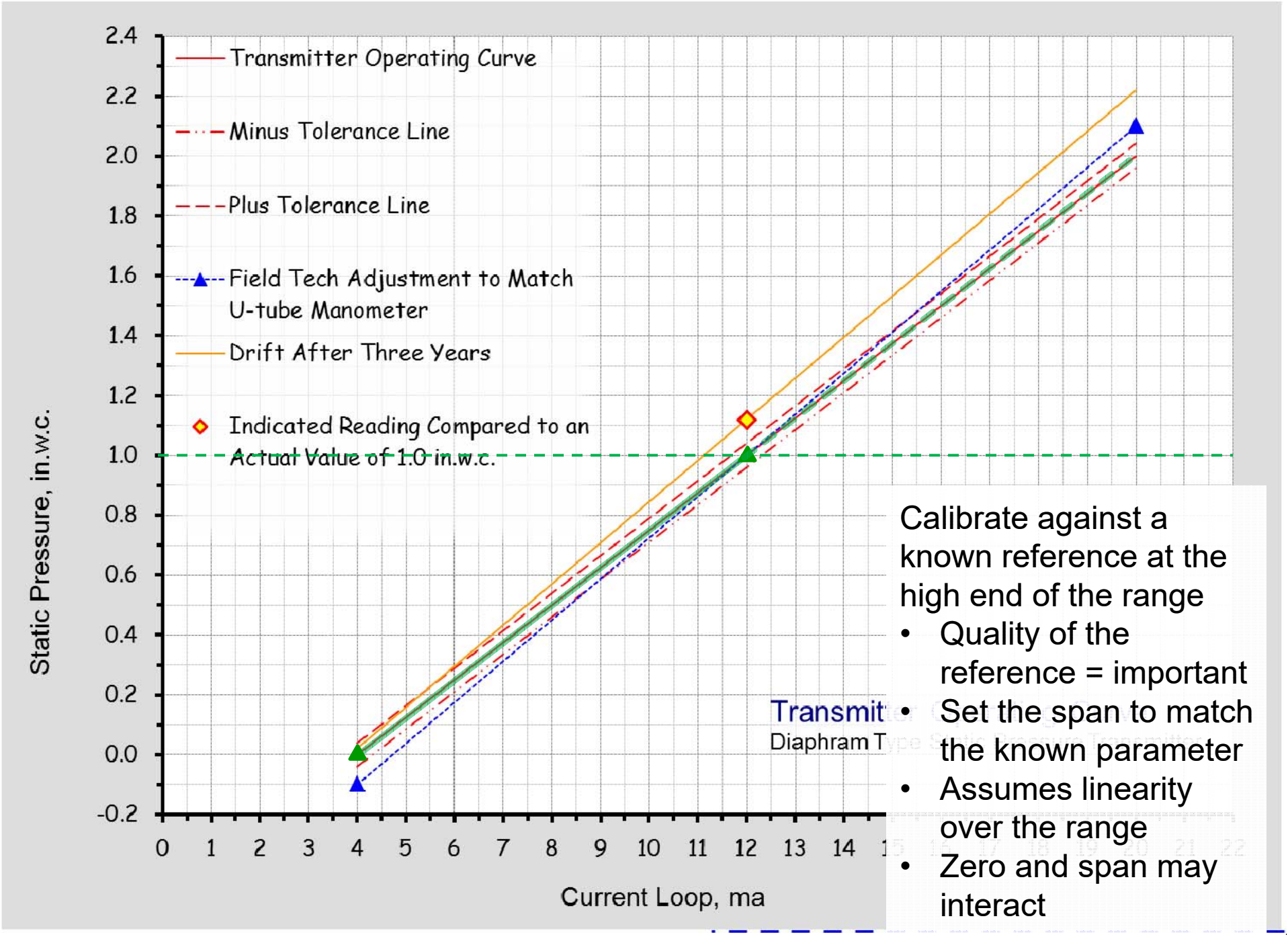
Calibrate against a known reference at the high end of the range

- Quality of the reference = important
- Set the span to match the known parameter



Calibrate against a known reference at the high end of the range

- Quality of the reference = important
- Set the span to match the known parameter
- Assumes linearity over the range

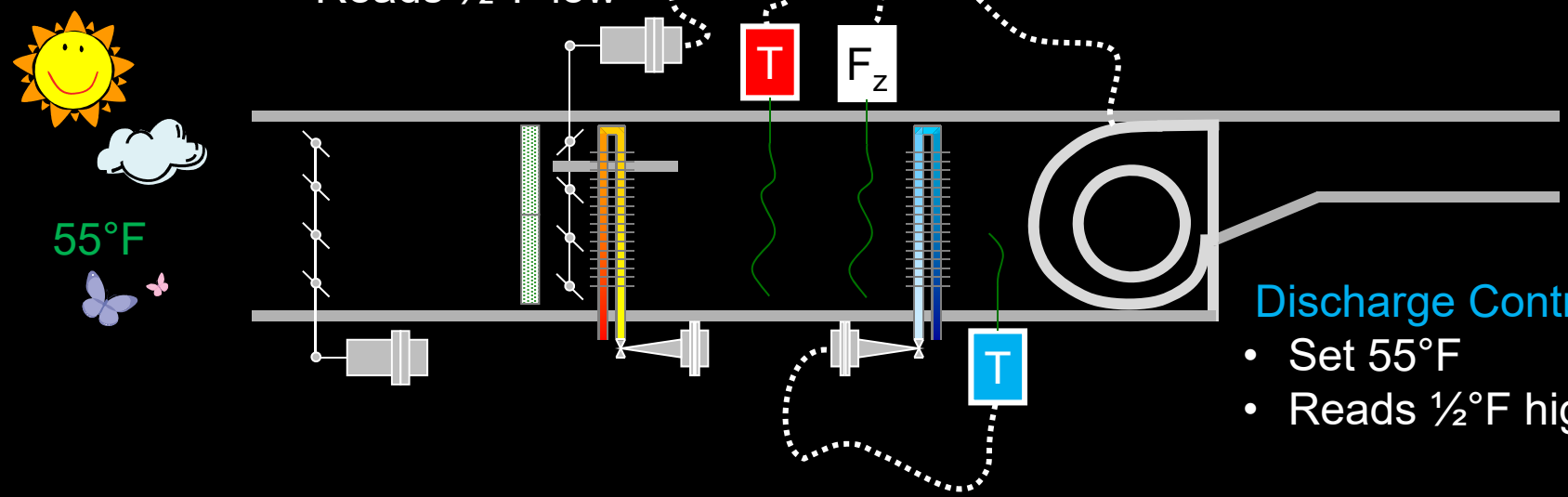


Calibrate against a known reference at the high end of the range

- Quality of the reference = important
- Set the span to match the known parameter
- Assumes linearity over the range
- Zero and span may interact

