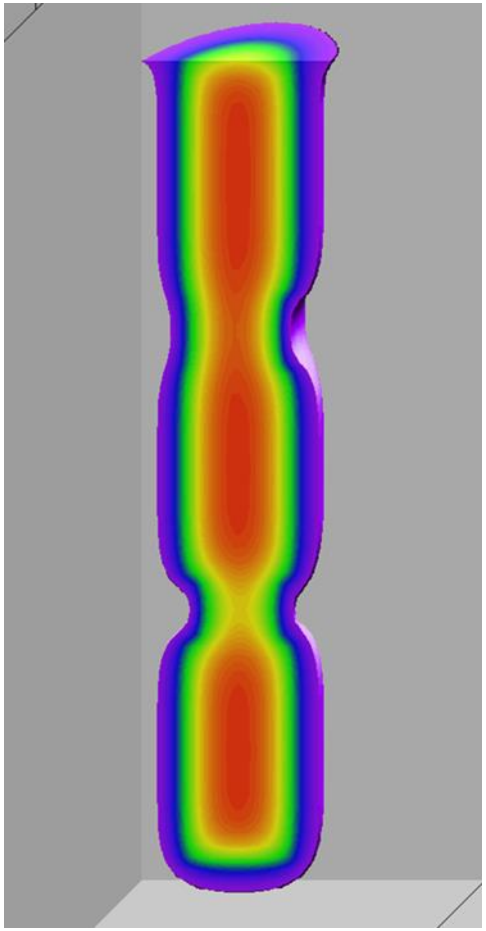
Optimizing the Use of Thermal Integrity System for Evaluating Auger-Cast Piles



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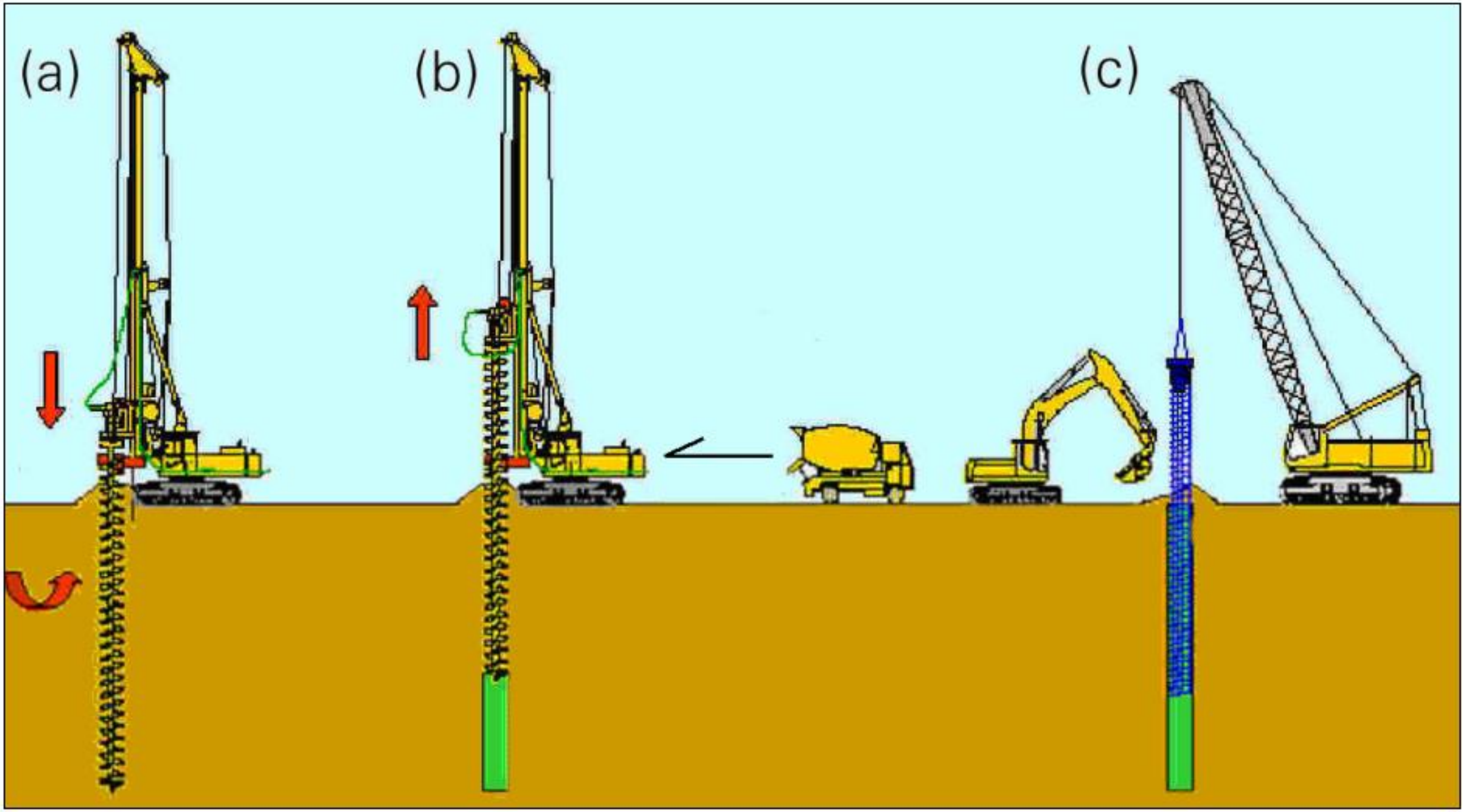
Problem Statement

- Thermal Integrity Profiling (TIP) has proven to be an effective method for evaluating the as-built integrity of drilled shafts.
- However, TIP is rarely used for evaluating auger-cast-in-place (ACIP) piles, as current practices do not require installation of standard integrity access tubes.
- Current integrity methods for ACIP piles is limited, thus their FDOT use has been limited to foundations for sound walls.
- GOAL: **Translate the use of thermal integrity technology to an effective method for evaluating ACIP piles**.

ACIP Piles
Construction



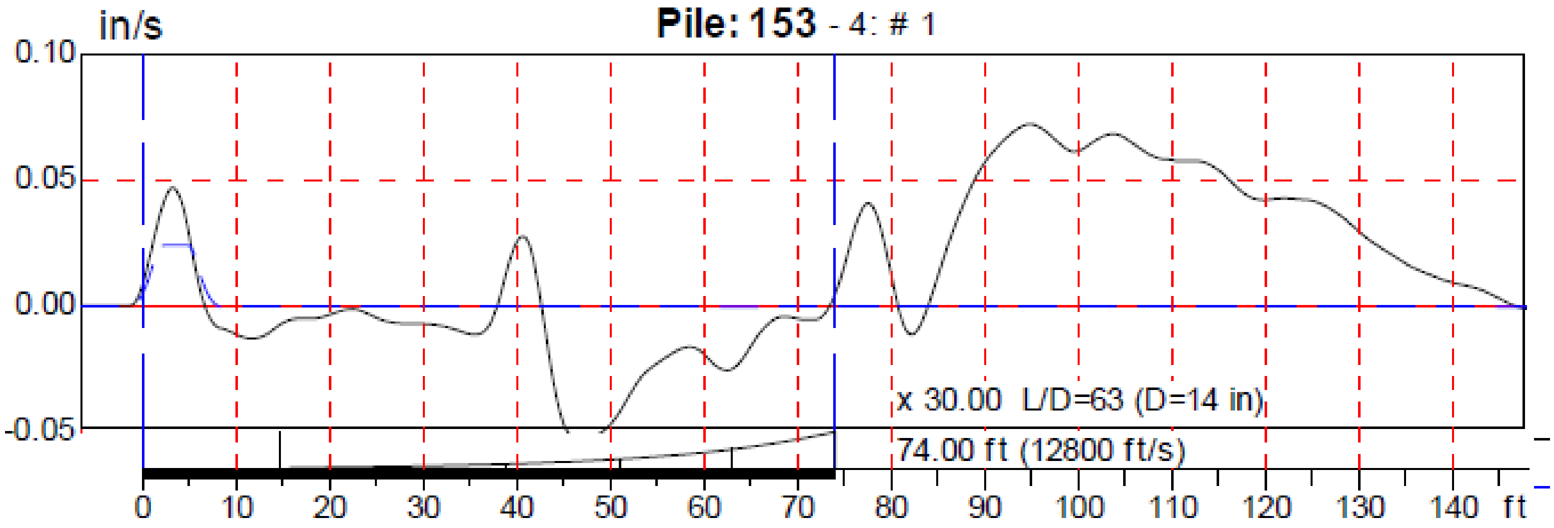
Source: Dan Brown et al., FHWA-HIF-07-03

ACIP Piles

Construction

ACIP Piles
Quality Assurance

Surface methods involving stress wave propagation analysis are the most common form of integrity testing for ACIP piles.

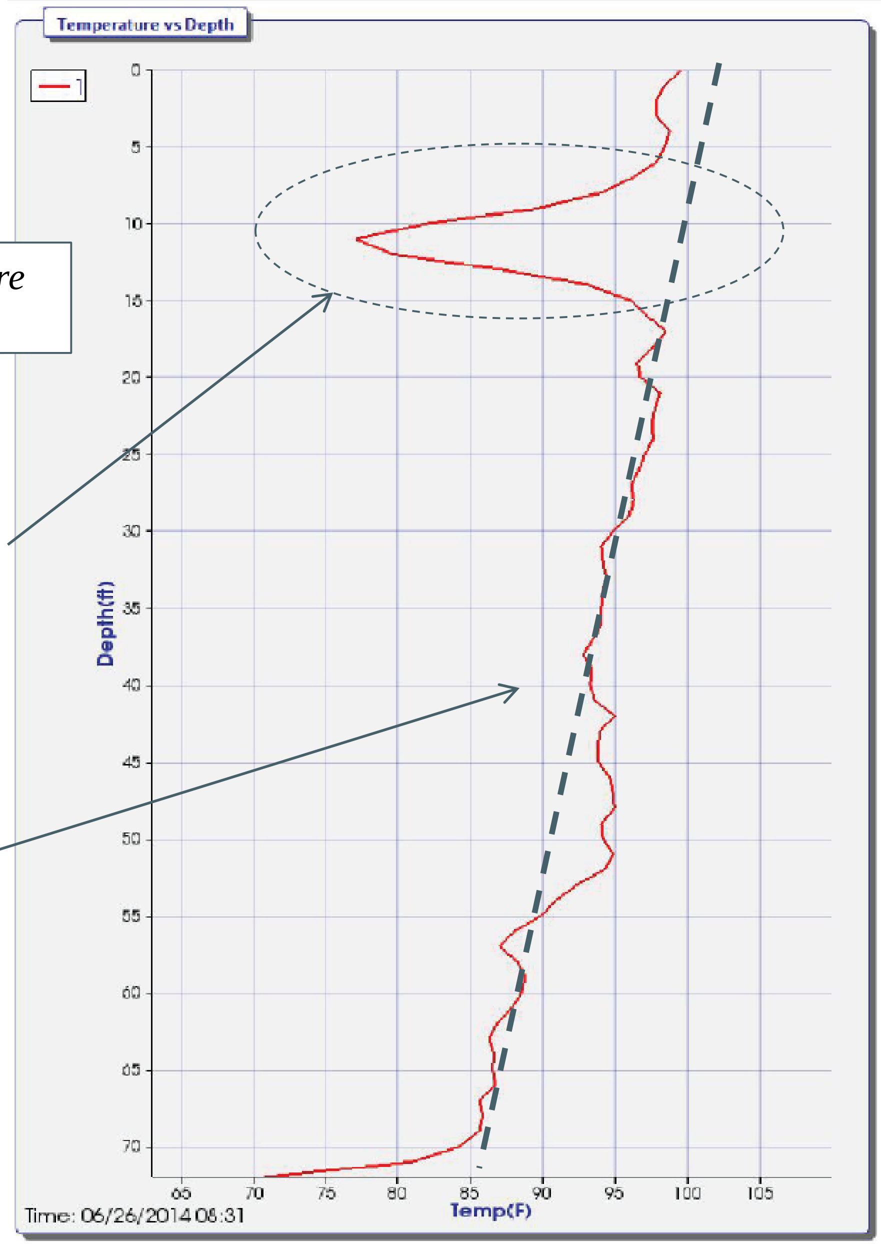


ACIP Piles
Quality Assurance

Single thermal wire tied to center bar

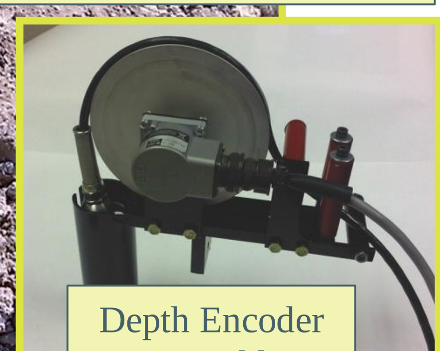
Single Center Wire Detects Anomaly

Inclination / alignment not quantifiable



TIP Methods
Infrared Probe

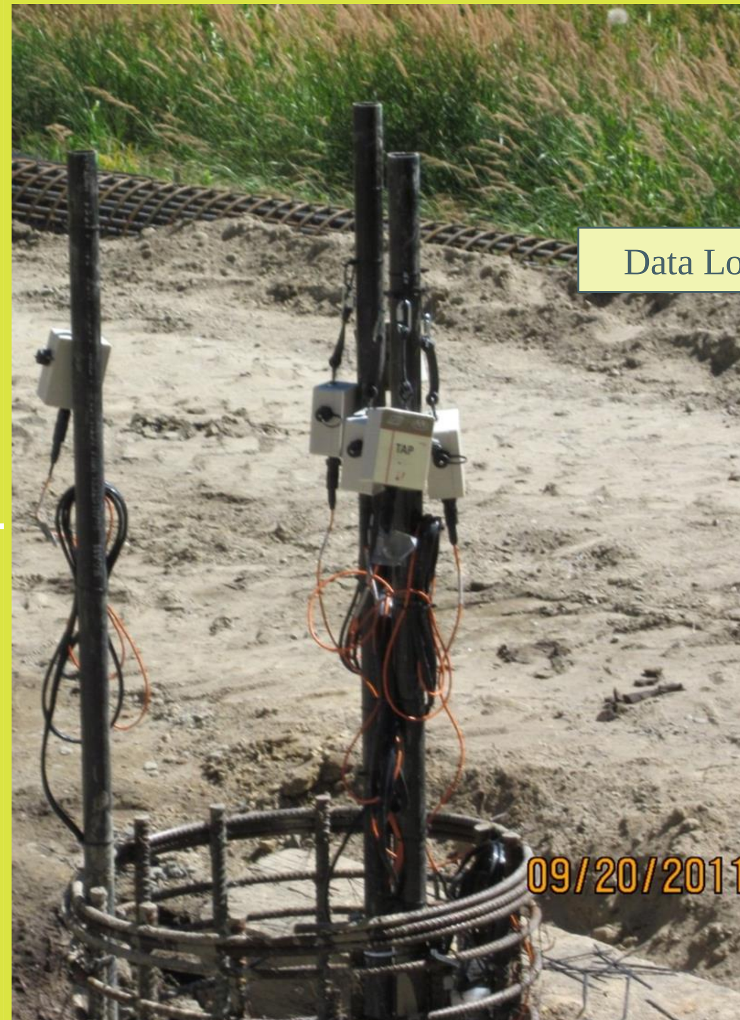
Thermal Probe w/ Infrared Sensors



Depth Encoder Assembly

Data Collection System

TIP Methods
Thermal Wire

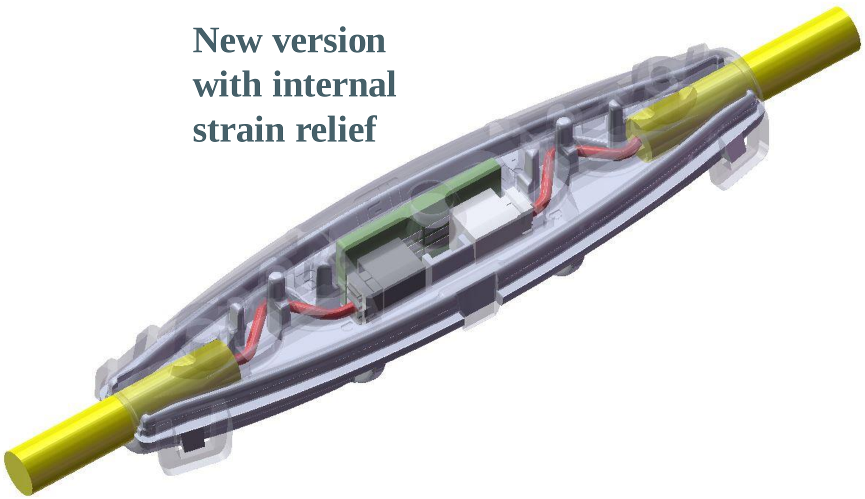


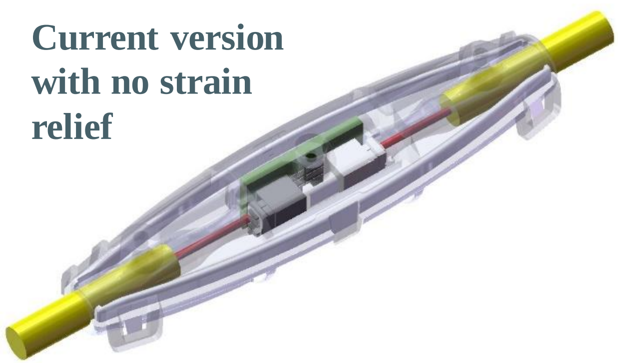
New Thermal Wire

Thermal Wire:

- New version of Thermal Wire in production now is much stronger and requires far less cable ties, greatly reducing potential data loss and speeding installation.

*The new version of the wire has been deployed on numerous shafts with excellent results



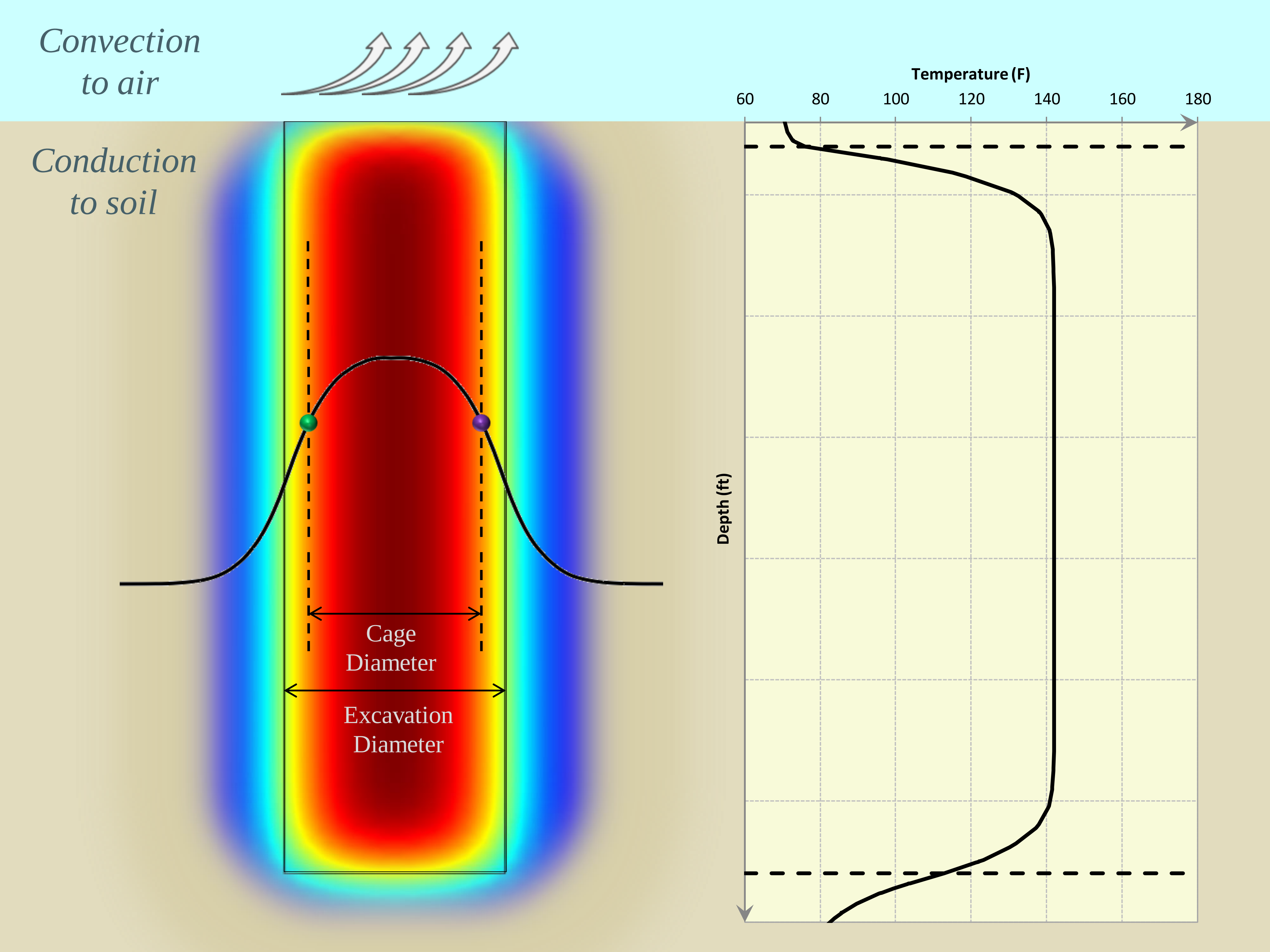


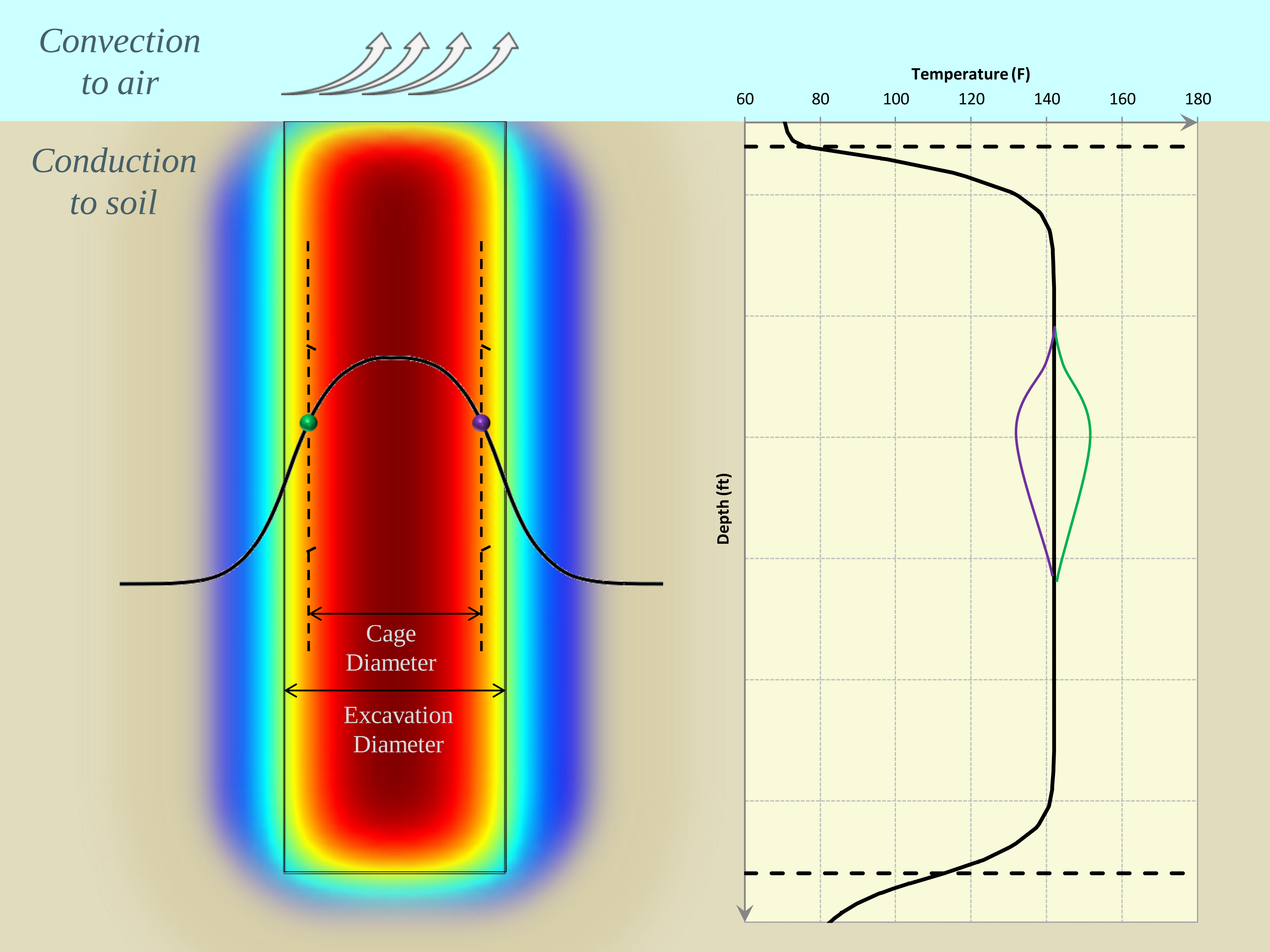
TIP Analysis – Concepts

- Integrity of a shaft can be affected by
  - reduced cross section,
  - cage offset resulting in decreased cover, and
  - inclusions of compromised or poor quality concrete,
  - all affect the heat production and temp of the shaft.

- Effective Radius – *the radius of intact, uniform quality concrete that would produce the measured temperature.*

- $Temperature \propto Effective\ Radius$


Convection to air
Conduction to soil
Cage Diameter
Excavation Diameter
Temperature (F)
60
80
100
120
140
160
180
Depth (ft)



Convection to air
Conduction to soil
Cage Diameter
Excavation Diameter
Temperature (F)
60
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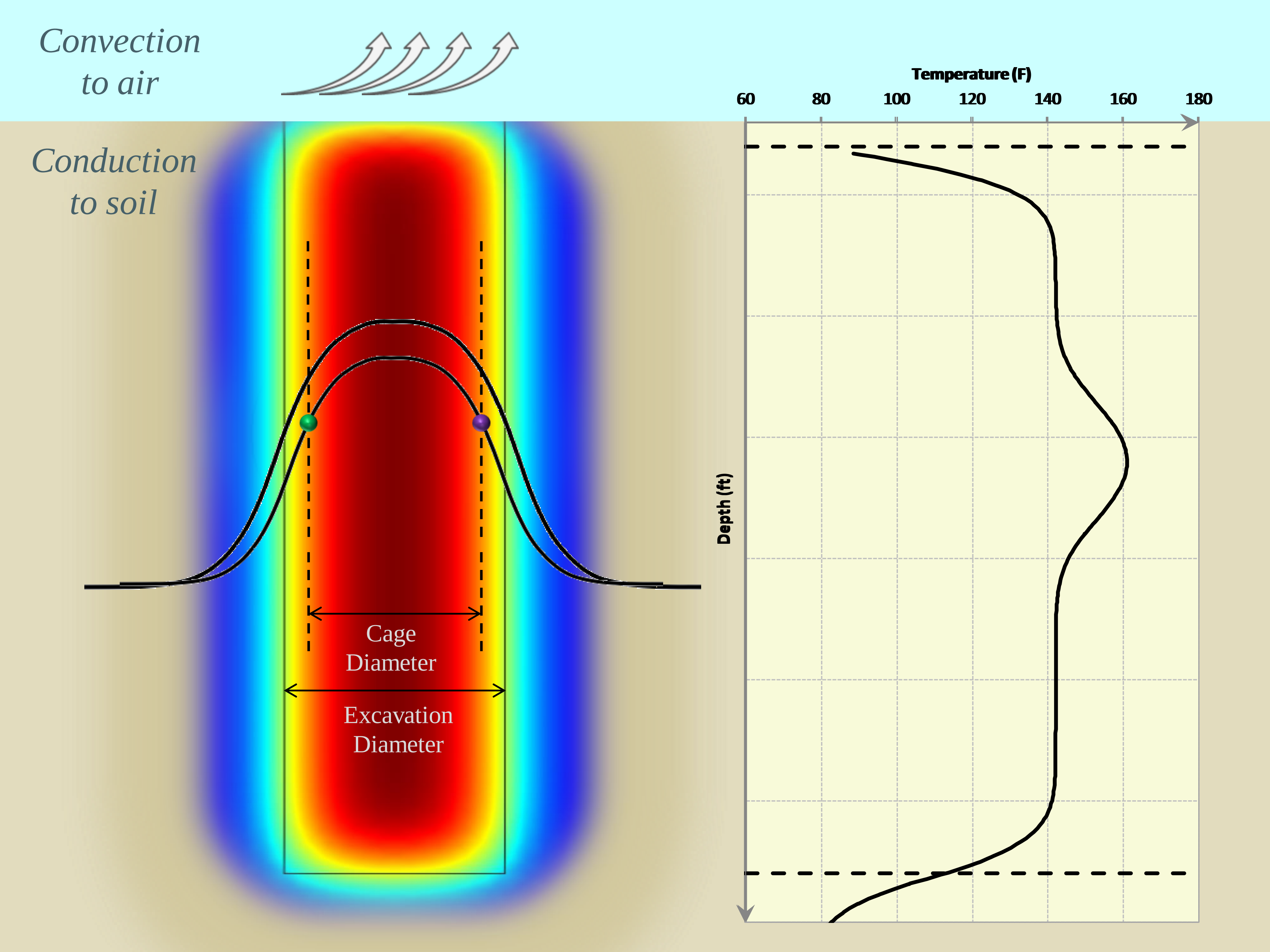
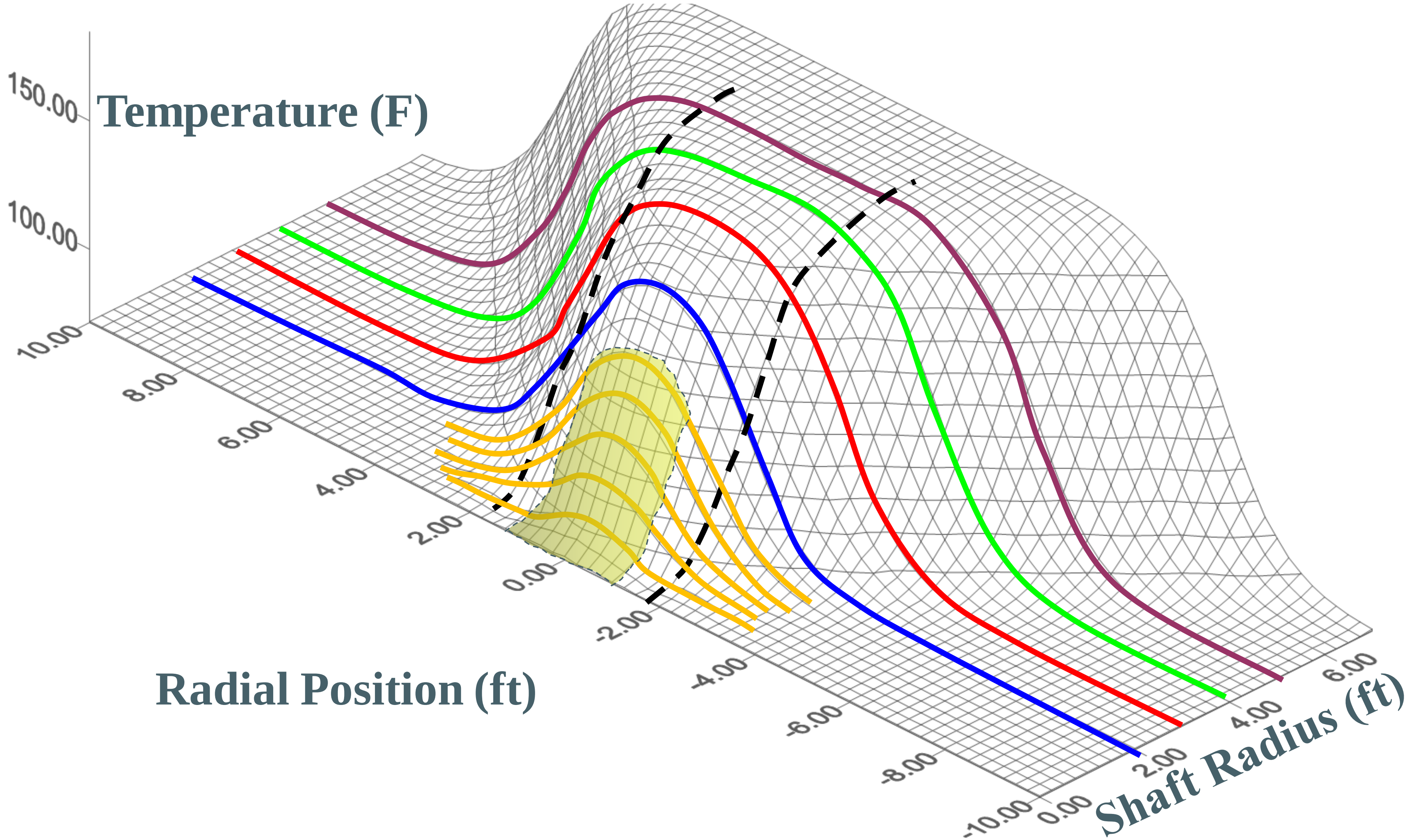
Depth (ft)


Convection to air
Conduction to soil
Cage Diameter
Excavation Diameter
Temperature (F)
60
80
100
120
140
160
180
Depth (ft)

Effects of Alignment and Shaft Radius



TIP Analysis
Methods & Levels of Analyzing TIP Data

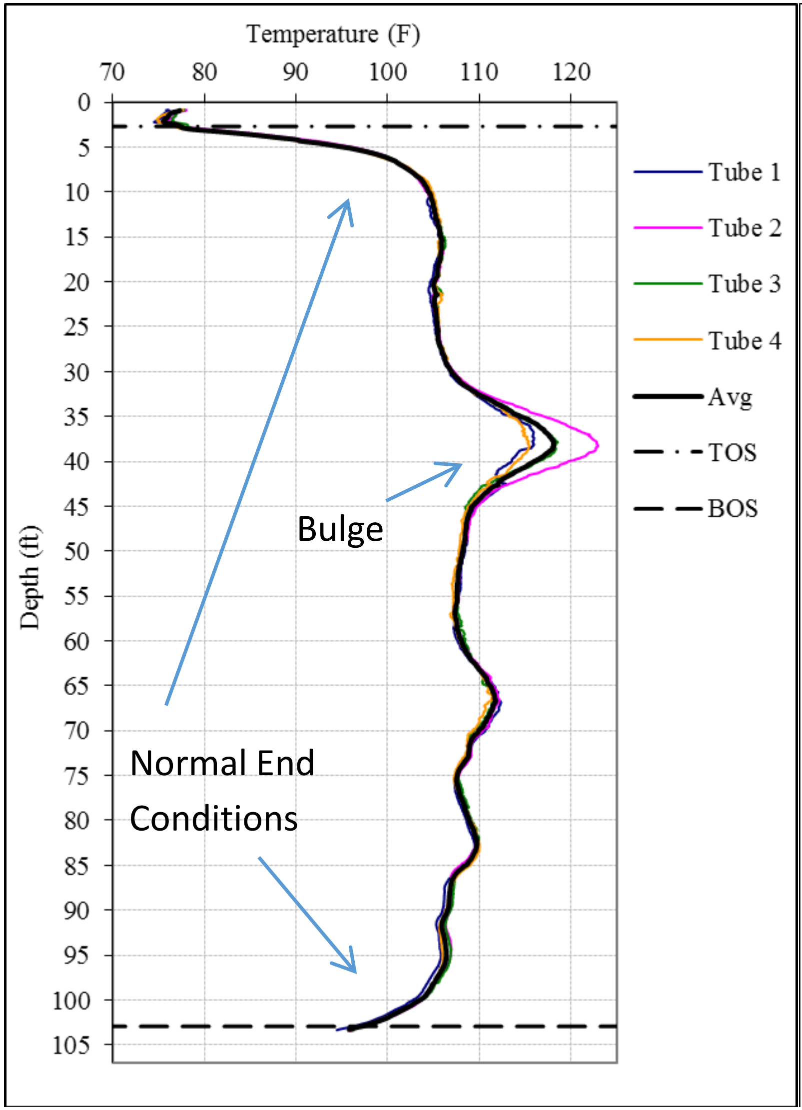
Level 1: Direct observation of the temperature profiles.

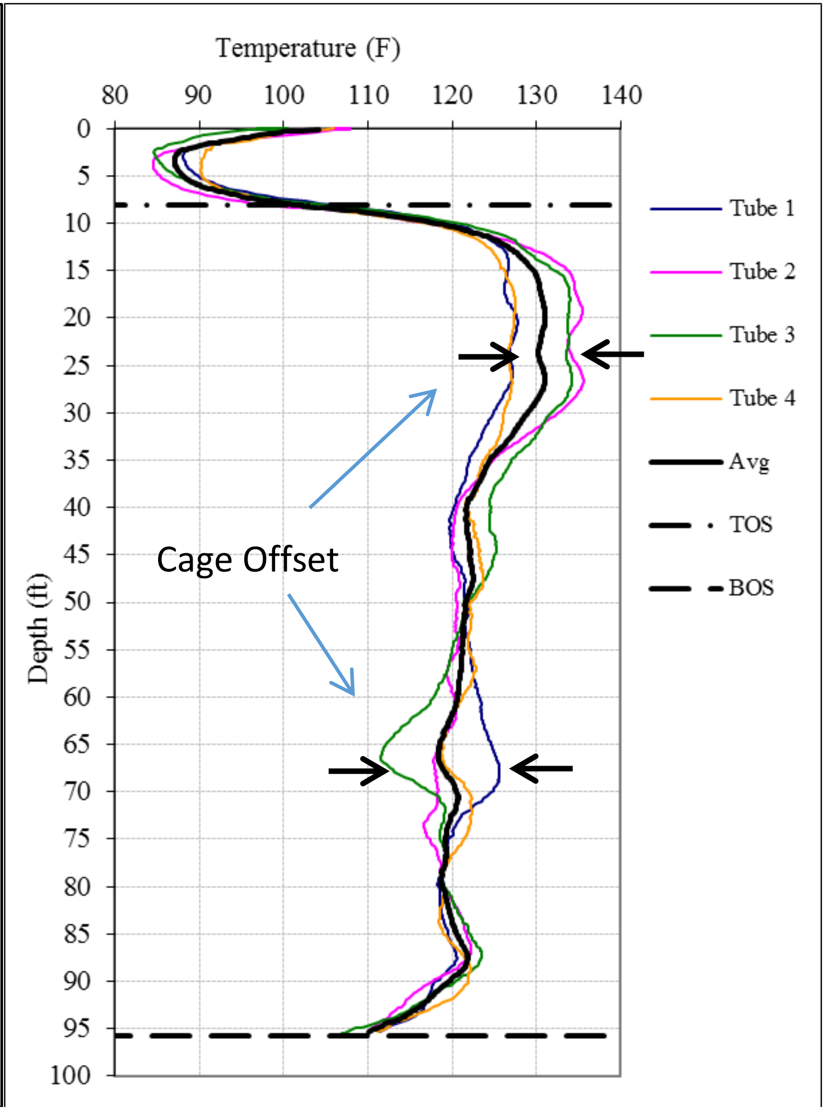
Level 2: Superimposed construction logs and concrete yield data. MOST COMMON

Level 3: Three dimensional thermal modeling.

