Thermal Integrity Profiling

Quality Assurance Test Method to Detect Drilled Shaft Defects

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AFS30 Committee Meeting, TRB 2011

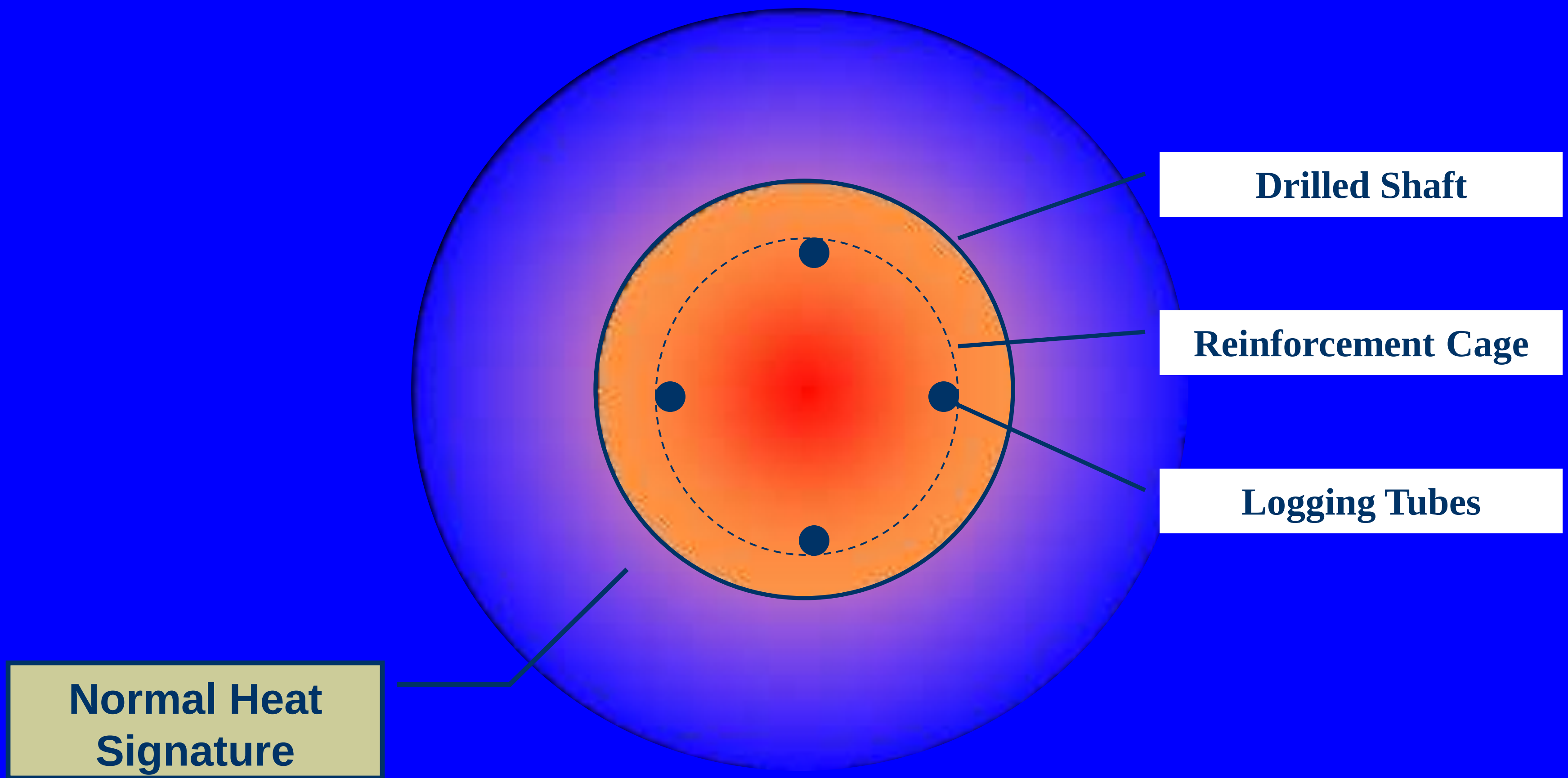
Pile Dynamics, Inc.