Preheat Controller

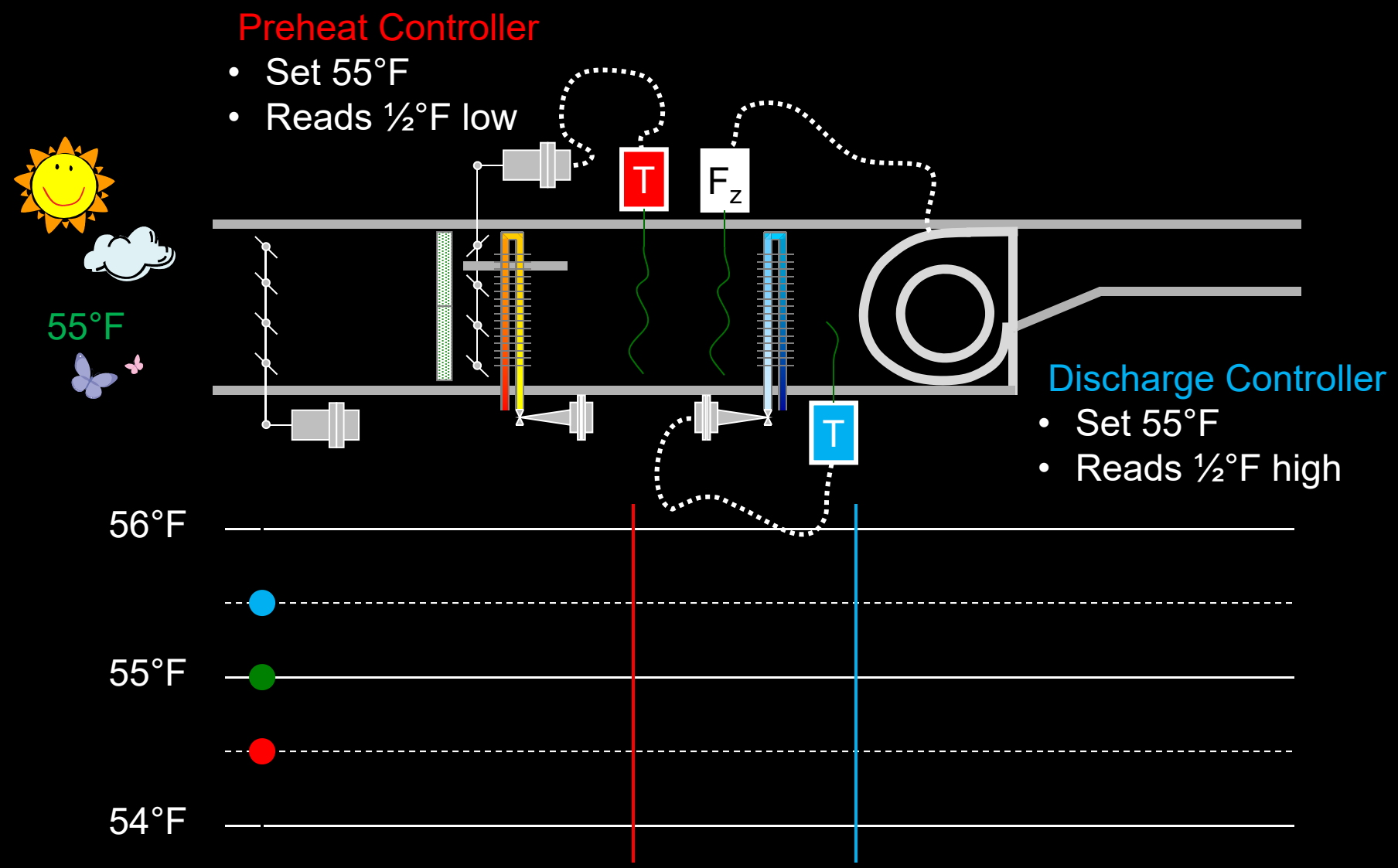
- Set 55°F
- Reads ½°F low



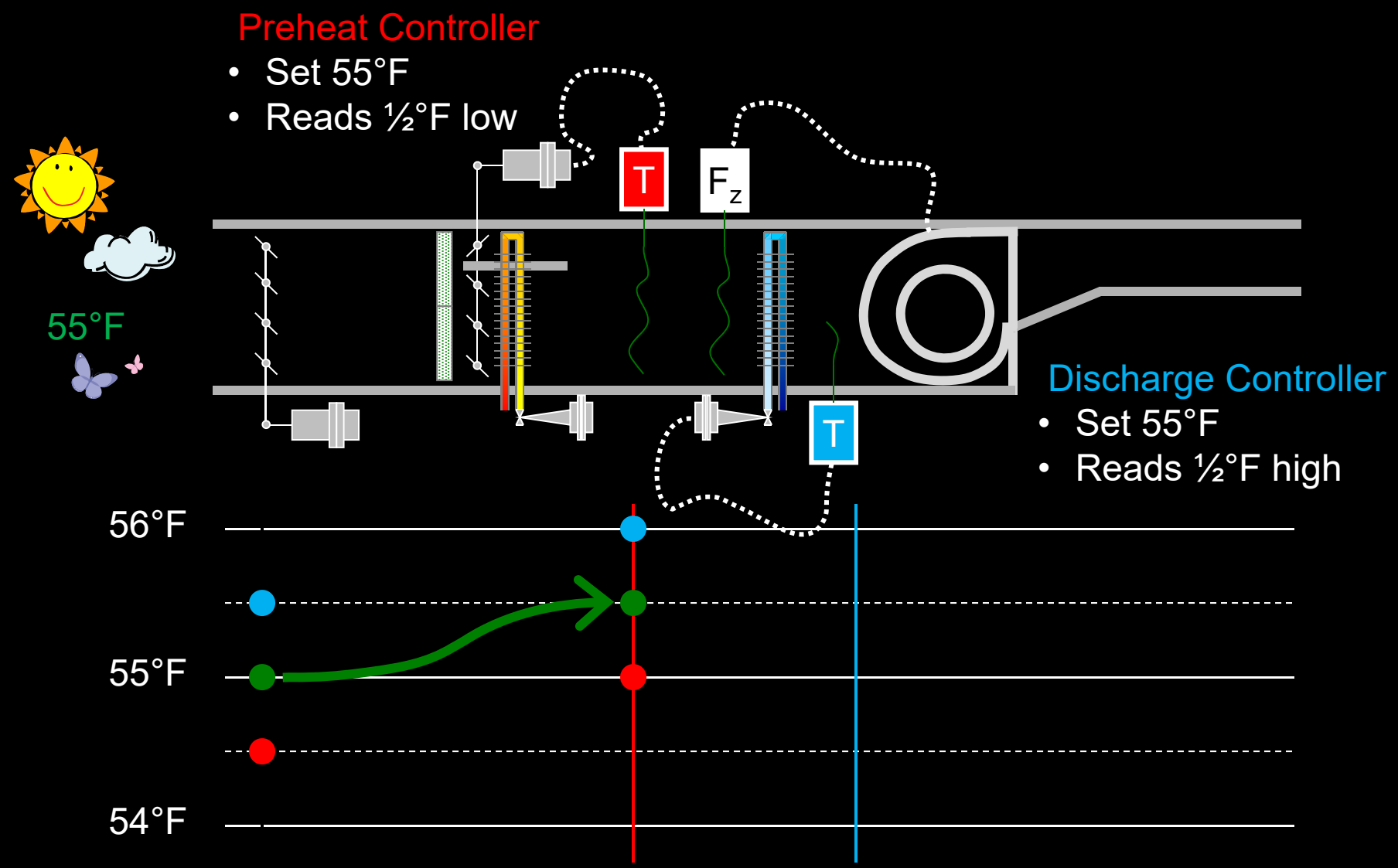
Discharge Controller

- Set 55°F
- Reads ½°F high

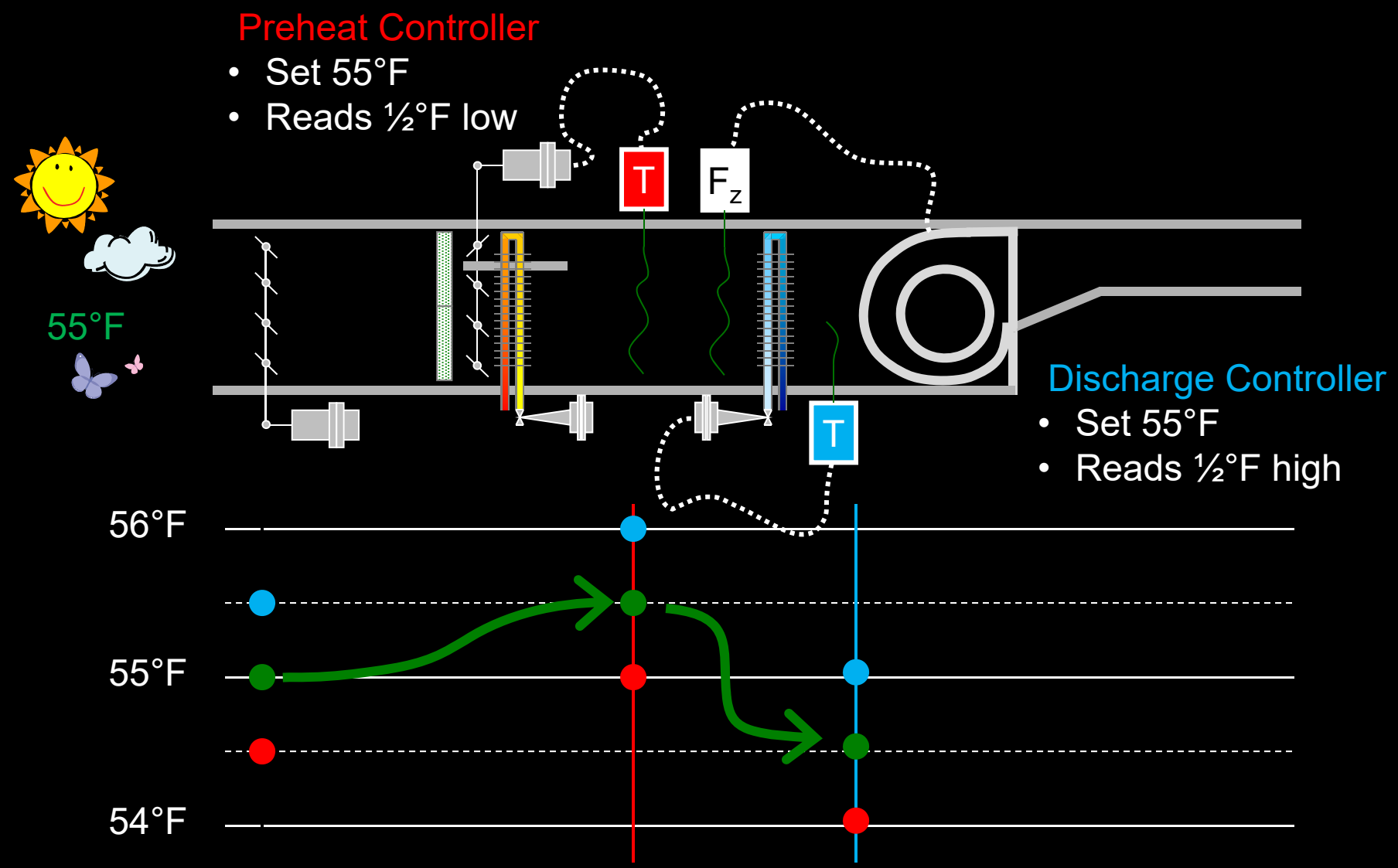
Relative Calibration/Accuracy



Relative Calibration/Accuracy



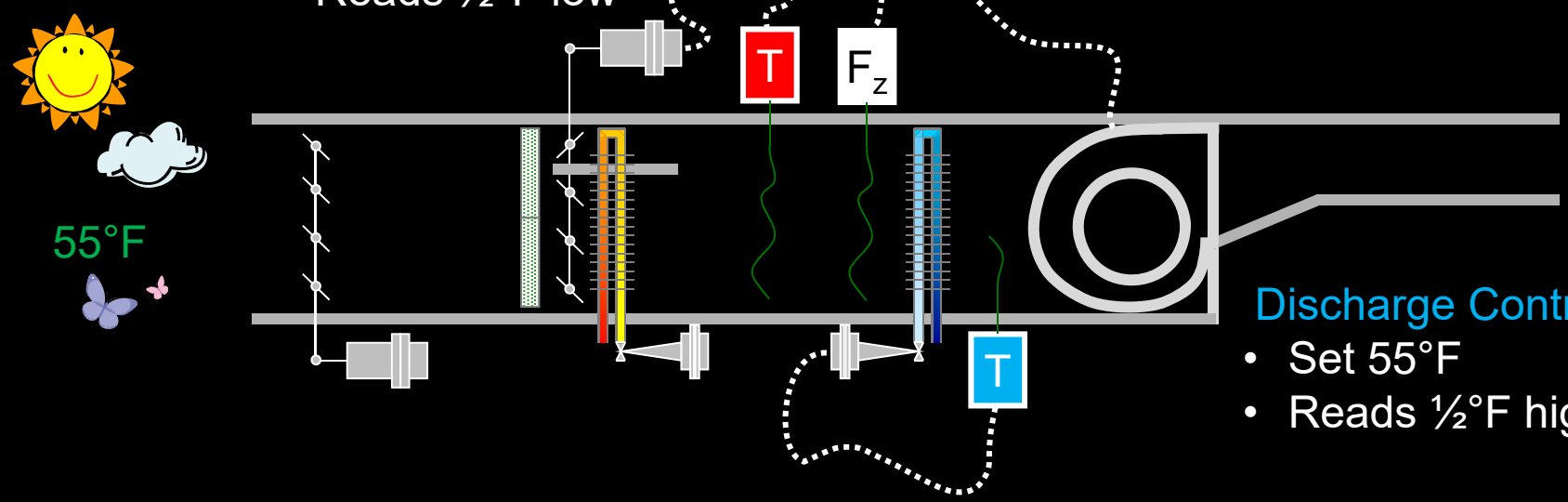
Relative Calibration/Accuracy



Relative Calibration/Accuracy

Preheat Controller

- Set 55°F
- Reads ½°F low



Discharge Controller

- Set 55°F
- Reads ½°F high

Bottom Line:

Because of relative vs. absolute accuracy, two sensors that met their specs (+/-0.5°F accuracy) took air that was the temperature you desired and used energy to heat and cool it to deliver it at the wrong temperature

Relative Calibration/Accuracy

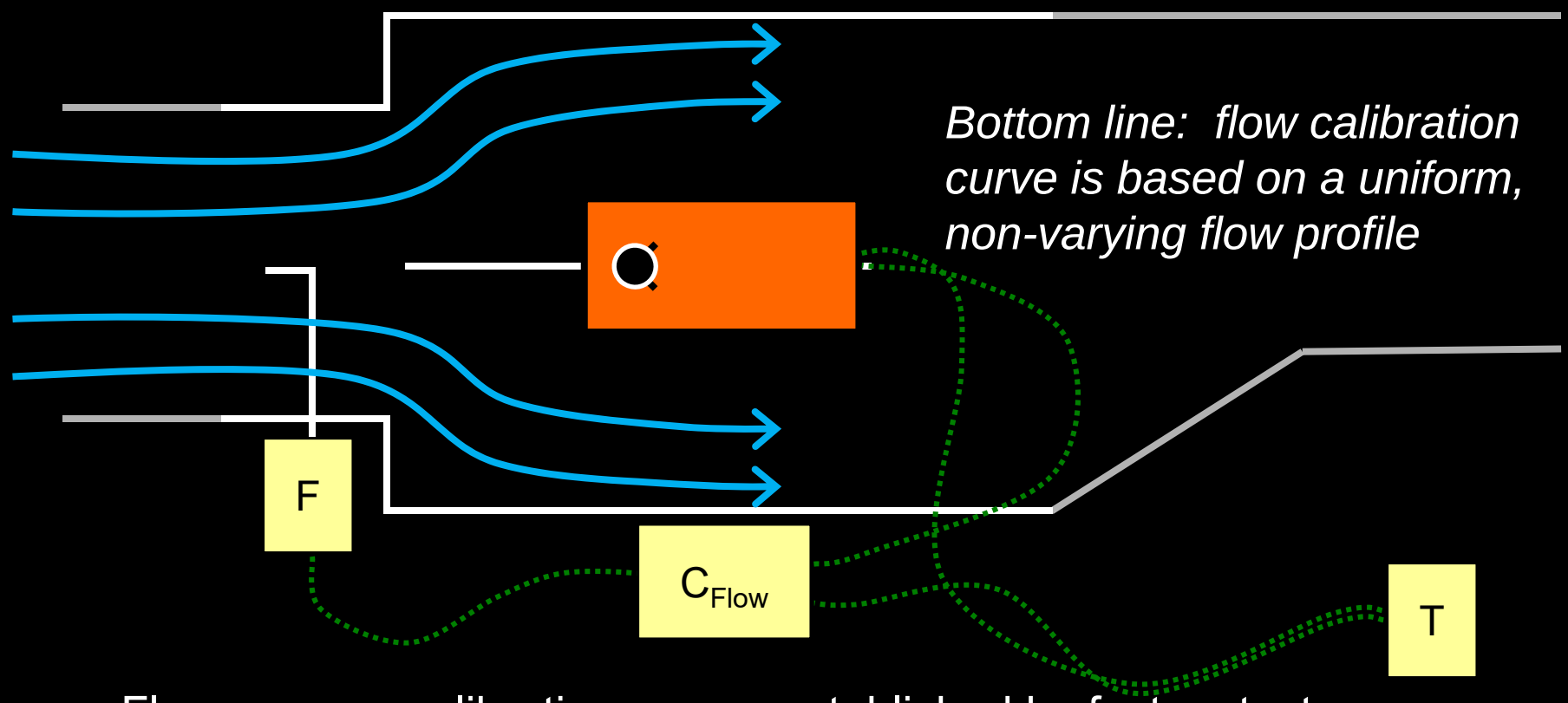
Similar Issues Exist for Other Sensing Technologies; Measuring Flow For Example

- Many flow measurement systems are velocity pressure based
  - Velocity pressure varies as the square of the flow
  - A 50% flow reduction reduces the measured signal to 25% of what it was at 100% flow