Level 4: Signal matching numerical models to field data.

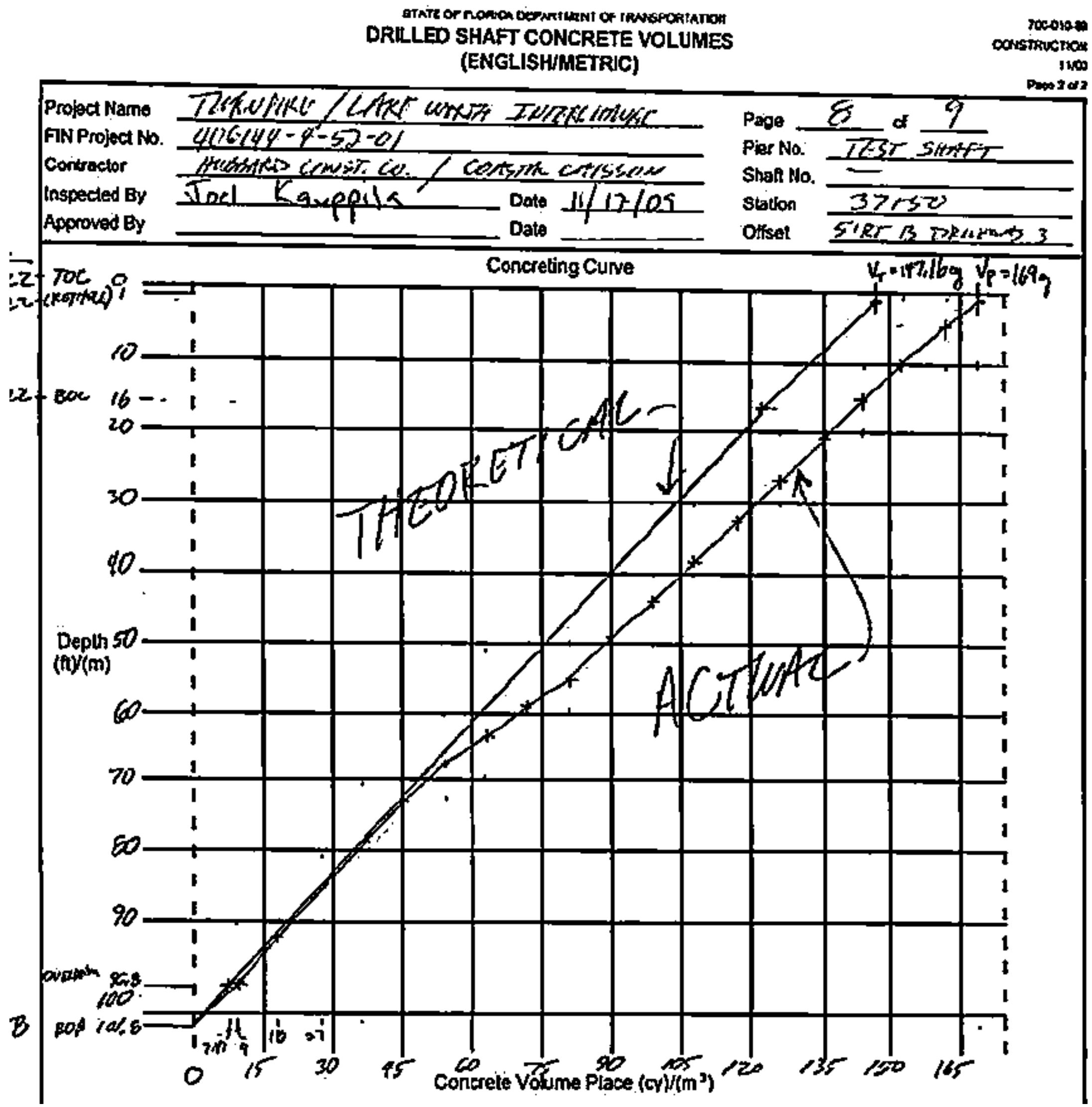
TIP Analysis - Direct Observation





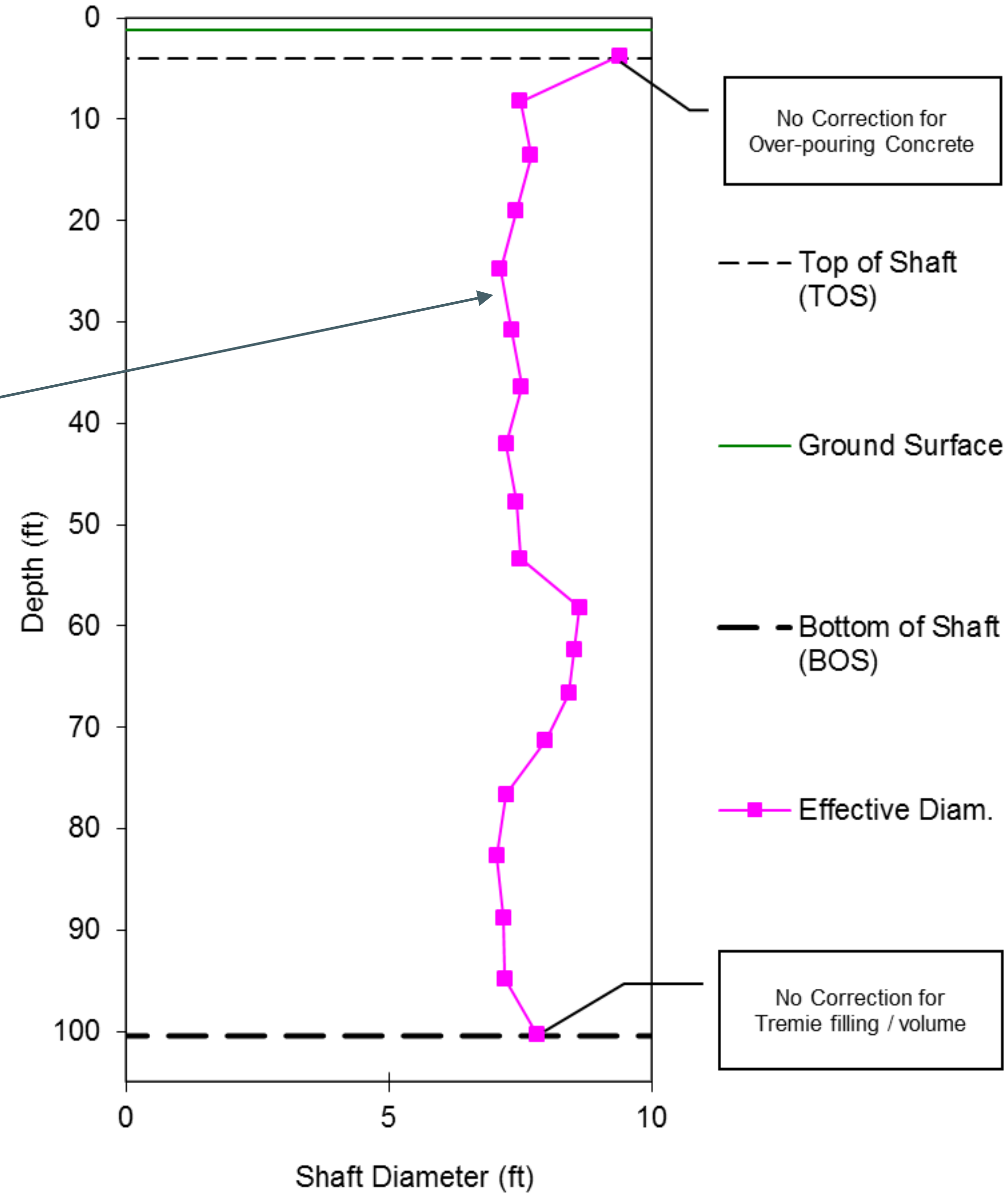
TIP Analysis - Superimposed Construction Logs & Concrete Yield Data

Yield plots provide a record of concrete volume vs. change in height for each truck



TIP Analysis

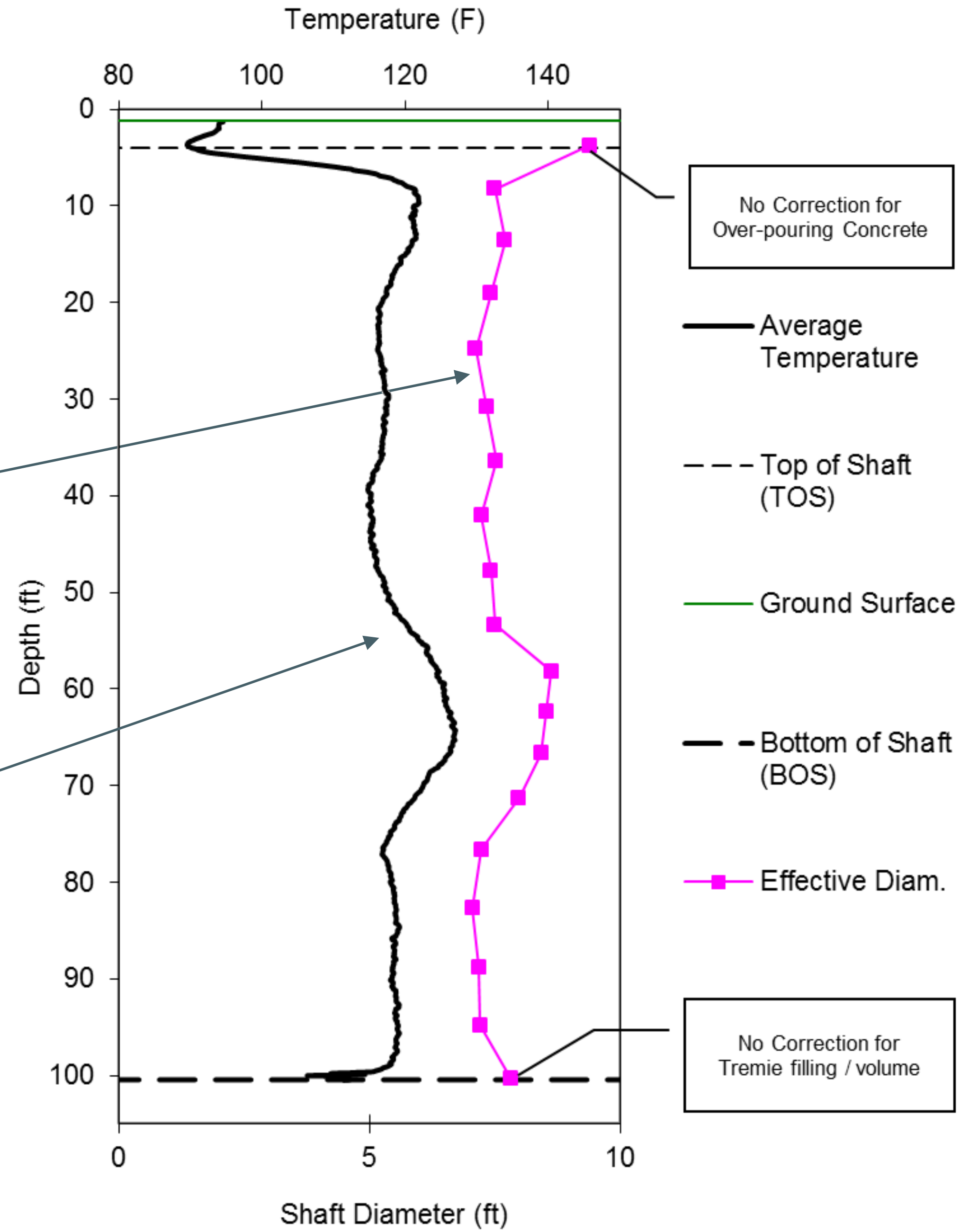
Yield plot converted to effective diameter vs. depth



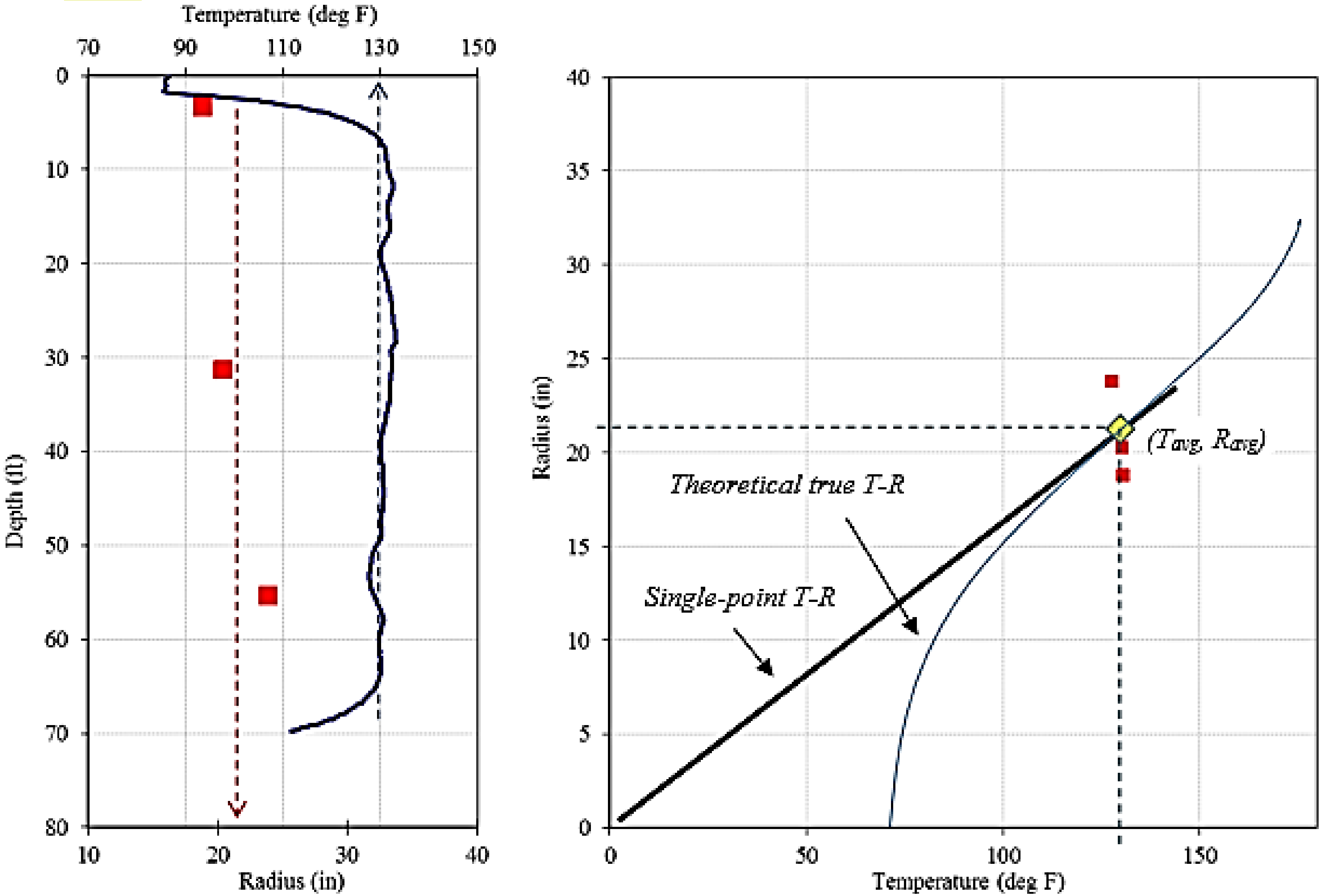
TIP Analysis

Yield plot converted to effective diameter vs. depth

Measured temperature profile



TIP Analysis - Superimposed Construction Logs



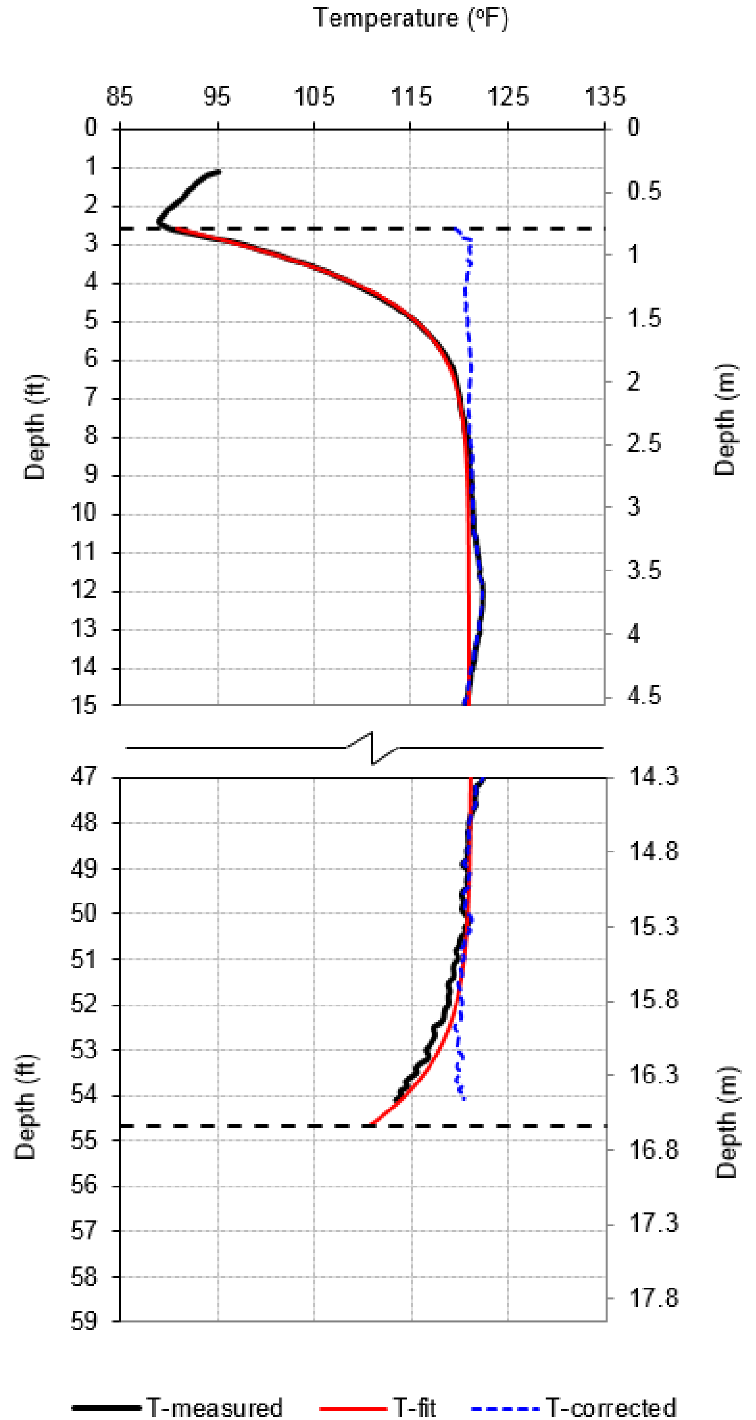
Hyperbolic Temperature Corrections

$$T_{fit} = \pm\left(\frac{T_{max} - T_{min}}{2}\right)\tanh\left(\frac{z - z_0}{\alpha}\right) + T_0$$

T_{max} = *Max. asymptotic temperature* (°F)
T_{min} = *Min. asymptotic temperature* (°F)
T_0 = *Inflection point temperature* (°F)
z_0 = *Inflection point depth* (*ft*)
α = *Vertical stretch* (*ft*)

$$T_{cor} = (T_{meas} - T_{fit})\left(\frac{T_{norm}}{T_{fit}}\right) + T_{norm}$$

T_{meas} = *Measured temperature* (°F)
T_{norm} = *Normalizing temperature* (°F)
(T_{max} *for top & bottom, depends for transitions*)



Summary of hyperbolic parameter selections

	Top Roll-off	Bottom Roll-off	Mid-shaft
T_{max}	Observed from TIP profile. **Confidence: Strong**	Observed from TIP profile. **Confidence: Strong**	Observed from TIP profile. **Confidence: Strong**
T_{min}	X	Average annual temperature of region. **Confidence: Strong**	Observed from TIP profile. **Confidence: Strong**
T_0	Average recent air temperature. **Confidence: Medium**	X	X
Z_0	TOS +/- 1ft **Confidence: Strong**	BOS +/- 1ft **Confidence: Strong**	Observed from TIP profile/ corroborated by boring logs **Confidence: Medium**
a	$= f(\sqrt{t})$ Typical range: 1-5 **Confidence: Medium**	$= f(\sqrt{t})$ Typical range: 1-5 **Confidence: Medium**	$= f(\sqrt{t})$ Typical range: 1-5 **Confidence: Medium**

Hyperbolic Abuse

- As with any signal matching approach, good matches can be found with physically impractical parameters.

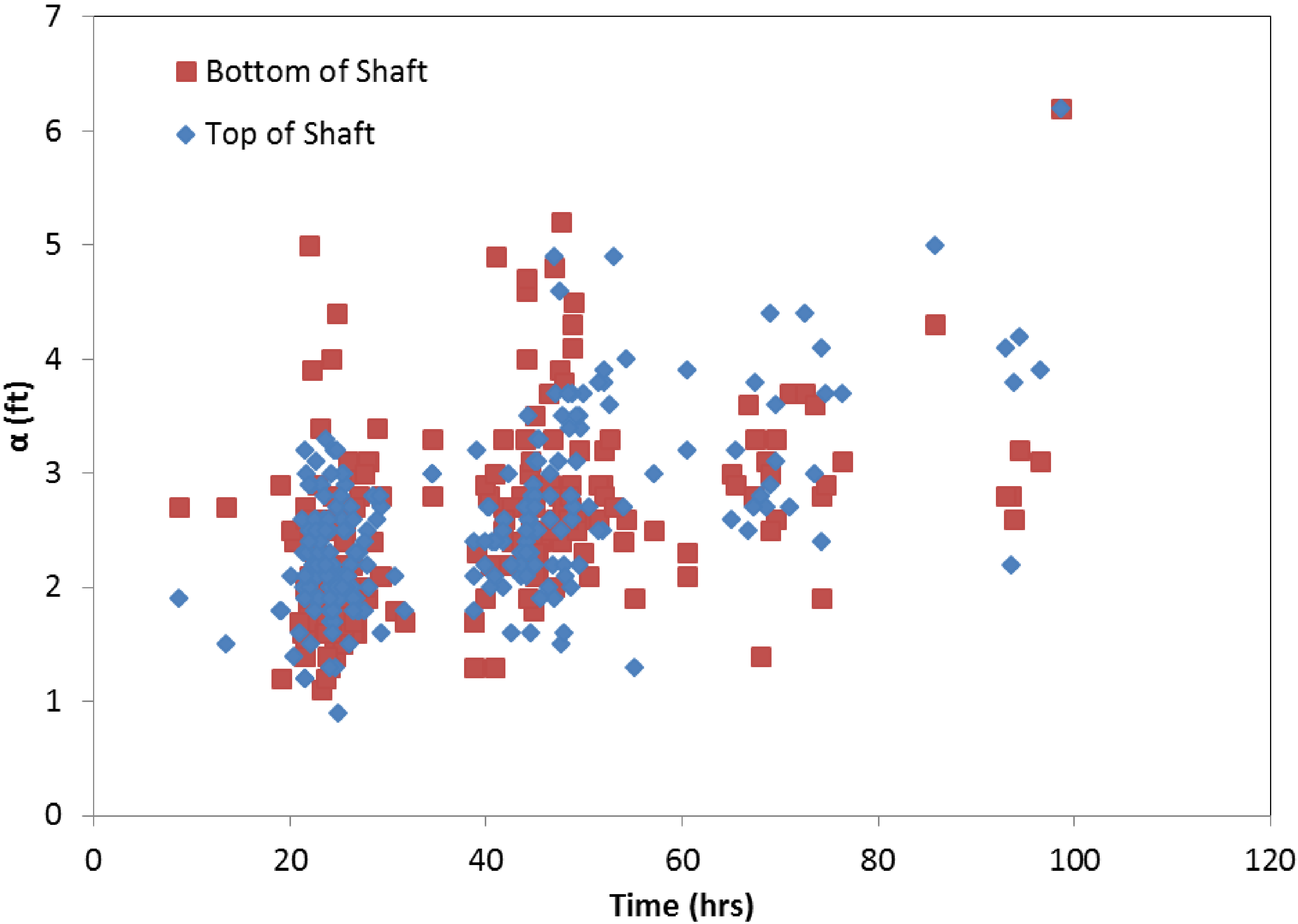
- TOS & BOS corrections are almost always warranted, but parameters should be correctly selected based on actual air / soil temperatures and time of testing (e.g. $\alpha = 0.3\sqrt{t}$)

- Mid-shaft hyperbolic corrections should only be applied when justified (e.g. over-water shafts). Actual radius changes exhibit similar patterns and should not be mistakenly corrected.

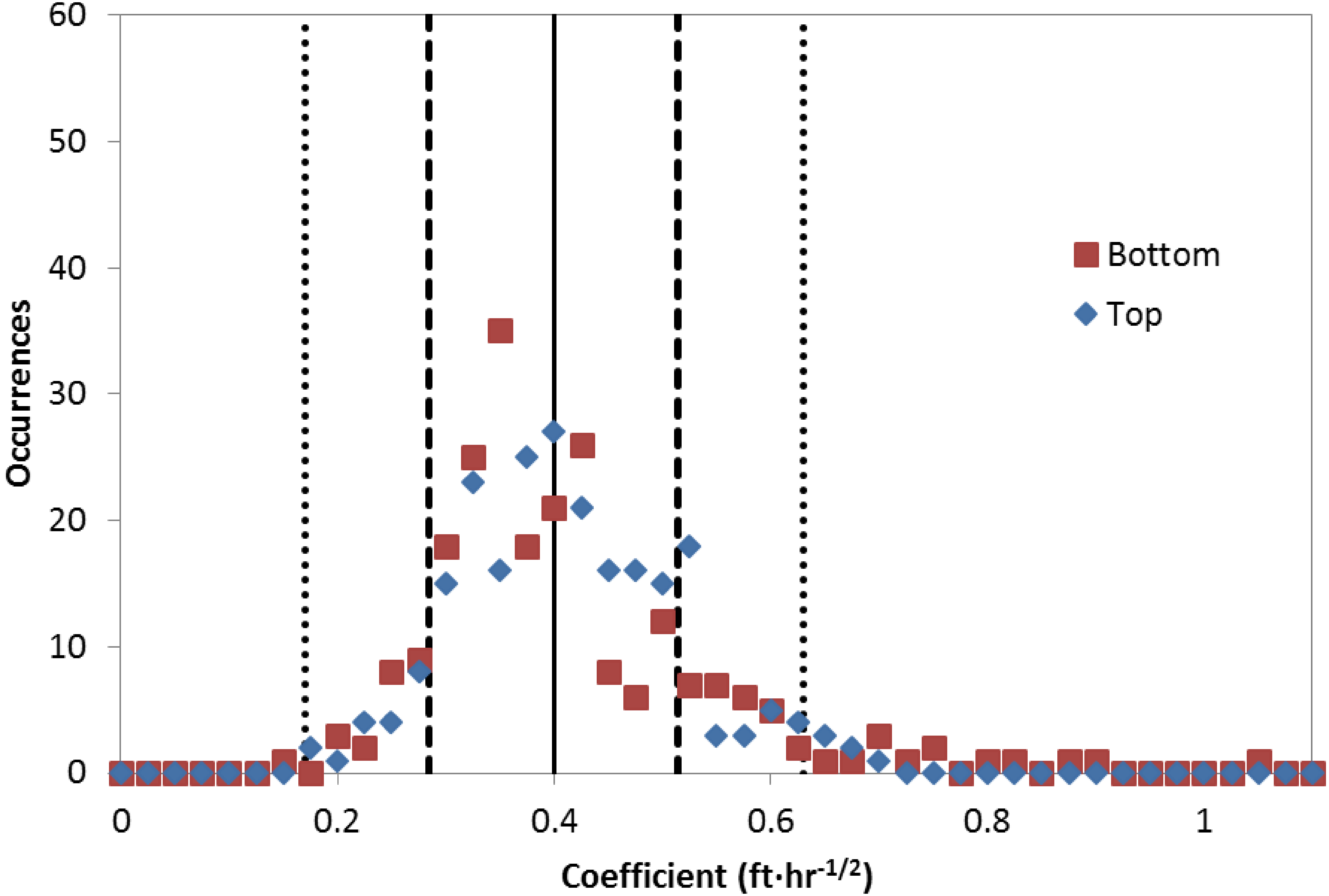
Proper Selection of Hyperbolic Parameters

- Over 400 shafts tested and analyzed
- Top and bottom roll-offs fitted with hyperbolic function
- Hyperbolic parameters iterated by algorithm to achieve best fit
- Results analyzed to identify trends