F G E

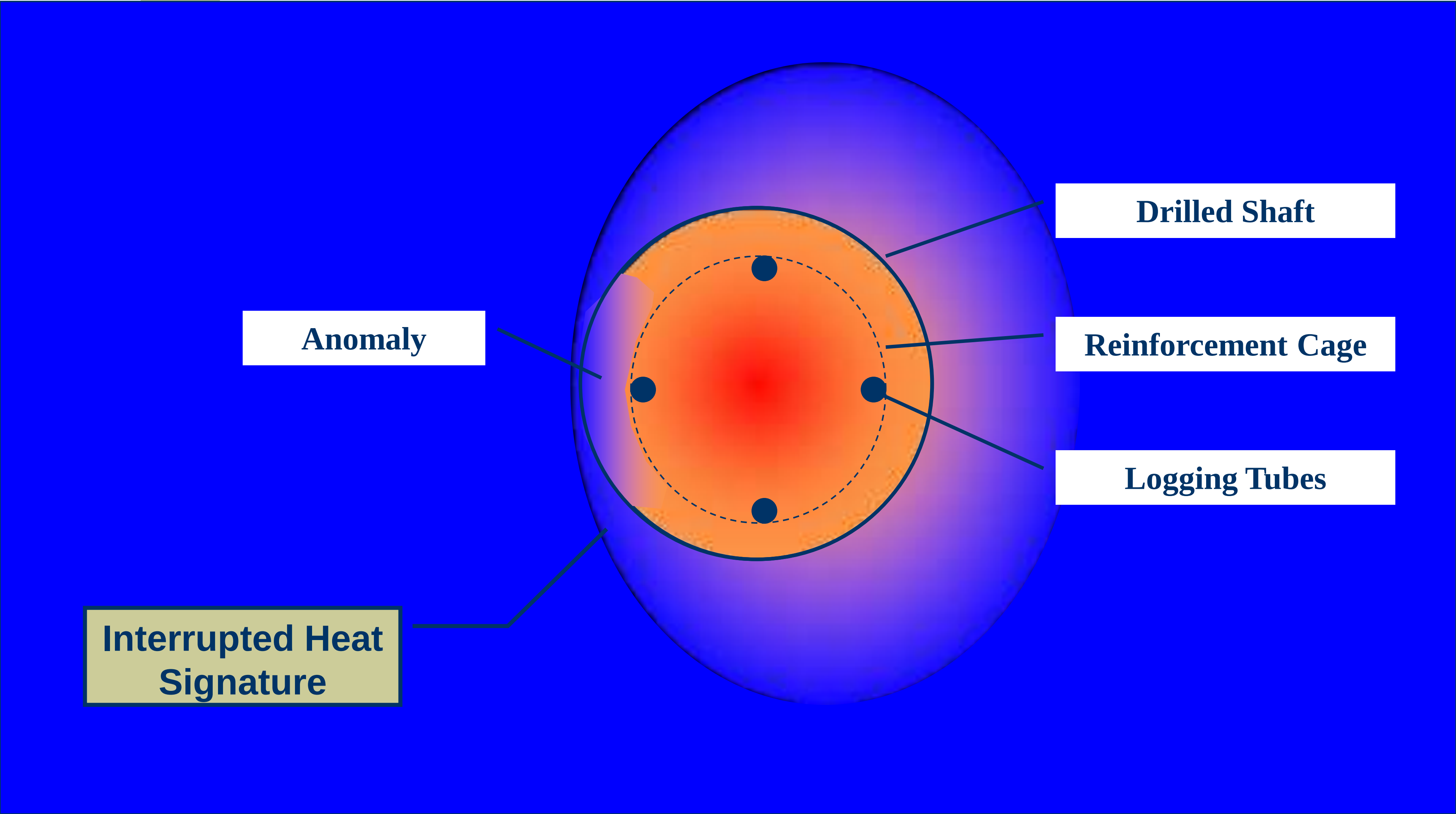
Overview

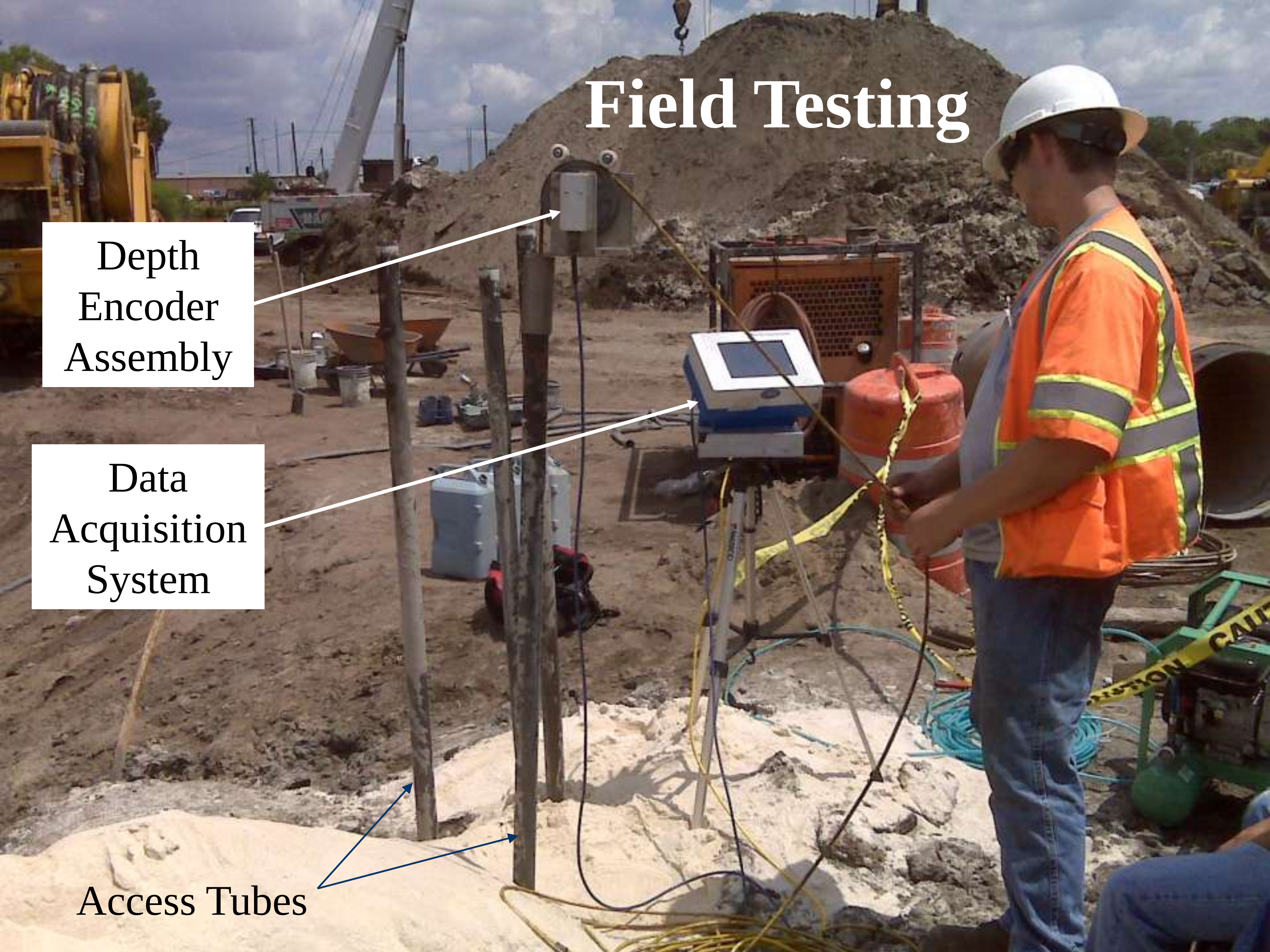
- Thermal Integrity Profiling uses the measured internal shaft temperature generated by hydrating concrete to assess the presence or absence of intact concrete.
- The energy produced in one 9 yd truck of concrete is equivalent to 450 lbs of TNT.