  Flow sensors assume a uniform velocity profile
  - For many HVAC systems, the conditions entering and leaving the flow sensor can distort the flow profile and thus the accuracy of the measurement
  - In the video that follows, watch the waves in the stream as the water approaches and departs from the rocks in it

http://tinyurl.com/3bsy6bj

Flow Calibration; One Point *Doesn't* Fit All



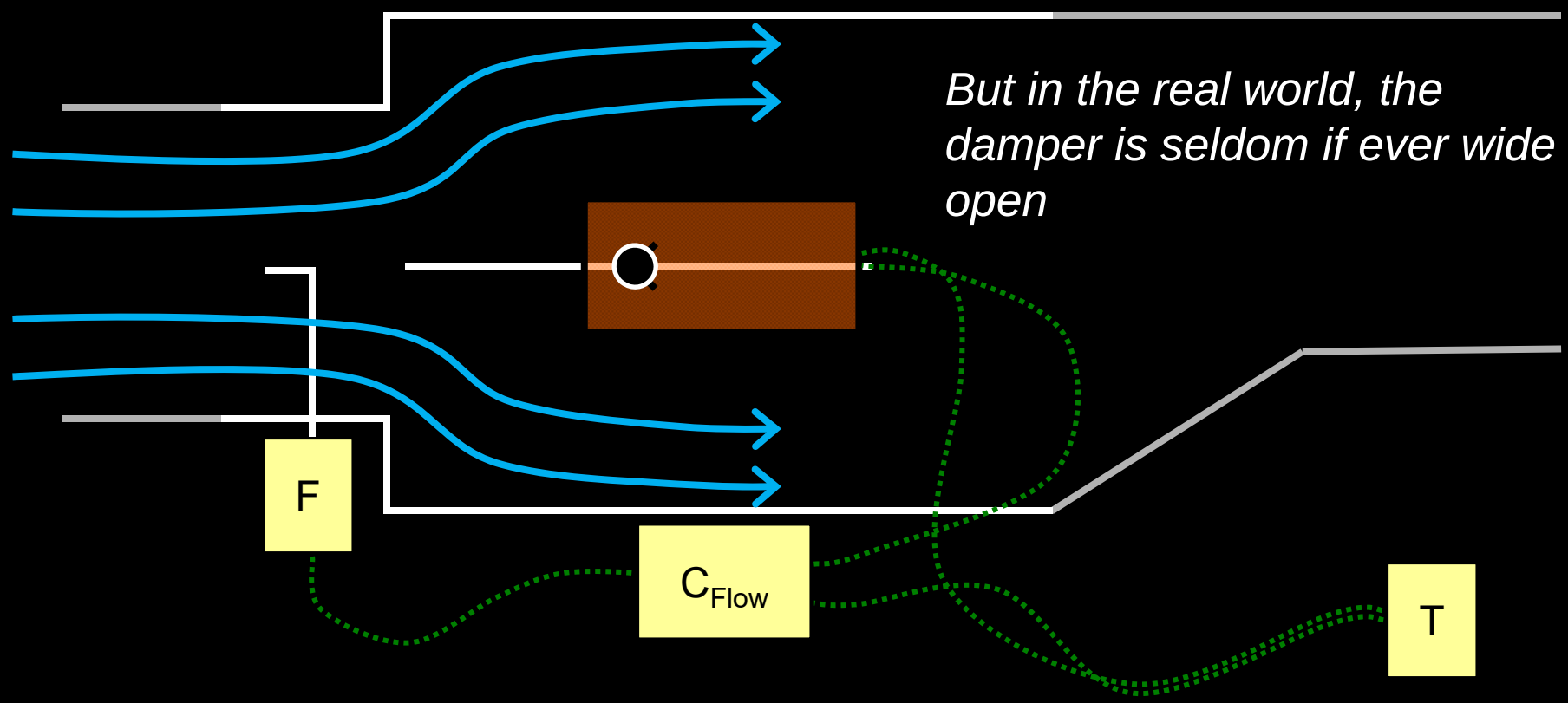
Bottom line: flow calibration curve is based on a uniform, non-varying flow profile

Flow sensors calibration curves established by factory test

Damper held fully open for the entire flow range

Flow varied by varying fan speed on the fan in the test rig

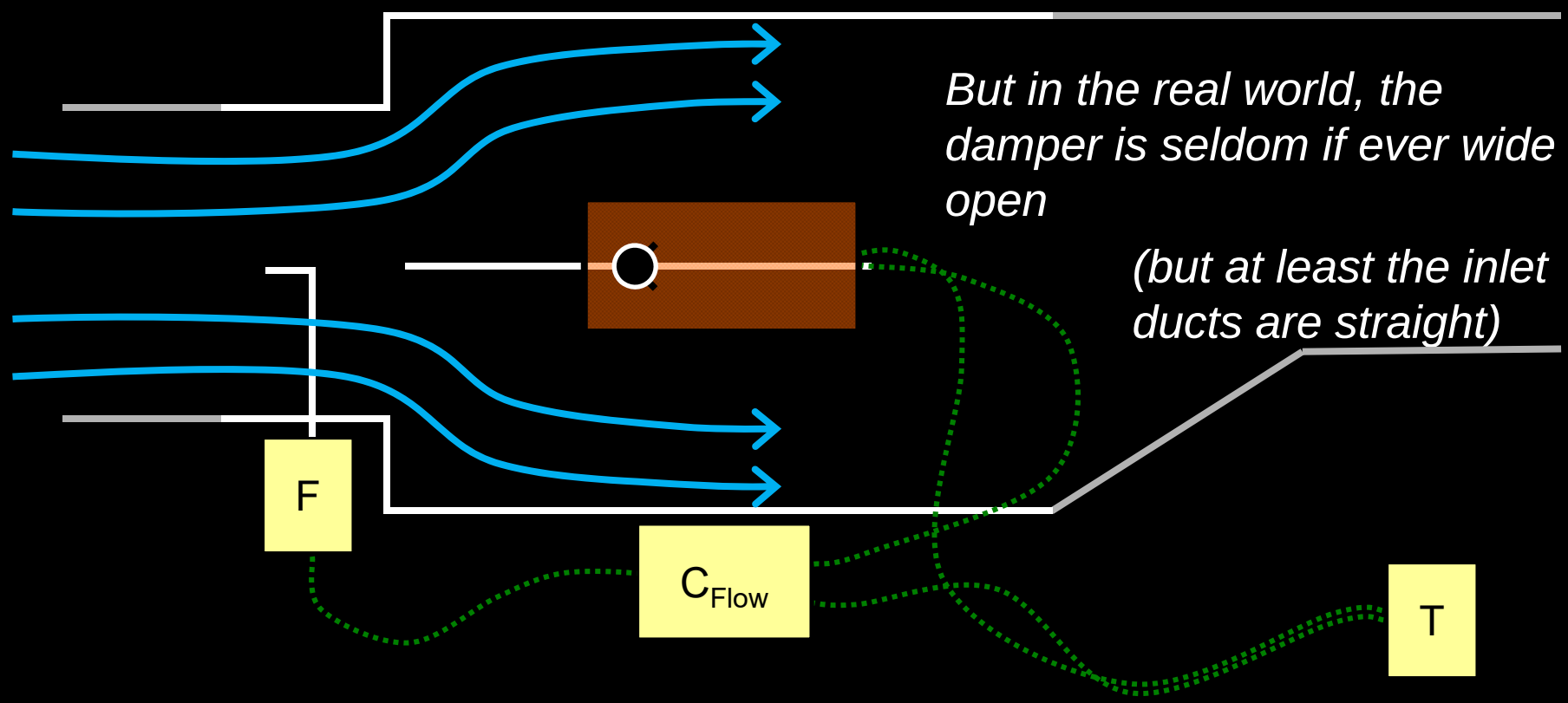
Flow Calibration; One Point *Doesn't* Fit All



But in the real world, the damper is seldom if ever wide open

In the real world, with a good inlet condition and a wide open damper, things tend to match up pretty well

Flow Calibration; One Point *Doesn't* Fit All



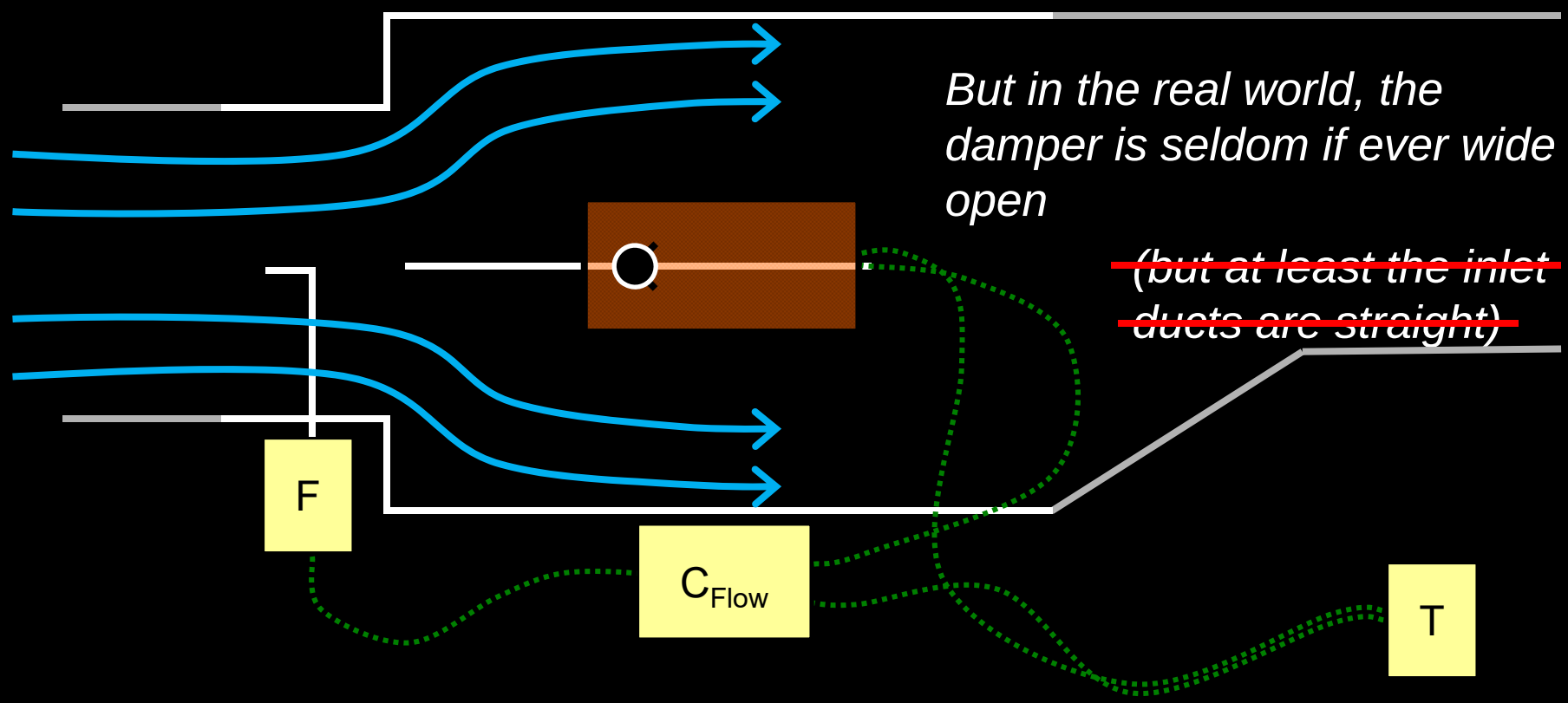
But in the real world, the damper is seldom if ever wide open

(but at least the inlet ducts are straight)

In the real world, with a good inlet condition and a wide open damper, things tend to match up pretty well