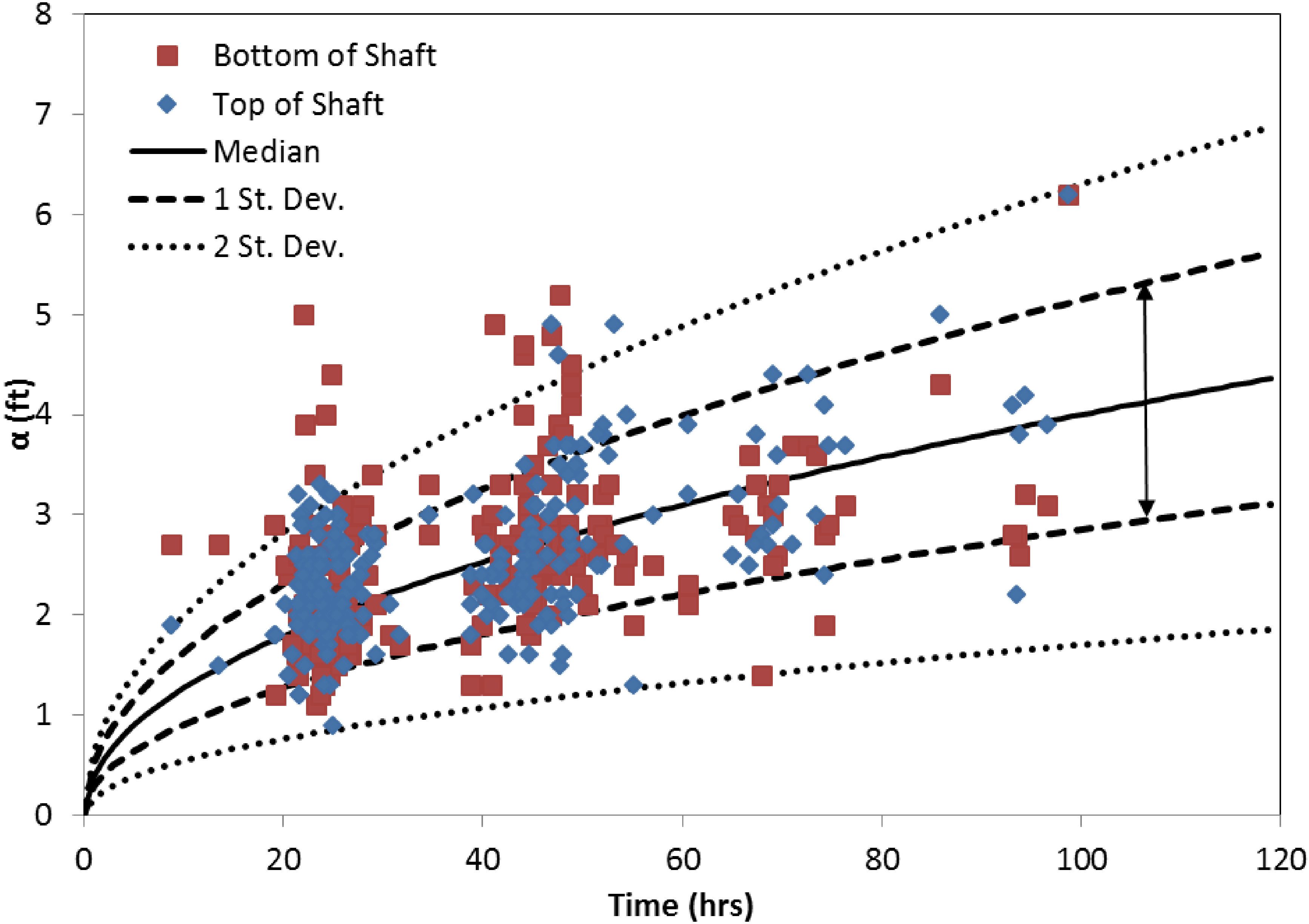
α vs. time of testing



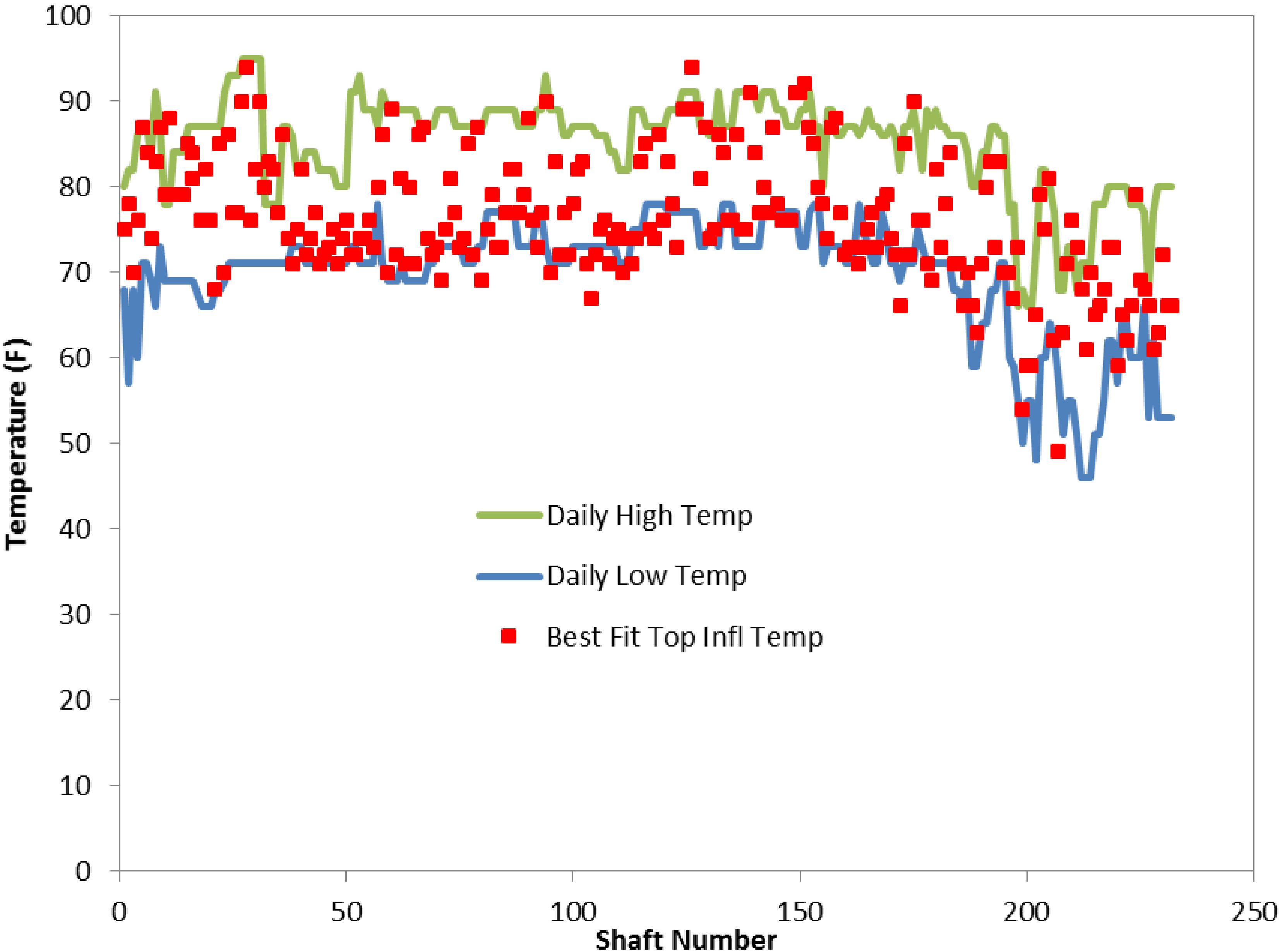
$$\alpha = c\sqrt{t}$$



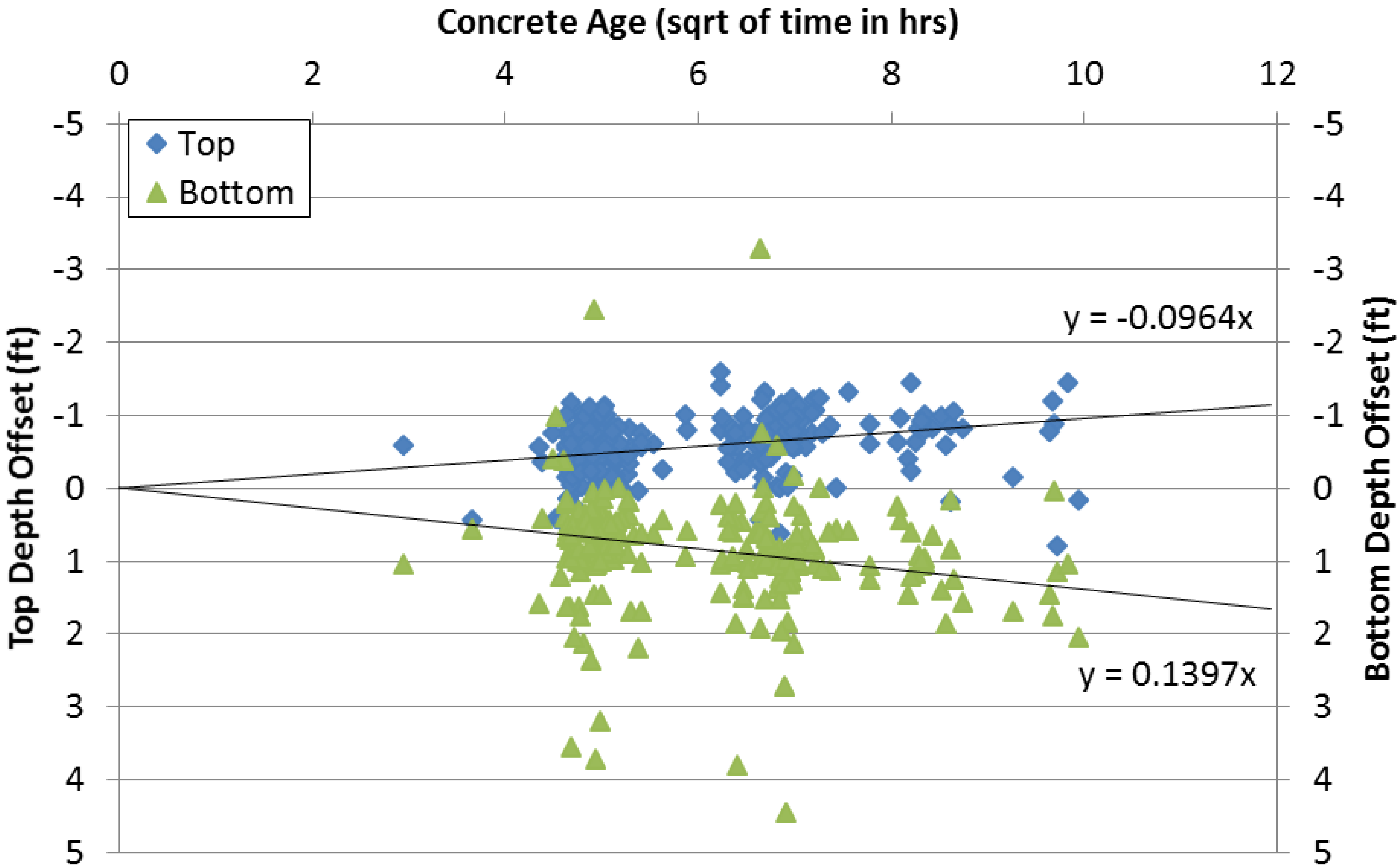
$$\alpha = 0.4\sqrt{t}$$



Top Inflection Point Temperature

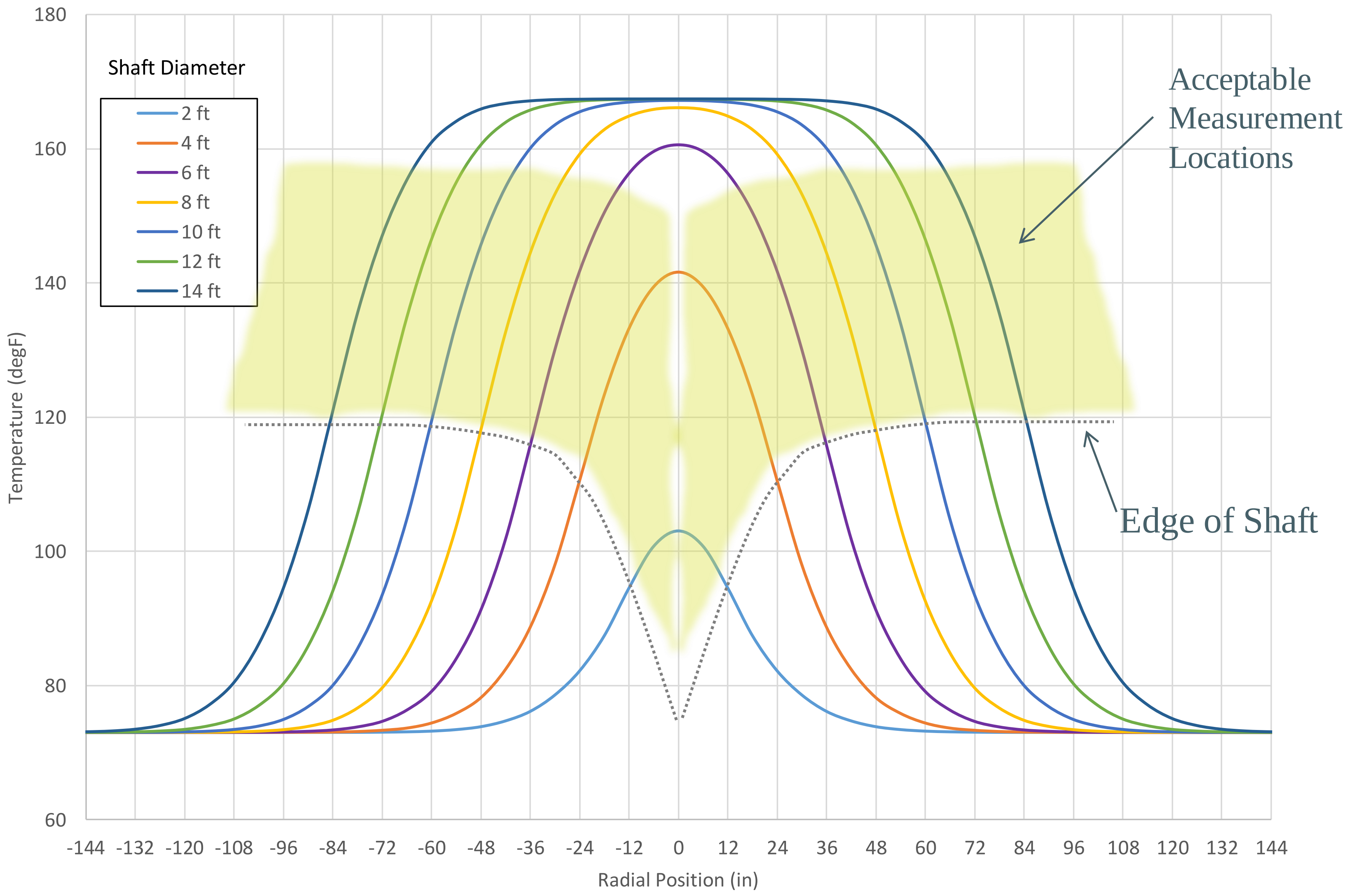


Inflection Point Depth Offset

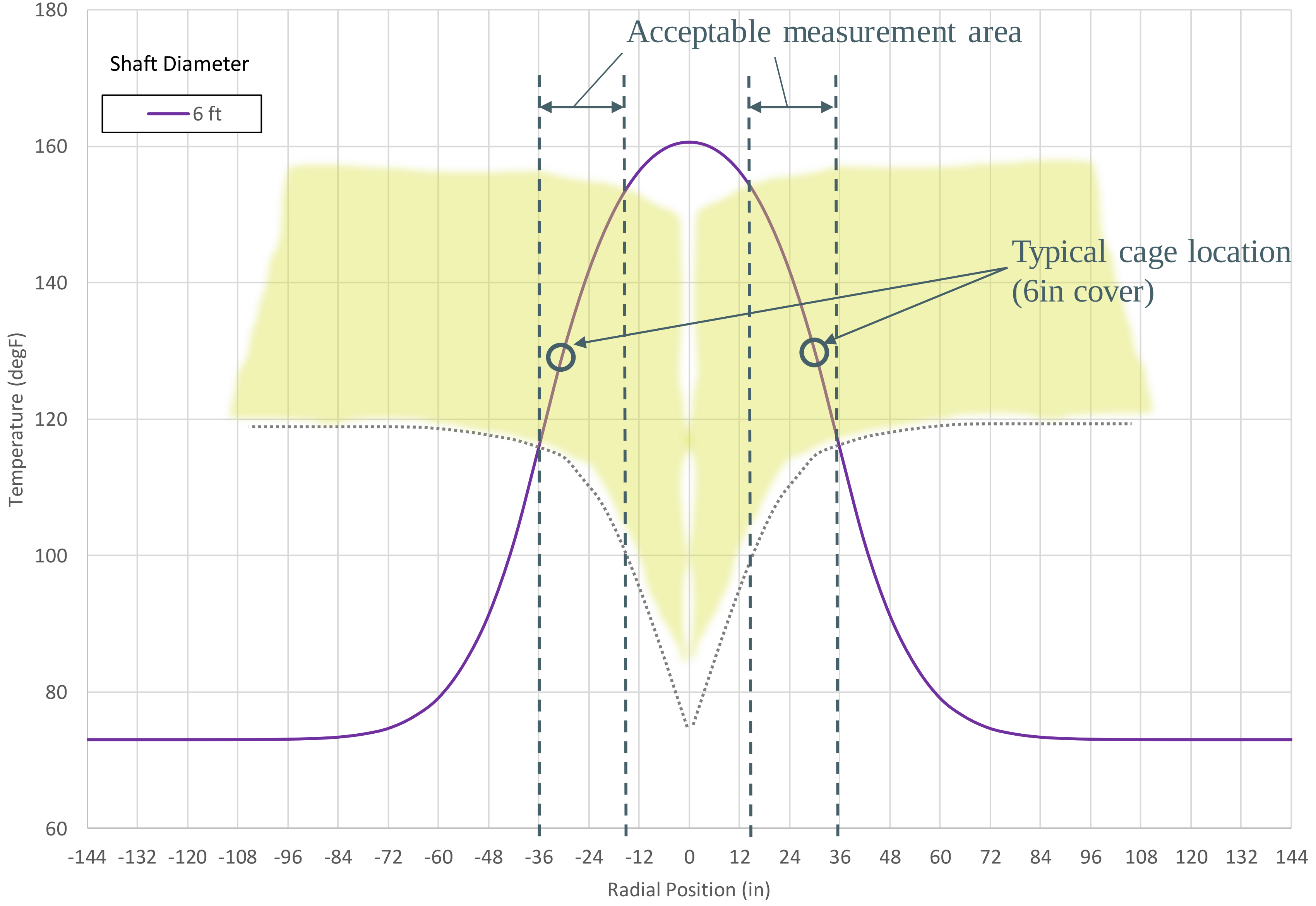


Numerical Modeling

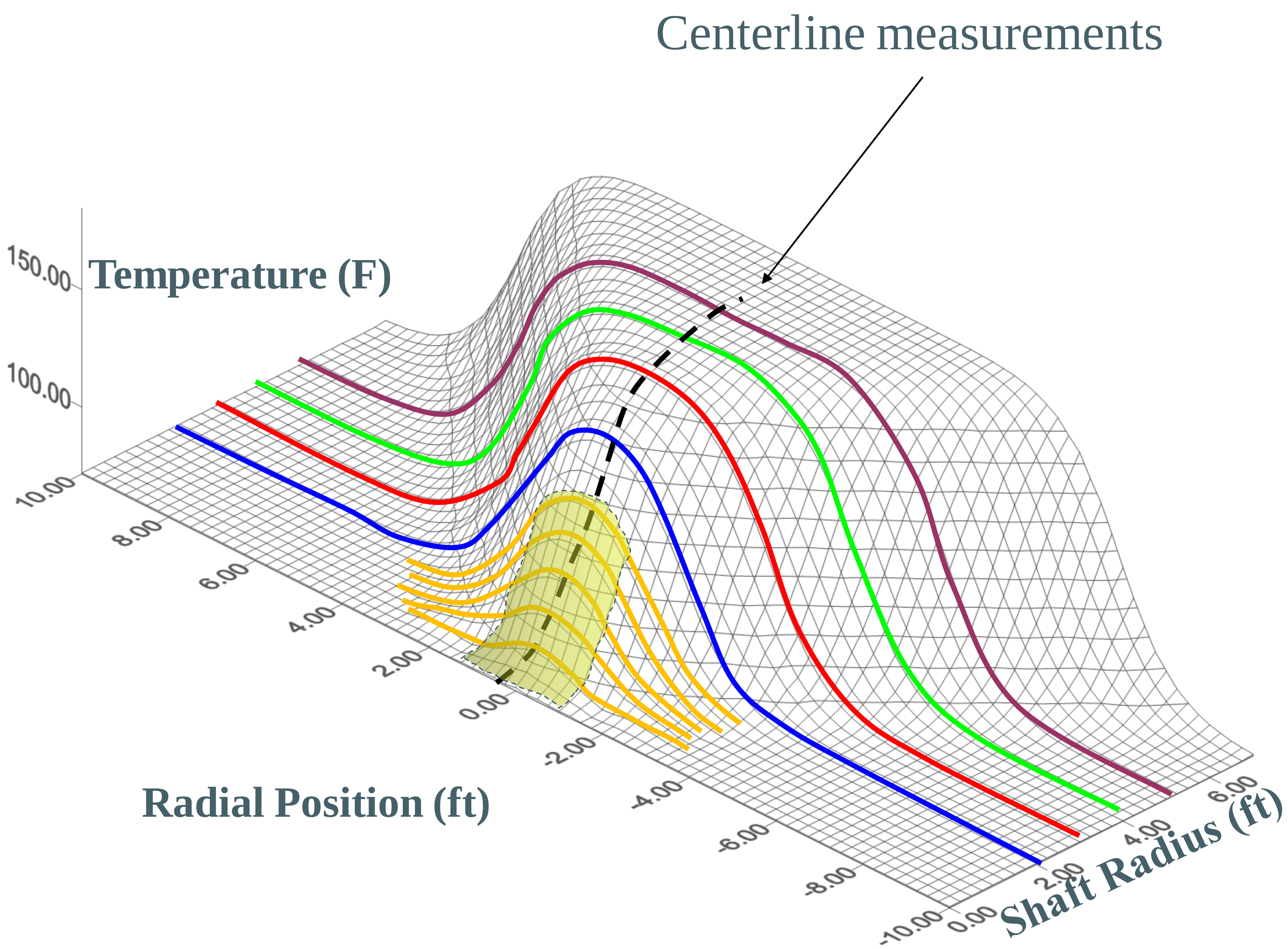
- Trends and patterns which give further insight and enhance traditional analysis
- Range of times for analysis/testing
- Best locations for placing sensors/tubes
- Minimum number of tubes/wire
- Size of anomaly that is detected with minimal sensors/tubes
- Effects of drastic changes in external environment (above ground in water or air)



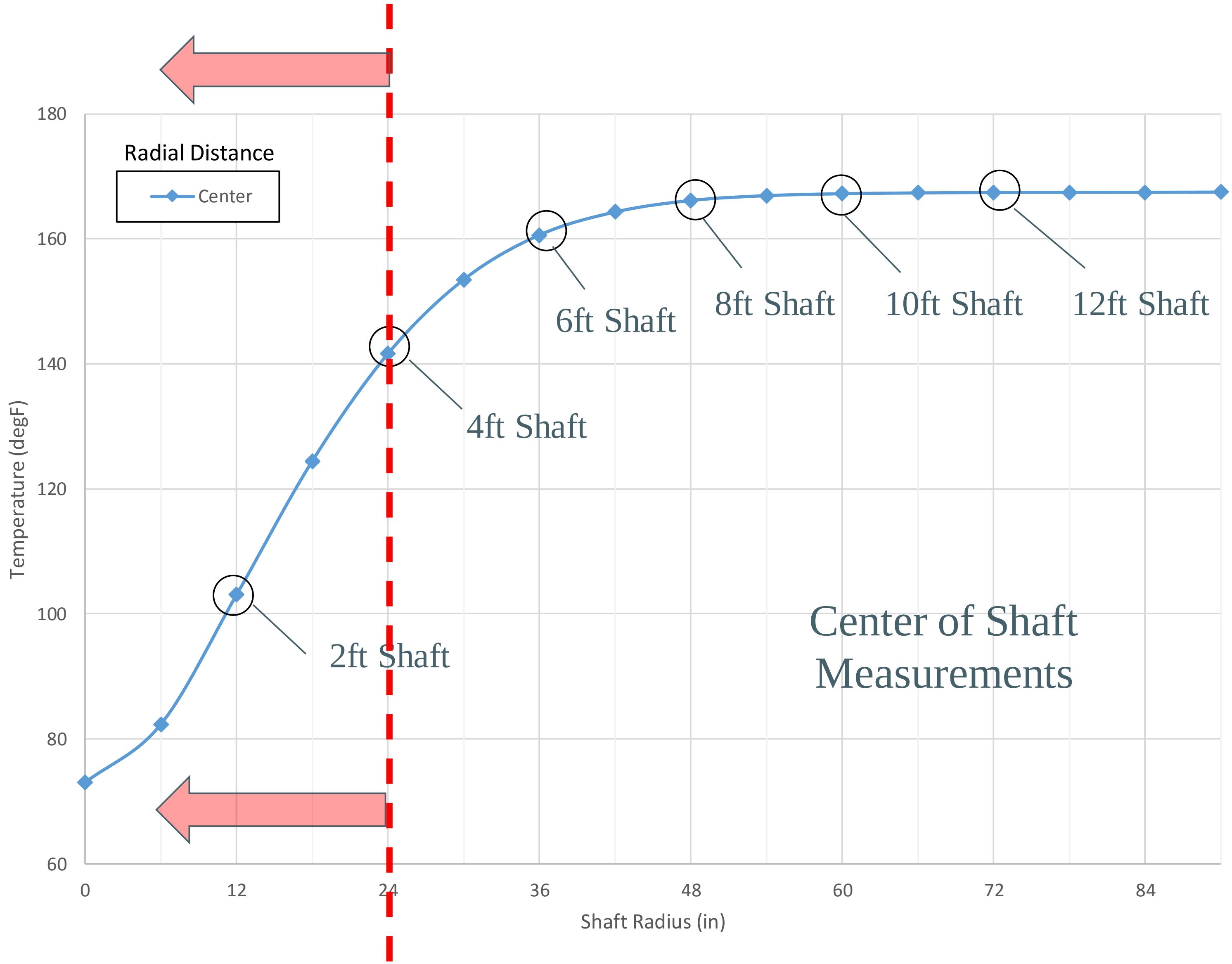
Shaft Diameter
2 ft
4 ft
6 ft
8 ft
10 ft
12 ft
14 ft
Acceptable Measurement Locations
Edge of Shaft
Temperature (degF)
Radial Position (in)
180
160
140
120
100
80
60
-144
-132
-120
-108
-96
-84
-72
-60
-48
-36
-24
-12
0
12
24
36
48
60
72
84
96
108
120
132
144



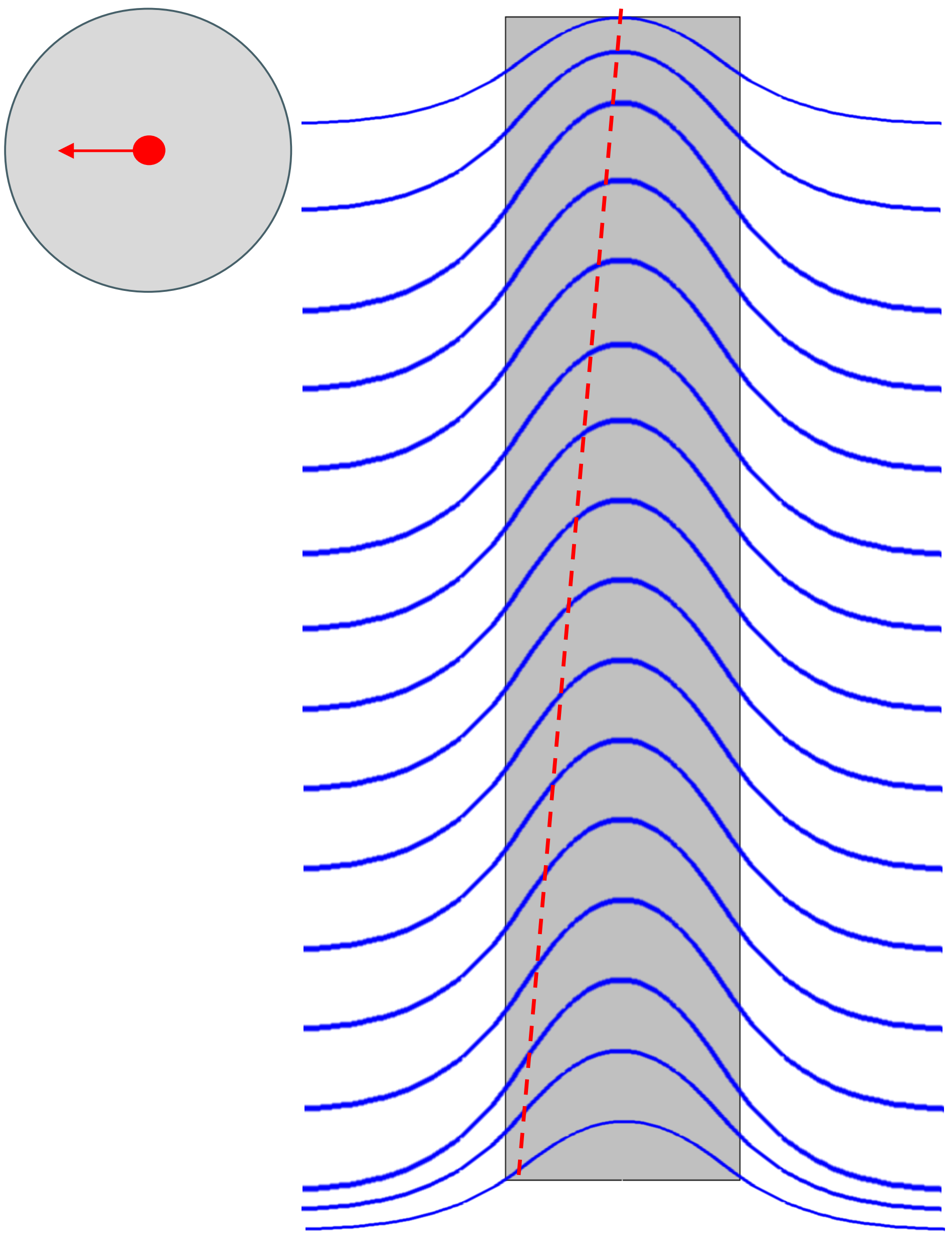
Acceptable measurement area
Shaft Diameter
6 ft
Typical cage location
(6in cover)
Temperature (degF)
180
160
140
120
100
80
60
-144
-132
-120
-108
-96
-84
-72
-60
-48
-36
-24
-12
0
12
24
36
48
60
72
84
96
108
120
132
144
Radial Position (in)

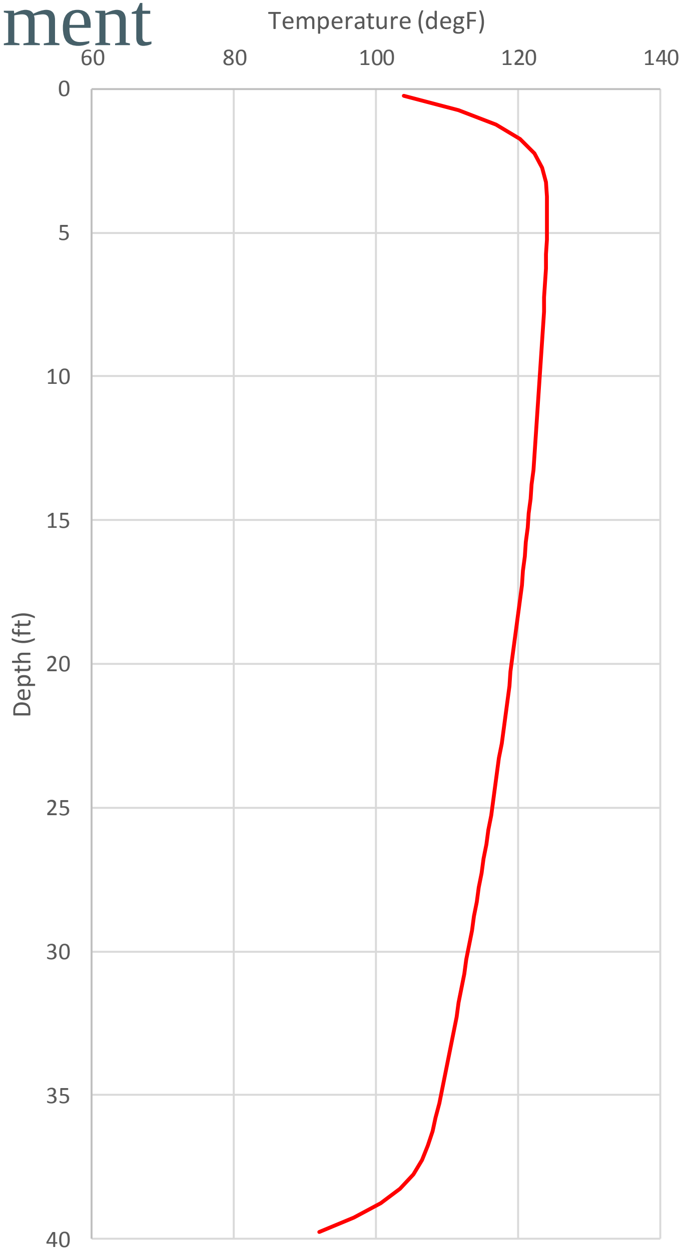

Centerline measurements
Temperature (F)
150.00
100.00
10.00
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
Radial Position (ft)
0.00
2.00
4.00
6.00
Shaft Radius (ft)

Centerline measurements

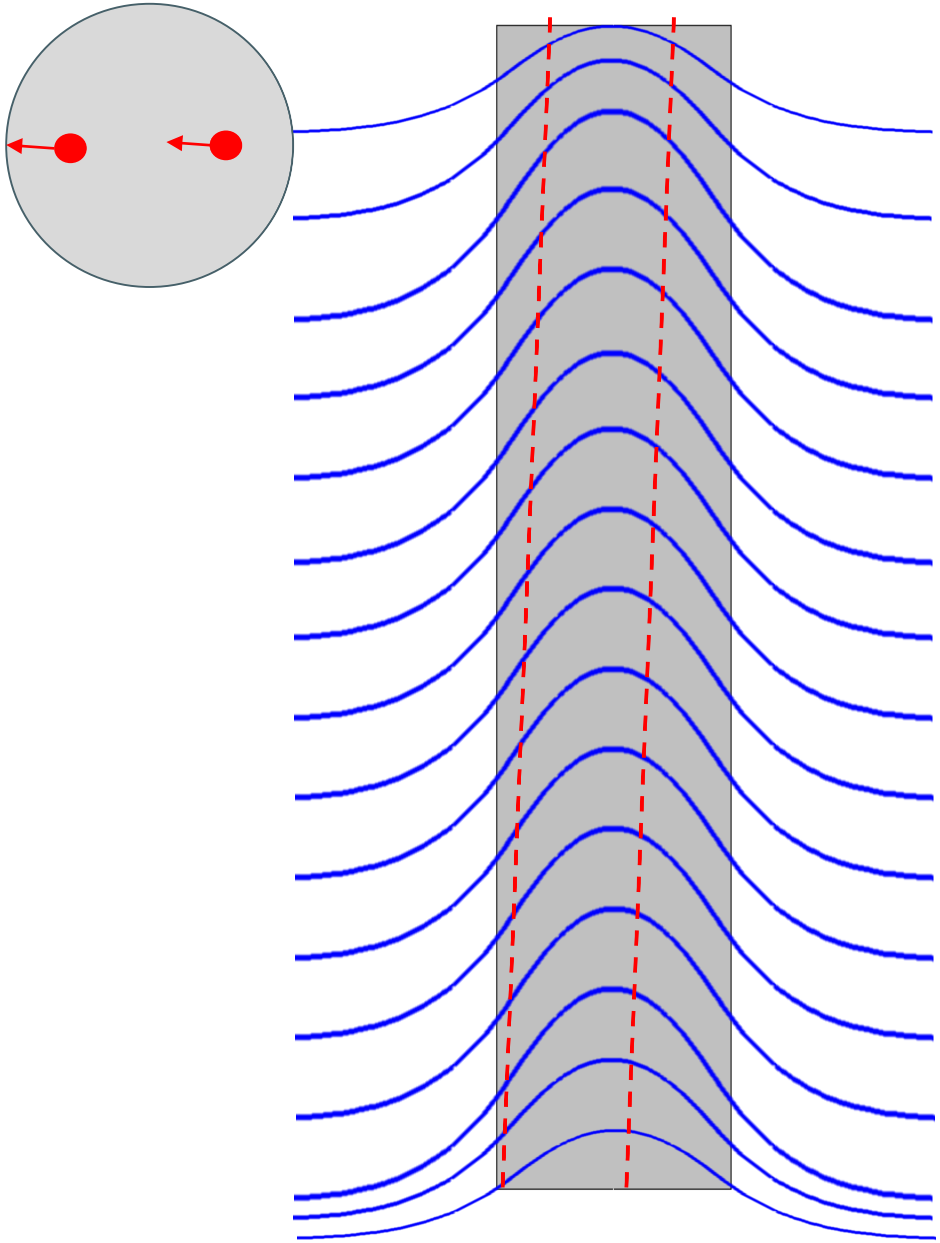


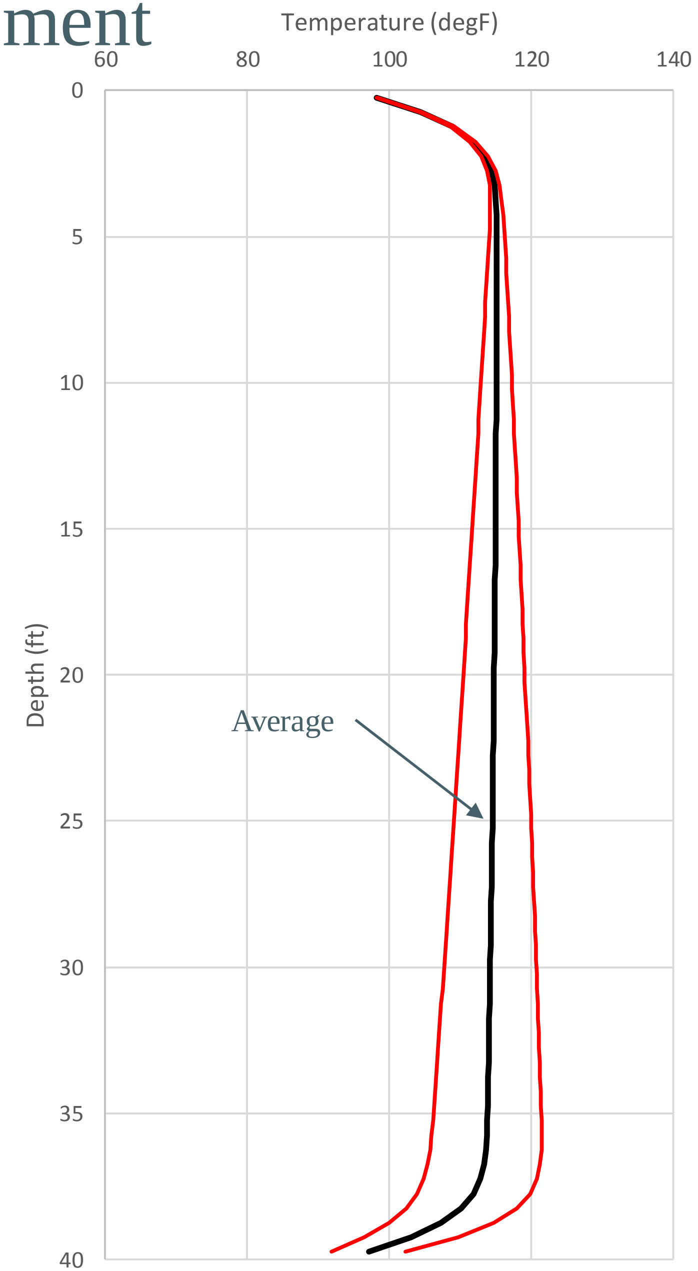
Number of Sensors
Effects of cage movement



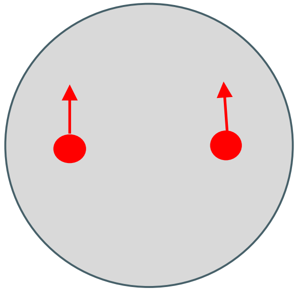


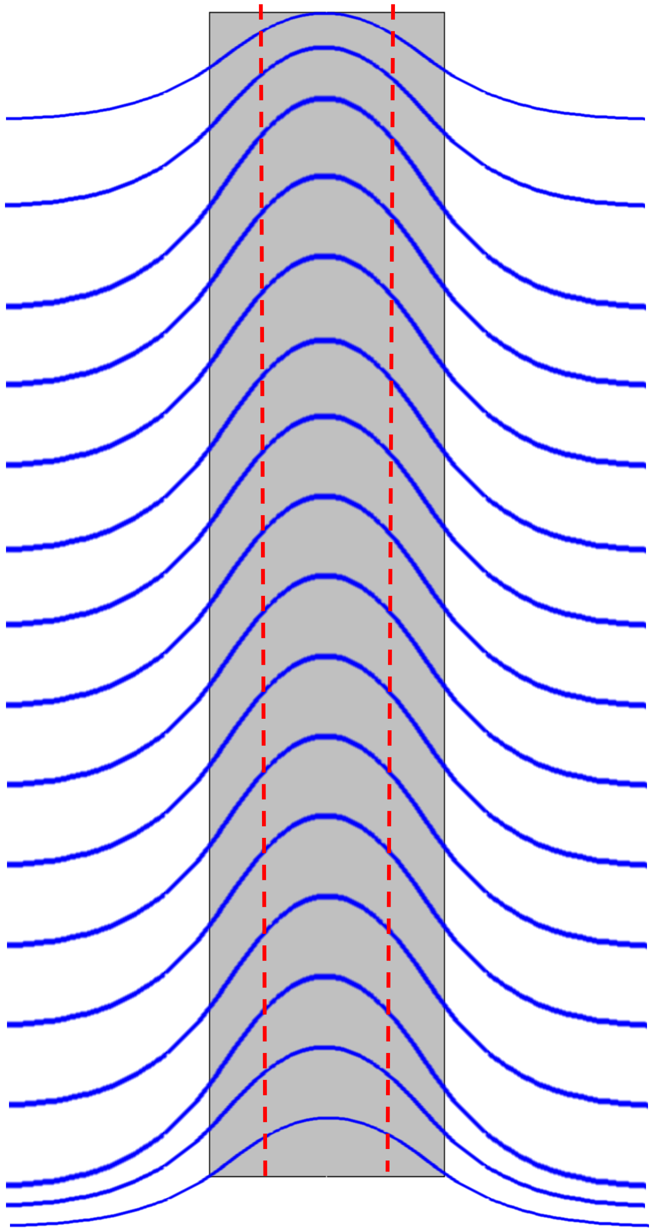
Number of Sensors
Effects of cage movement