Thermal Integrity Profiling



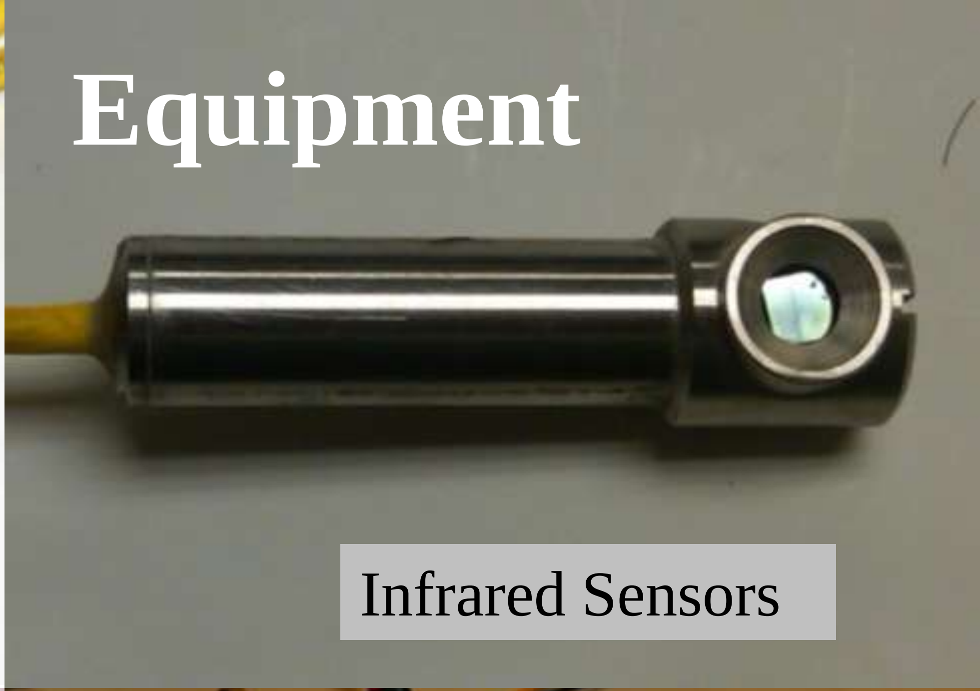
Thermal Integrity Profiling



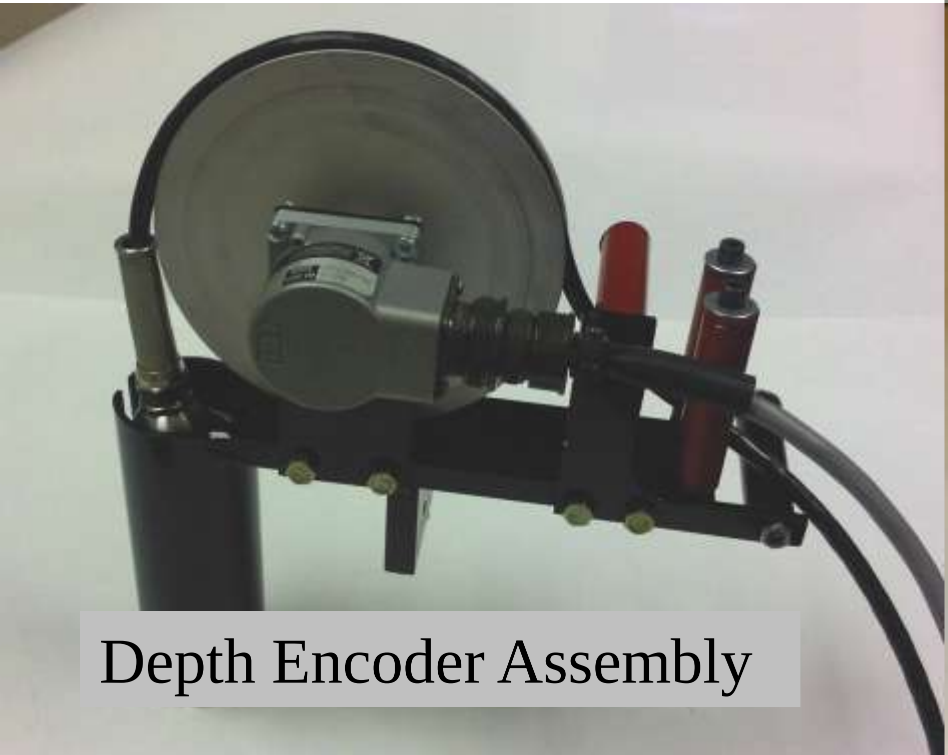

Field Testing
Depth Encoder Assembly
Data Acquisition System
Access Tubes

Equipment

Thermal Probe



Infrared Sensors



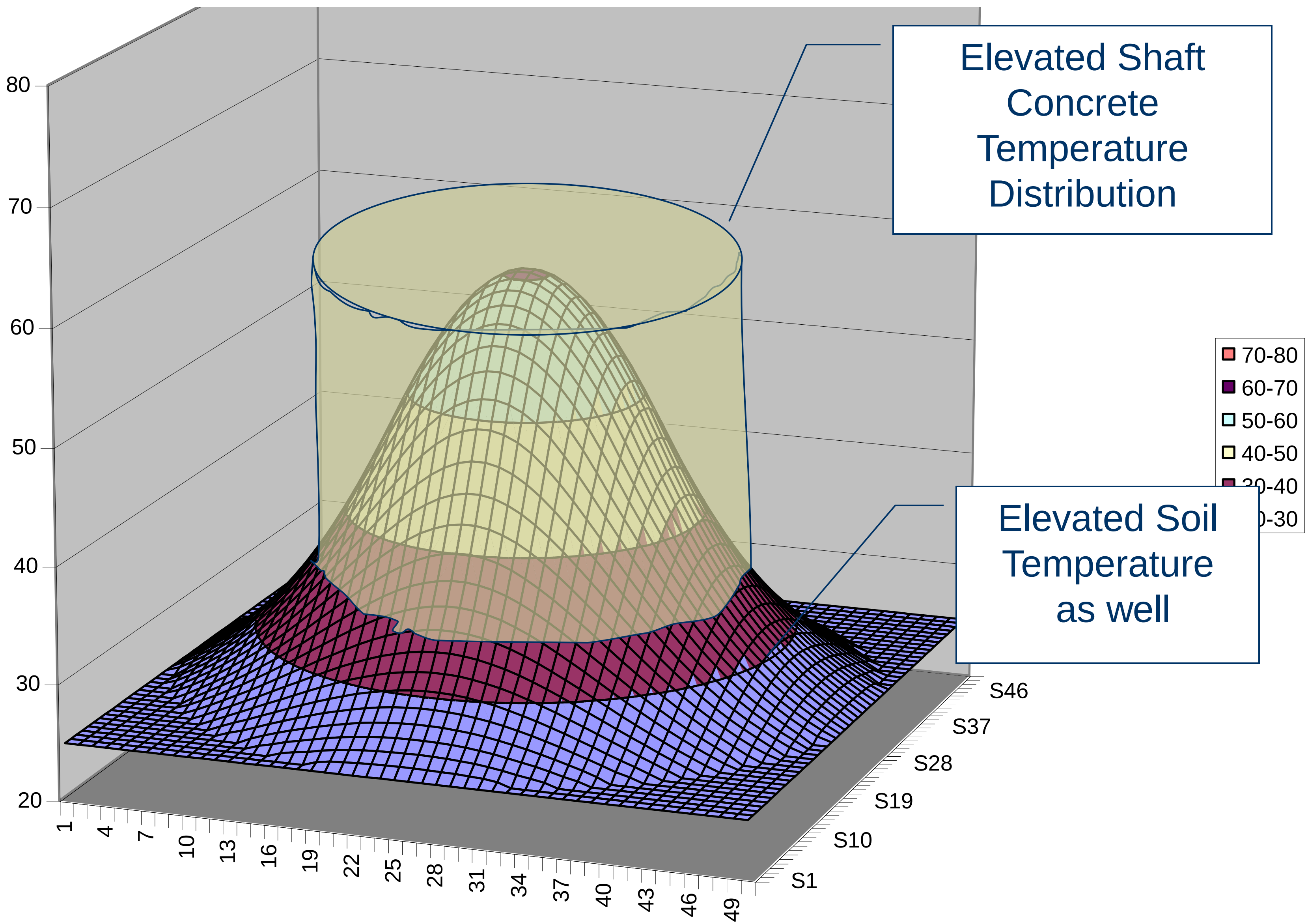
Depth Encoder Assembly

Data Acquisition System

Analysis

- Internal temperature measurements are sensitive to necking, bulging, inclusions, and cage alignment.