FRONT
UNION MADE
INSULATION THICKNESS – NOM. 1½"
THERMAL CONDUC
SMOKE DEVELOPED – LESS
FLAME SPREAD – LESS THAN 25

Flow Calibration; One Point *Doesn't* Fit All

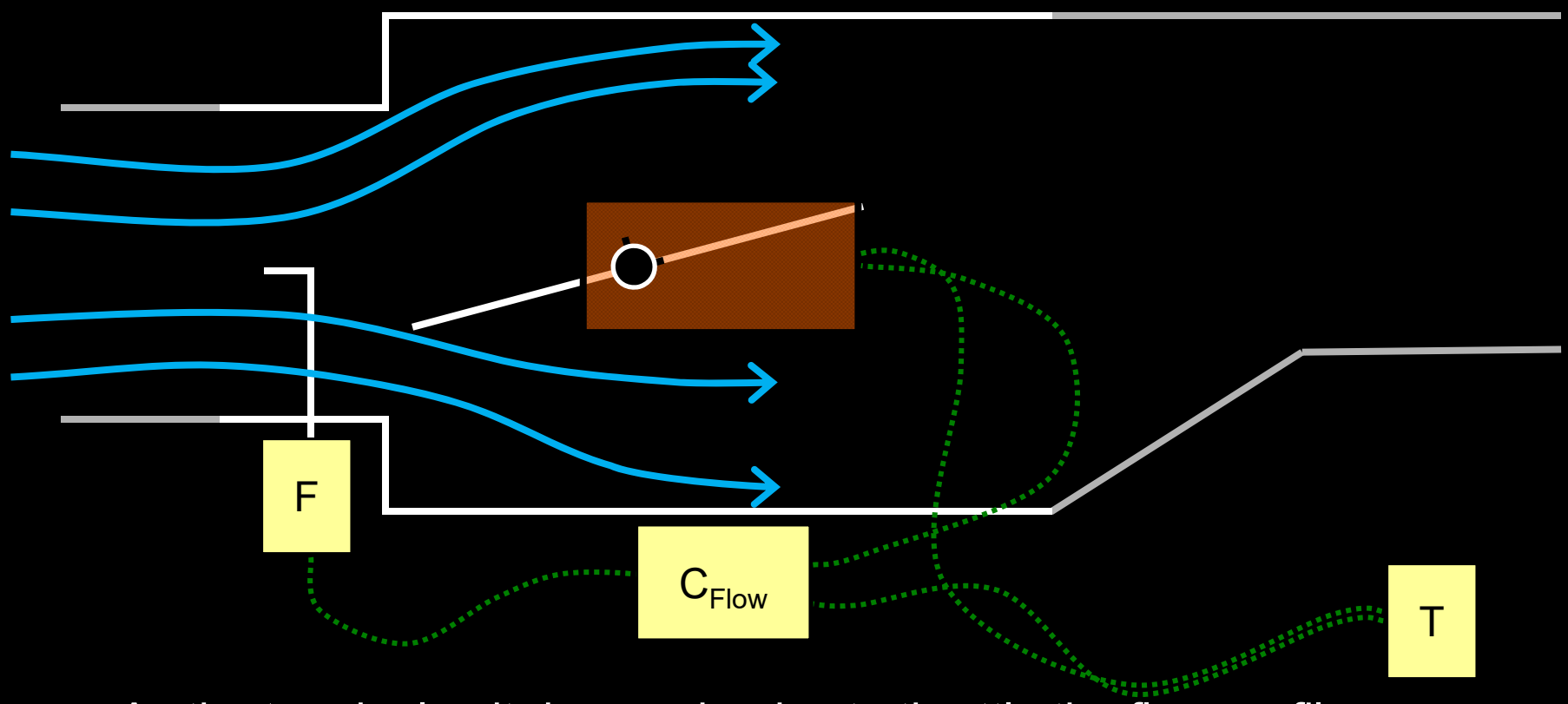


But in the real world, the damper is seldom if ever wide open

~~*(but at least the inlet ducts are straight)*~~

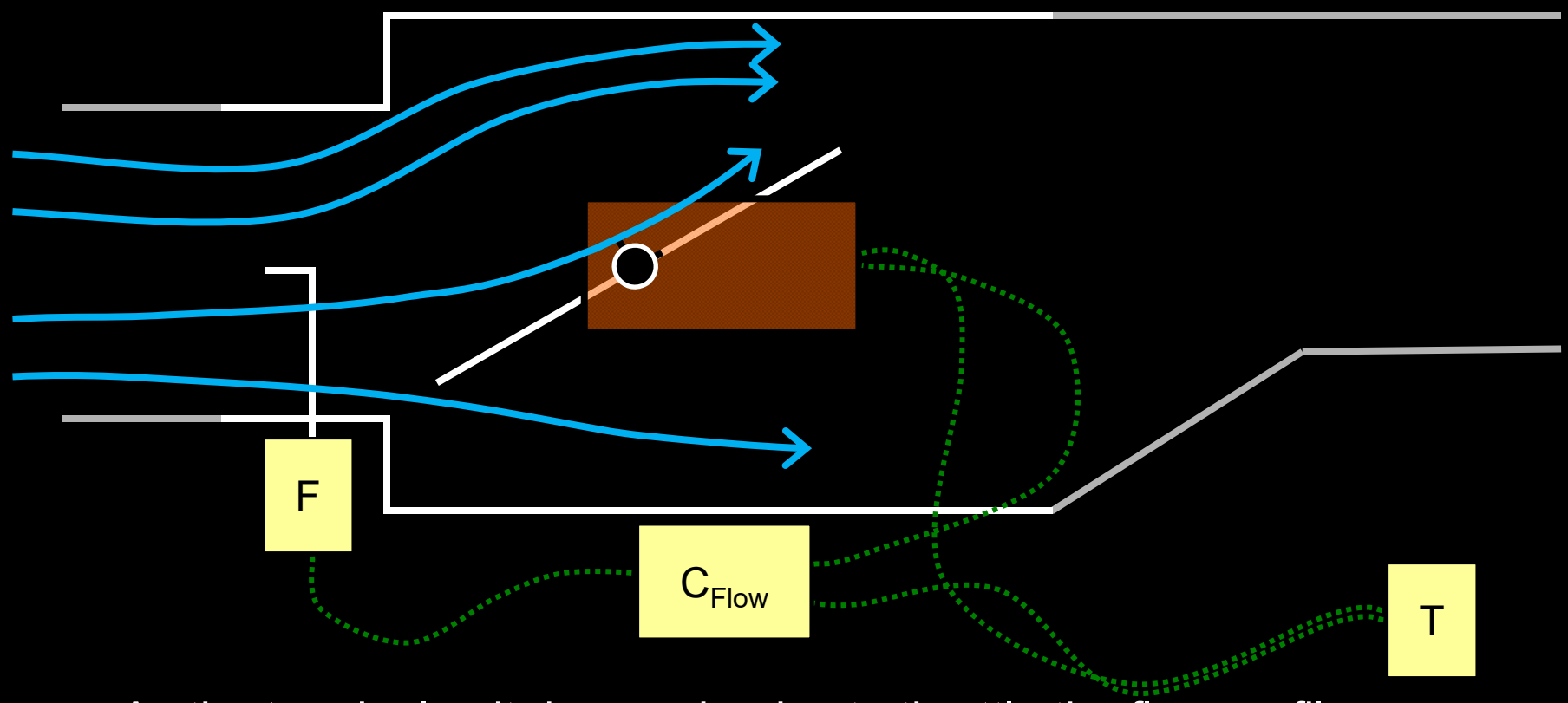
In the real world, with a good inlet condition and a wide open damper, things tend to match up pretty well

Flow Calibration; One Point *Doesn't* Fit All



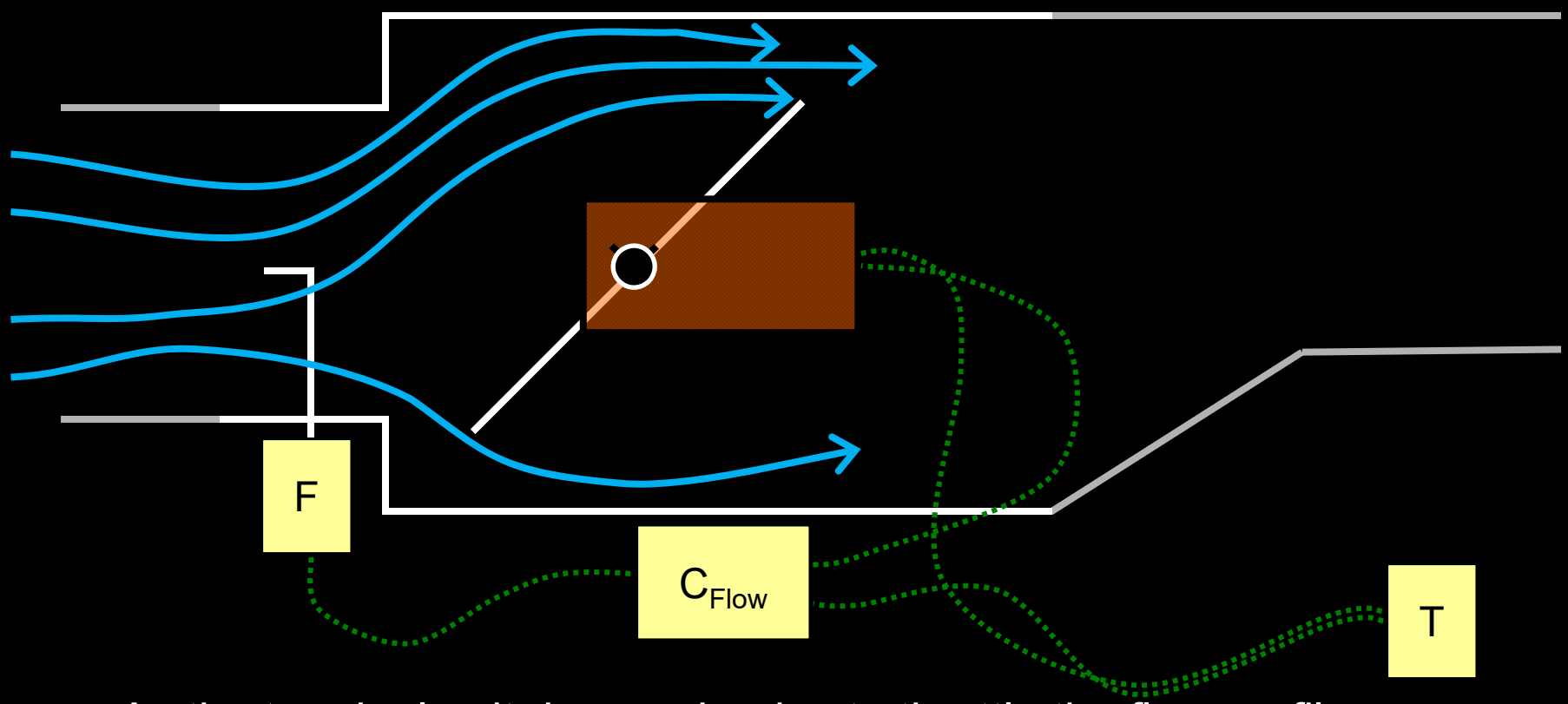
As the terminal unit damper begins to throttle the flow profile upstream of it begins to distort because the air is directed towards the sides of the box and accelerated by the closing damper

Flow Calibration; One Point *Doesn't* Fit All



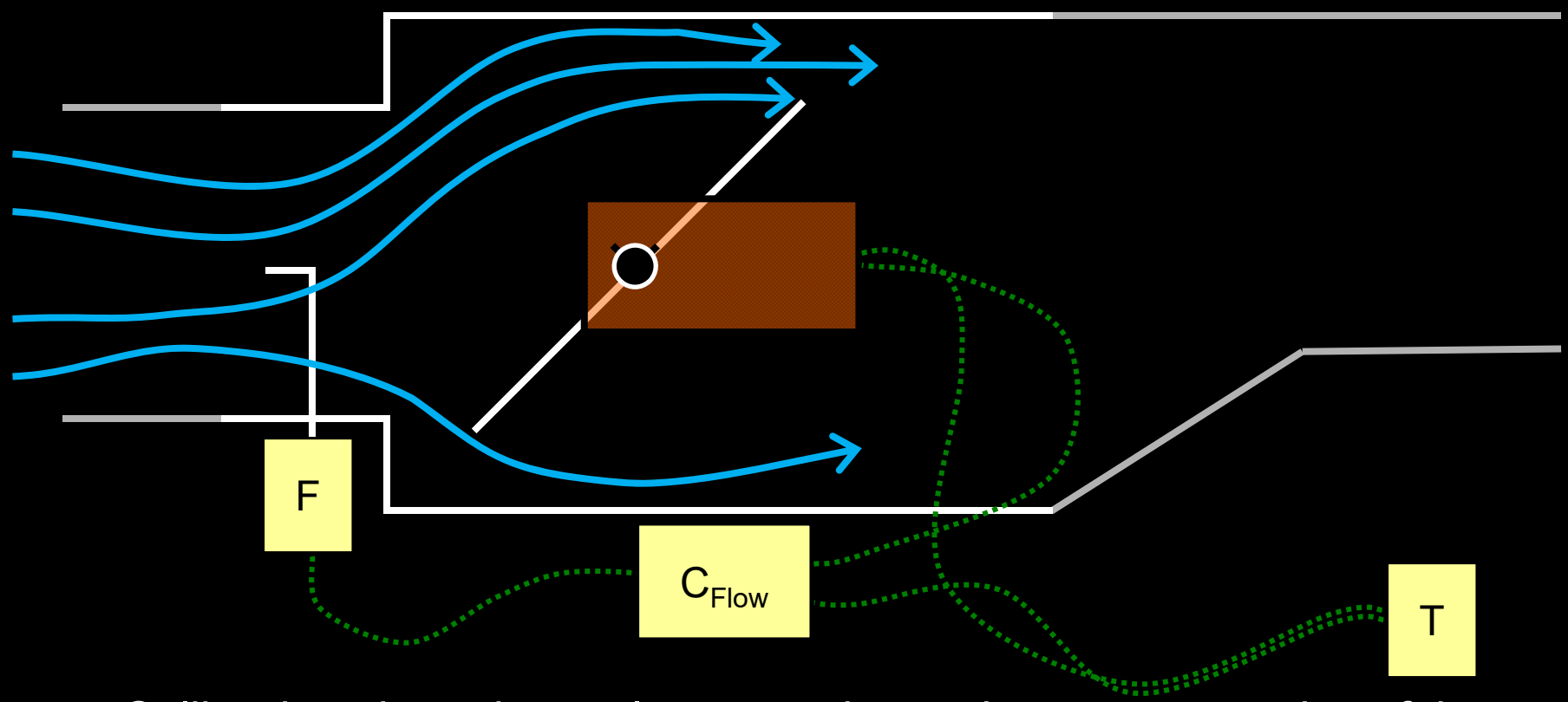
As the terminal unit damper begins to throttle the flow profile upstream of it begins to distort because the air is directed towards the sides of the box and accelerated by the closing damper