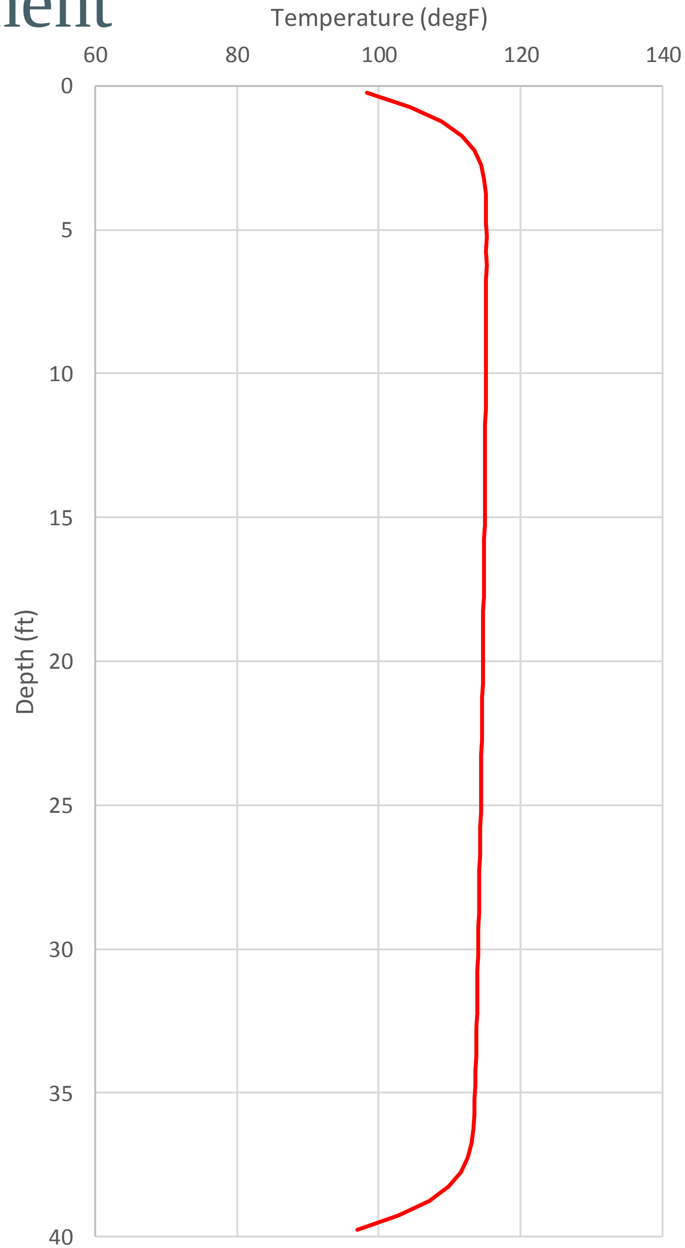


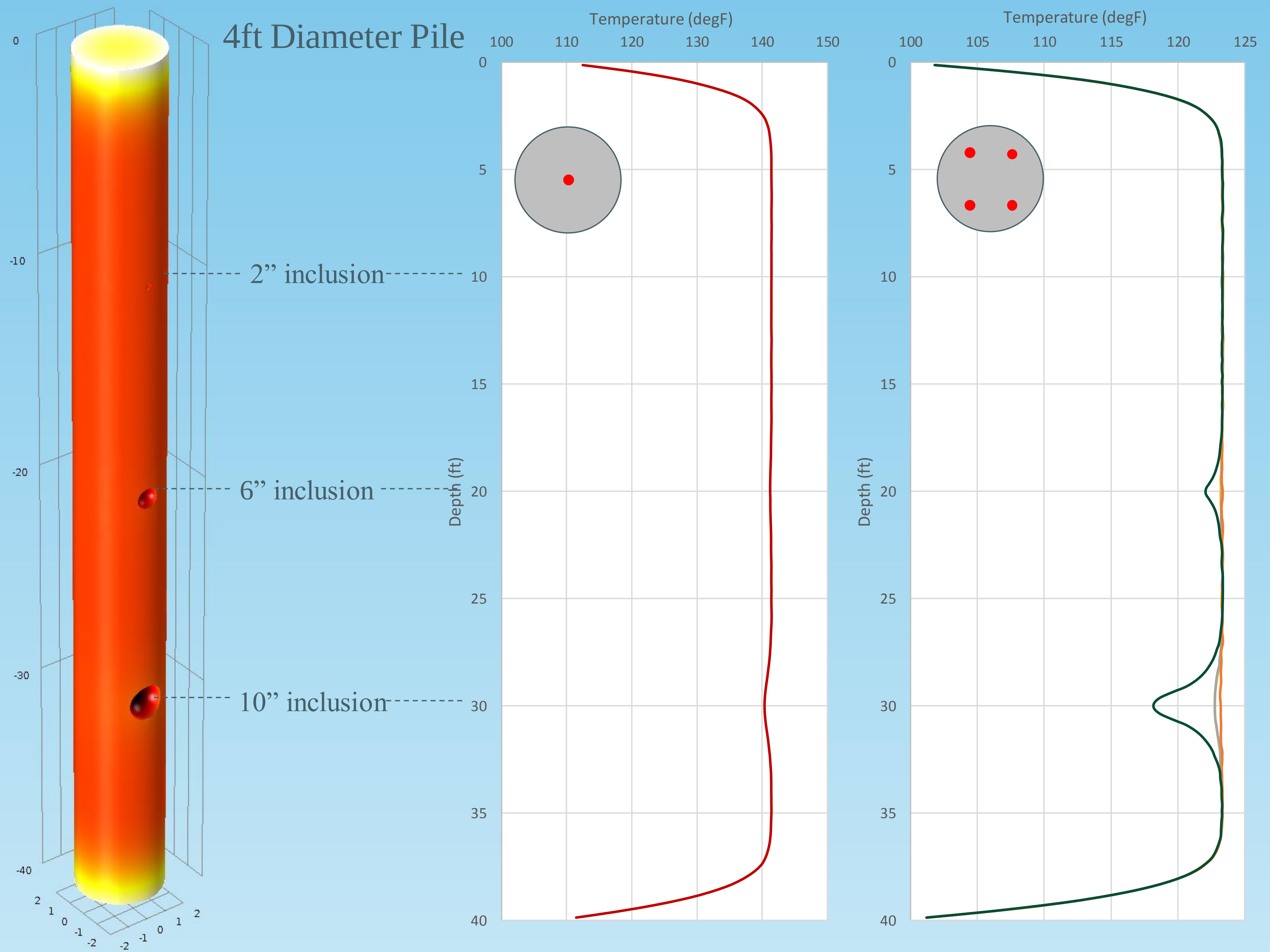


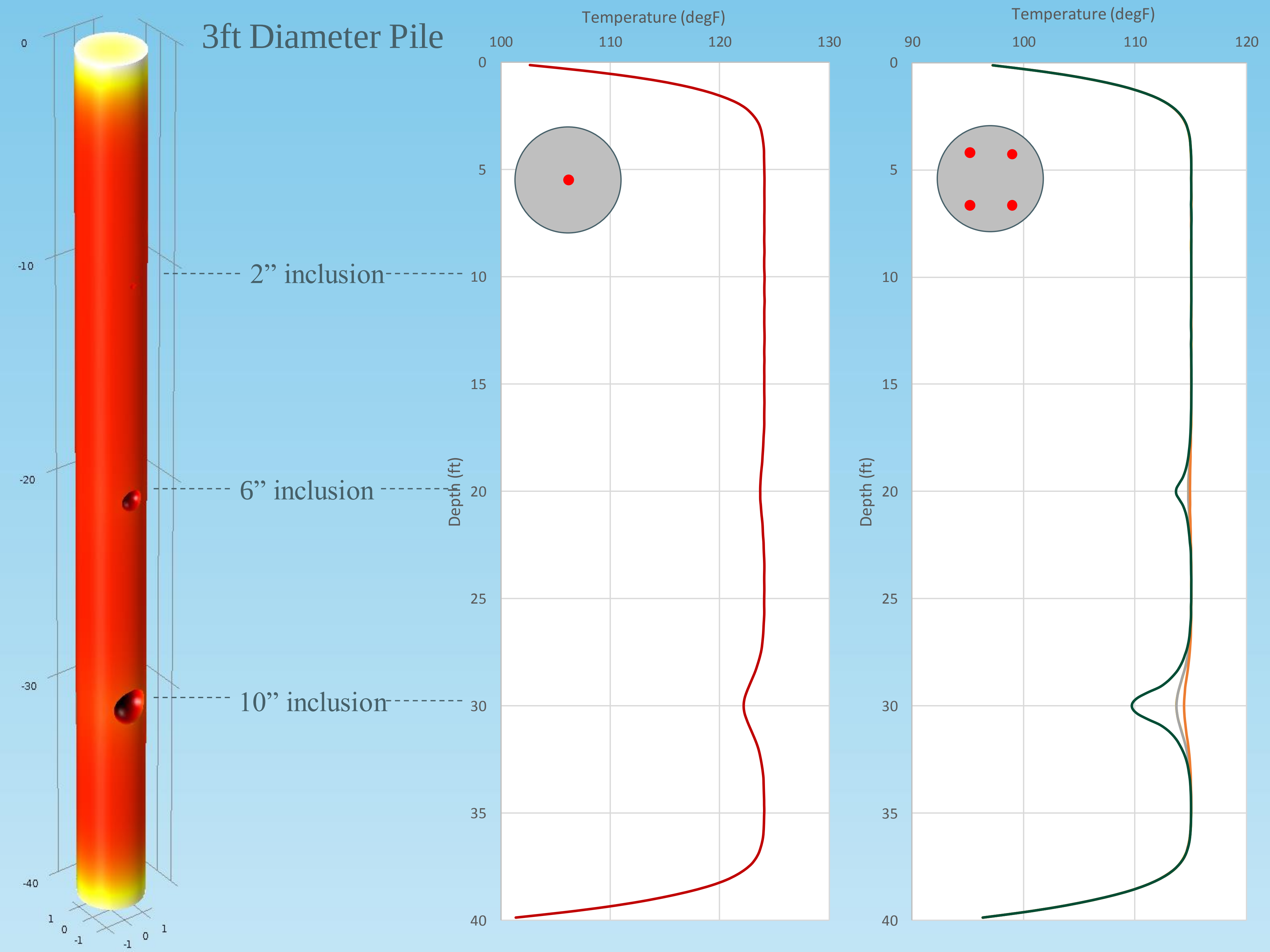
Number of Sensors
Effects of cage movement



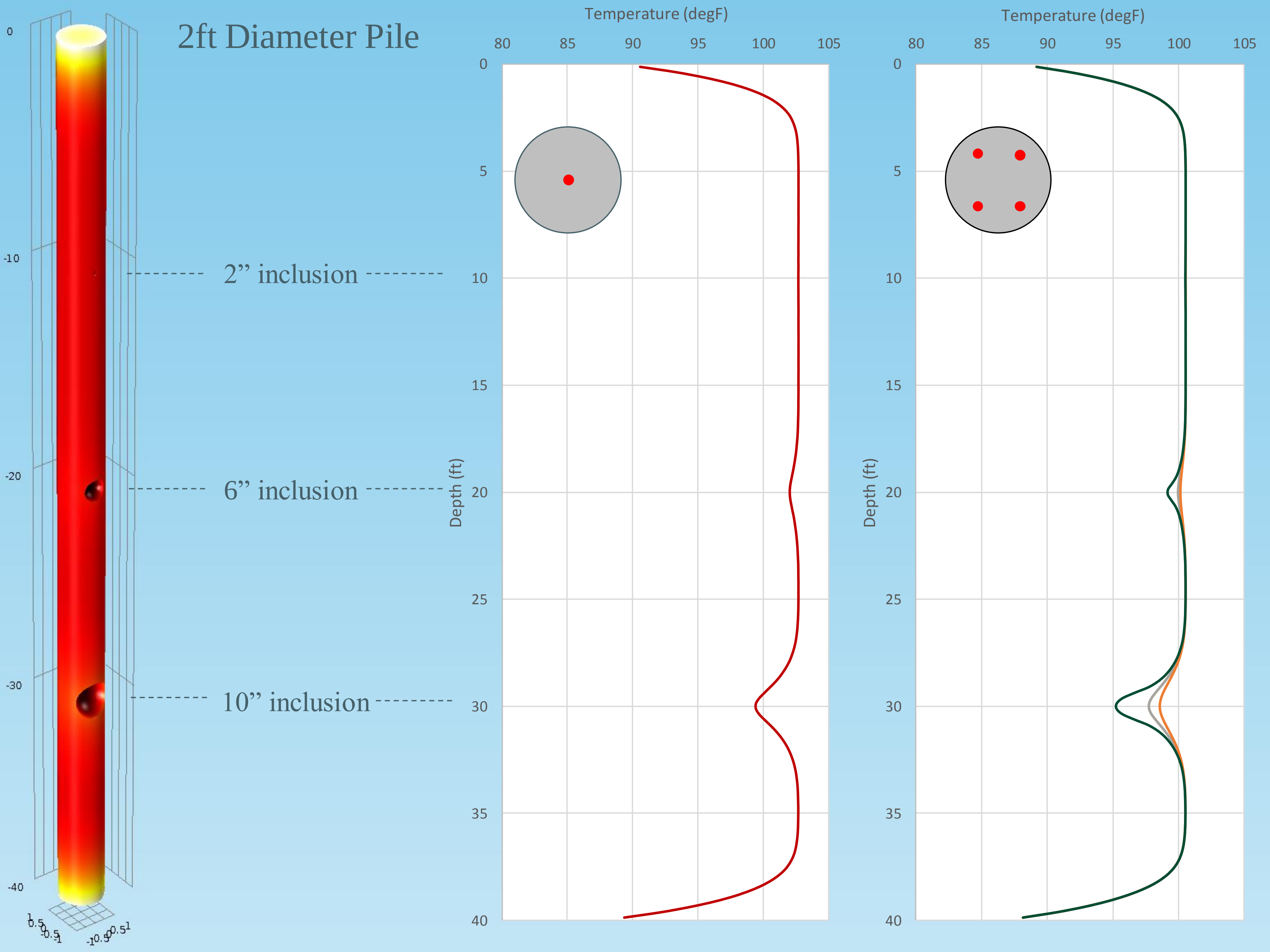





4ft Diameter Pile
2” inclusion
6” inclusion
10” inclusion
Temperature (degF)
Depth (ft)
Temperature (degF)
Depth (ft)


3ft Diameter Pile
2” inclusion
6” inclusion
10” inclusion
Temperature (degF)
100
110
120
130
Depth (ft)
0
5
10
15
20
25
30
35
40
Temperature (degF)
90
100
110
120
Depth (ft)
0
5
10
15
20
25
30
35
40

2ft Diameter Pile



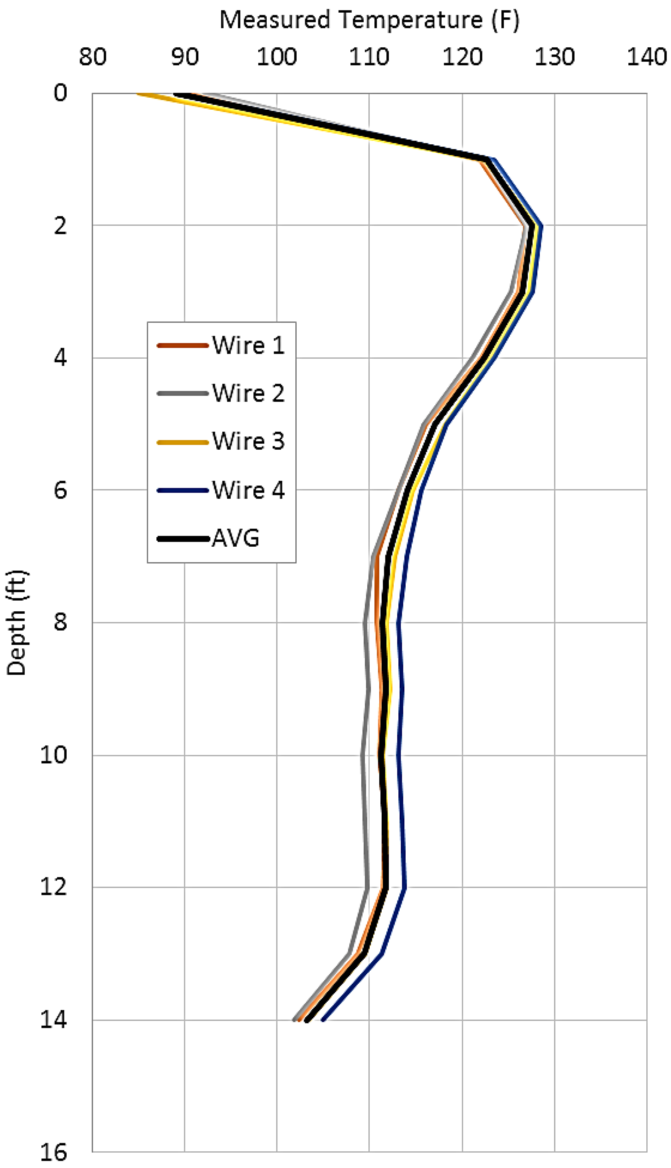
Field Testing

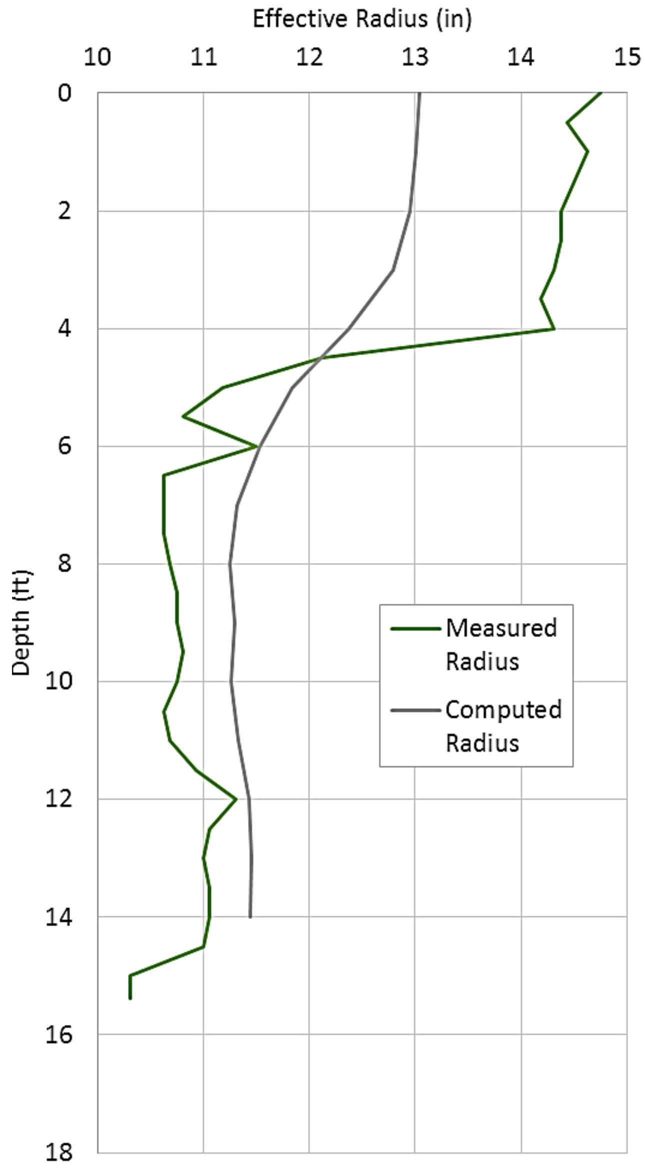
- 26 piles / small shafts tested and analyzed

- Various instrumentation schemes
  - Single center wire
  - Single center tube
  - 4 center wires
  - 4 cage wires
  - 2 cage wires

- Traditional as well as advanced analysis methods

Case Study: 22” shafts with 4 wires around single center bar





Observations

Thermal data shows top of shaft location and part of bottom roll-off (shaft deeper than last sensor)

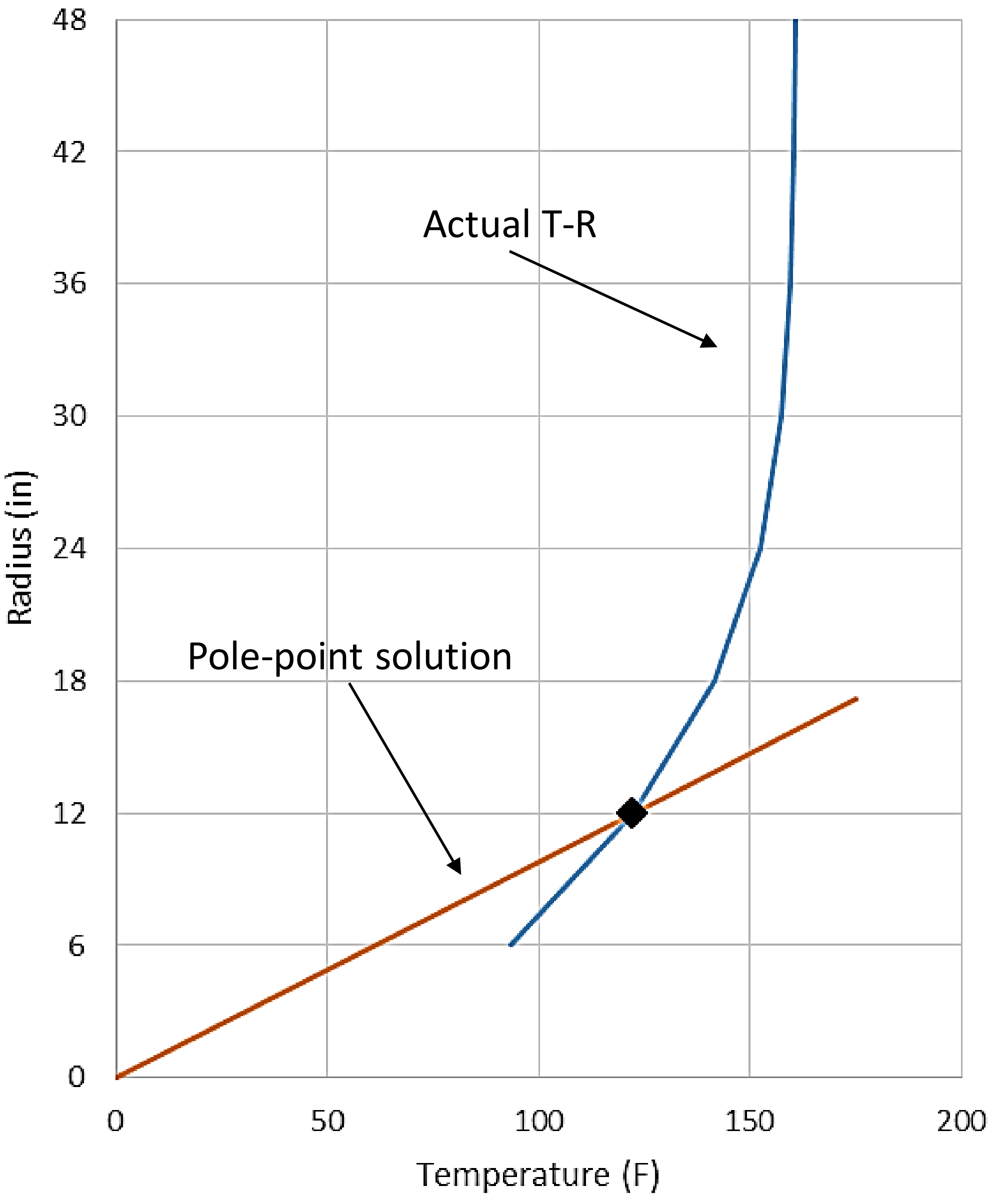
Computed radius matches general shape of pile, but with less definition

Center bar eccentricity indicated by variations from sensors 2in with separation

Integrity assessment reasonably successful; pile is good

Case Study: 22” shafts with 4 wires around single center bar

Advanced Analysis: Hyperbolic T-R Relationship



Case Study: 22” shafts with 4 wires around single center bar

Advanced Analysis: Hyperbolic T-R Relationship

$$T = \left(\frac{T_{max} - T_{min}}{2}\right) \tanh\left(\frac{R - R_0}{\alpha}\right) + T_0$$

T_{max} = Upper asymptotic temperature = Adiabatic temperature of concrete

**Modeling required*

T_{min} = Lower asymptotic temperature

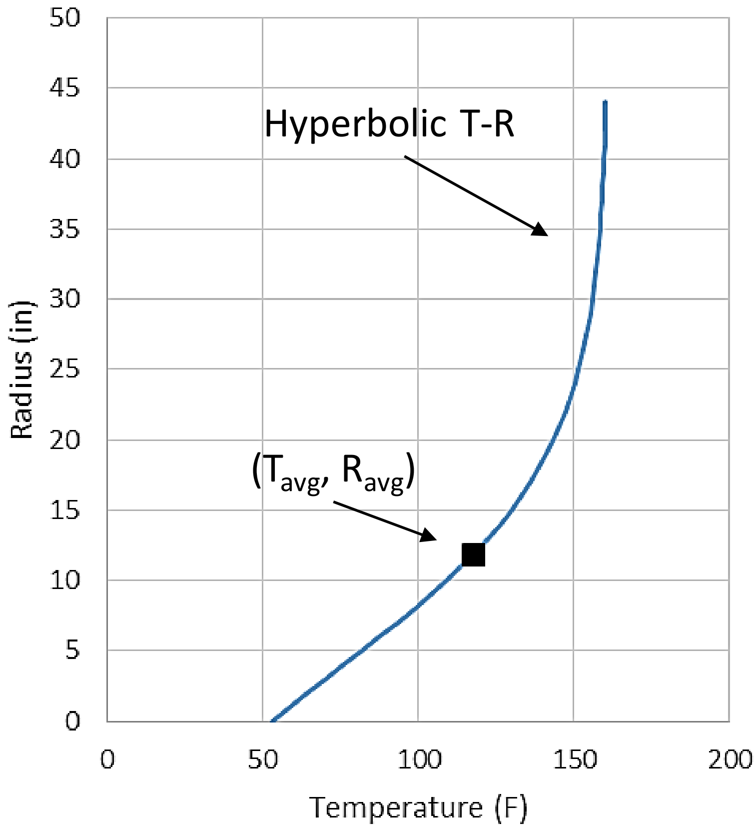
T_0 = Inflection point temperature

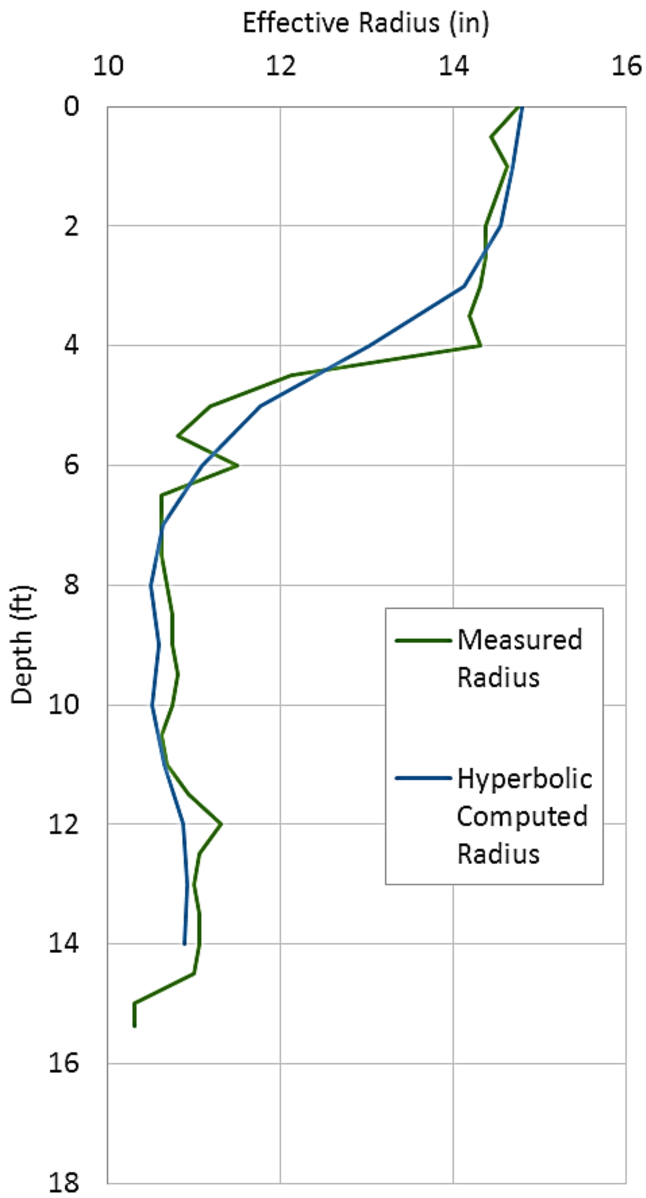
R_0 = Inflection point radius = Radius at which measurements are taken

α = Time factor

Case Study: 22” shafts with 4 wires around single center bar

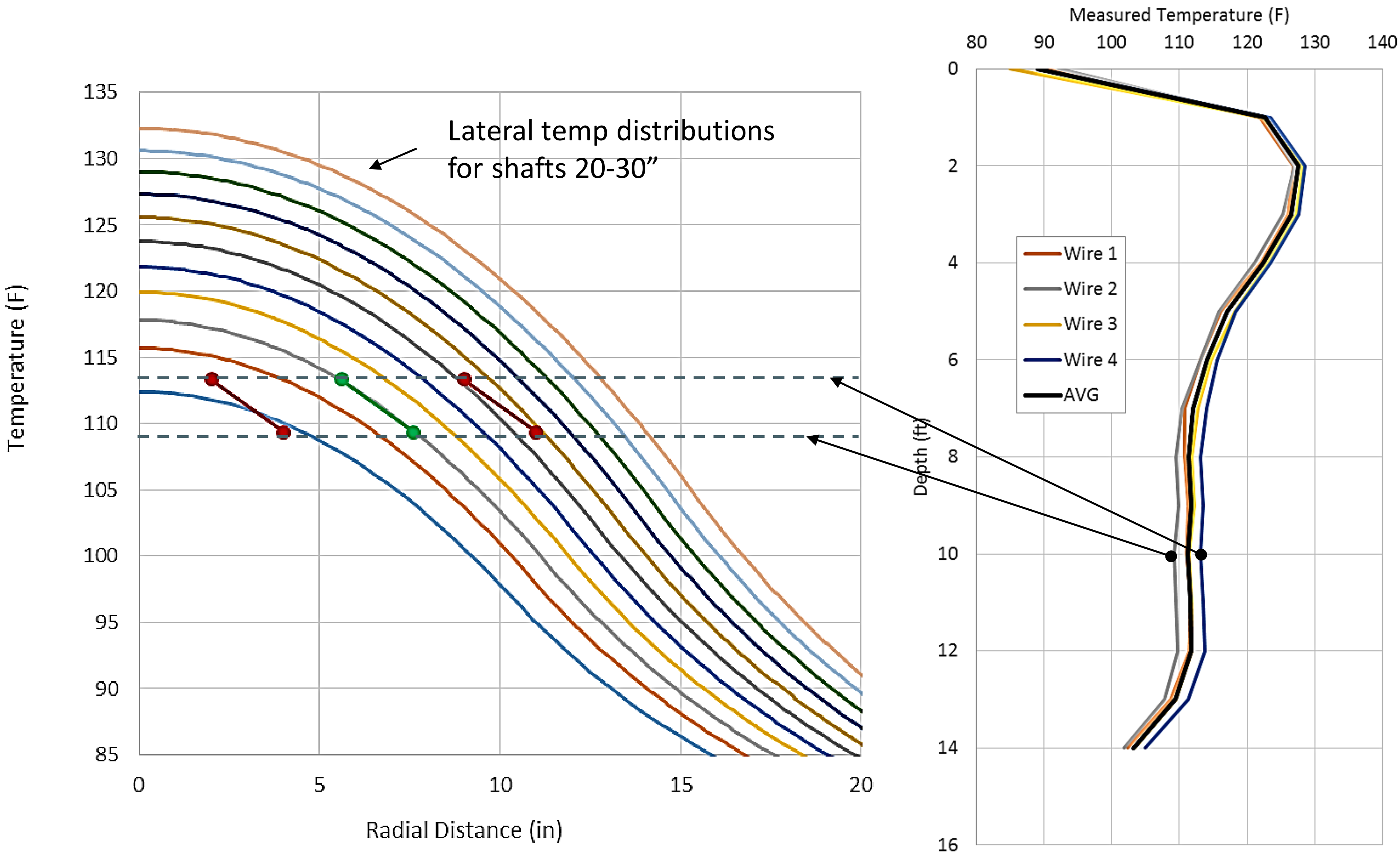
Advanced Analysis: Hyperbolic T-R Relationship





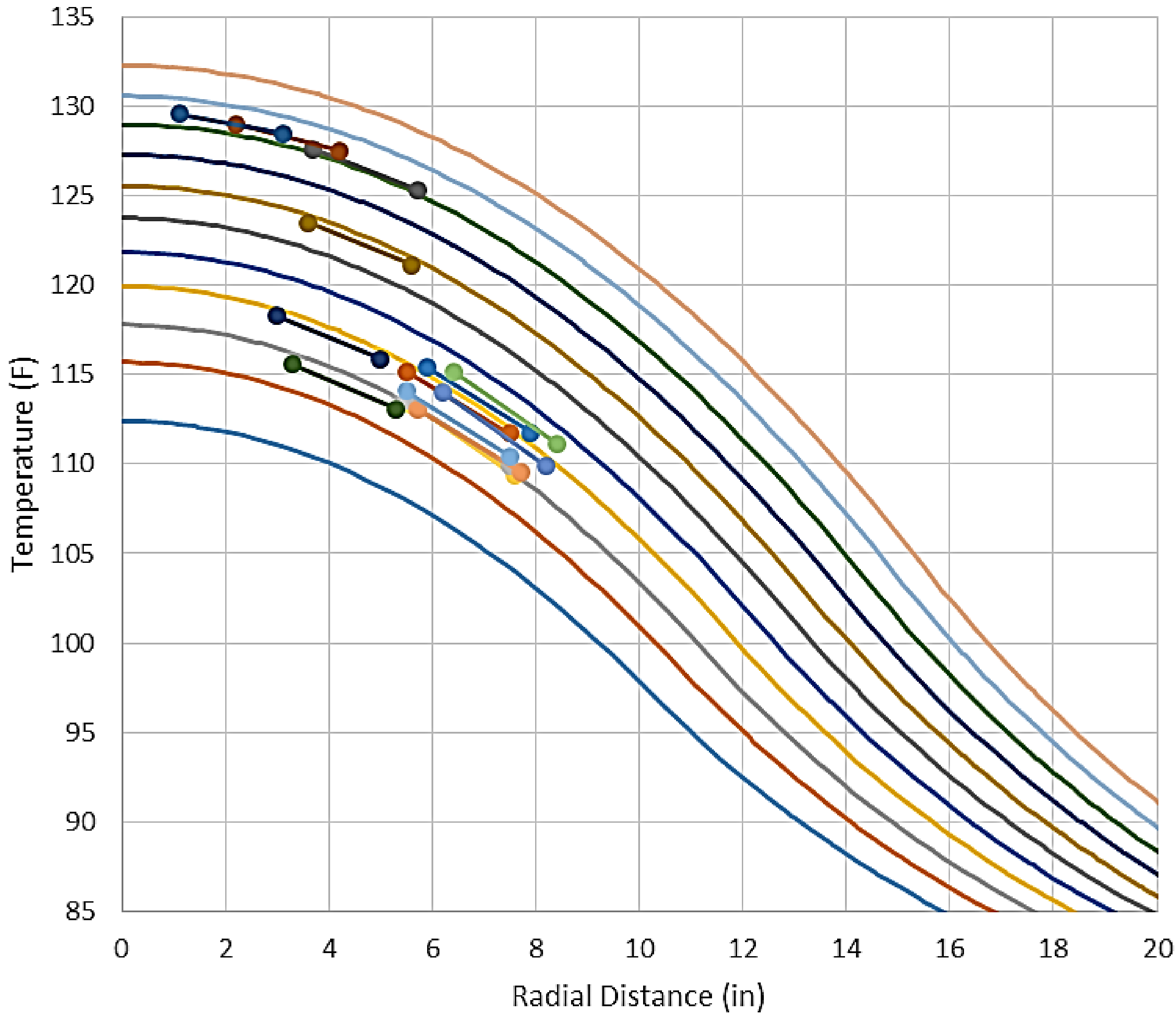
Case Study: 22" shafts with 4 wires around single center bar

Advanced Analysis: Gradient Signal Matching



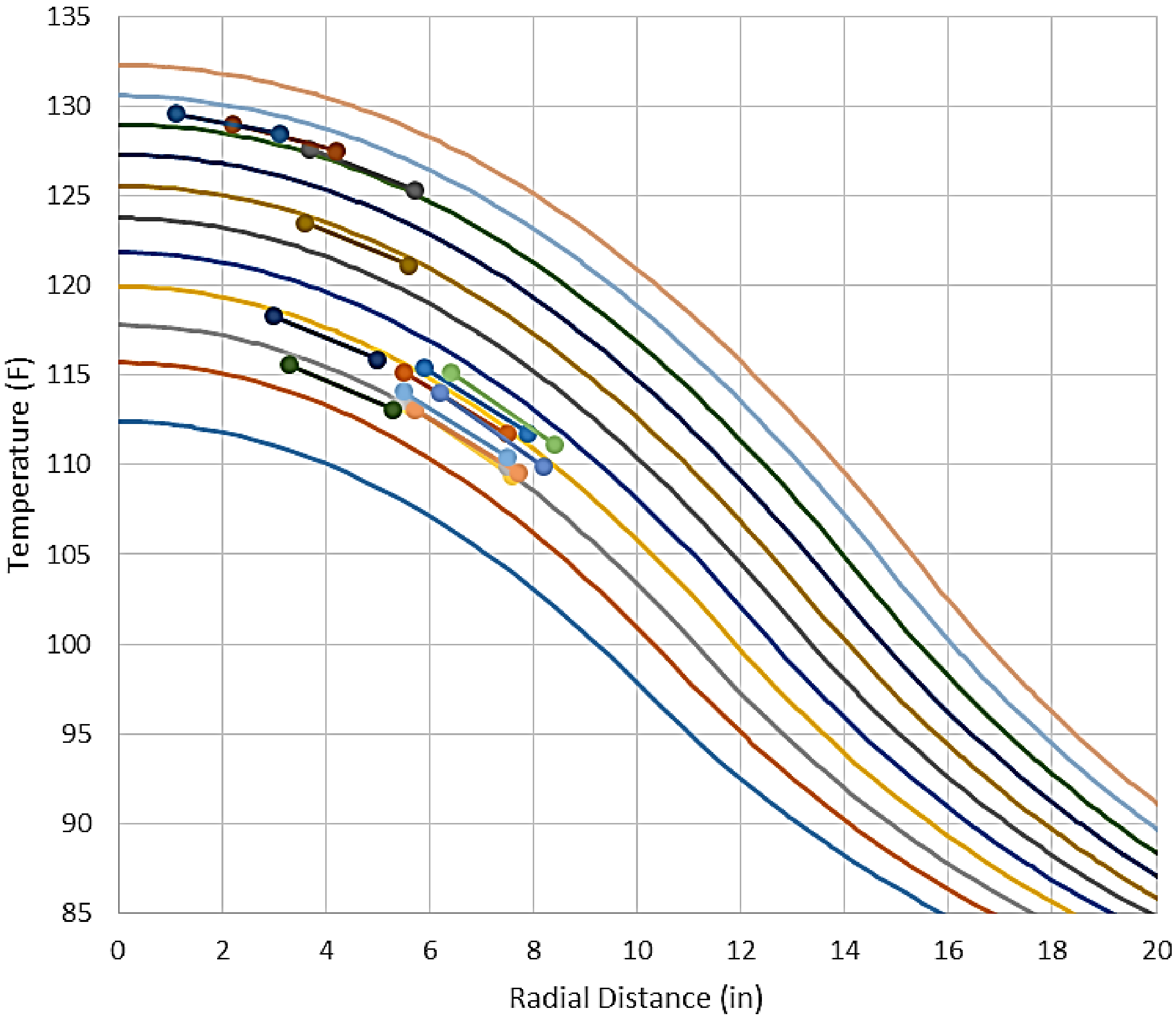
Case Study: 22” shafts with 4 wires around single center bar

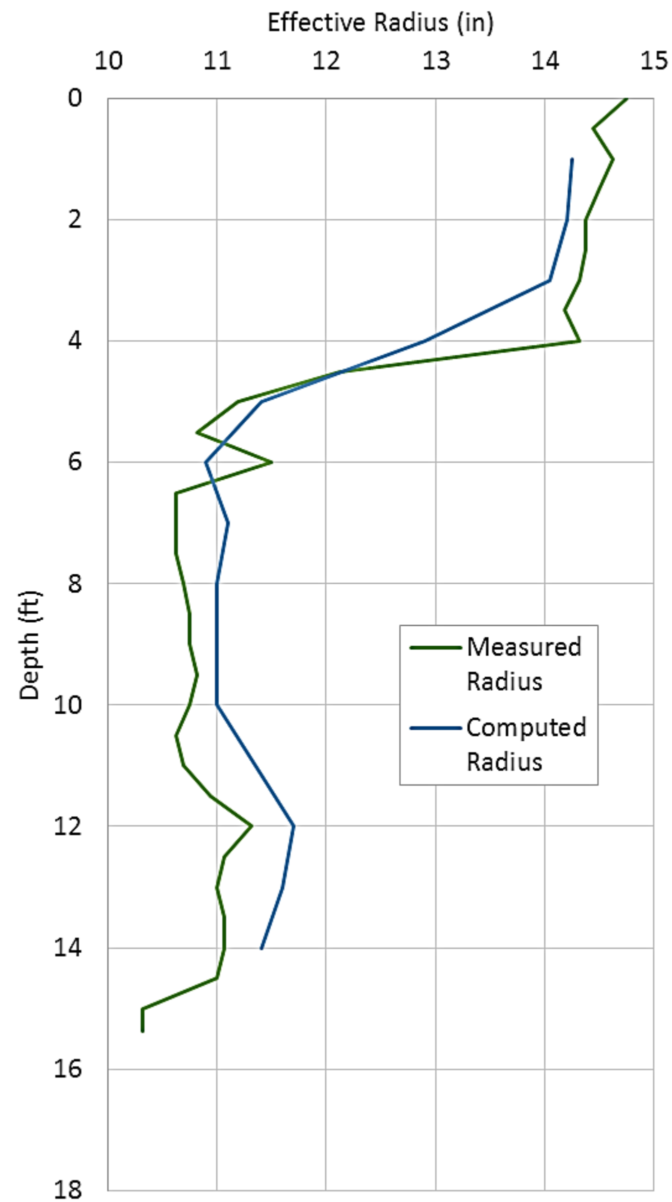
Advanced Analysis: Gradient Signal Matching



Case Study: 22” shafts with 4 wires around single center bar

Advanced Analysis: Gradient Signal Matching



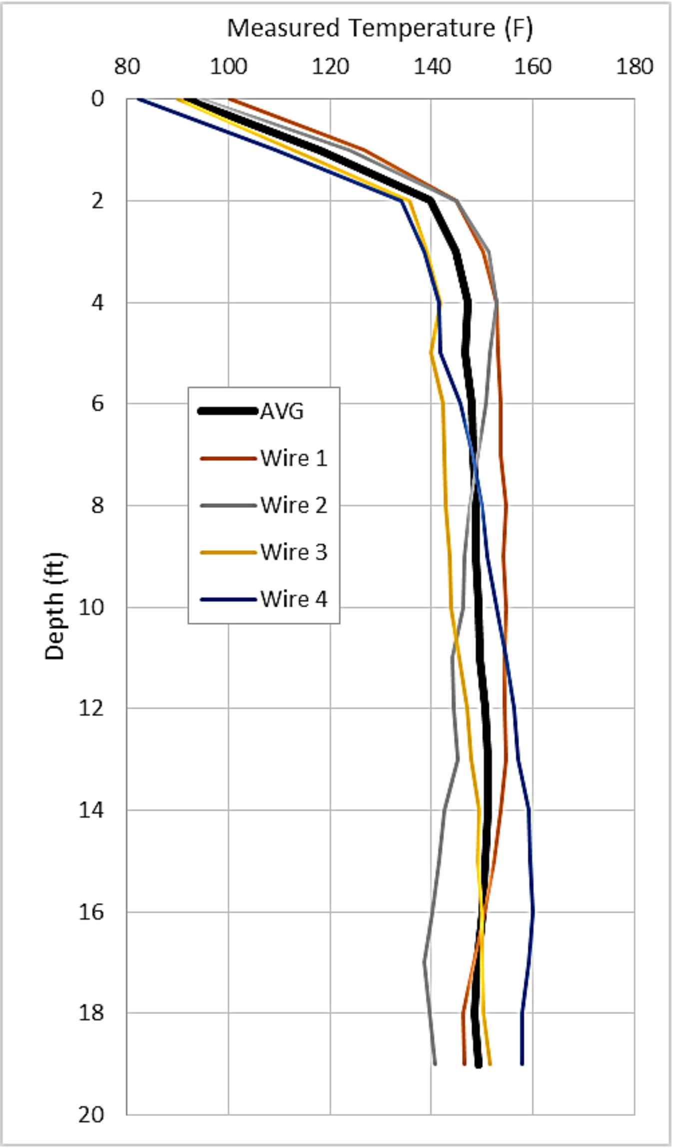


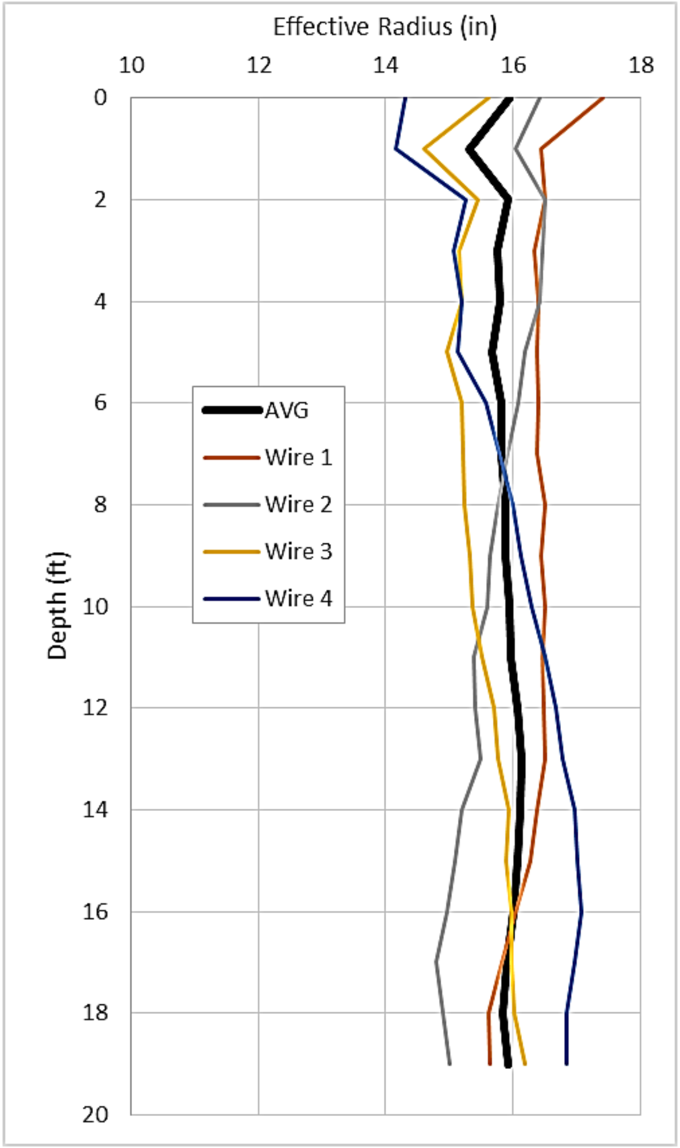
Case Study: 14" ACIP piles with a single wire on single center bar

Of 14 piles instrumented, 3 experienced complete data loss and 4 produced only partial data, likely due to damage from internally protruding hooks on the upper reinforcing cage. All other piles yielded reasonably straight profiles with little to no indication of bar movement.