- The available time of testing is dictated by the shaft diameter and mix design.
  - The timeframe for testing (in days) equals the diameter (in feet).
  - High slag content mixes extend testing time.

Single Shaft Heat Signature

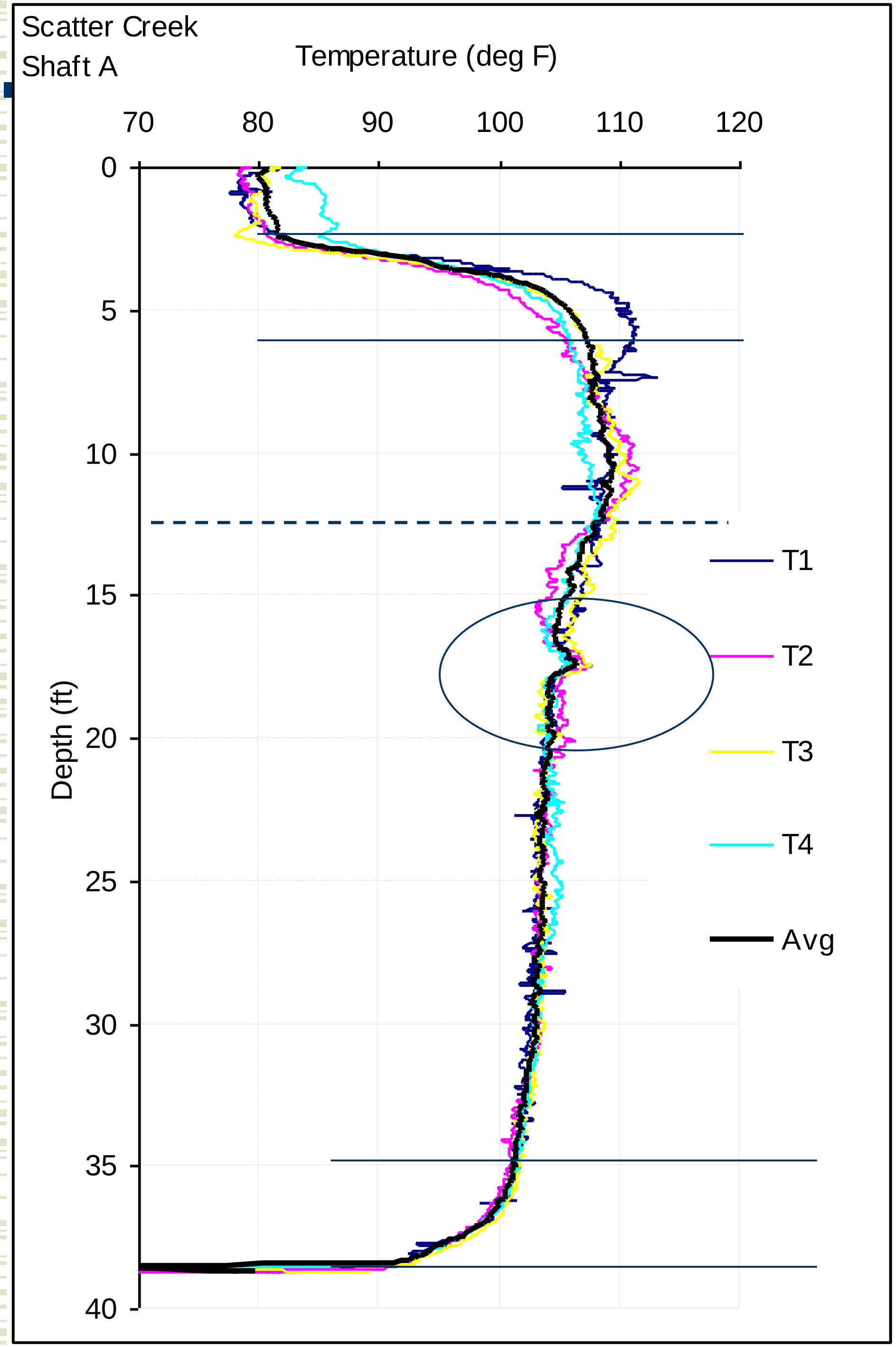


Levels of Analysis

- Level 1
  - Direct Observation of Temperature Profiles
- Level 2
  - Superimposed Construction Logs / Concrete Yield
- Level 3
  - 3-D Thermal Modeling
- Level 4
  - Signal Matching
- Additional / Optional
  - Inclination Measurements