Flow Calibration; One Point *Doesn't* Fit All



As the terminal unit damper begins to throttle the flow profile upstream of it begins to distort because the air is directed towards the sides of the box and accelerated by the closing damper

Flow Calibration; One Point *Doesn't* Fit All



Calibrations based on at least two data points representative of the actual extreme operating conditions of the terminal unit will generally provide better results vs. a one point calibration

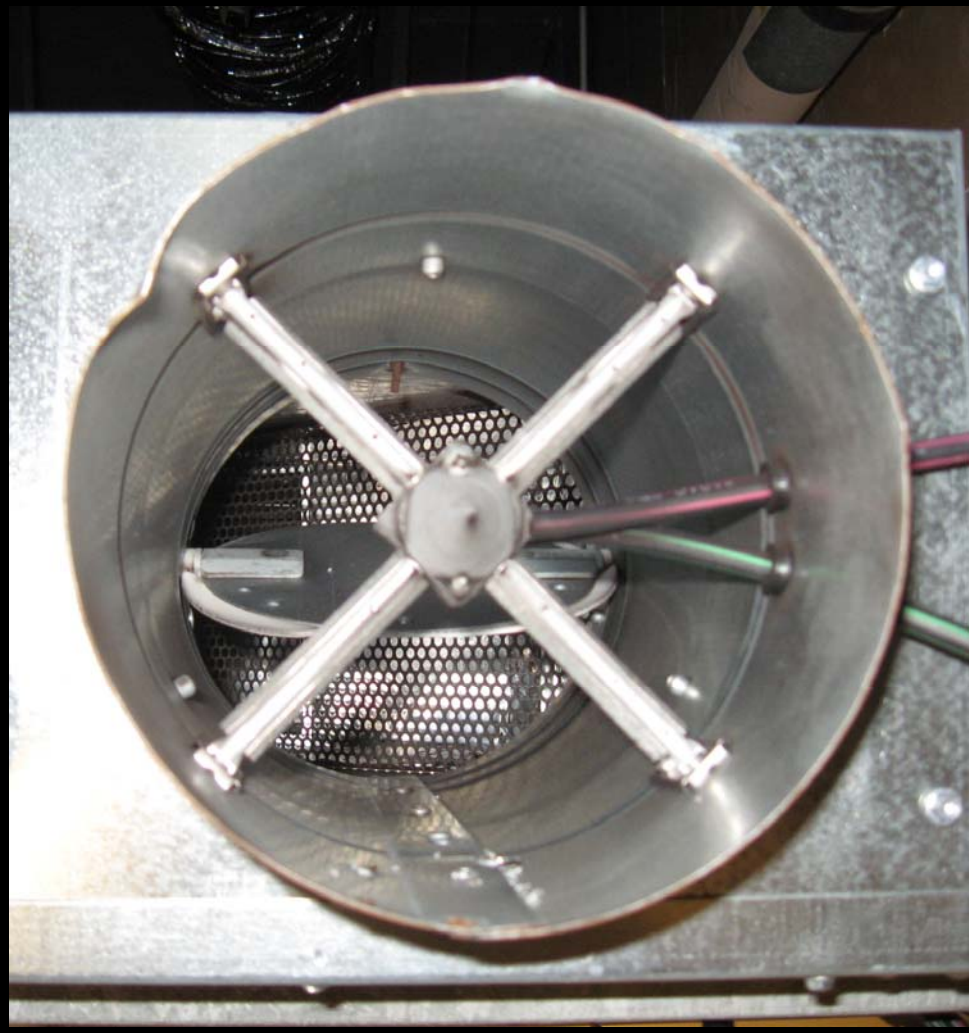
Field Data from the “Show Me” State

Building Control System Data

Set point	1,800 cfm
Indicated Flow	1,835 cfm
	(102% of set point)
Set point	700 cfm
Indicated flow	717 cfm
	(102% of set point)

Field Test Data (Traverse basis)

Set point	1,800 cfm
Traversed flow	1,962 cfm
	(107% of indicated)
Set point	700 cfm
Traversed flow	1,125 cfm
	(157% of indicated)



Field Data from the “Show Me” State

Read the paper and the presentation from NCBC 2013 at http://tinyurl.com/RonNCBC2013Presentation and http://tinyurl.com/RonNCBC2013Paper

Control Systems: Design, Performance and Commissioning Issues

Inputs

Aliasing and the Nyquist Theorem

Instructor:

David Sellers

Senior Engineer

Facility Dynamics Engineering

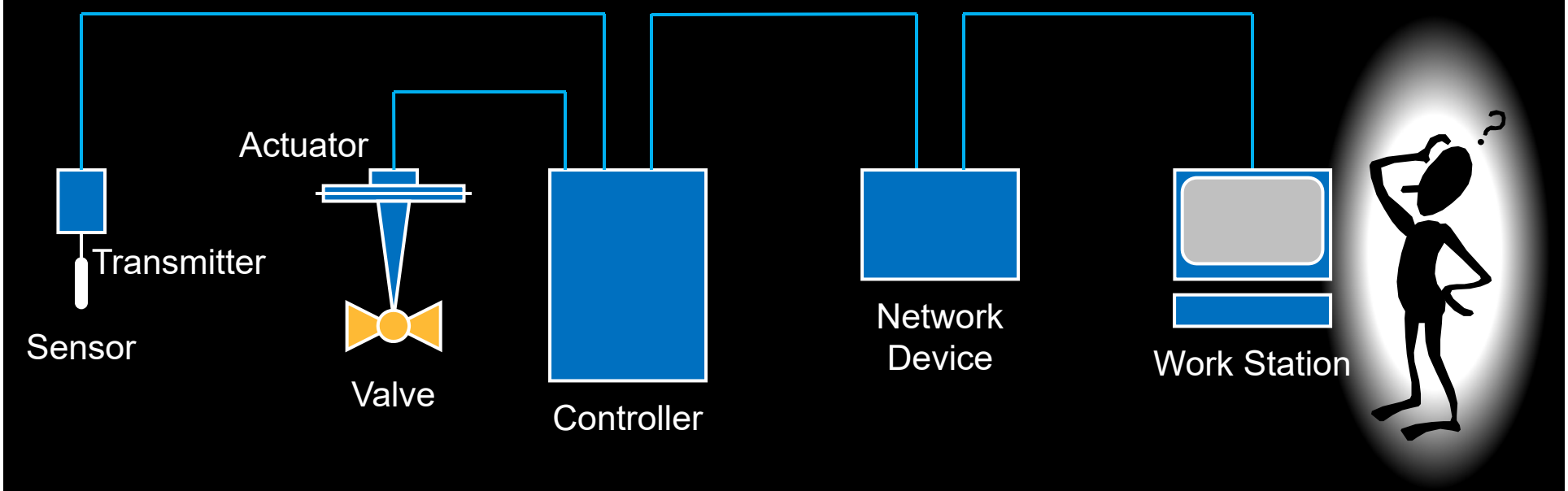
October 23, 2017

What You See is What You Get;

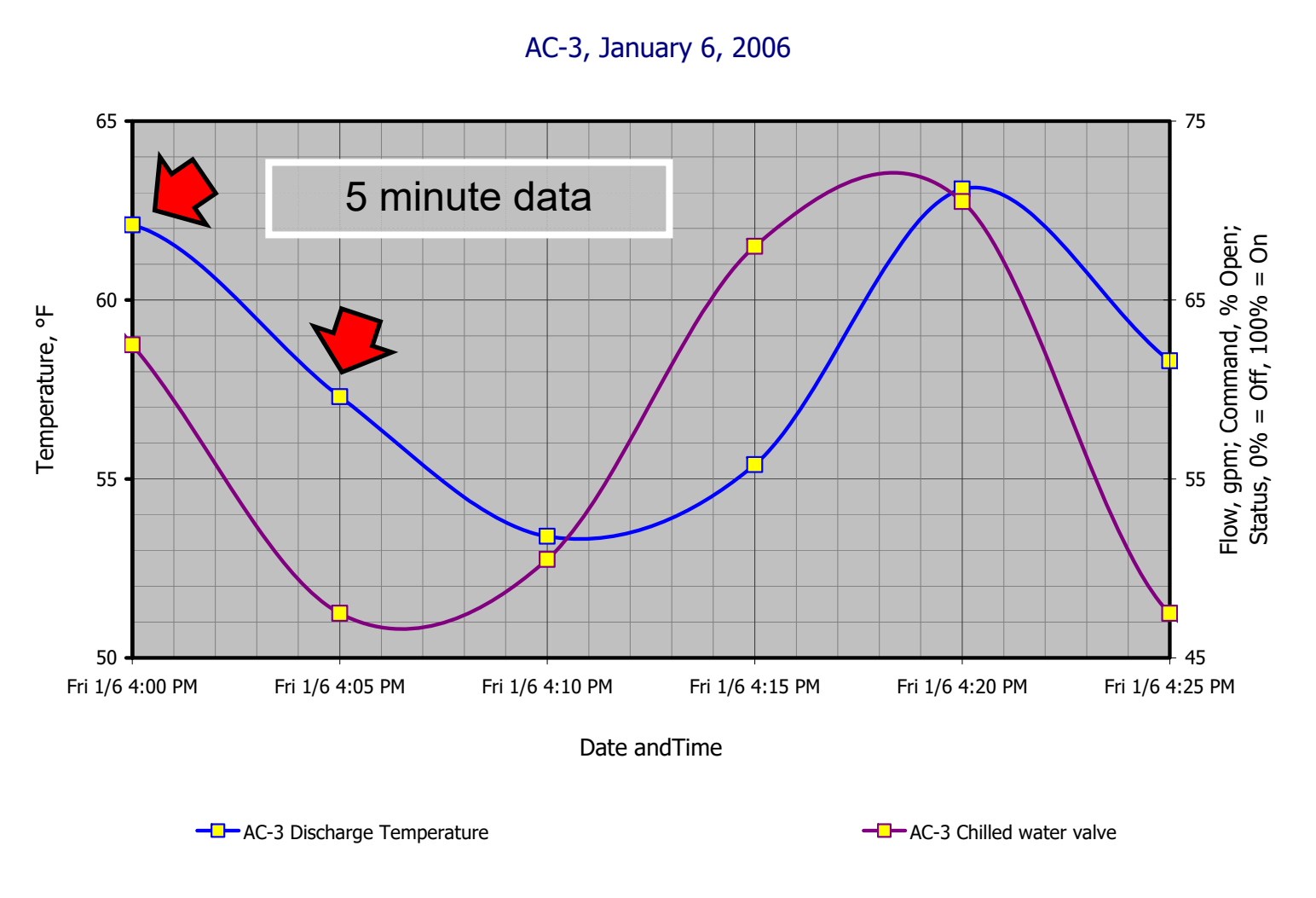
Maybe …

… or maybe not

- There are many elements between the sensor and the observer and the observer and the actuator
- All of them can impact accuracy, precision, and performance