Case Study: 30” ACIP piles with full cage, comparison of 2 & 4 wire instrumentation

Case Study: 30” ACIP piles with full cage, comparison of 2 & 4 wire instrumentation





4 Wire System

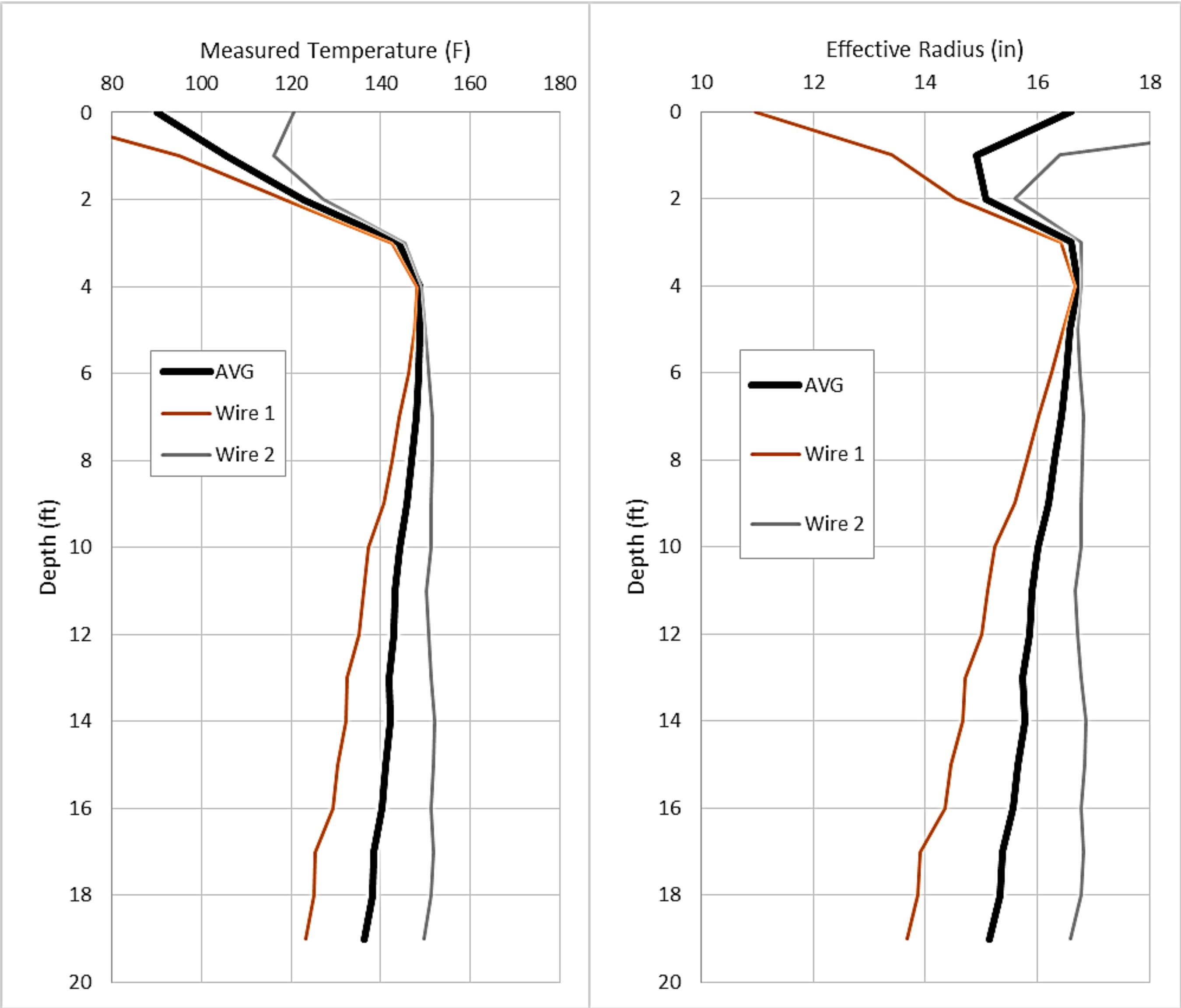
Thermal data shows top but not bottom of pile. Pile extends deeper than reinforcing cage.

Straight / vertical average temperature profile, 16” effective radius throughout

1” cage movement in various directions over the depth of the pile

Integrity assessment reasonably successful; pile is good

Case Study: 30" ACIP piles with full cage, comparison of 2 & 4 wire instrumentation



2 Wire System

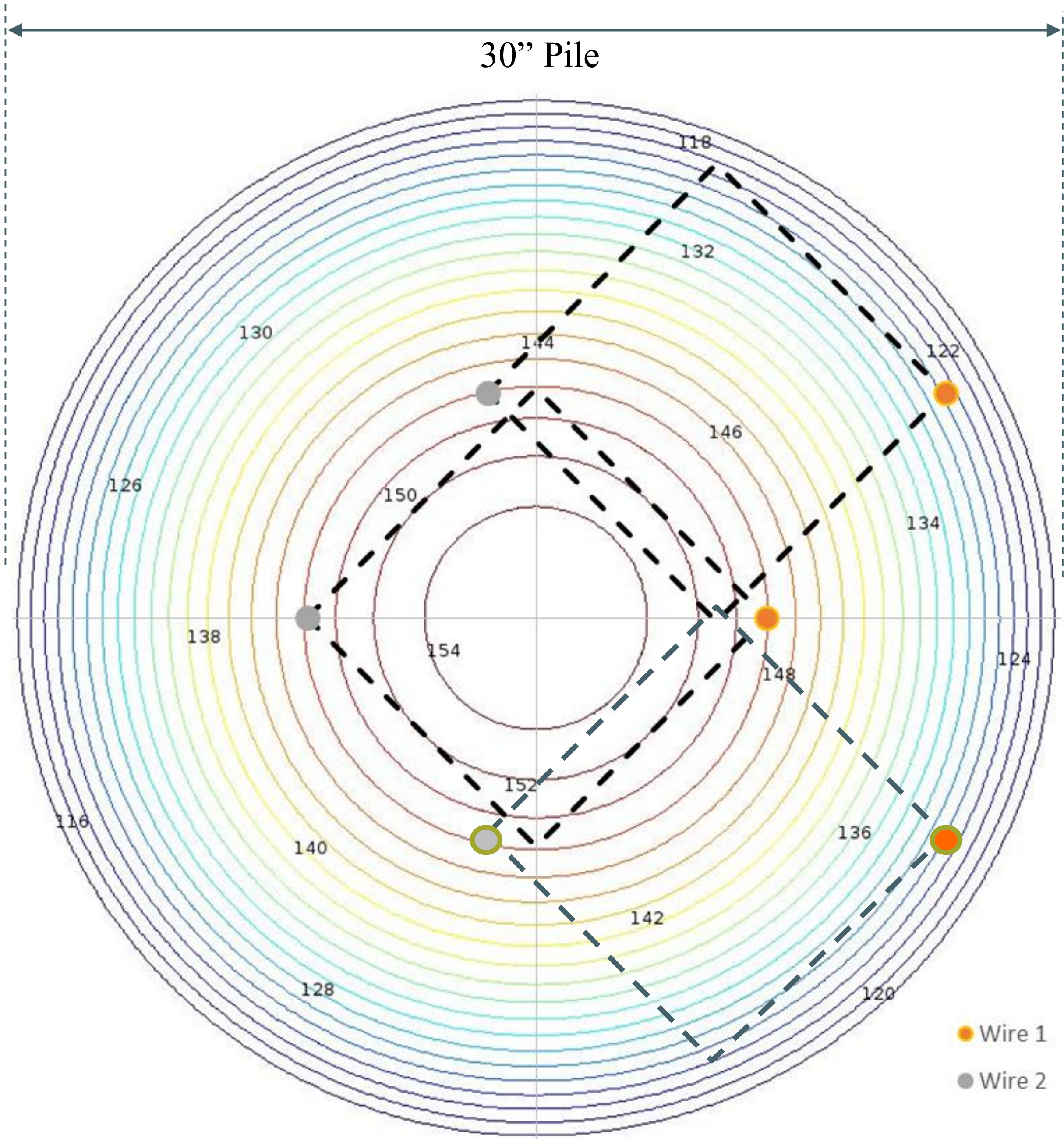
Thermal data shows top but not bottom of pile. Pile extends deeper than reinforcing cage.

Average temperature profile exhibits an uncharacteristic slope over the entire length

Variation among wires indicates cage movement

Integrity assessment is inconclusive

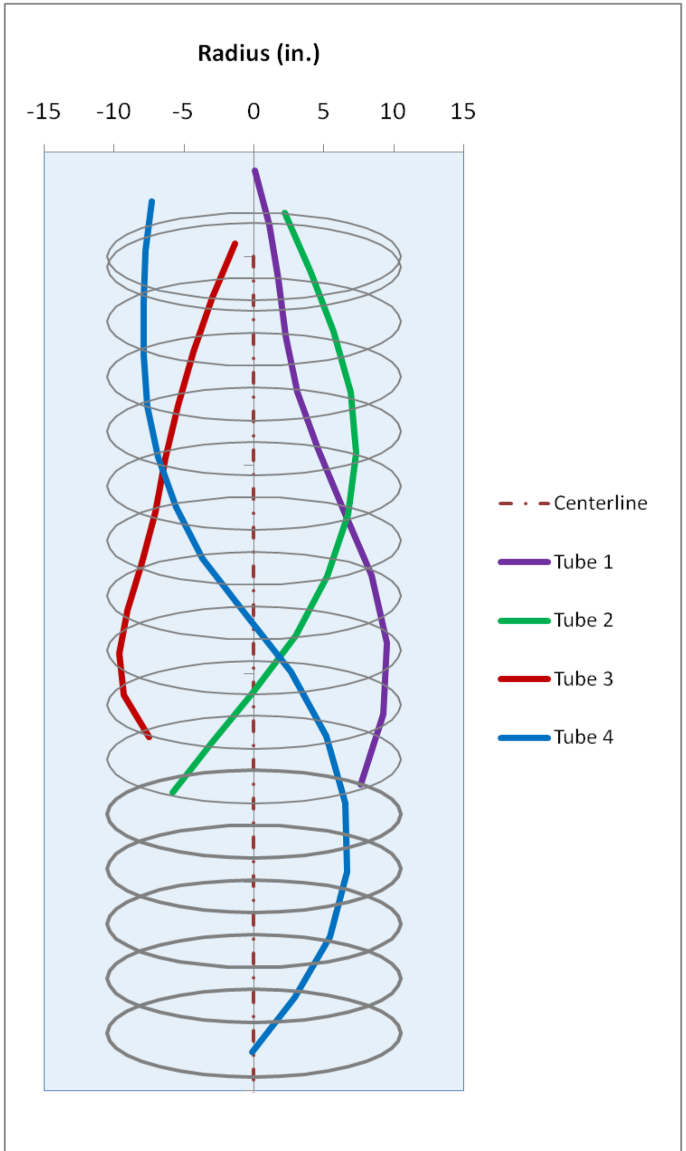
Case Study: 30" ACIP piles with full cage, comparison of 2 & 4 wire instrumentation



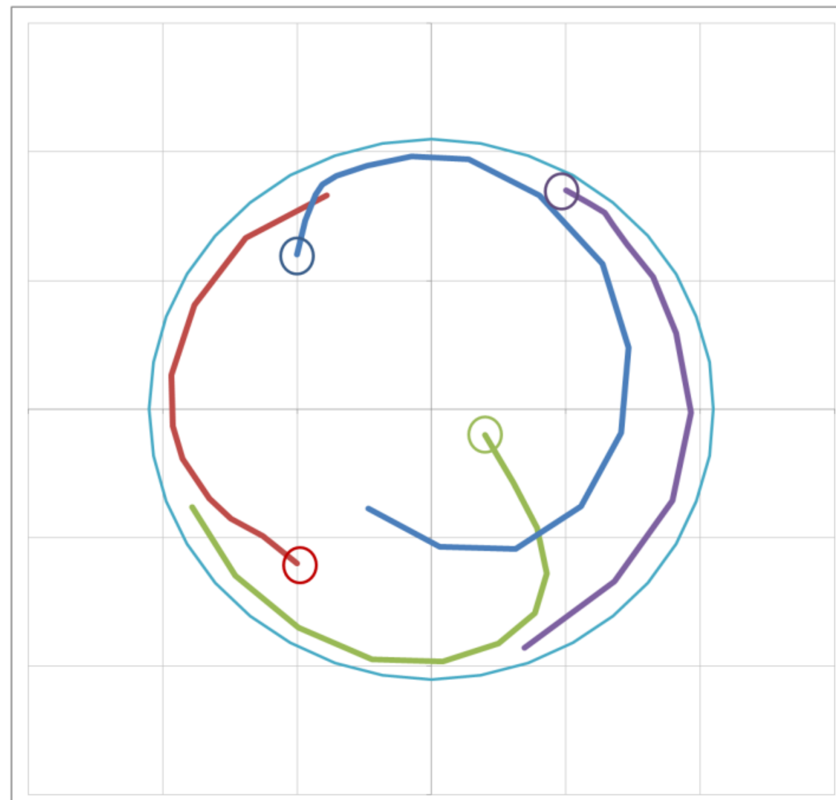
Cage and wire locations are laid over an isothermal contour plot resulting from a signal matched model of the pile. Movement of the cage over the contours reveals two possible solutions which satisfy the thermal profile.

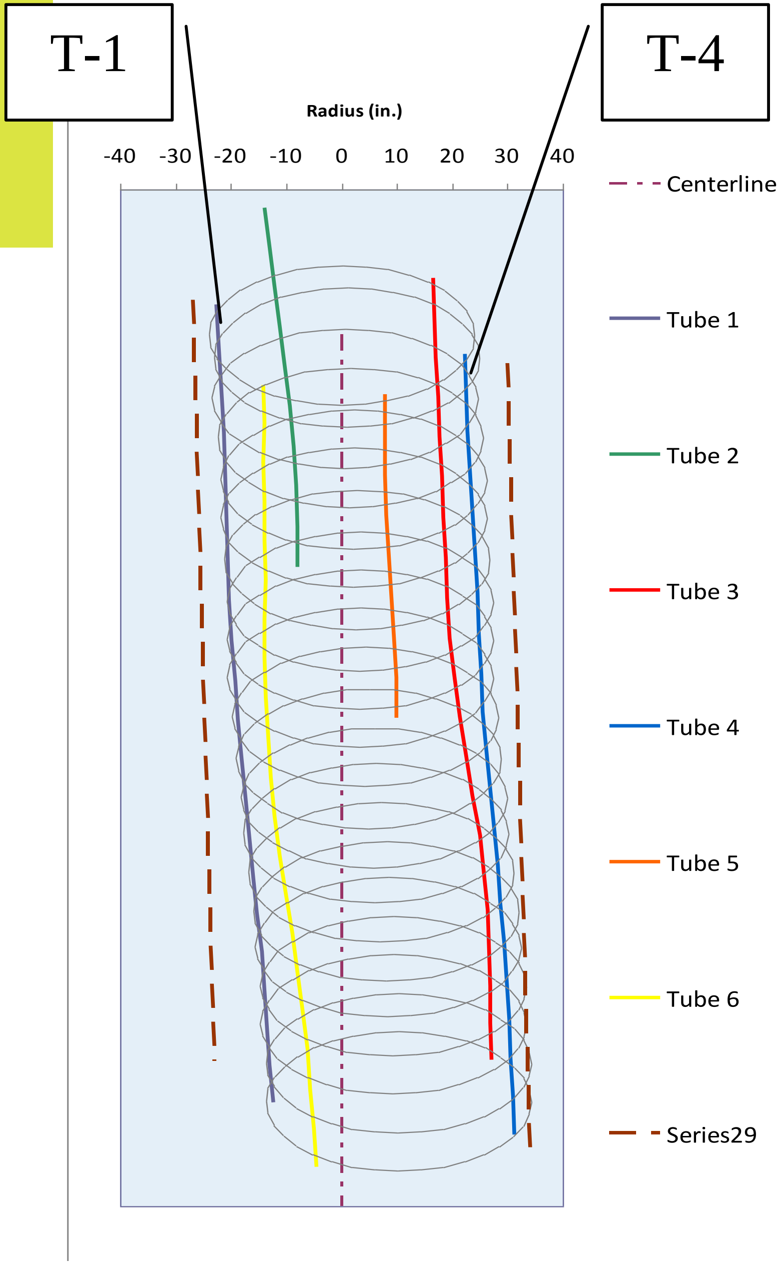
Inclination Measurements

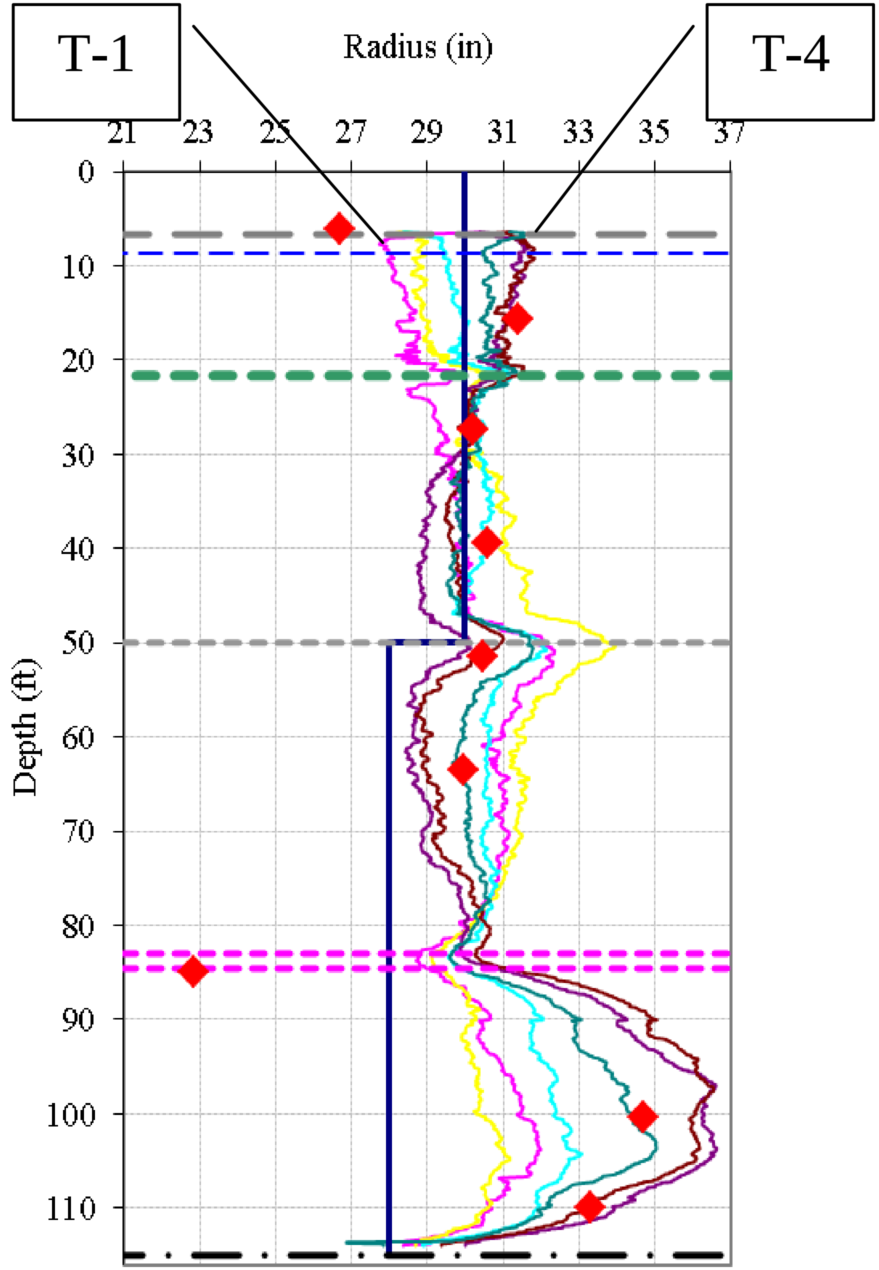
Inclination Measurements



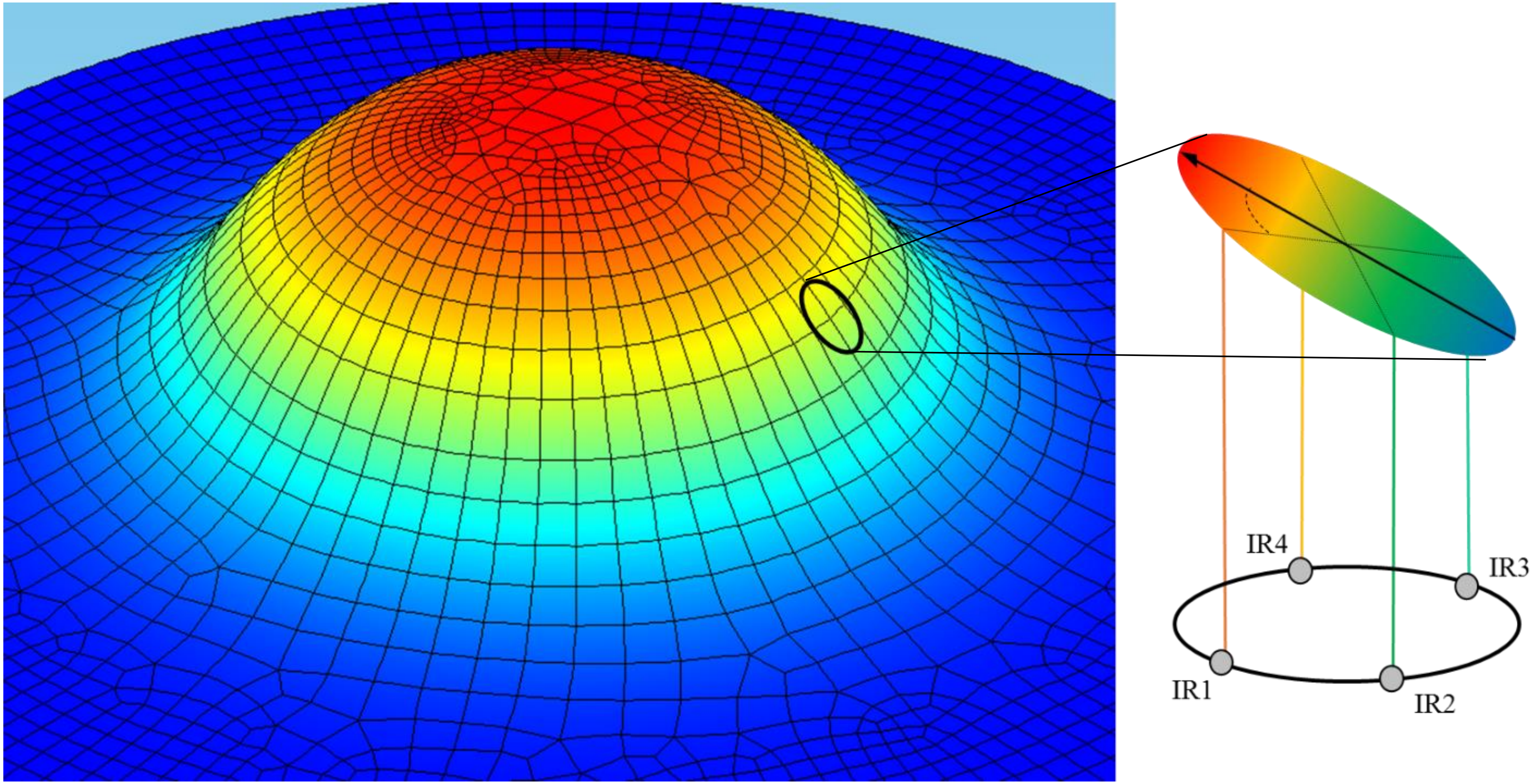
Severe cage deformation during casing removal!



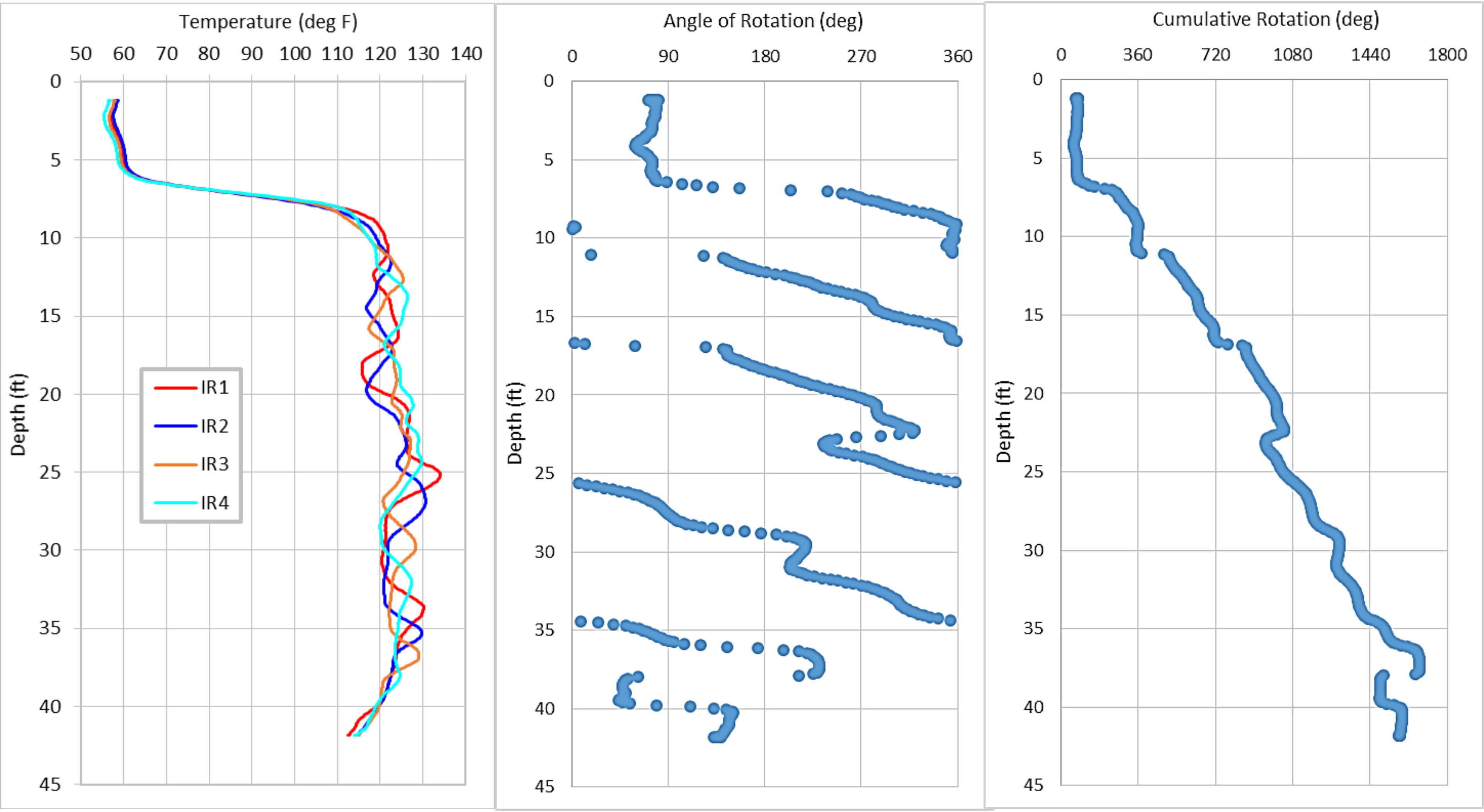

T-1
T-4
Radius (in.)
-40 -30 -20 -10 0 10 20 30 40
Centerline
Tube 1
Tube 2
Tube 3
Tube 4
Tube 5
Tube 6
Series29


T-1
T-4
Radius (in)
21 23 25 27 29 31 33 35 37
Depth (ft)
0 10 20 30 40 50 60 70 80 90 100 110

Tracking probe rotation from thermal gradient between IR sensors



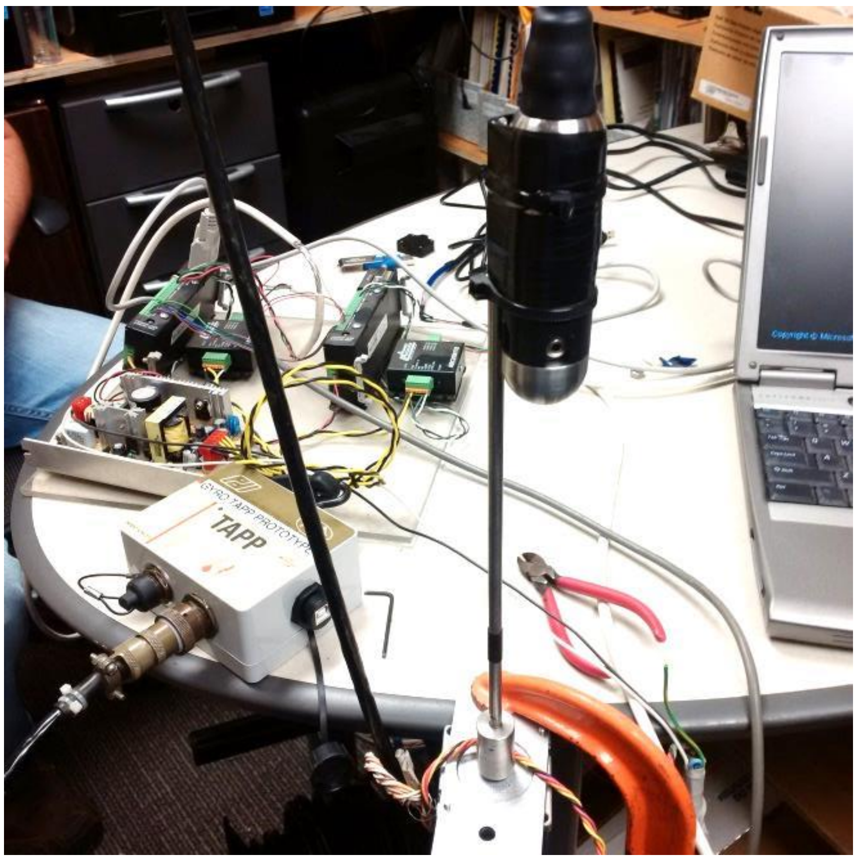
Tracking probe rotation from thermal gradient between IR sensors



InvenSense MPU-6000	Accelerometer	Gyroscope
Measurement range	±2g	250º/sec
Resolution	0.06mg	0.0076º/sec
Sampling rate	1kHz	8kHz
Communication	Serial (I^2C or SPI)	
Power source	2.375 – 3.46 Vdc	
Operating temperature	-40ºF to +221ºF	
Mechanical shock limit	10,000g for 0.2ms	

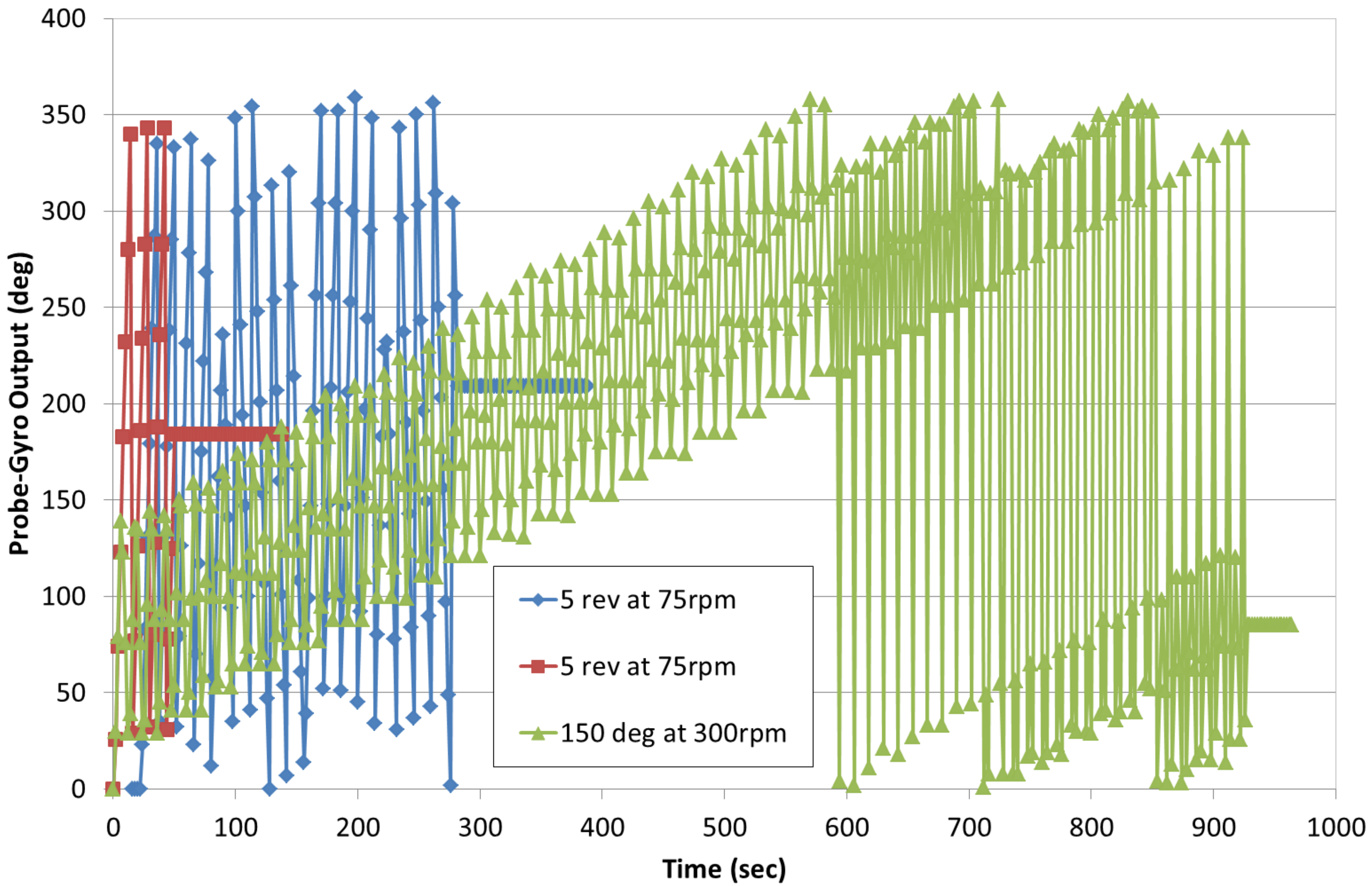
Rotation Tracking

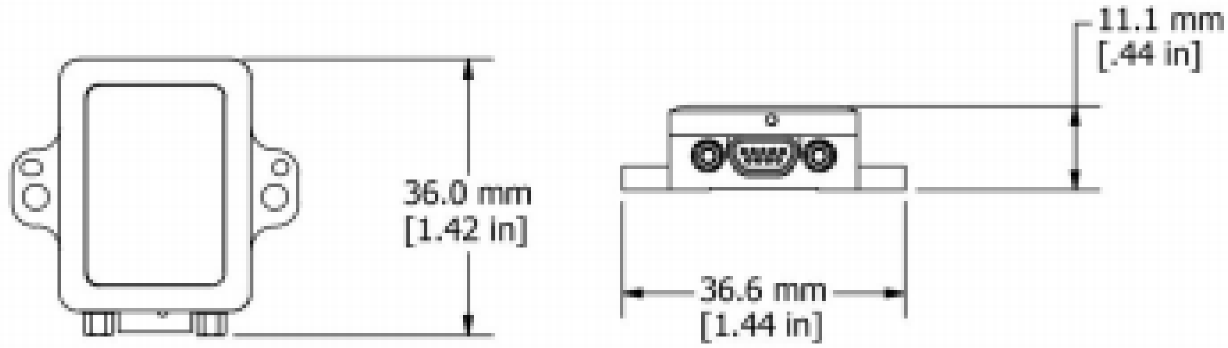
Programmable stepper motor assembly from Anaheim Automation



Rotation Tracking – Probe Based System

- Digital communication timed out after short periods of time
- Accuracy lost due to output drift.
- Drift not able to be corrected as all calculations are performed onboard the sensor.