Level 1: Direct Observation (Field)

- Identify top and bottom of shaft
- Verify shaft length
- Confirm cage alignment
- Locate changes in shaft diameter
- Locate immediate areas of concern



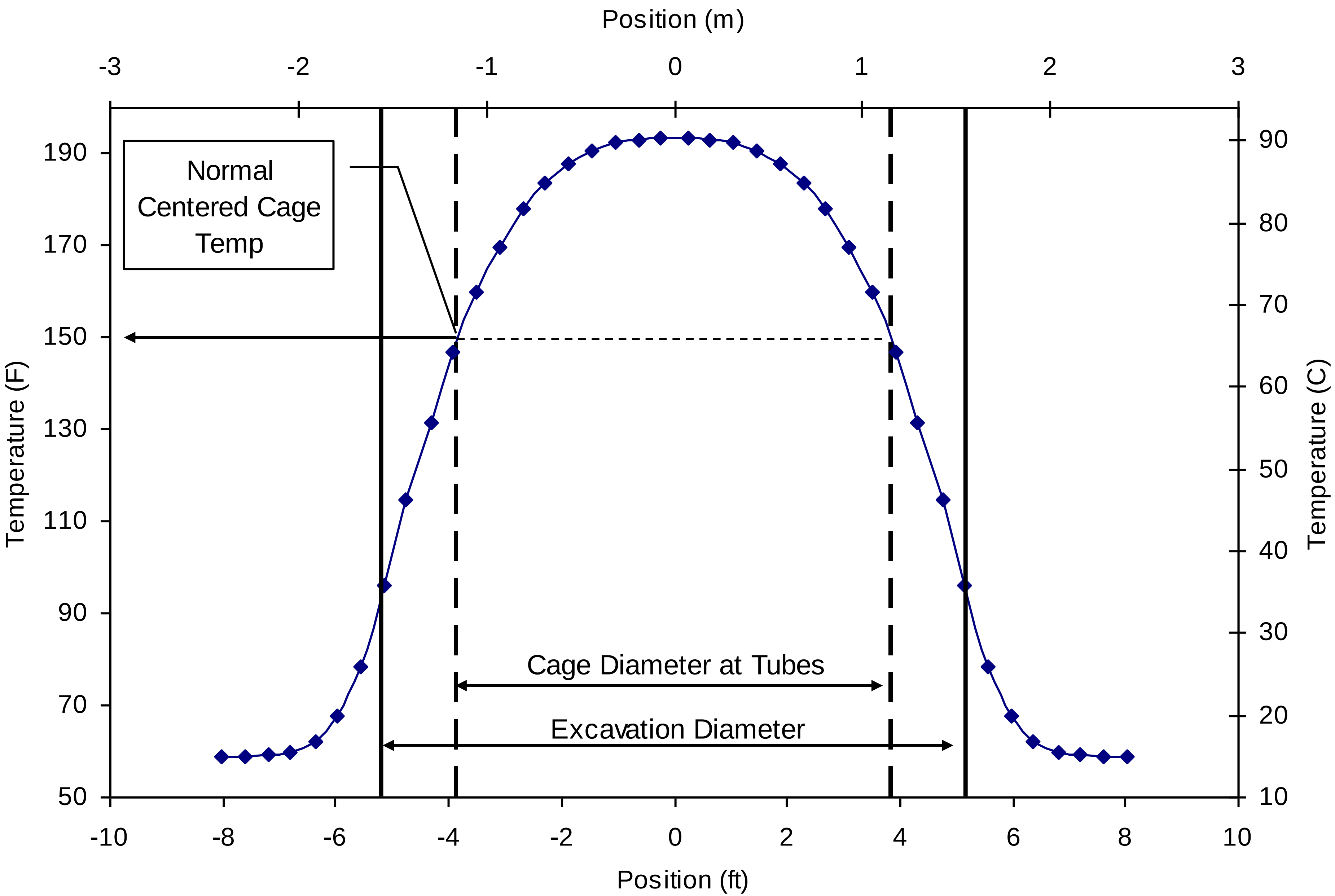
Field Observations

- Little to no cage eccentricity *(all tubes same temp throughout)*
- Water table at 17-18' *(causes sloughing until slurry is fully in place)*
- Bottom of casing at 12-13'
- Clean top and toe signature *(approximate 1 diameter temperature roll-off top and bottom)*
- Good Shaft