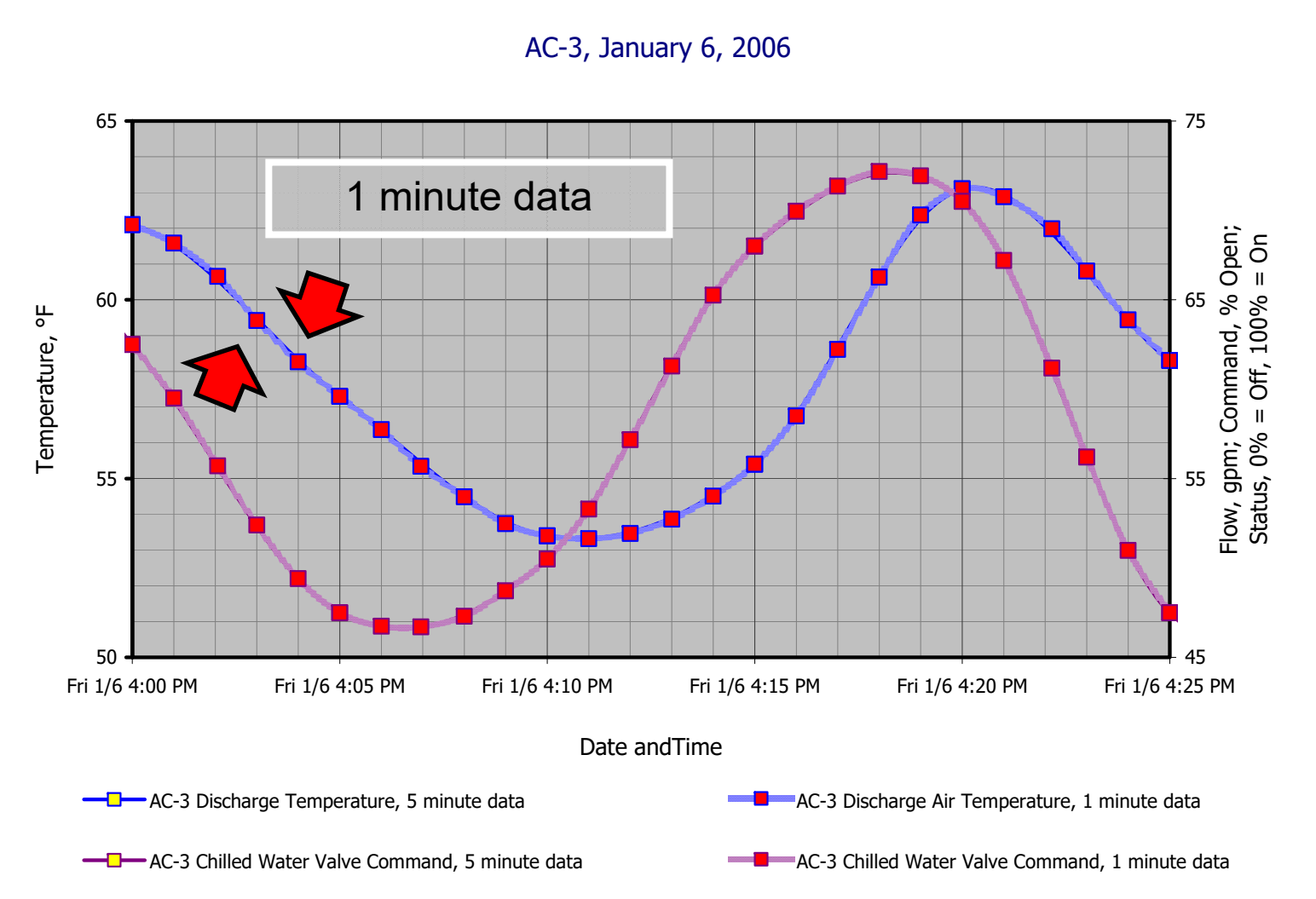


What You Sense is What You Get;



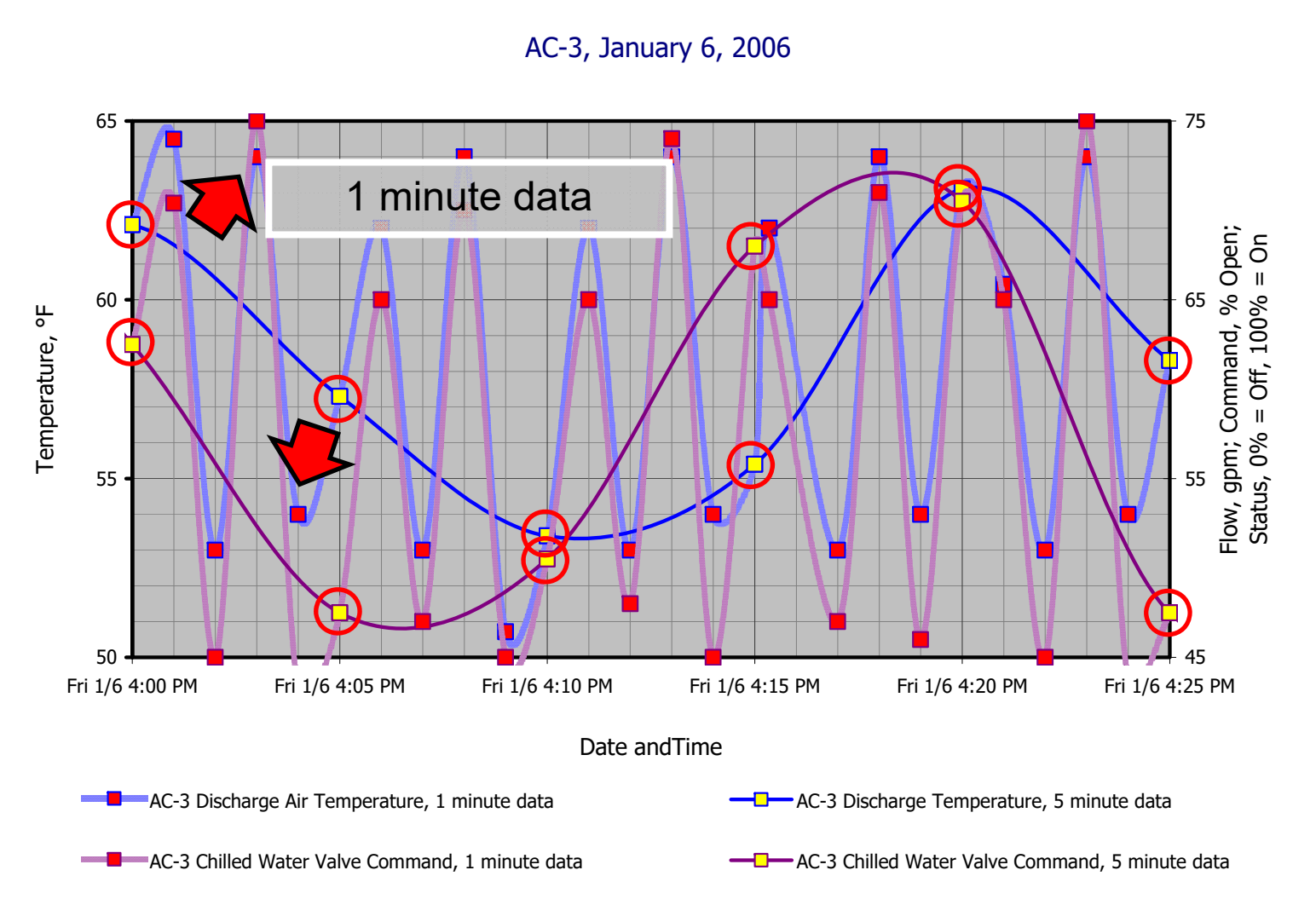
What You Sense is What You Get;

Maybe …



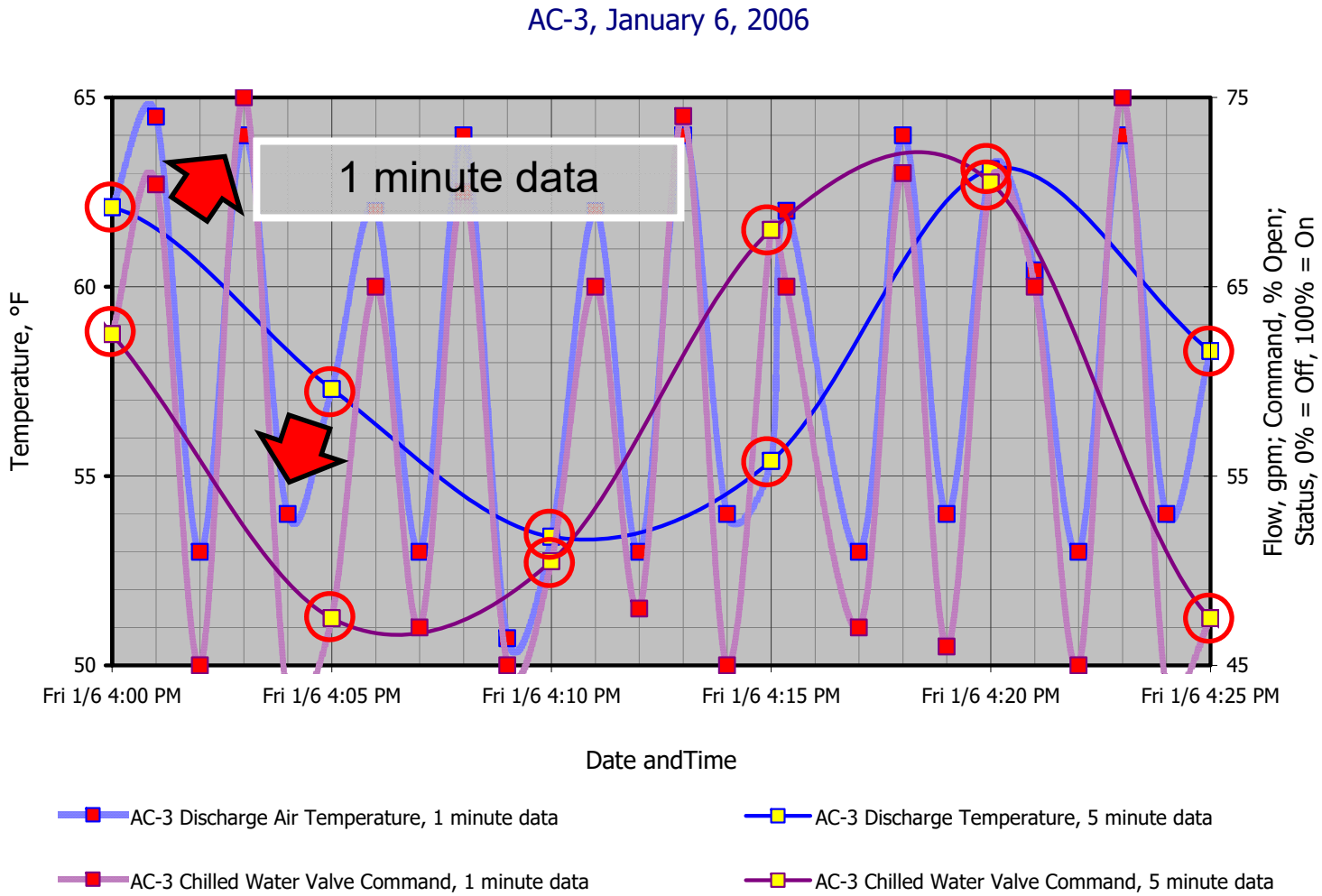
What You Sense is What You Get;

Or Maybe Not!



What You Sense is What You Get;

Or Maybe Not!



Bottom Lines

To avoid aliasing, you need to sample a process at twice the frequency of the fastest disturbance

- At this sampling rate, the wave form will be about the right shape
- It may be shifted in time from the actual wave form depending on where the samples were taken in the cycle

The faster you sample the waveform, the closer your data will be to matching the real time disturbance

For more on aliasing, see Aliasing and Other Factors Affecting the Accuracy of Field Data at www.Av8rDAS.Wordpress.com

The Nyquist Theorem a.k.a the Sampling Theorem

The Theory Behind the Generalization

$$f_s \geq 2 \times f_c$$

Where:

f_s = The sampling frequency

f_c = The highest frequency contained in the signal

In words:

The sampling frequency should be at least twice the highest frequency contained in the signal.

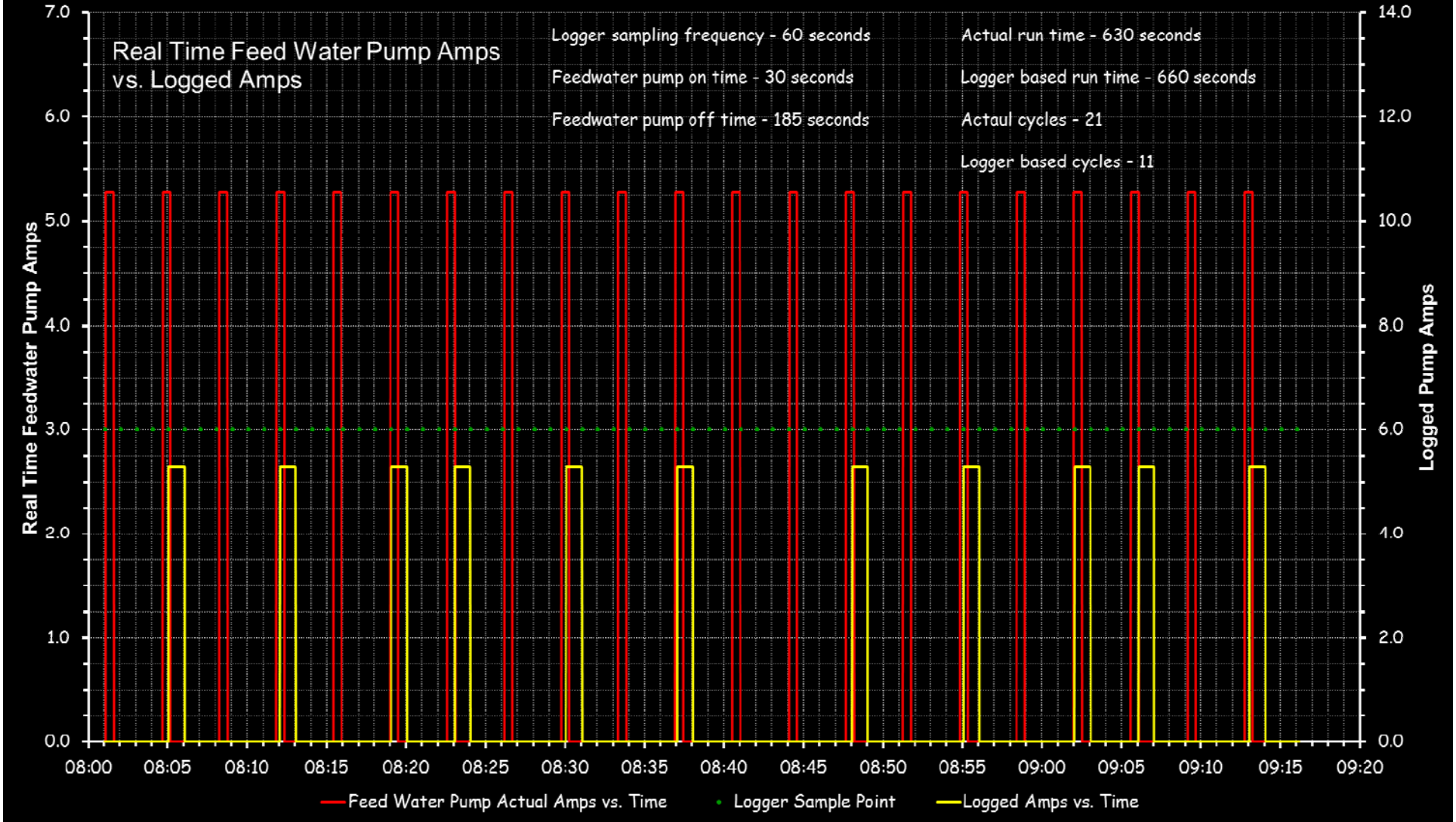
Aliasing; Also a Concern with Binary Data;
An Example