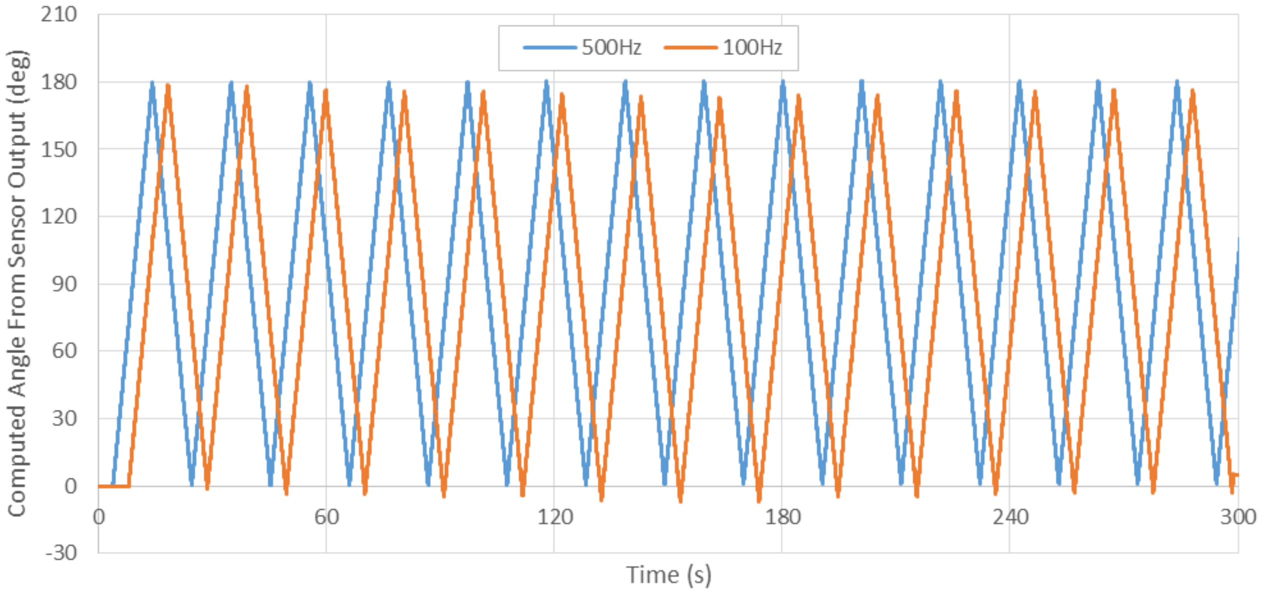




LORD Microstrain 3DM-GX4	Accelerometer	Gyroscope
Measurement range	±5g	300º/sec
Resolution	<0.1mg	<0.008º/sec
Sampling rate	4kHz	4kHz
Communication	USB 2.0	
Power source	+3.2 to +36 Vdc	
Operating temperature	-40ºF to +185ºF	
Mechanical shock limit	500g (calibration unaffected) 1000g (bias may change) 5000g (un-powered survivability)	

Rotation Tracking – IMU Sensor

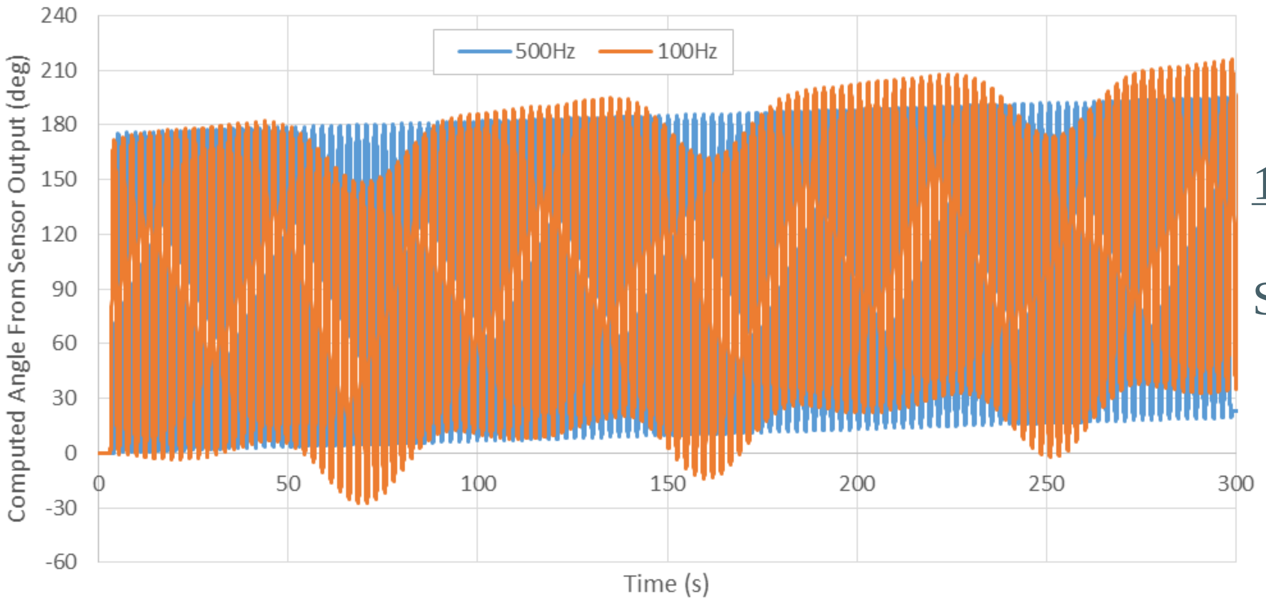
- Experienced drift at low sampling frequencies and high rotational rates



<u>180º oscillations at 17 deg/sec</u>

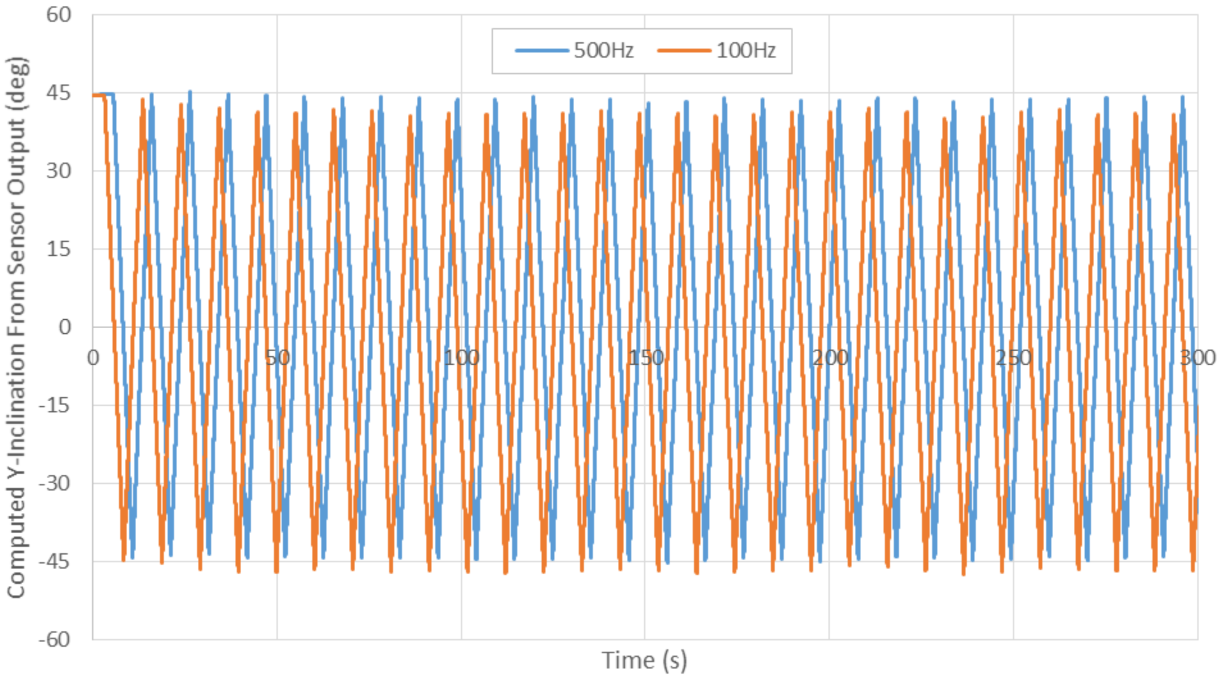
Some drift at 100kHz

No drift at 500kHz



<u>180º oscillations at 450 deg/sec</u>

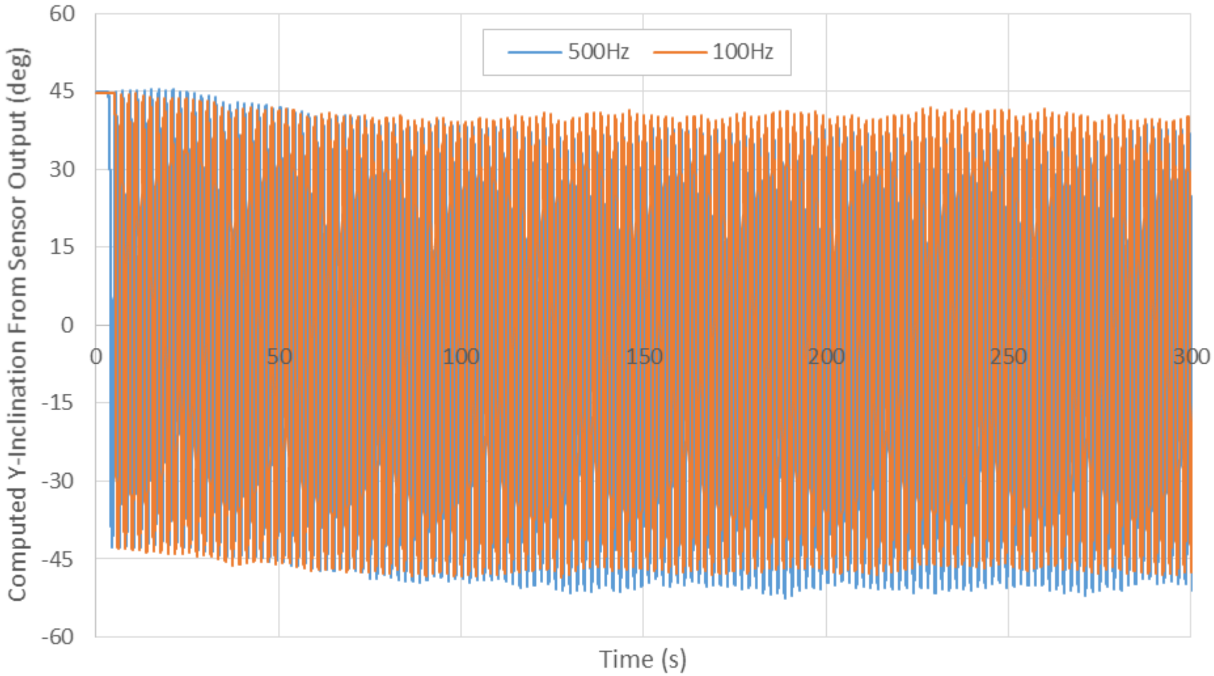
Some drift at 100 and 500kHz



<u>45º oscillations at 17 deg/sec</u>

Some drift at 100kHz

Negligible drift at 500kHz

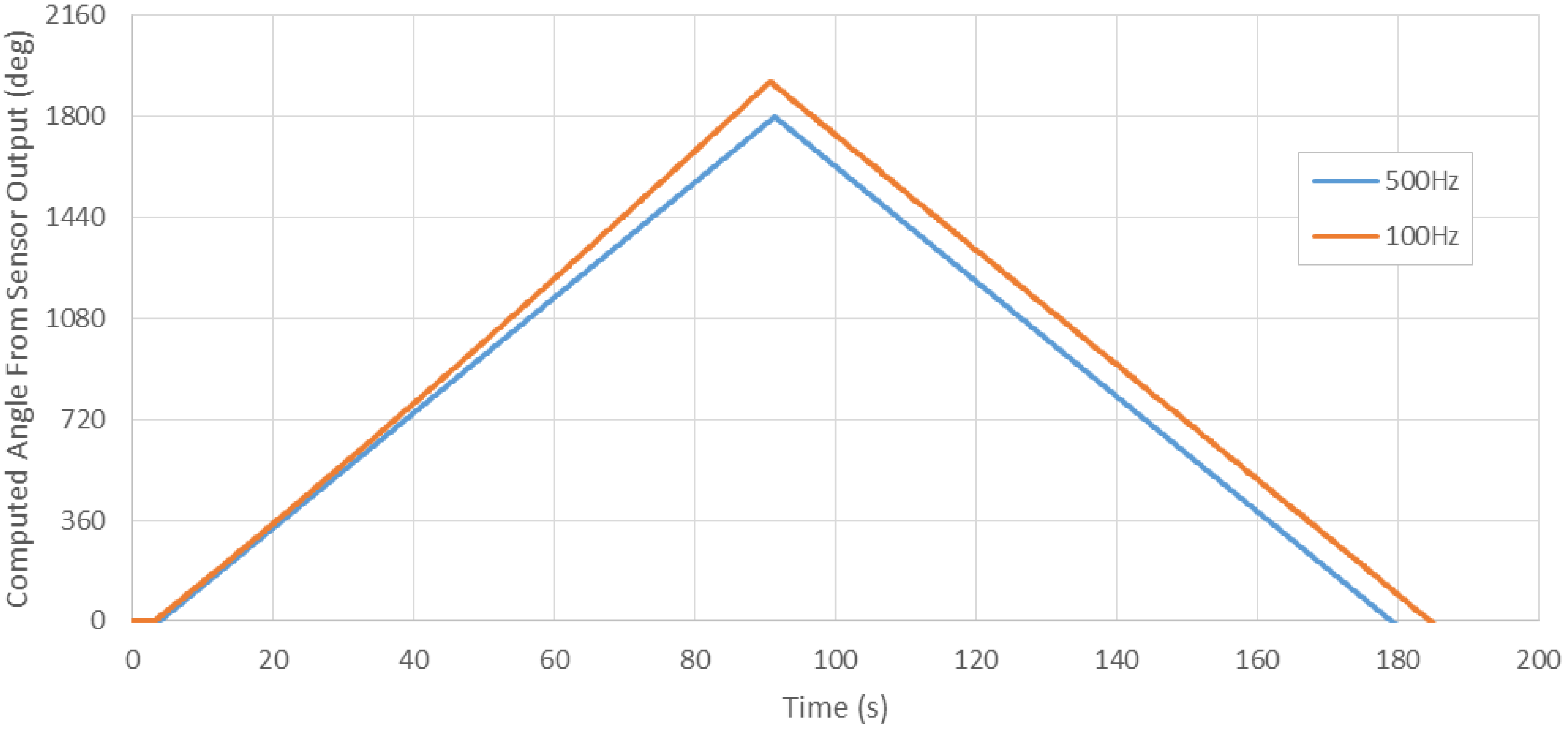


<u>45º oscillations at 450 deg/sec</u>

Some drift at 100 and 500kHz

Rotation Tracking – IMU Sensor

- Experienced drift at low sampling frequencies and high rotational rates



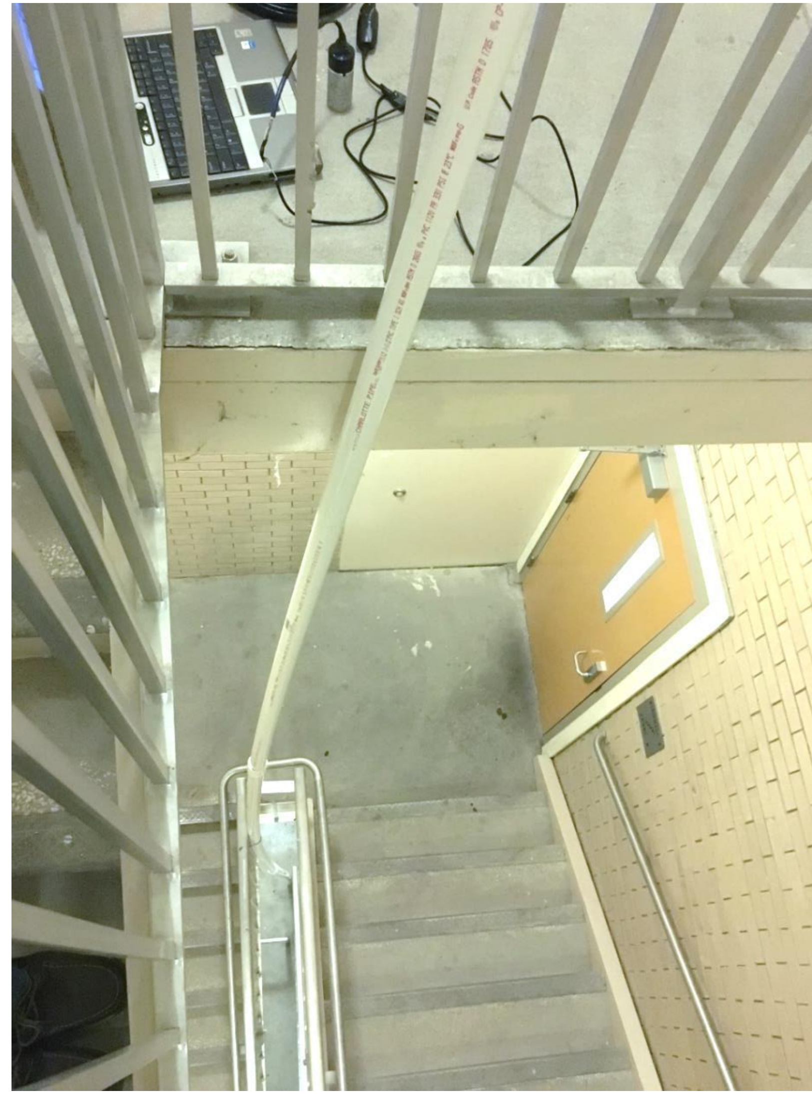
<u>5 revolutions CW and CCW at 20 deg/sec</u>

Drift at 100kHz yielding ~90^o error over 5 revolutions

No drift at 500kHz

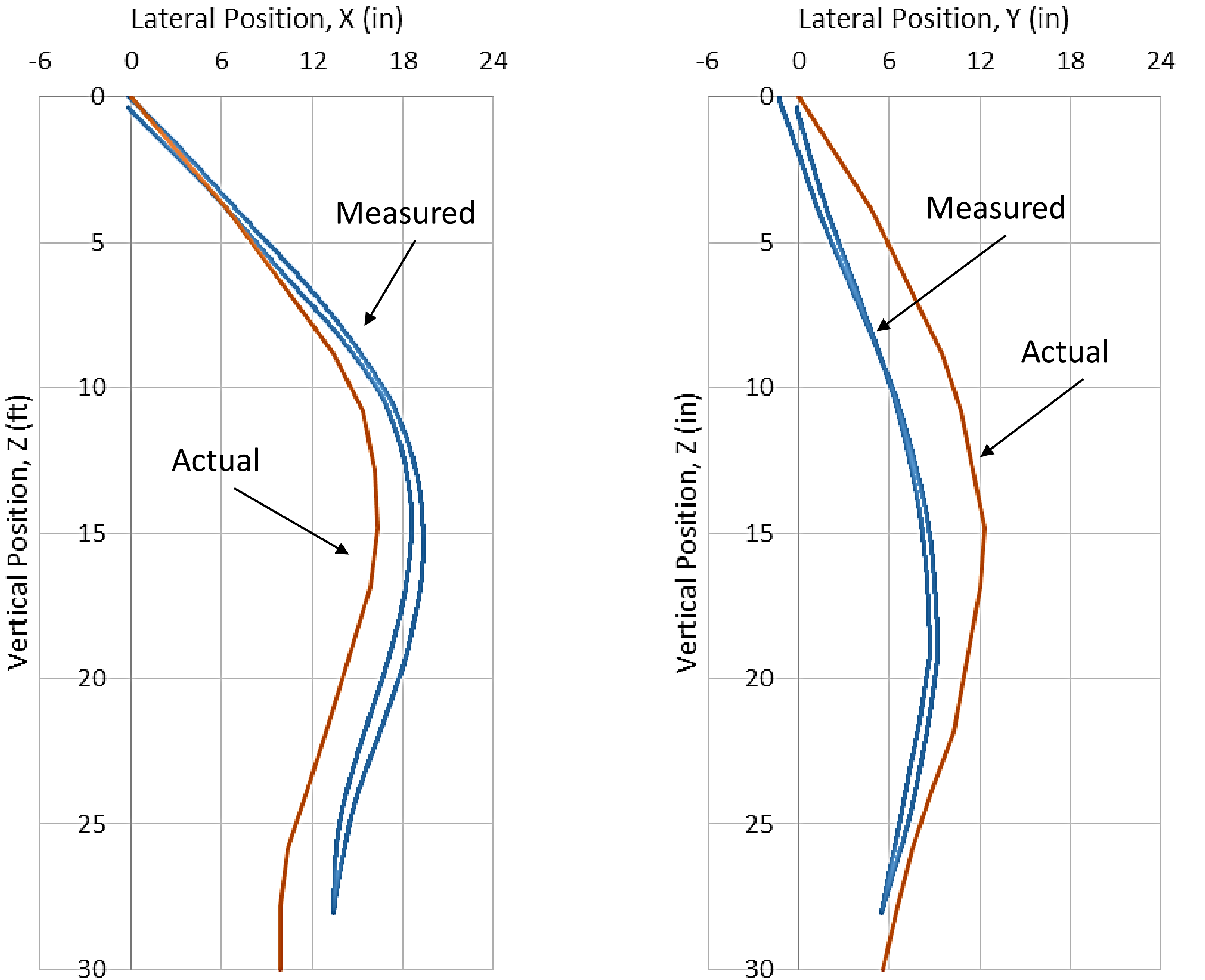
3-D Position Tracking – IMU Sensor

Specially fabricated probe body to house IMU sensor

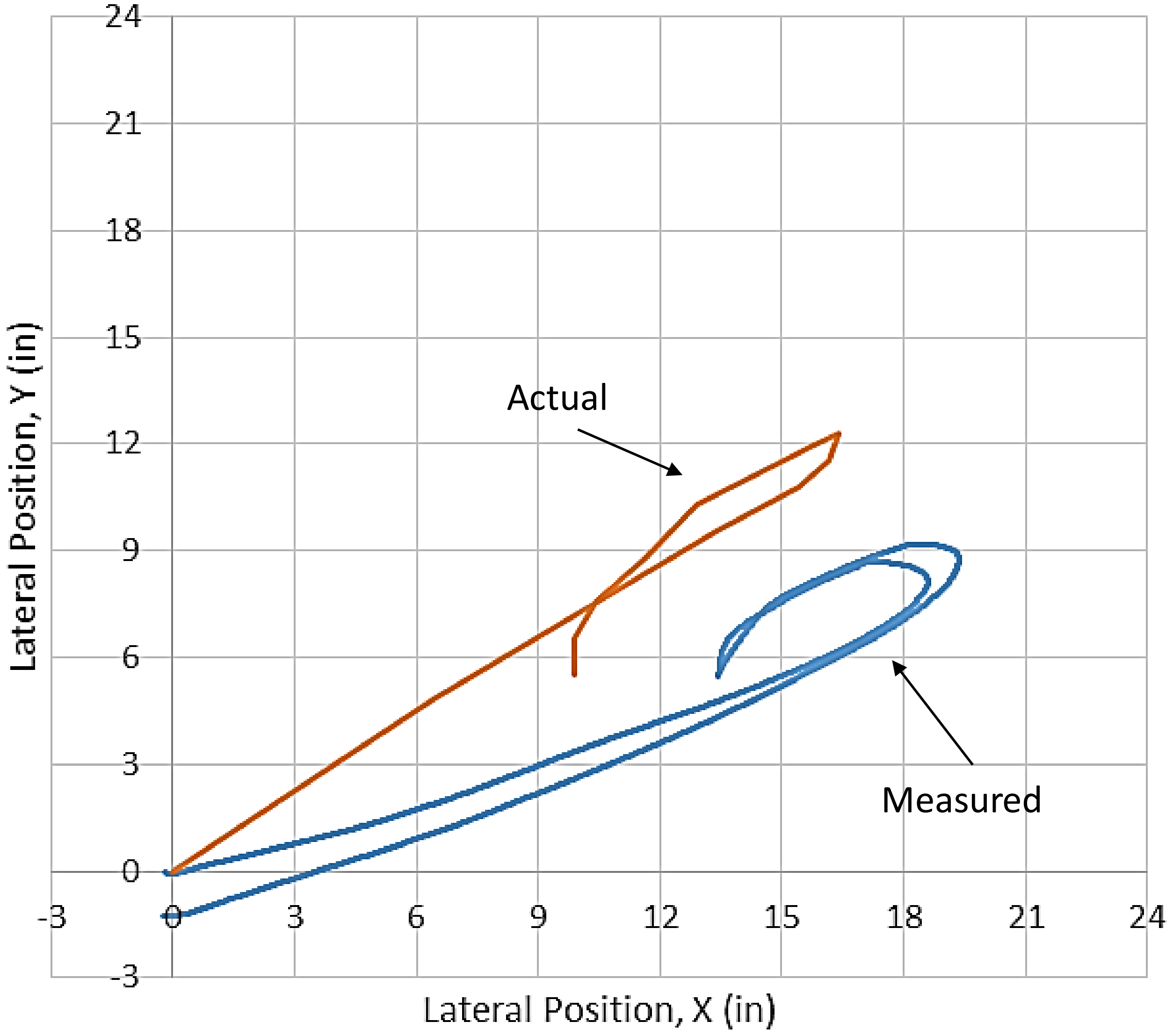


30ft 1.5in PVC pipe with prescribed lateral deflections

3-D Position Tracking – IMU Sensor

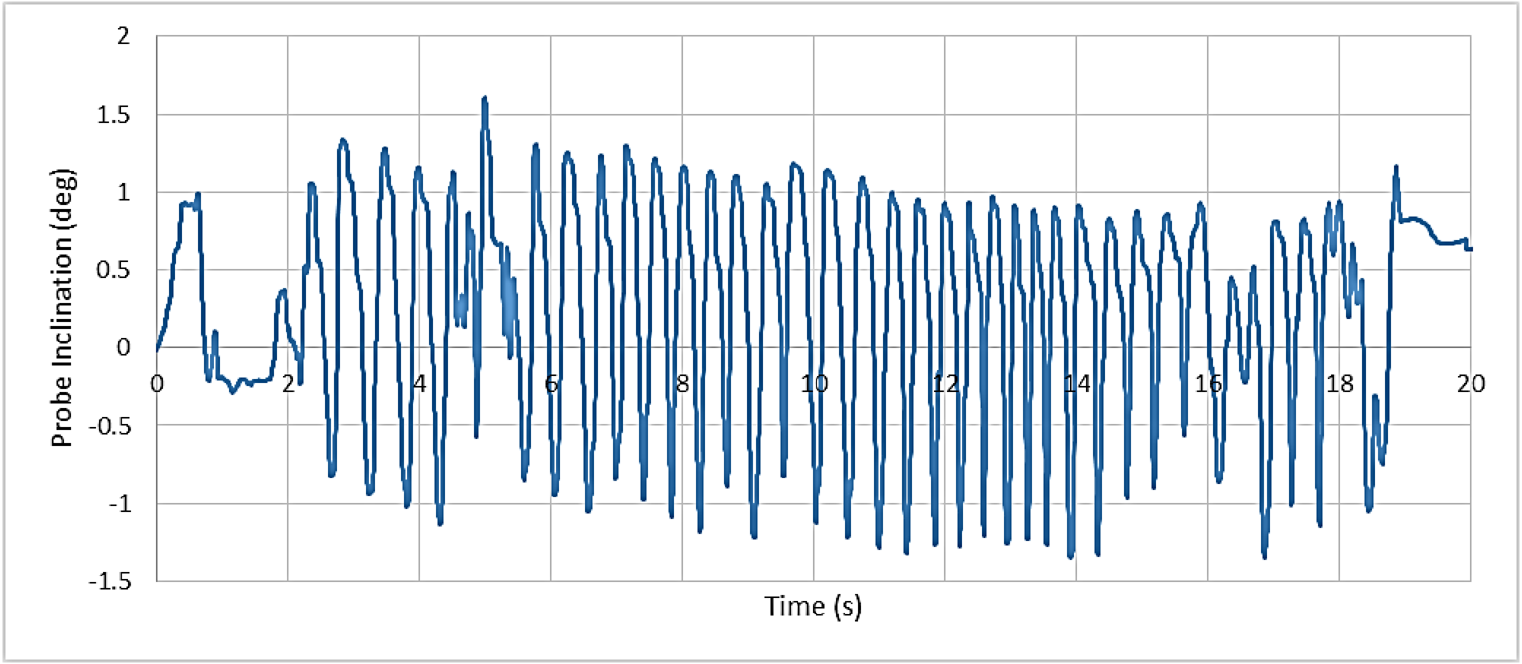


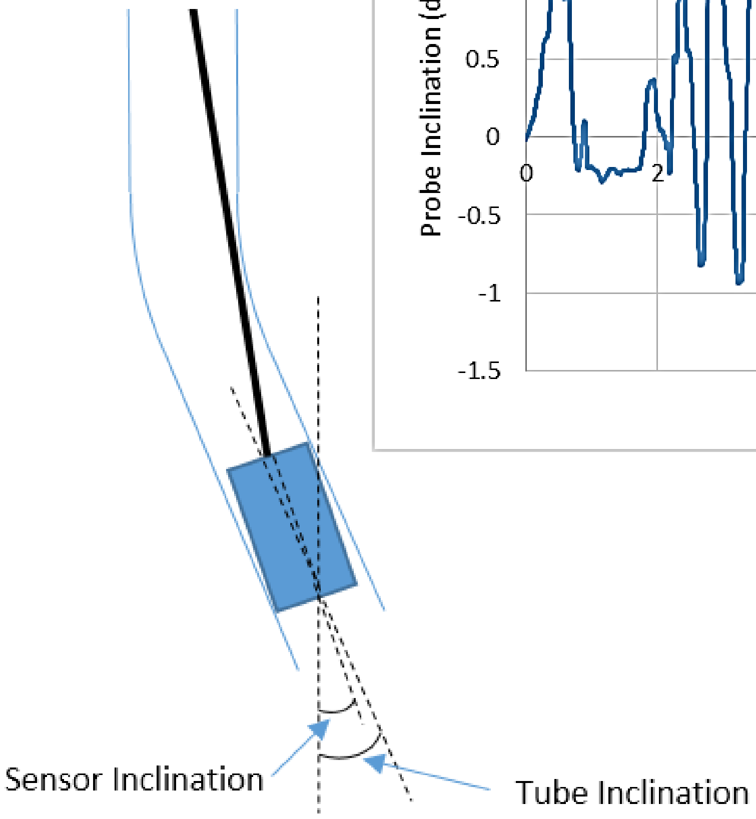
3-D Position Tracking – IMU Sensor



3-D Position Tracking – IMU Sensor

Error due to diameter tolerance between tube and probe which allows sensor to be oriented and an inclination misaligned with the that of the tube.

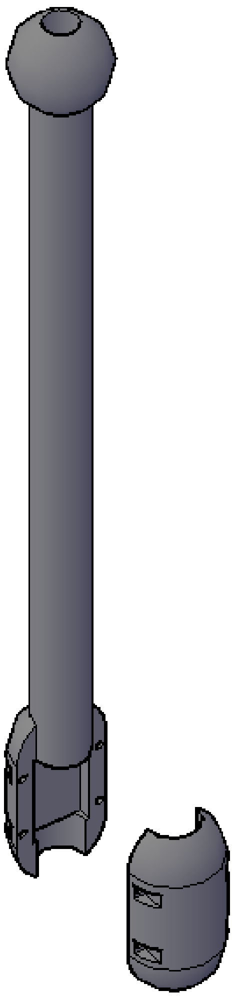


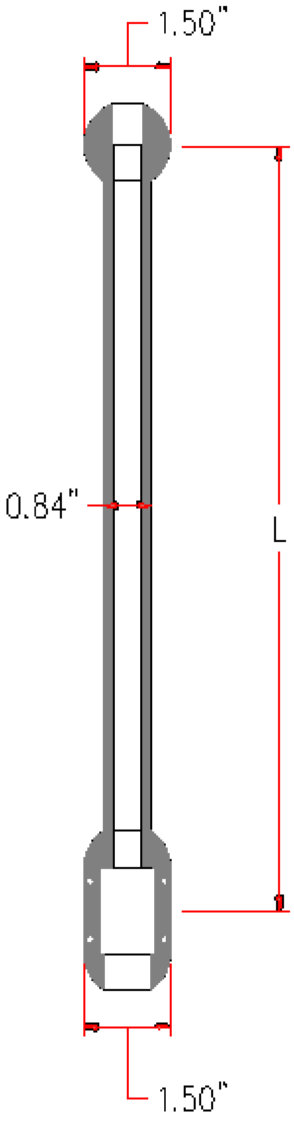


0.09in diameter tolerance yields ~+/-1.25° angle difference, which equates to 4in error over 15ft. Results showed similar error.