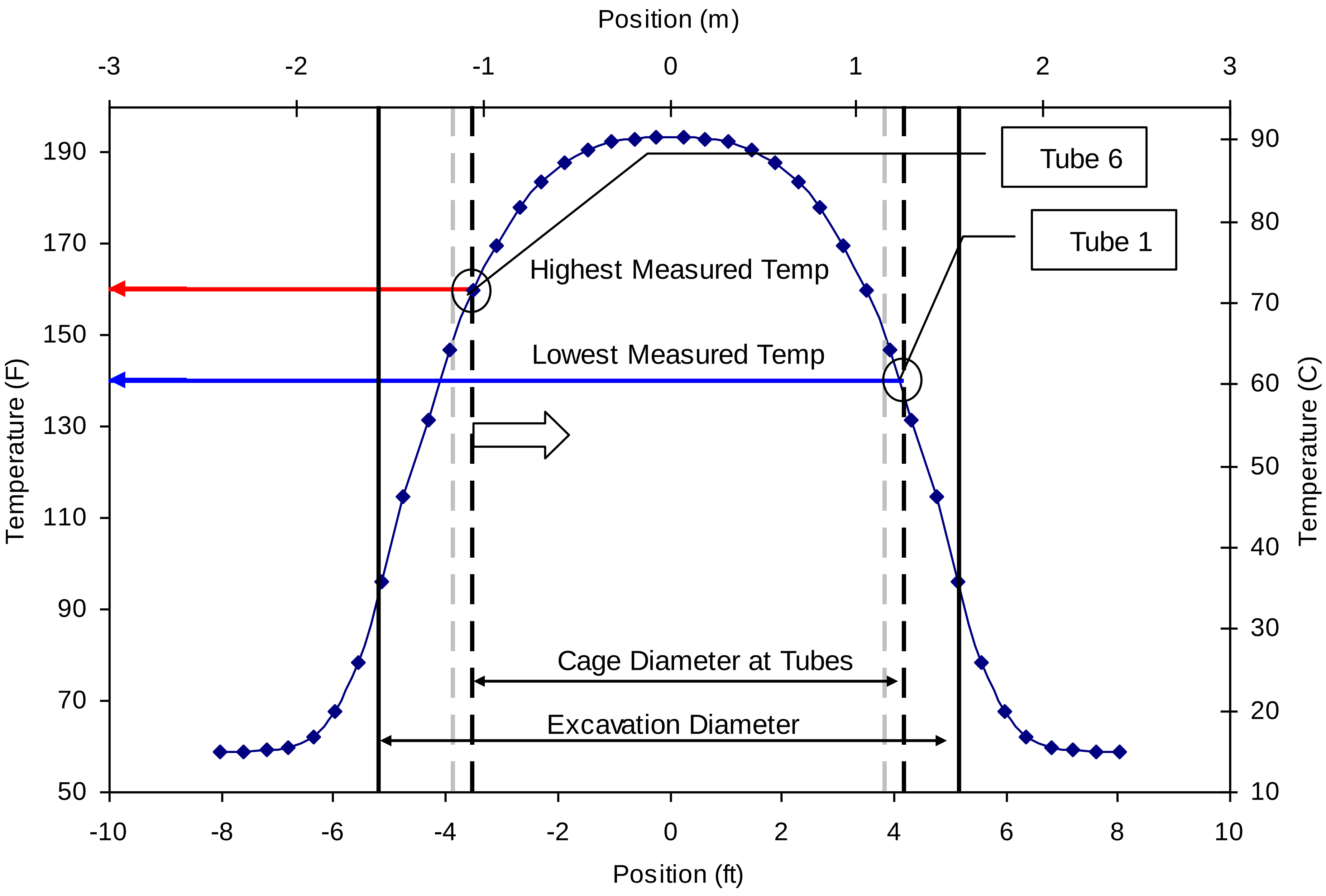
Cage Alignment (Level 1)

- All tubes have same temperature when cage is concentric.
- A normal cylindrical shaft with an offset cage is shown as equally higher and lower temperatures on opposite sides of cage.
- Average of all tubes represents the centered cage temperature

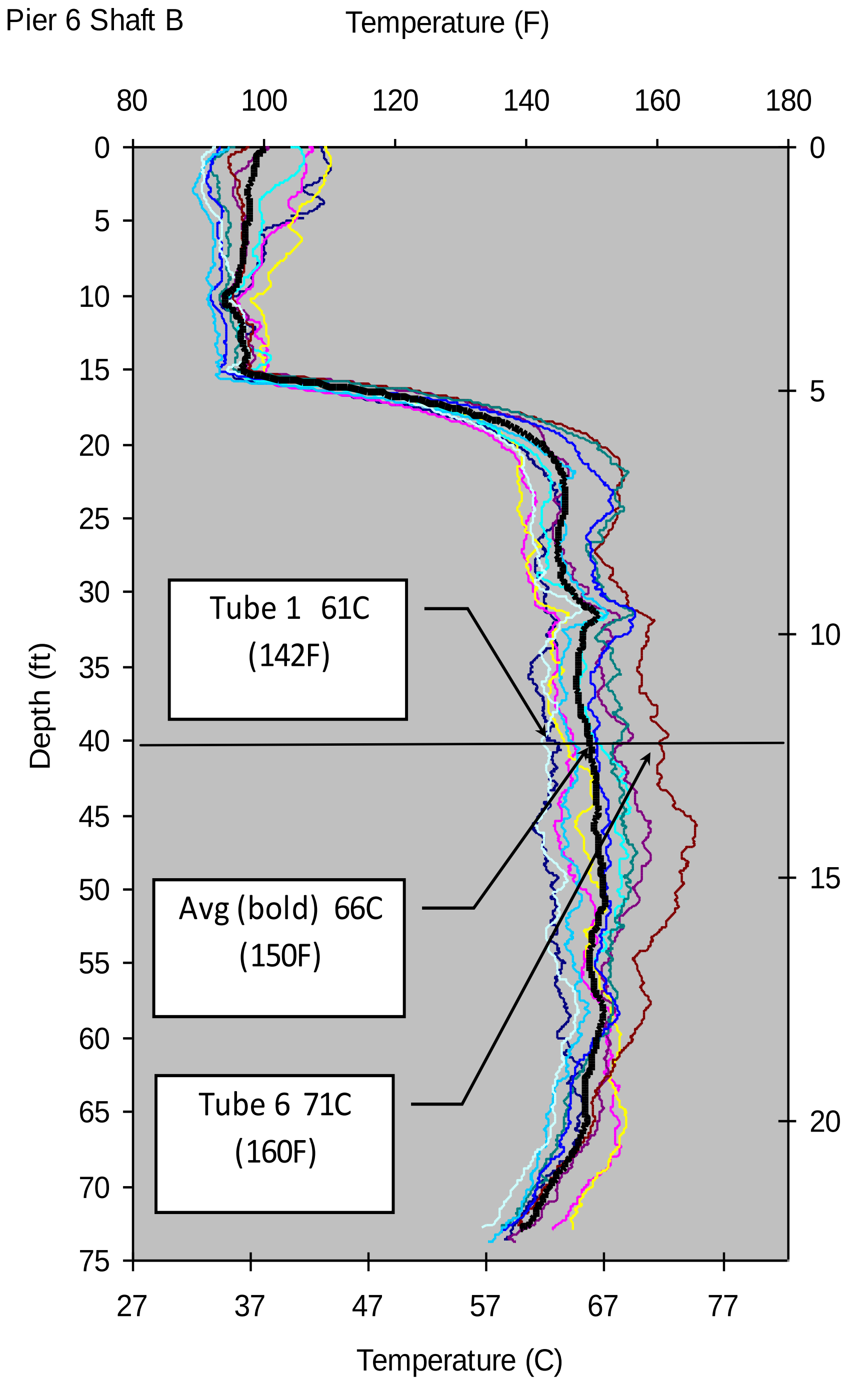
Temperature Distribution (10 ft diameter shaft)