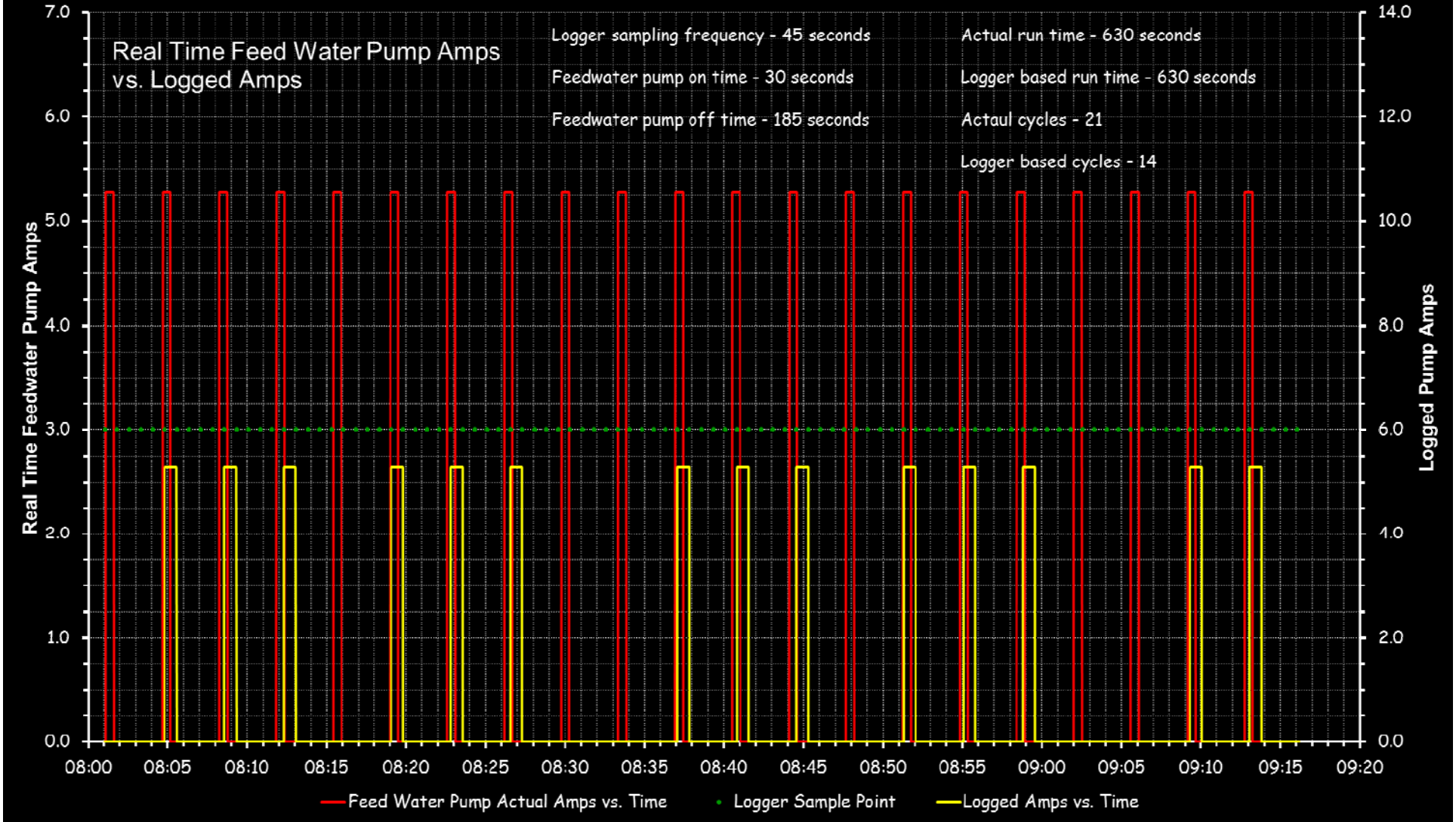
- A data logger has been installed to log feed water pump operation to develop a boiler load profile
  - See *Assessing Steam Consumption with an Alarm Clock* blog posts for the technique
  - http://tinyurl.com/LoadProfile
- Sampling time is critical in terms of having the logger capture an accurate picture of the true operating pattern
  - In general, the logger needs to sample at least twice as fast as the shortest disturbance in the process you are observing

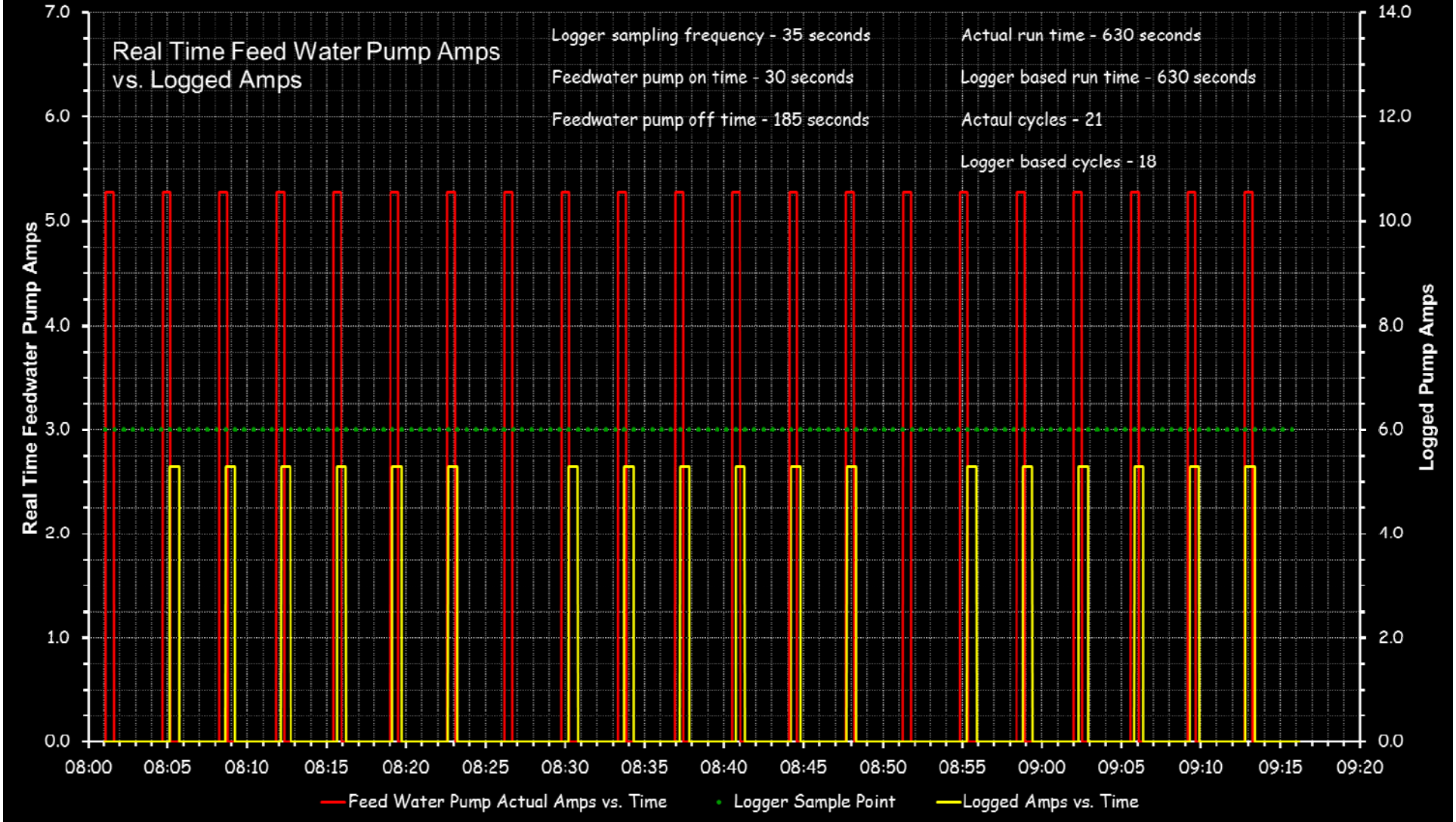
Aliasing; Also a Concern with Binary Data;
An Example

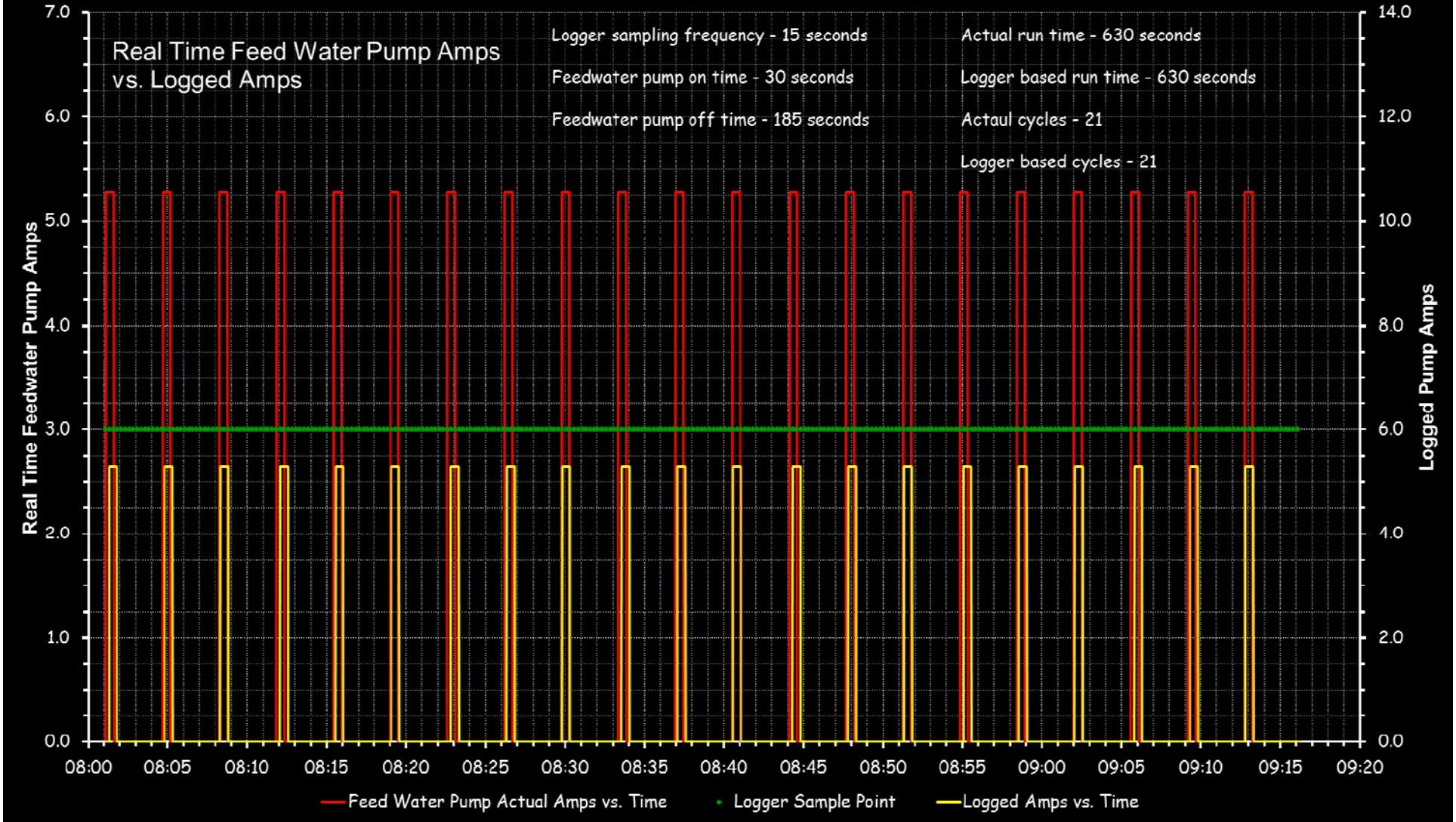
The slides that follow use a spreadsheet model to compare the number of pump cycles and total operating time predicted by data from a logger with the real time data stream