3-D Position Tracking – IMU Sensor

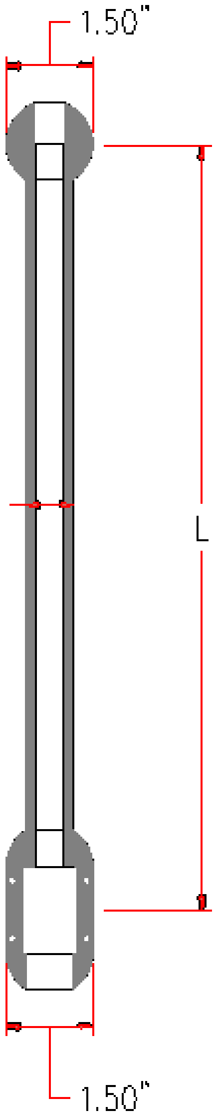
New Probe Design

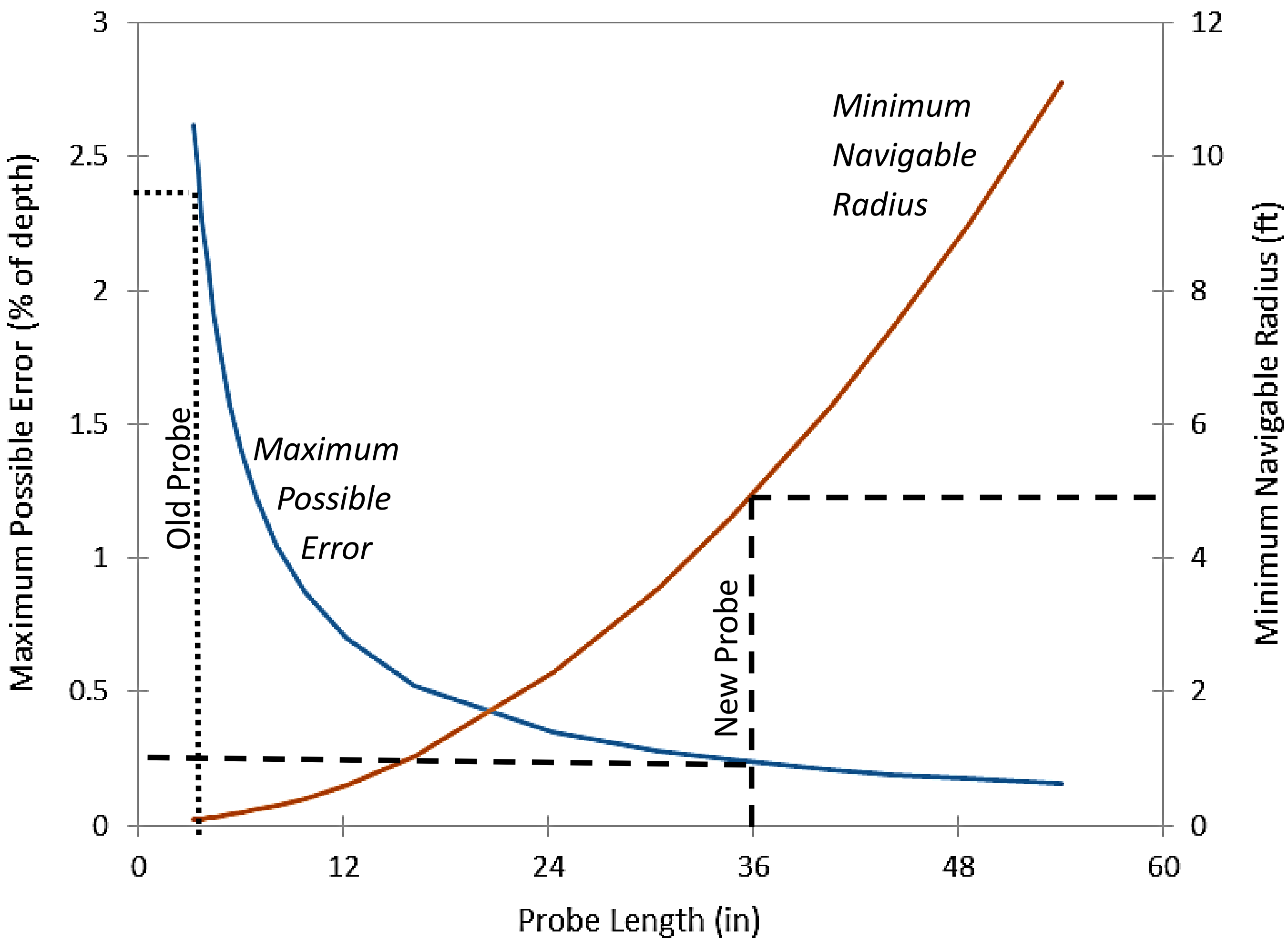


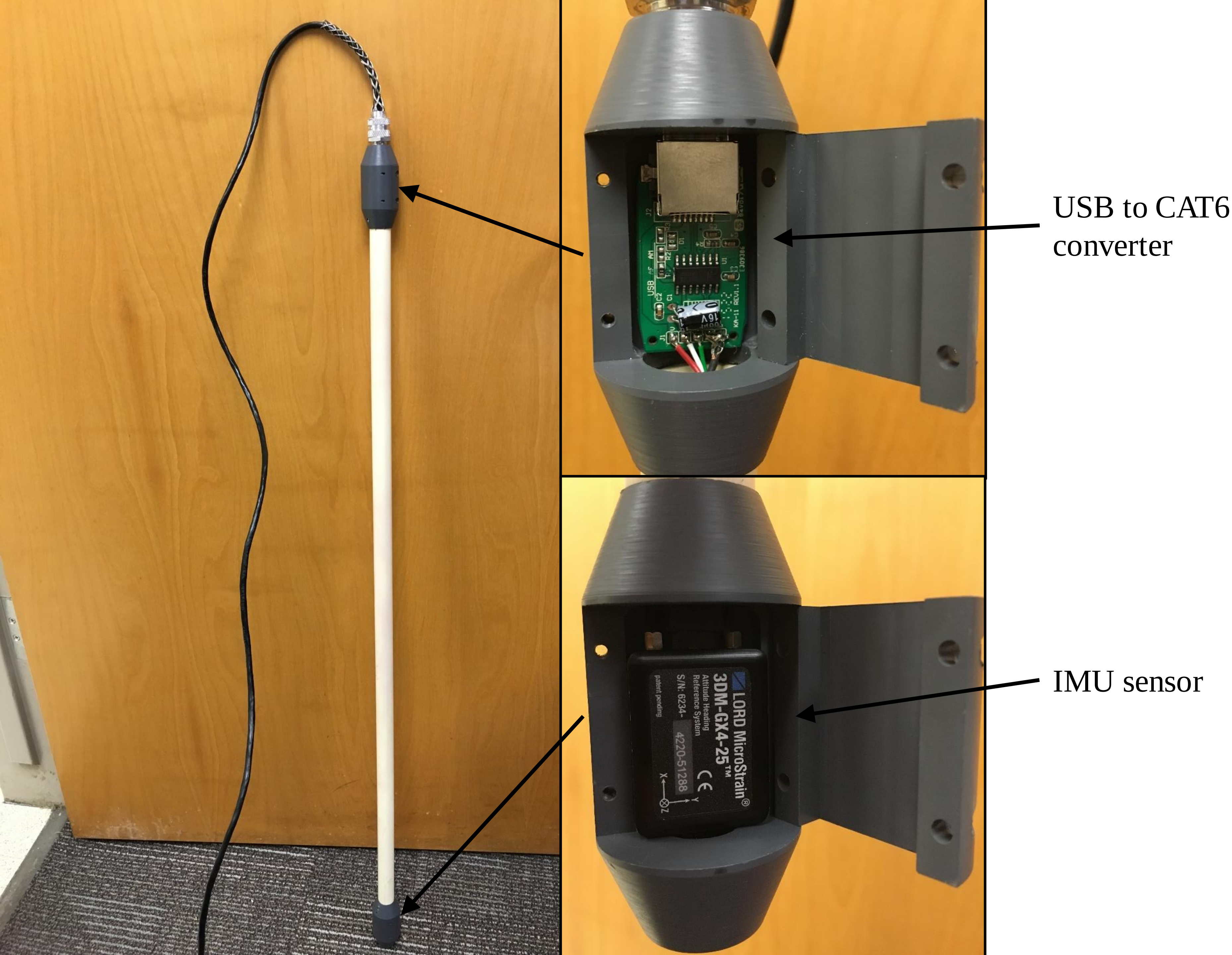


3-D Position Tracking – IMU Sensor

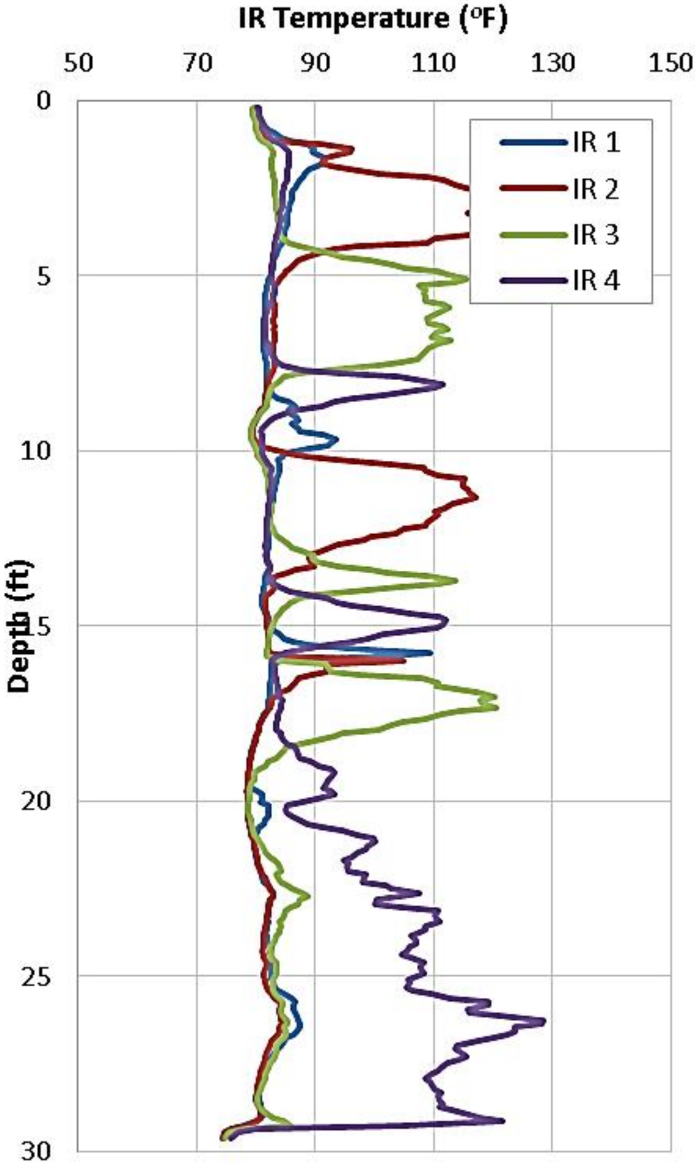
New Probe Design

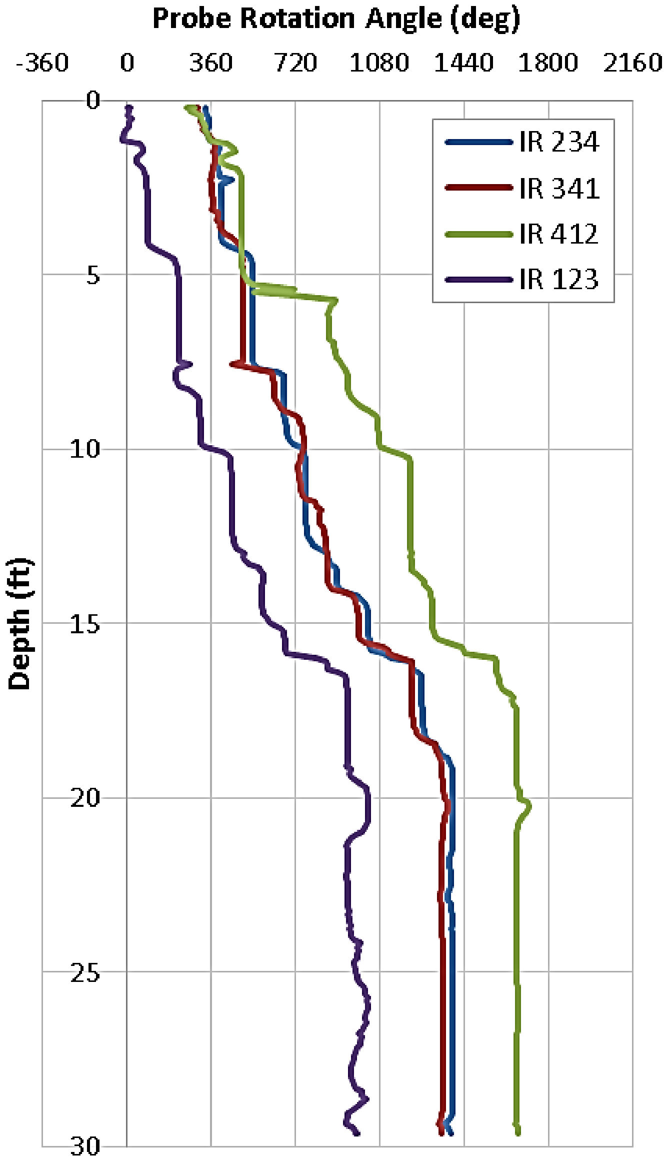





USB to CAT6 converter
IMU sensor
LORD MicroStrain
3DM-GX4-25
Attitude Heading Reference System

Tracking probe rotation from thermal gradient between IR sensors





Summary

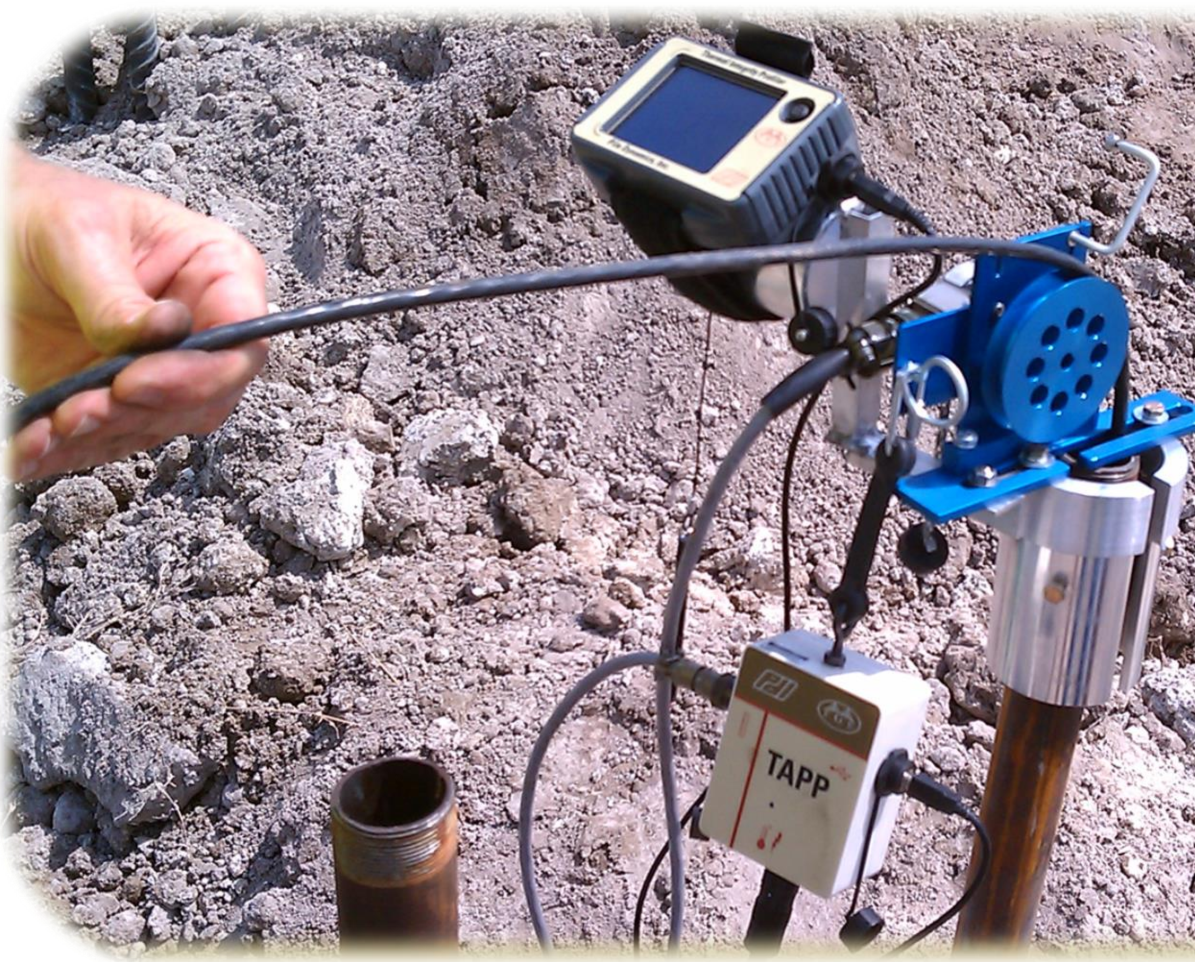
- TIP can work for ACIP, but advanced analysis methods must be used when instrumentation is minimal.

- Qualitative analysis works well, but present drilled shaft analysis methods do not work with small piles and near center measurements.

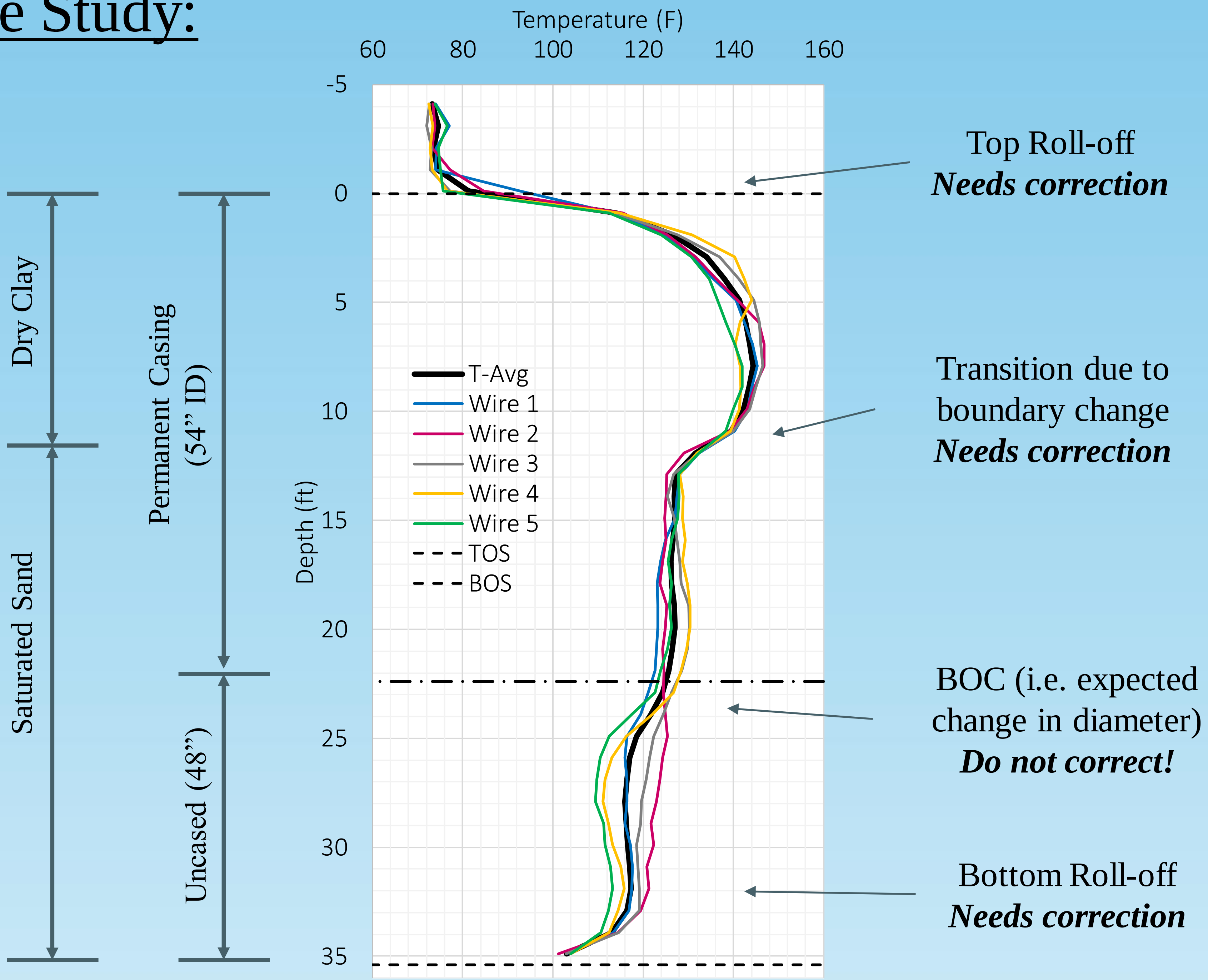
- Simplified T-soil method could solve problems.

- The addition of inclination measurement could greatly enhance TIP analysis for ACIP piles.

Questions?



Case Study:

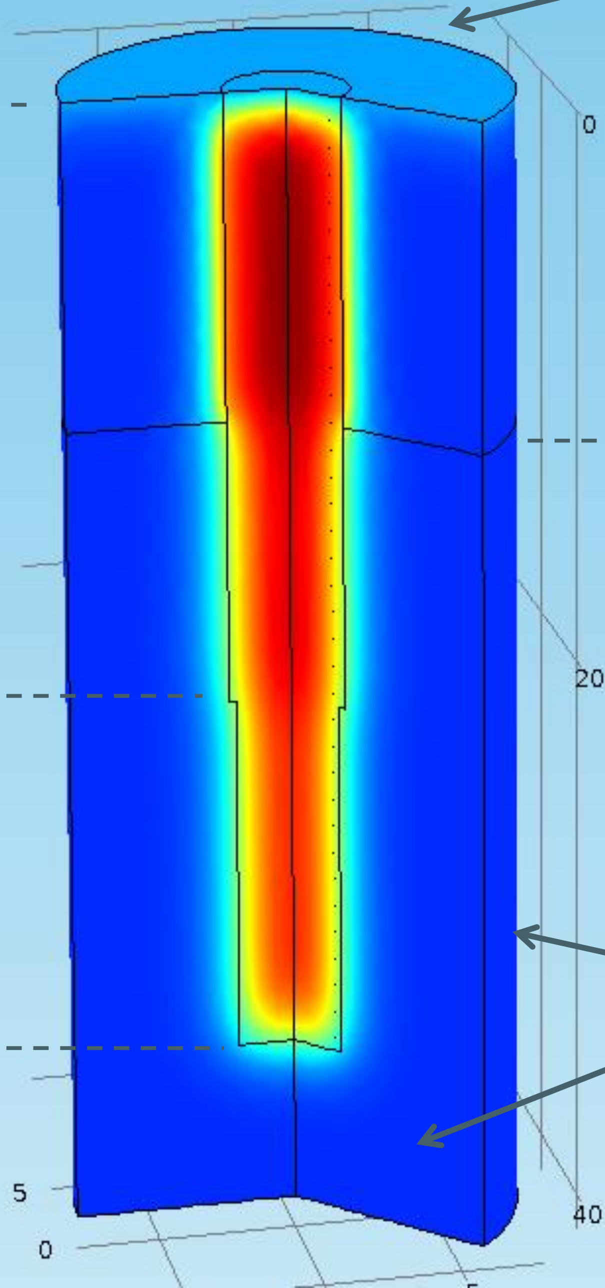


Temperature (F)
60
80
100
120
140
160
Depth (ft)
-5
0
5
10
15
20
25
30
35
T-Avg
Wire 1
Wire 2
Wire 3
Wire 4
Wire 5
TOS
BOS
Dry Clay
Saturated Sand
Permanent Casing
(54” ID)
Uncased (48”)
Top Roll-off
Needs correction
Transition due to boundary change
Needs correction
BOC (i.e. expected change in diameter)
Do not correct!
Bottom Roll-off
Needs correction

<u>Case Study:</u>
Model Analysis

Convective air cooling w/ diurnal temperatures 66-83 ^{o}F

TOS = GSE = 0ft



Low diffusivity overlying high diffusivity at 12ft

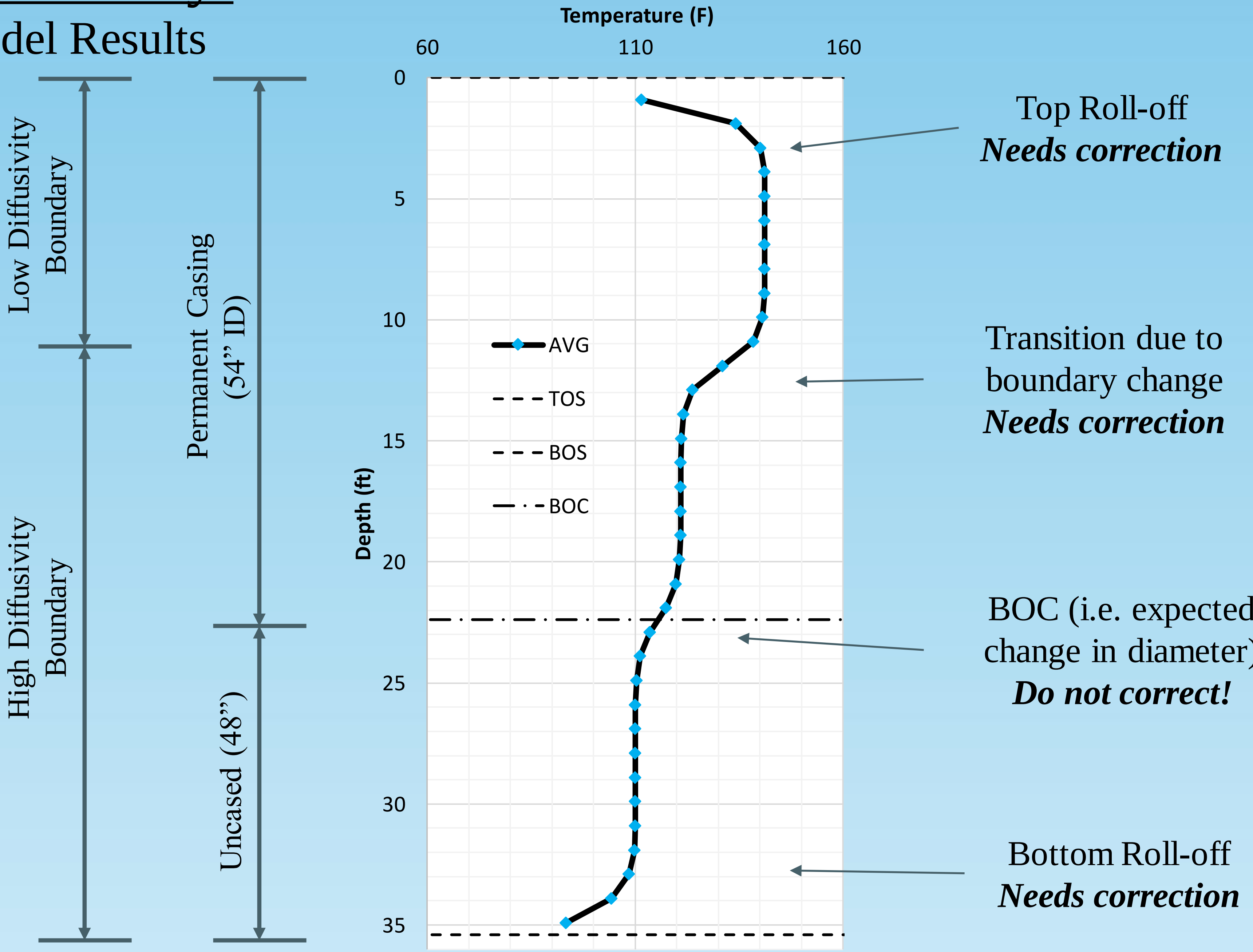
BOC = 22.4ft (54” cased, 48” uncased)

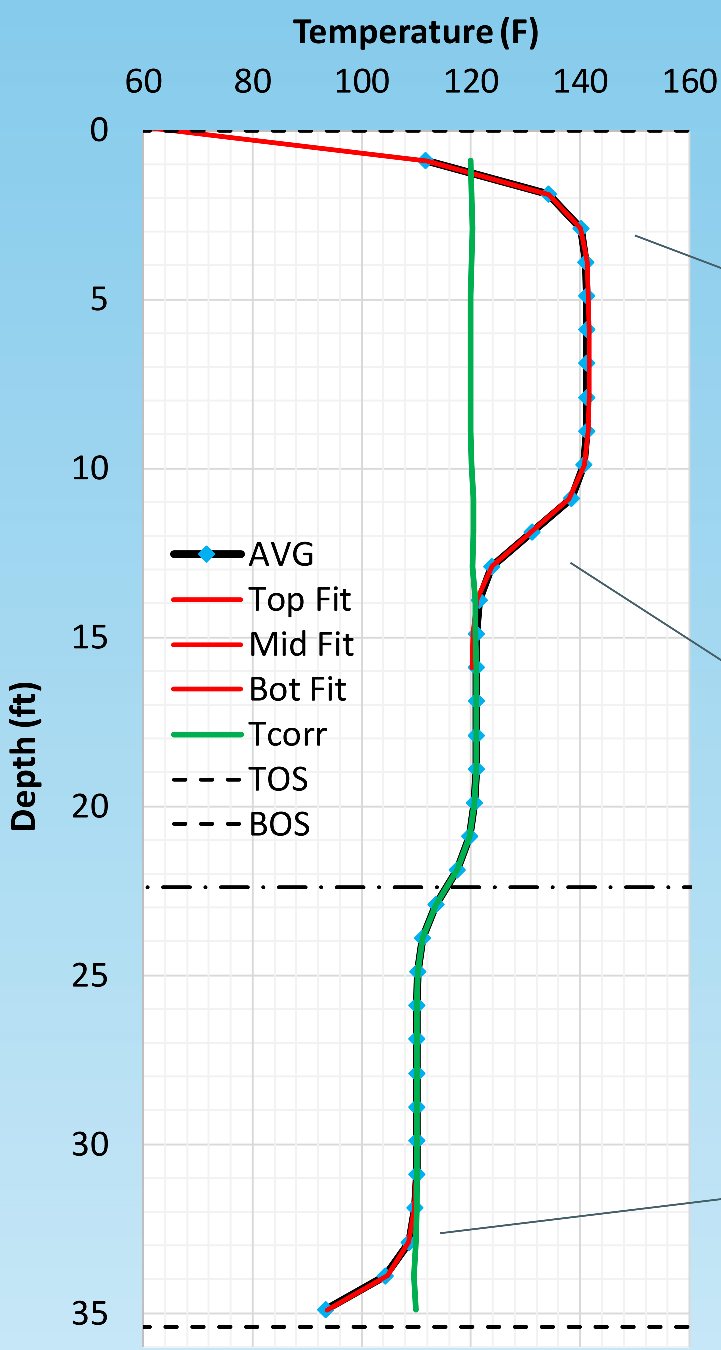
Ambient soil temperature = 60 ^{o}F

BOS = 35.4ft

Case Study:

Model Results





Top Roll-off

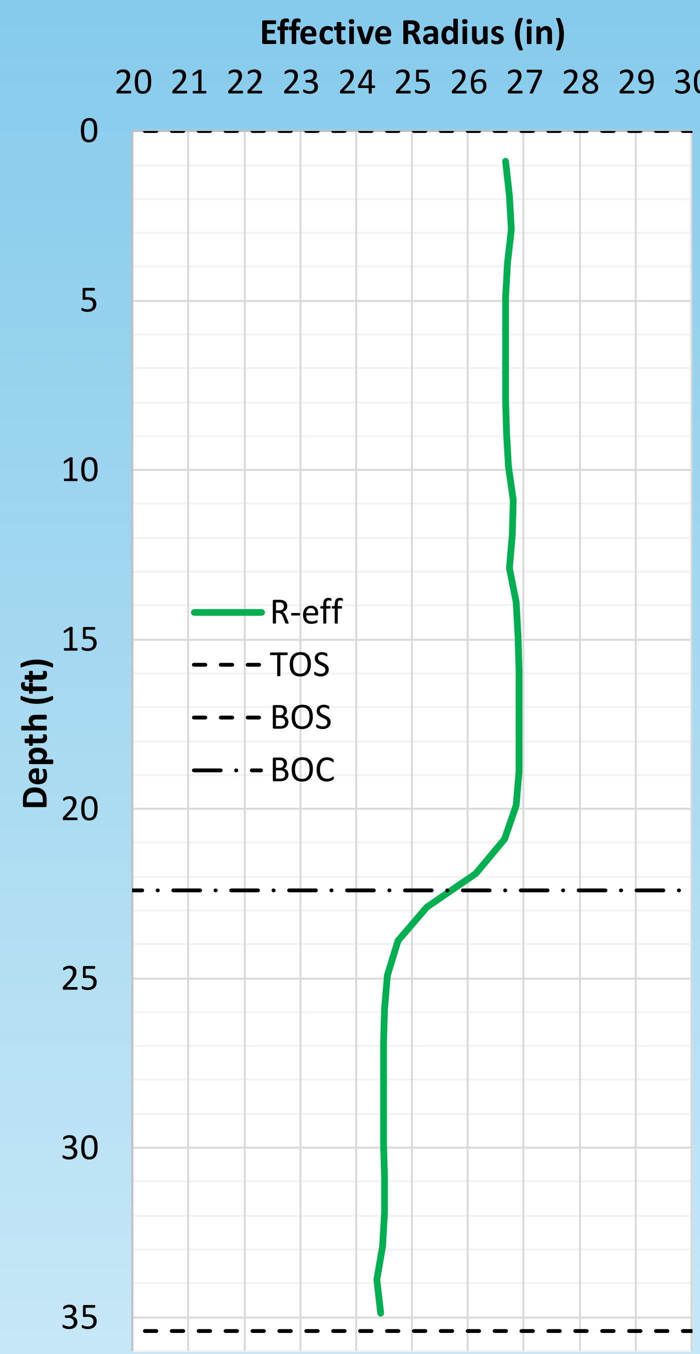
Z_0	= 0 ft
T_{max}	= 141.6 °F
T_0	= 66.3 °F
α	= 1.28

Soil Transition

Z_0	= 11.9 ft
T_{max}	= 141.6 °F
T_{0min}	= 120.2 °F
α	= 1.25

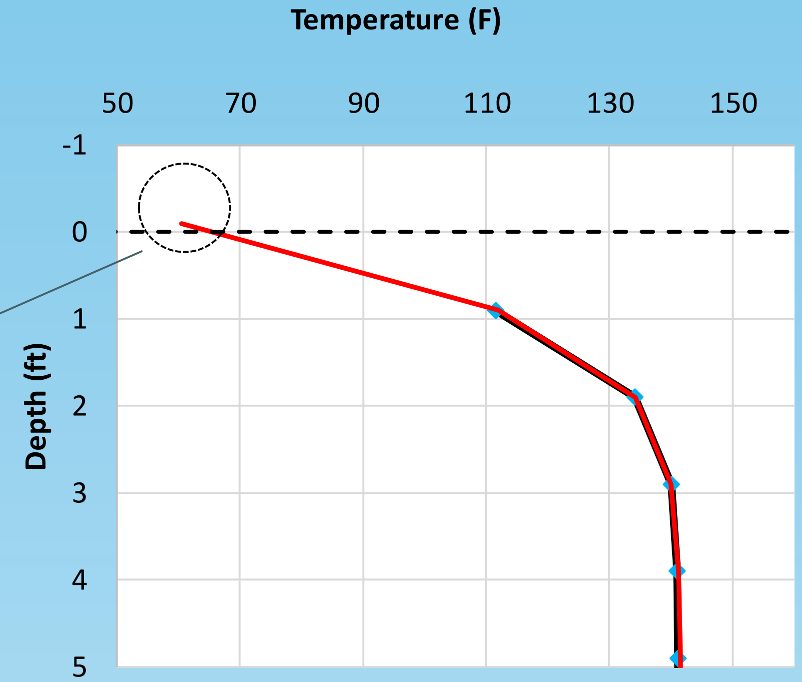
Bottom Roll-off

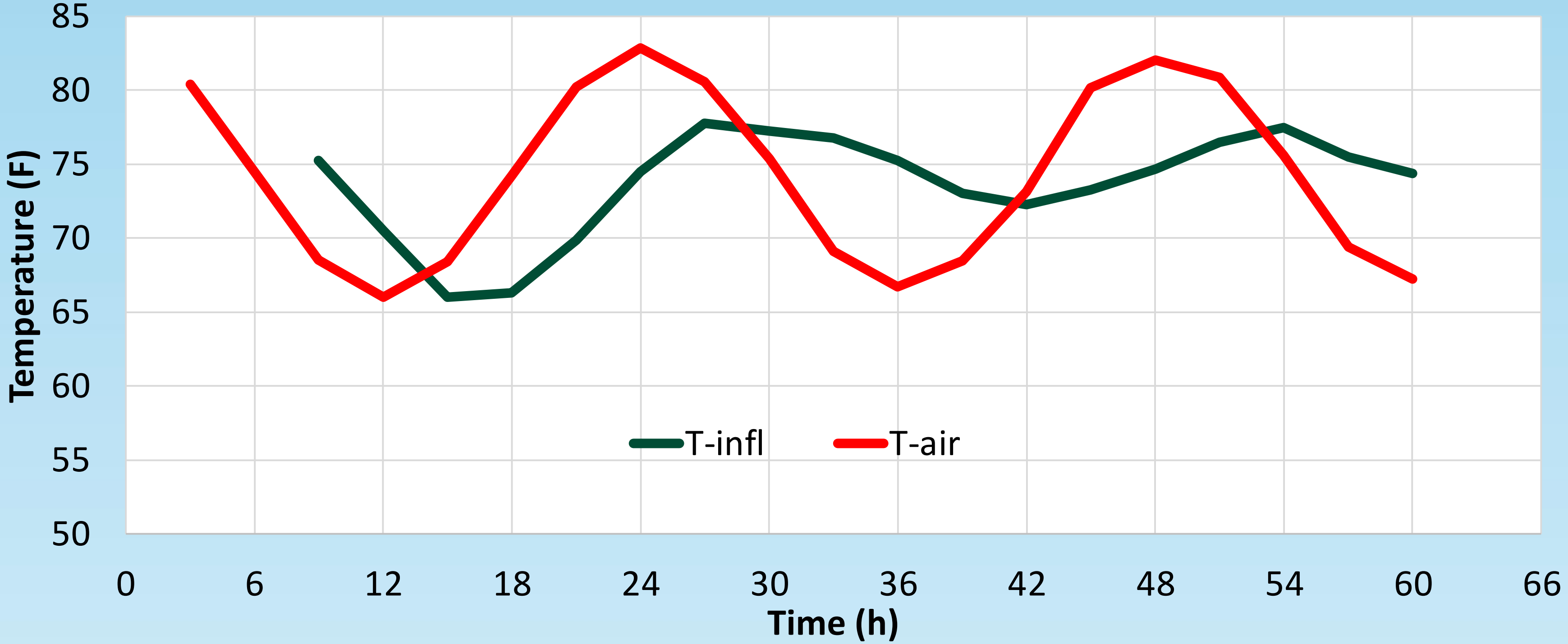
Z_0	= 35.4 ft
T_{max}	= 110 °F
T_{min}	= 60 °F
α	= 1.4



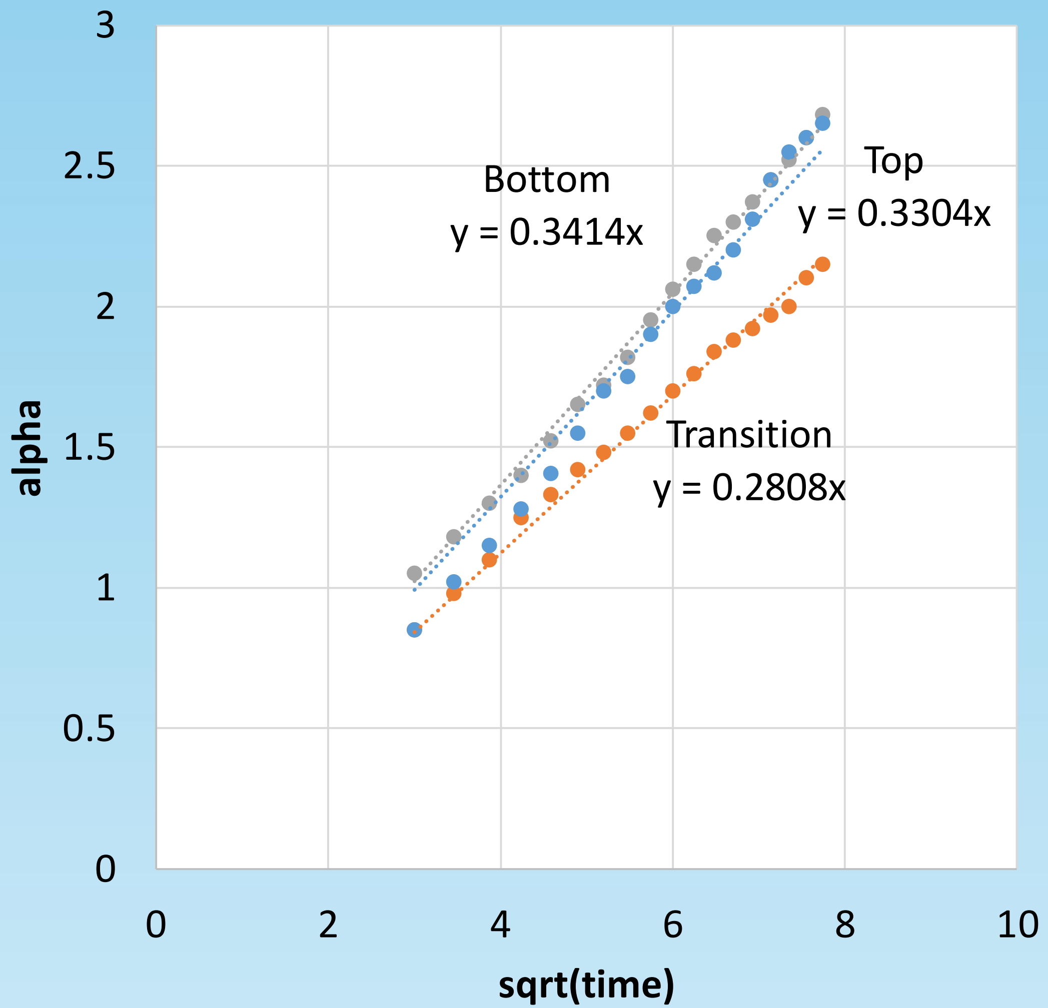
Selection of TOS Inflection Point

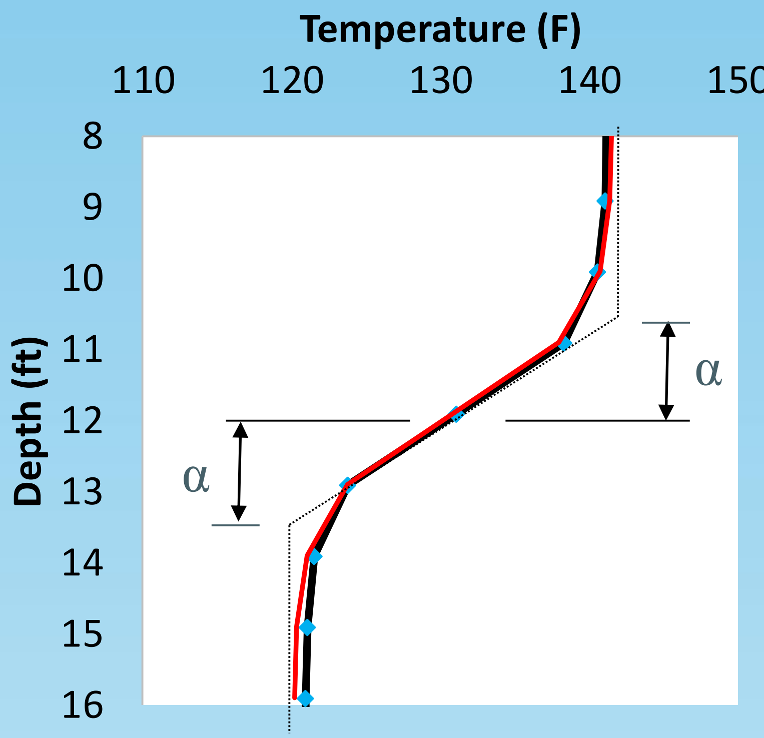
Inflection point influenced by air temperatures