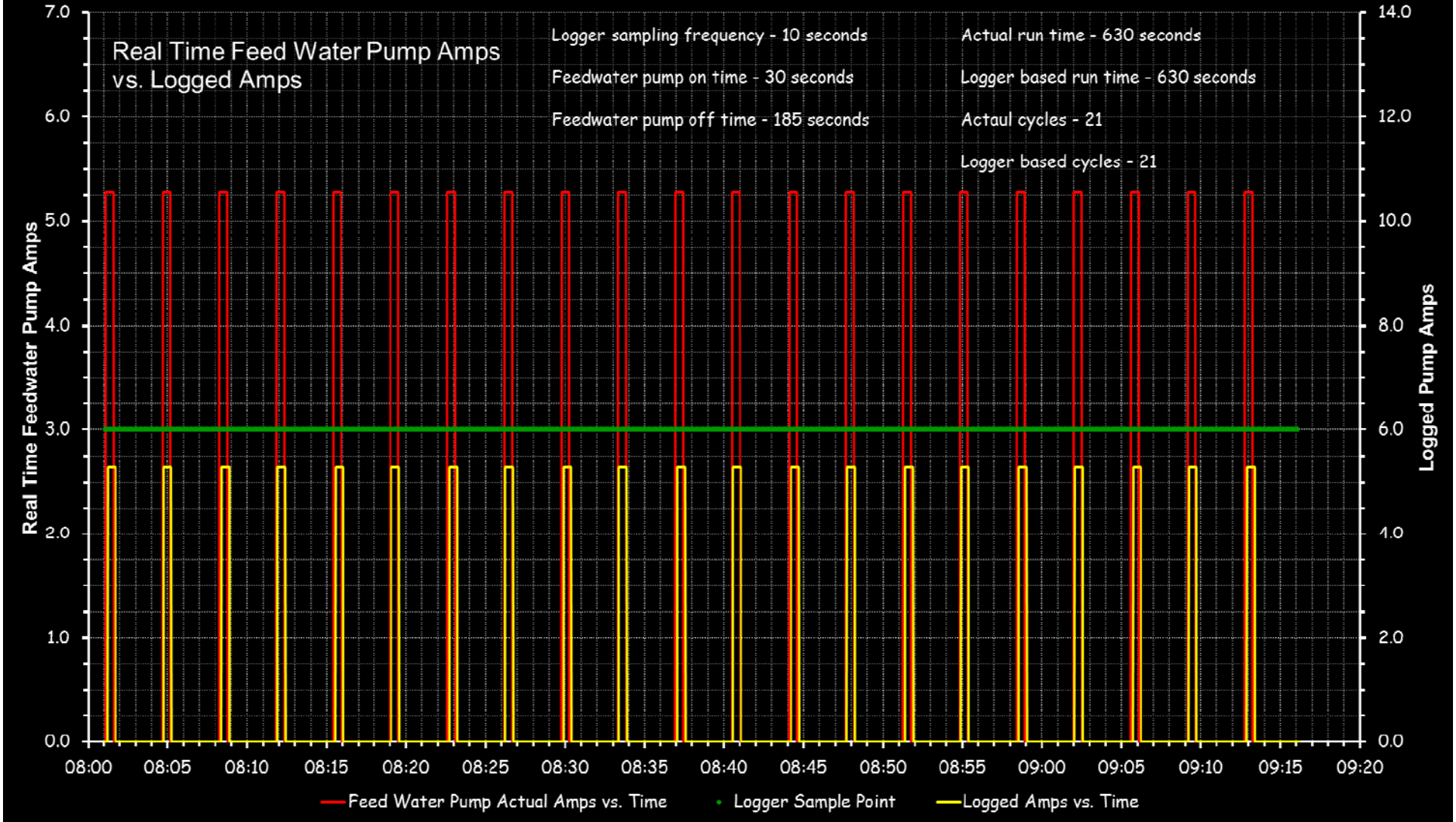
- The logger only knows what it sees at the time it takes its sample
- The logger is not averaging data between samples
- The logger sampling time starts out at twice the feed water pump run cycle time and is reduced to one third of the feed water pump run cycle time

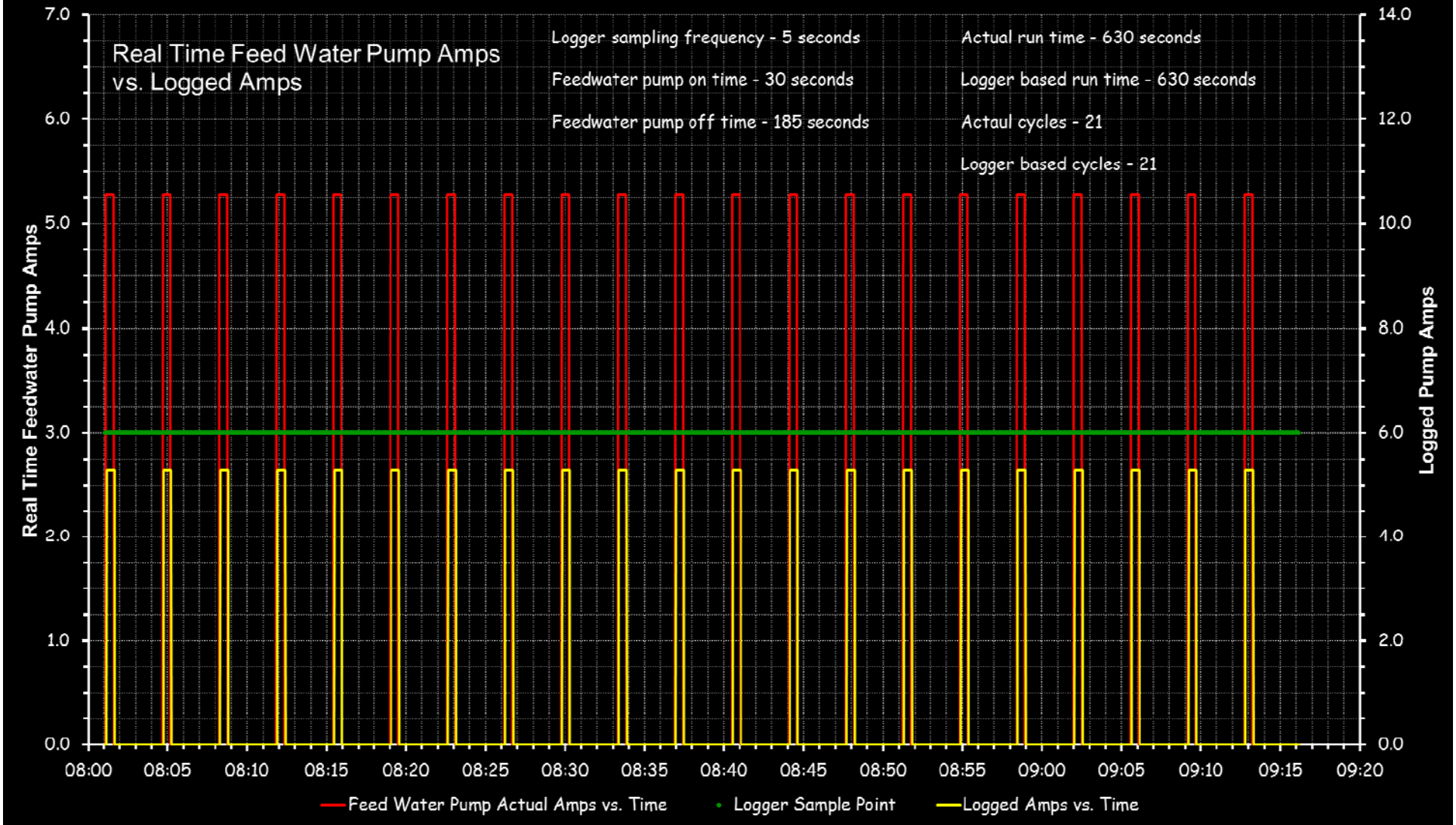

Real Time Feed Water Pump Amps
vs. Logged Amps
Logger sampling frequency - 60 seconds
Feedwater pump on time - 30 seconds
Feedwater pump off time - 185 seconds
Actual run time - 630 seconds
Logger based run time - 660 seconds
Actaul cycles - 21
Logger based cycles - 11
Real Time Feedwater Pump Amps
Logged Pump Amps
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
08:00
08:05
08:10
08:15
08:20
08:25
08:30
08:35
08:40
08:45
08:50
08:55
09:00
09:05
09:10
09:15
09:20
Feed Water Pump Actual Amps vs. Time
Logger Sample Point
Logged Amps vs. Time


Real Time Feed Water Pump Amps
vs. Logged Amps
Logger sampling frequency - 45 seconds
Feedwater pump on time - 30 seconds
Feedwater pump off time - 185 seconds
Actual run time - 630 seconds
Logger based run time - 630 seconds
Actaul cycles - 21
Logger based cycles - 14
Real Time Feedwater Pump Amps
Logged Pump Amps
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
08:00
08:05
08:10
08:15
08:20
08:25
08:30
08:35
08:40
08:45
08:50
08:55
09:00
09:05
09:10
09:15
09:20
Feed Water Pump Actual Amps vs. Time
Logger Sample Point
Logged Amps vs. Time


Real Time Feed Water Pump Amps
vs. Logged Amps
Logger sampling frequency - 35 seconds
Feedwater pump on time - 30 seconds
Feedwater pump off time - 185 seconds
Actual run time - 630 seconds
Logger based run time - 630 seconds
Actaul cycles - 21
Logger based cycles - 18
Real Time Feedwater Pump Amps
Logged Pump Amps
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
08:00
08:05
08:10
08:15
08:20
08:25
08:30
08:35
08:40
08:45
08:50
08:55
09:00
09:05
09:10
09:15
09:20
Feed Water Pump Actual Amps vs. Time
Logger Sample Point
Logged Amps vs. Time


Real Time Feed Water Pump Amps
vs. Logged Amps
Logger sampling frequency - 15 seconds
Feedwater pump on time - 30 seconds
Feedwater pump off time - 185 seconds
Actual run time - 630 seconds
Logger based run time - 630 seconds
Actaul cycles - 21
Logger based cycles - 21
Real Time Feedwater Pump Amps
Logged Pump Amps
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
08:00
08:05
08:10
08:15
08:20
08:25
08:30
08:35
08:40
08:45
08:50
08:55
09:00
09:05
09:10
09:15
09:20
Feed Water Pump Actual Amps vs. Time
Logger Sample Point
Logged Amps vs. Time


Real Time Feed Water Pump Amps
vs. Logged Amps
Logger sampling frequency - 10 seconds
Feedwater pump on time - 30 seconds
Feedwater pump off time - 185 seconds
Actual run time - 630 seconds
Logger based run time - 630 seconds
Actaul cycles - 21
Logger based cycles - 21
Real Time Feedwater Pump Amps
Logged Pump Amps
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
08:00
08:05
08:10
08:15
08:20
08:25
08:30
08:35
08:40
08:45
08:50
08:55
09:00
09:05
09:10
09:15
09:20
Feed Water Pump Actual Amps vs. Time
Logger Sample Point
Logged Amps vs. Time


Real Time Feed Water Pump Amps
vs. Logged Amps
Logger sampling frequency - 5 seconds
Feedwater pump on time - 30 seconds
Feedwater pump off time - 185 seconds
Actual run time - 630 seconds
Logger based run time - 630 seconds
Actaul cycles - 21
Logger based cycles - 21
Real Time Feedwater Pump Amps
Logged Pump Amps
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
08:00
08:05
08:10
08:15
08:20
08:25
08:30
08:35
08:40
08:45
08:50
08:55
09:00
09:05
09:10
09:15
09:20
Feed Water Pump Actual Amps vs. Time
Logger Sample Point
Logged Amps vs. Time

For More on Aliasing

More details and examples of alisasing can be found in the blog post titled *Aliasing and Other Factors Affecting the Accuracy of Field Data* on my blog at www.Av8rDAS.Wordpress.com