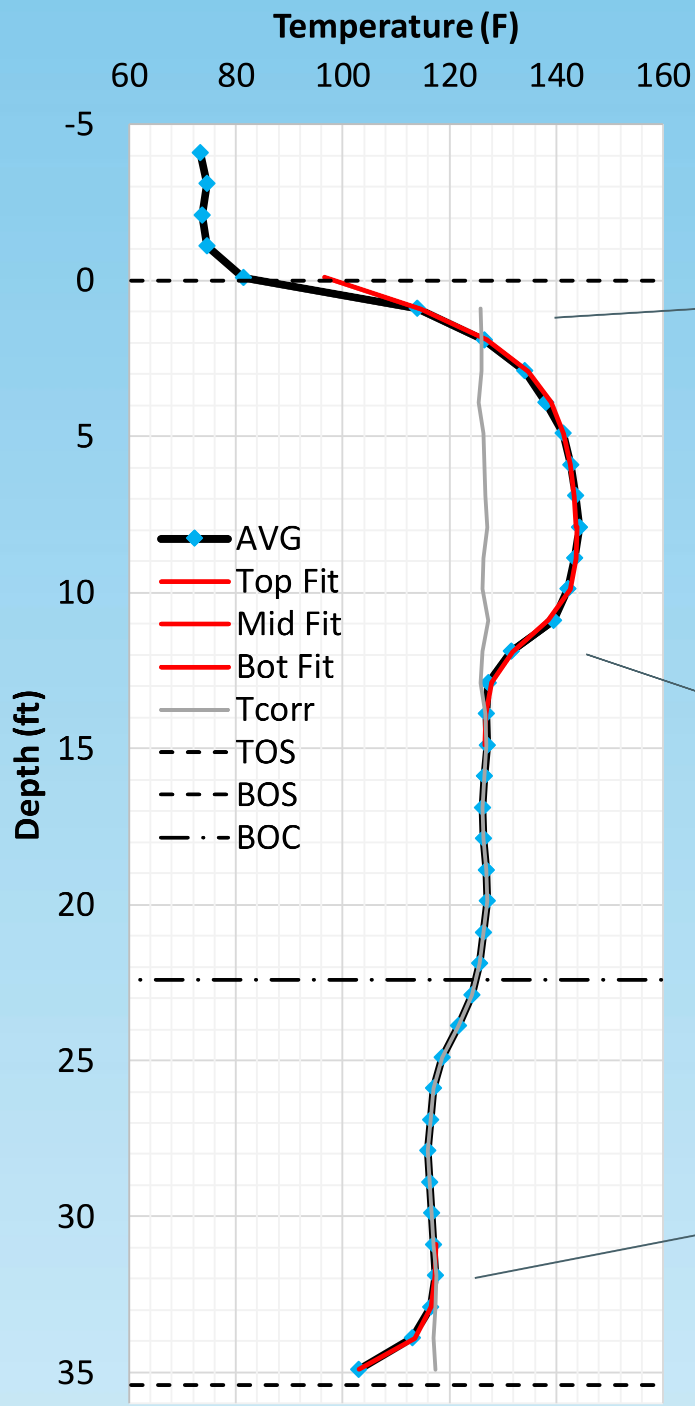


Selection of α time factor





$$\alpha \approx 0.3\sqrt{t}$$



<u>Top Roll-off</u>

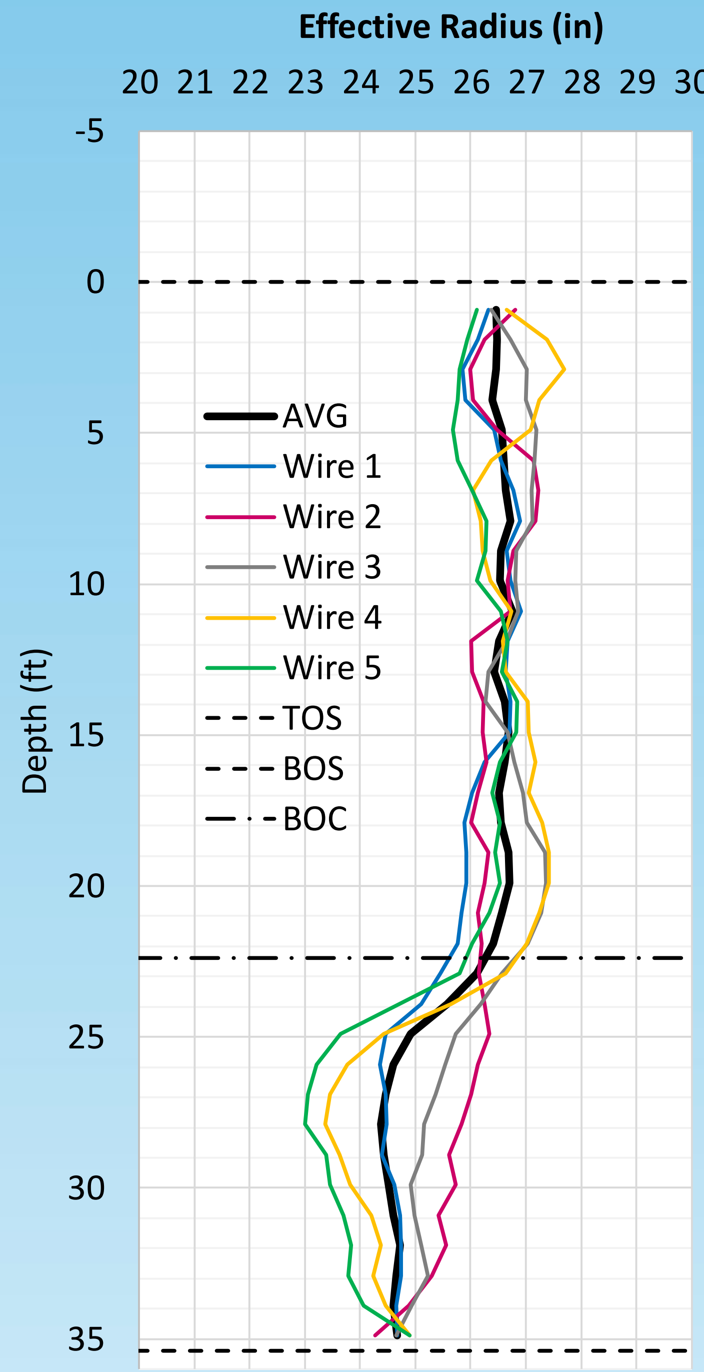
Z_0 = -1.0 ft
T_{max} = 144 °F
T_0 = 77 °F
α = 3.0

<u>Soil Transition</u>

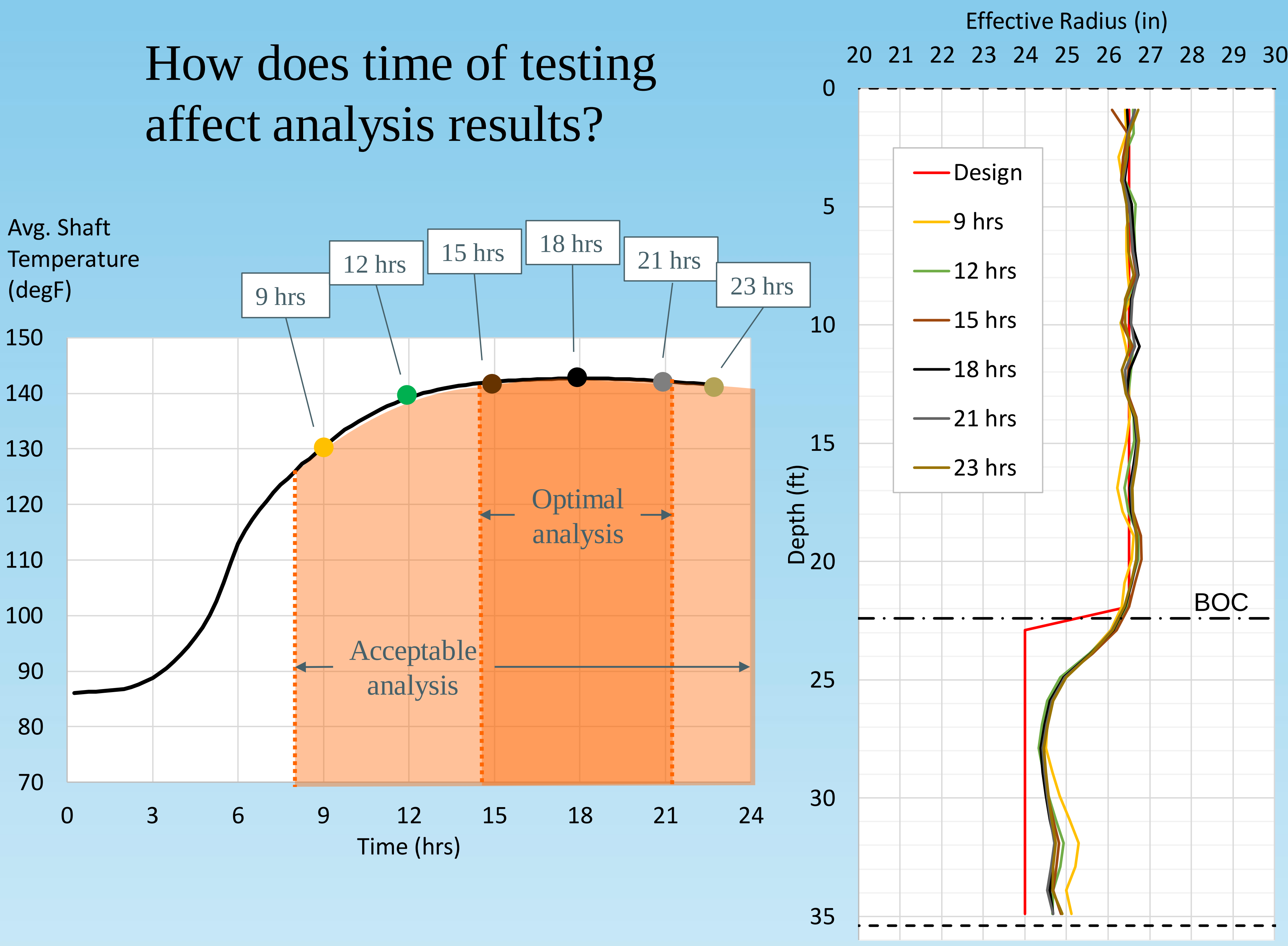
Z_0 = 11.4 ft
T_{max} = 144 °F
T_{min} = 126.5 °F
α = 1.25

<u>Bottom Roll-off</u>

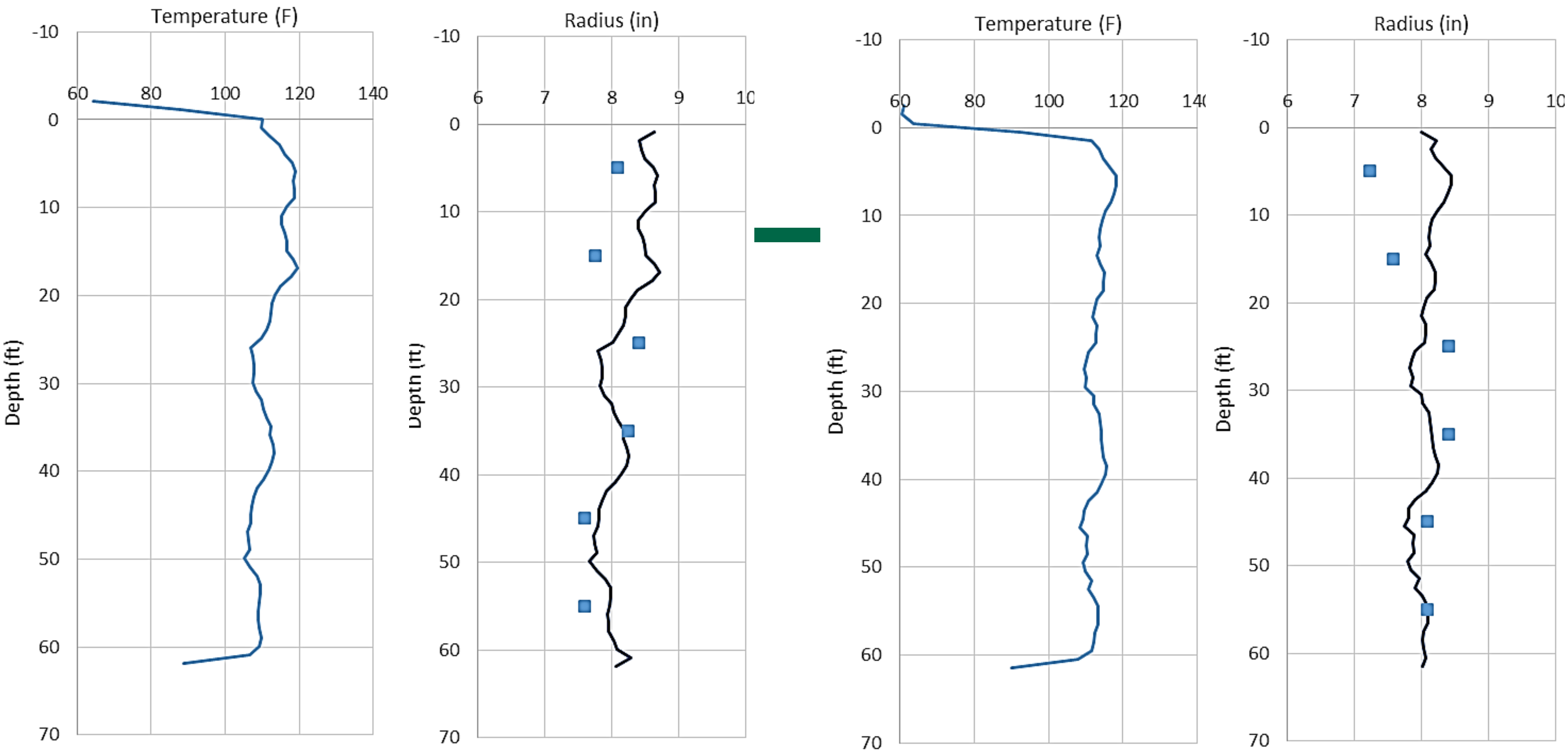
Z_0 = 35.7 ft
T_{max} = 117.5 °F
T_{min} = 55 °F
α = 1.33



How does time of testing affect analysis results?

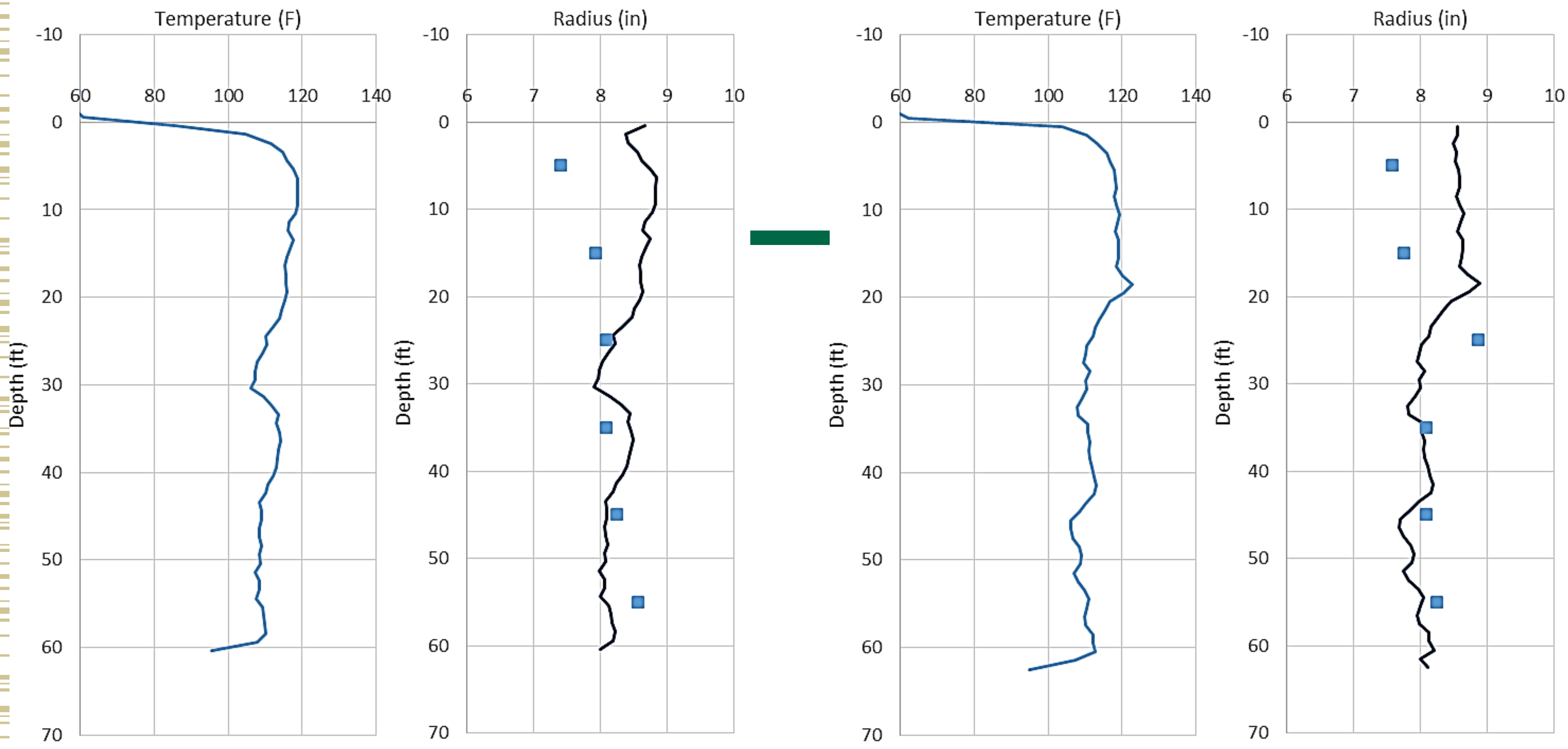


Case Study 3: 14” ACIP piles with a single wire on single center reinforcing bar



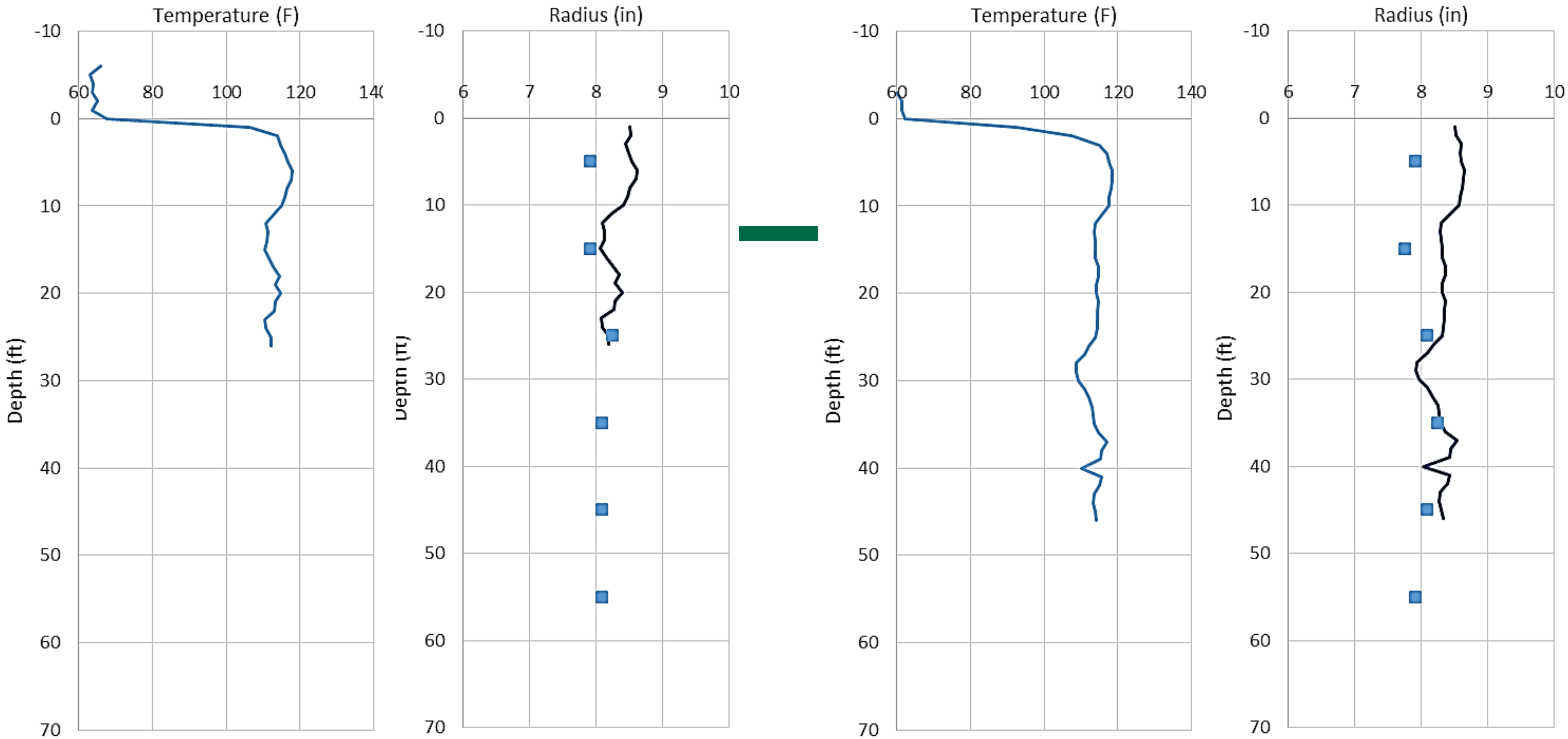
- Thermal data shows both top and bottom of pile
- Only subtle variations in temperature versus depth; no bar inclination evident
- Pump stroke computed radius generally agrees with predicted radius
- Integrity assessment reasonably successful; pile is good

Case Study 3: 14” ACIP piles with a single wire on single center reinforcing bar



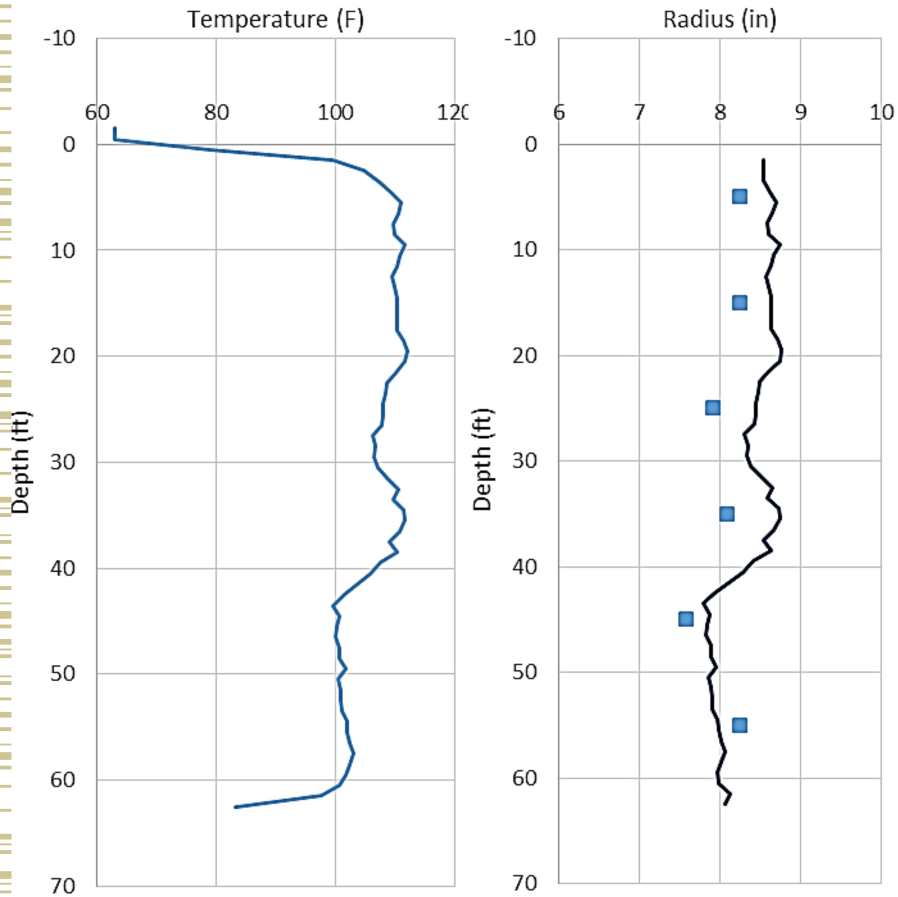
- Thermal data shows both top and bottom of pile
- Some variation in temperature with depth; bar inclination may be present
- Pump stroke computed radius generally agree with predicted radius
- Integrity assessment was reasonably successful; pile is good based on 7in nominal design radius and predicted effective radius exceeds that value throughout.

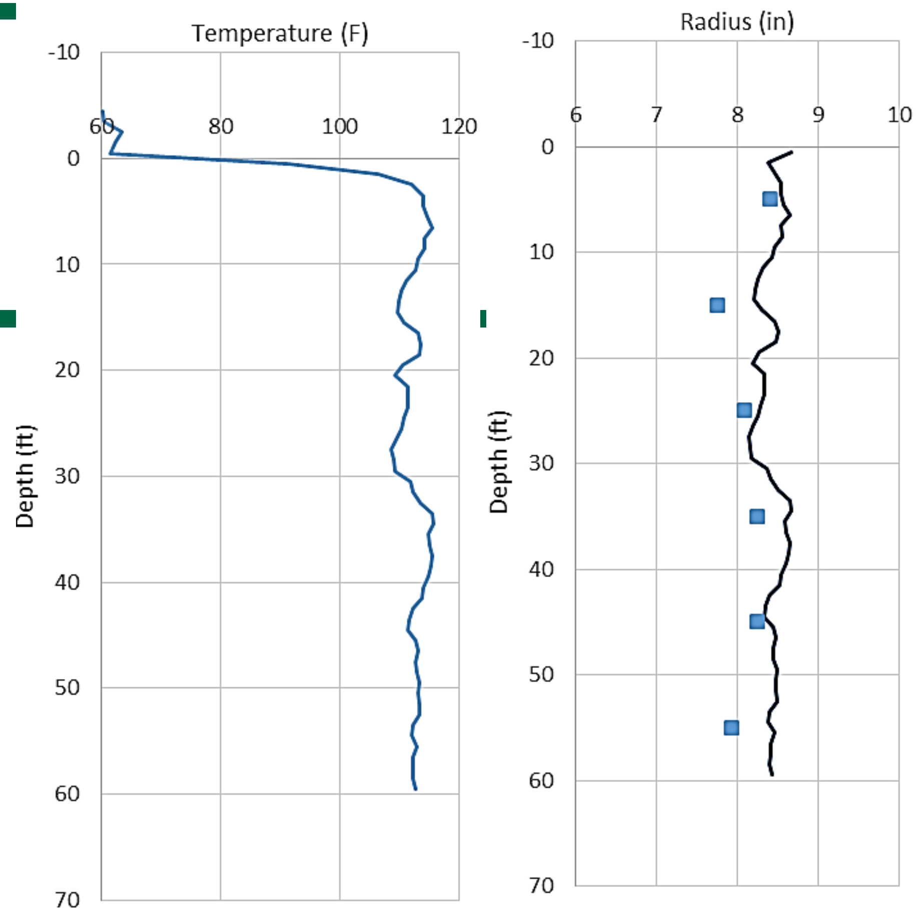
Case Study 3: 14” ACIP piles with a single wire on single center reinforcing bar



- Thermal data only shows top of pile which appears normal
- Only subtle variations in temperature versus depth for first 25ft (left) and 45ft (right); no bar inclination evident
- Pump stroke computed radius generally agrees with predicted radius
- Integrity assessment unsuccessful; broken wire prevented full analysis

Case Study 3: 14" ACIP piles with a single wire on single center reinforcing bar

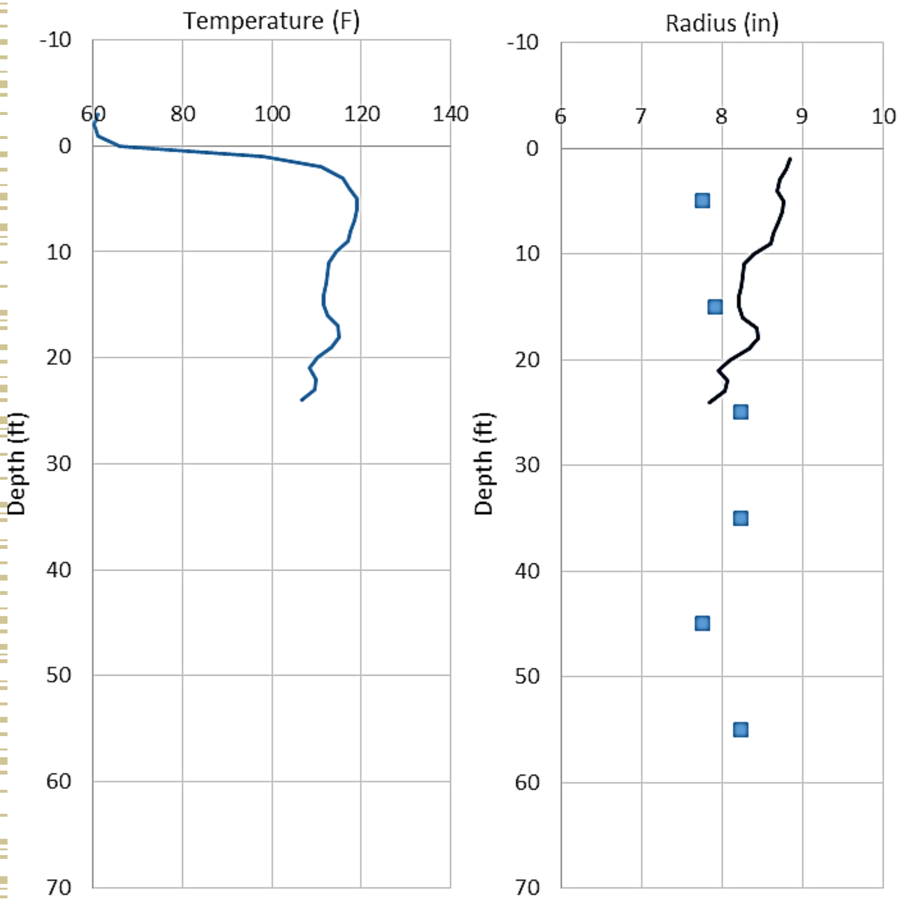


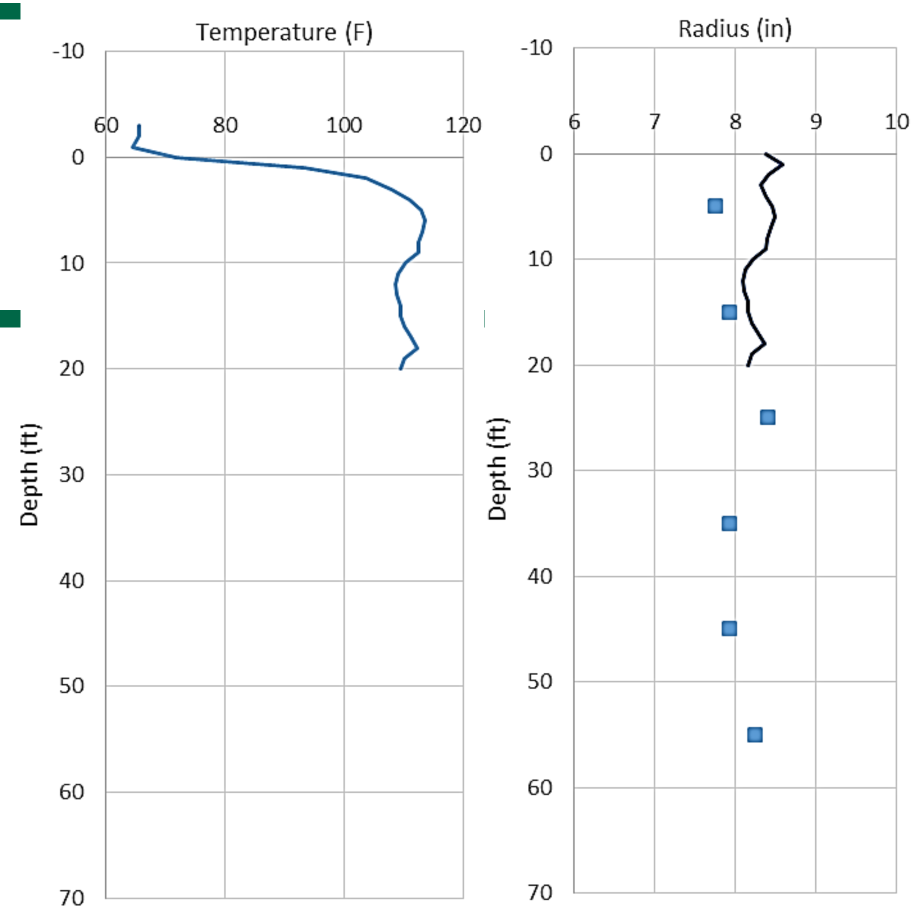


- Thermal data shows both top and bottom of pile
- Straight / vertical temperature profile; no bar inclination evident
- Small step in pile at 45ft; profile straight thereafter
- Pump stroke computed radius generally agrees with predicted radius
- Assessment reasonably successful; pile is good

- Thermal data shows top but not the bottom of pile
- Pile extends deeper than reinforcing bar (bottom most thermal sensor)
- Straight / vertical temperature profile; no bar inclination evident
- Pump stroke computed radius generally agrees with predicted radius
- Assessment reasonably successful; pile is good

Case Study 3: 14” ACIP piles with a single wire on single center reinforcing bar

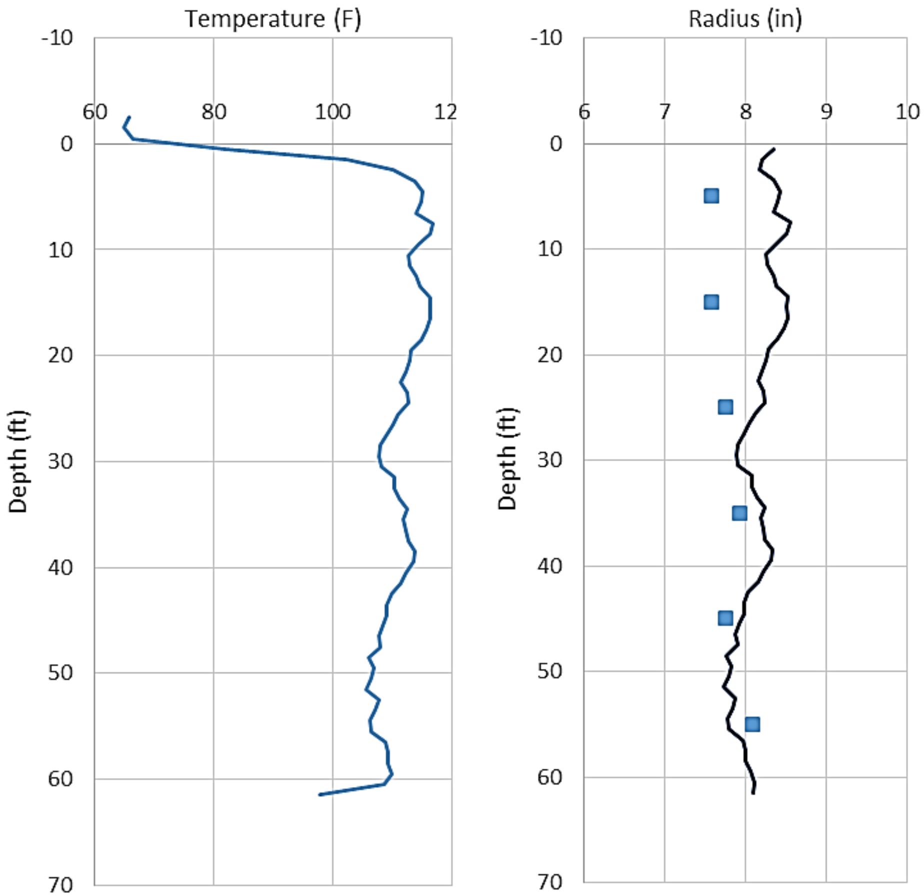




- Thermal data only shows top of pile which appears normal
- Variations in temperature versus depth for first 25ft; may indicate bar inclination
- Pump stroke computed radius versus predicted radius inconclusive
- Integrity assessment unsuccessful; broken wire prevented full analysis

- Thermal data only shows top of pile which appears normal
- Only subtle variations in temp vs depth for first 20ft; no apparent bar inclination over that depth
- Pump stroke computed radius versus predicted radius inconclusive
- Integrity assessment unsuccessful; broken wire prevented full analysis

Case Study 3: 14” ACIP piles with a single wire on single center reinforcing bar



- Thermal data shows both top and bottom of pile
- Straight / vertical temperature profile; no bar inclination evident
- Pump stroke computed radius generally agrees with predicted radius
- Integrity assessment reasonably successful; pile is good