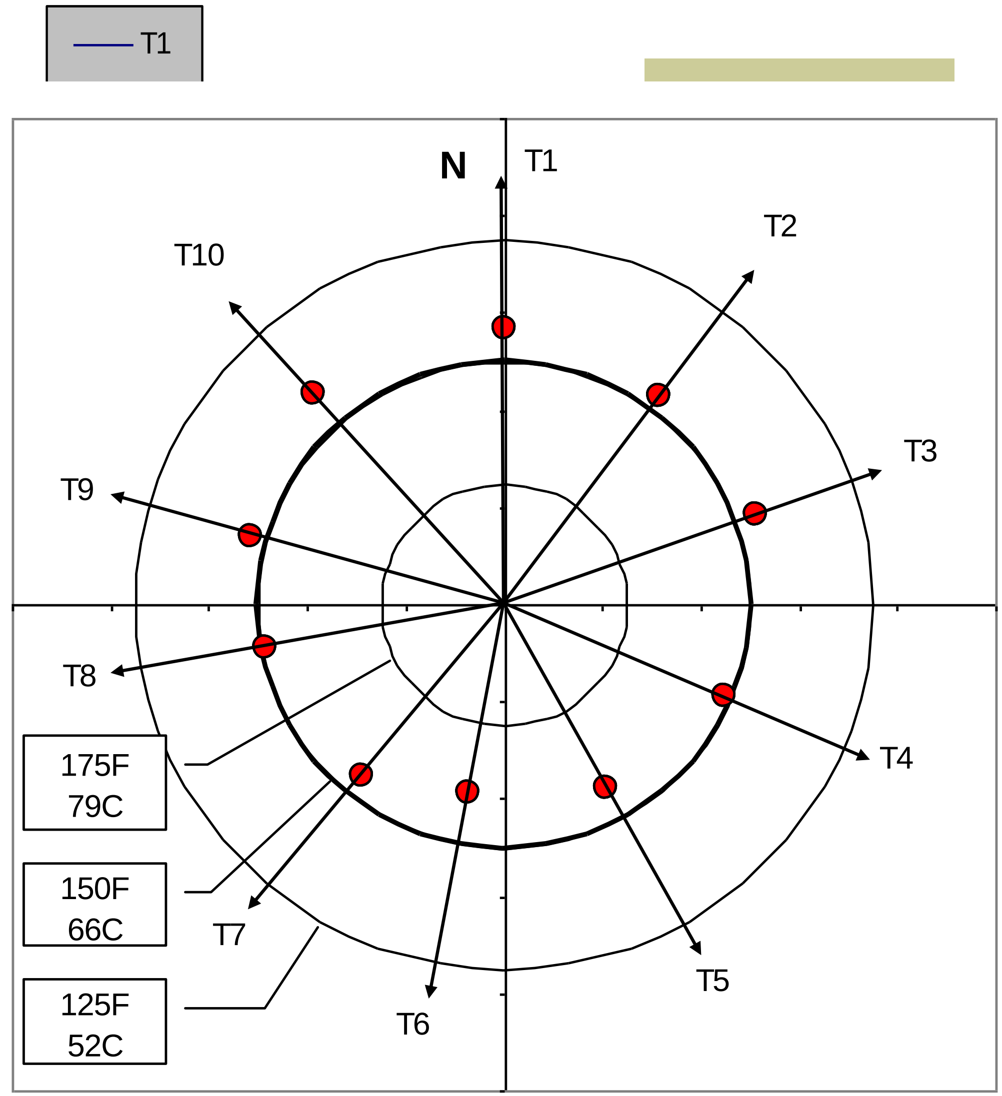


Effect of Cage Misalignment



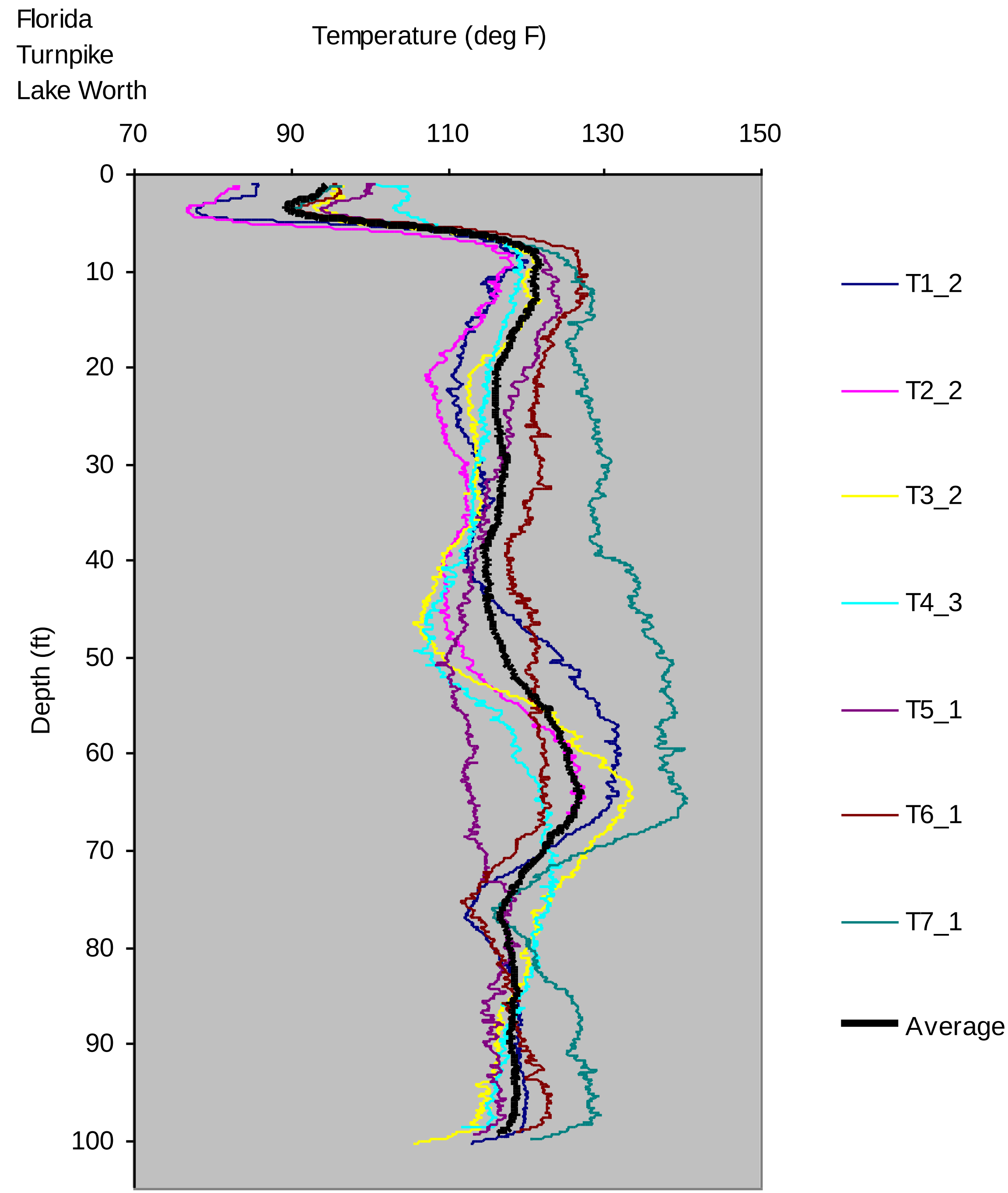
Cage Alignment





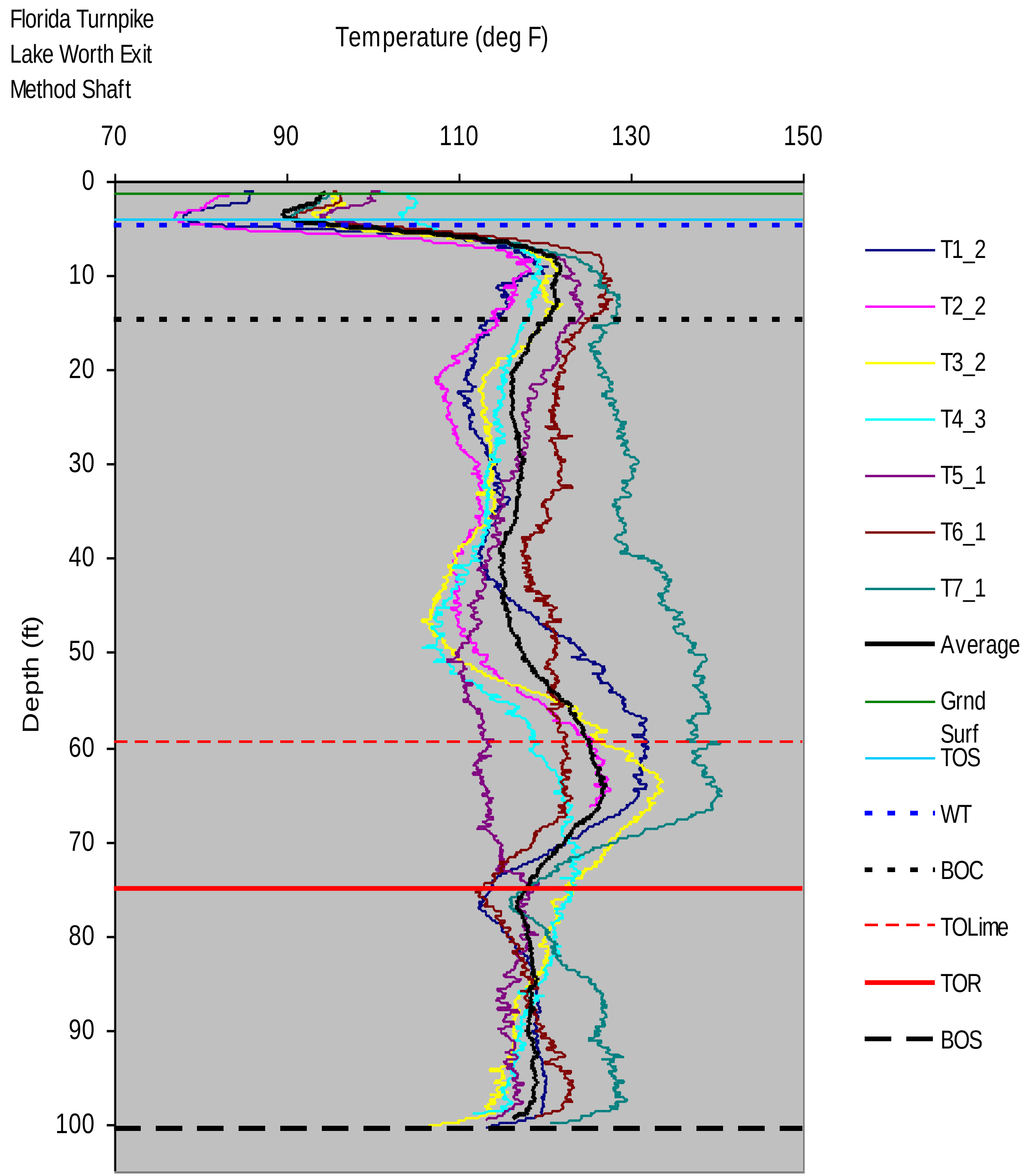
Level 2: Added Field Records

- Confirm direct observations
- Establish relationship between concrete volume placed and measured temperature
- Predict as-built shaft radius, shape, and cover
- Correlate soil strata to thermal conductivity and observe influence on less prominent temperature fluctuations



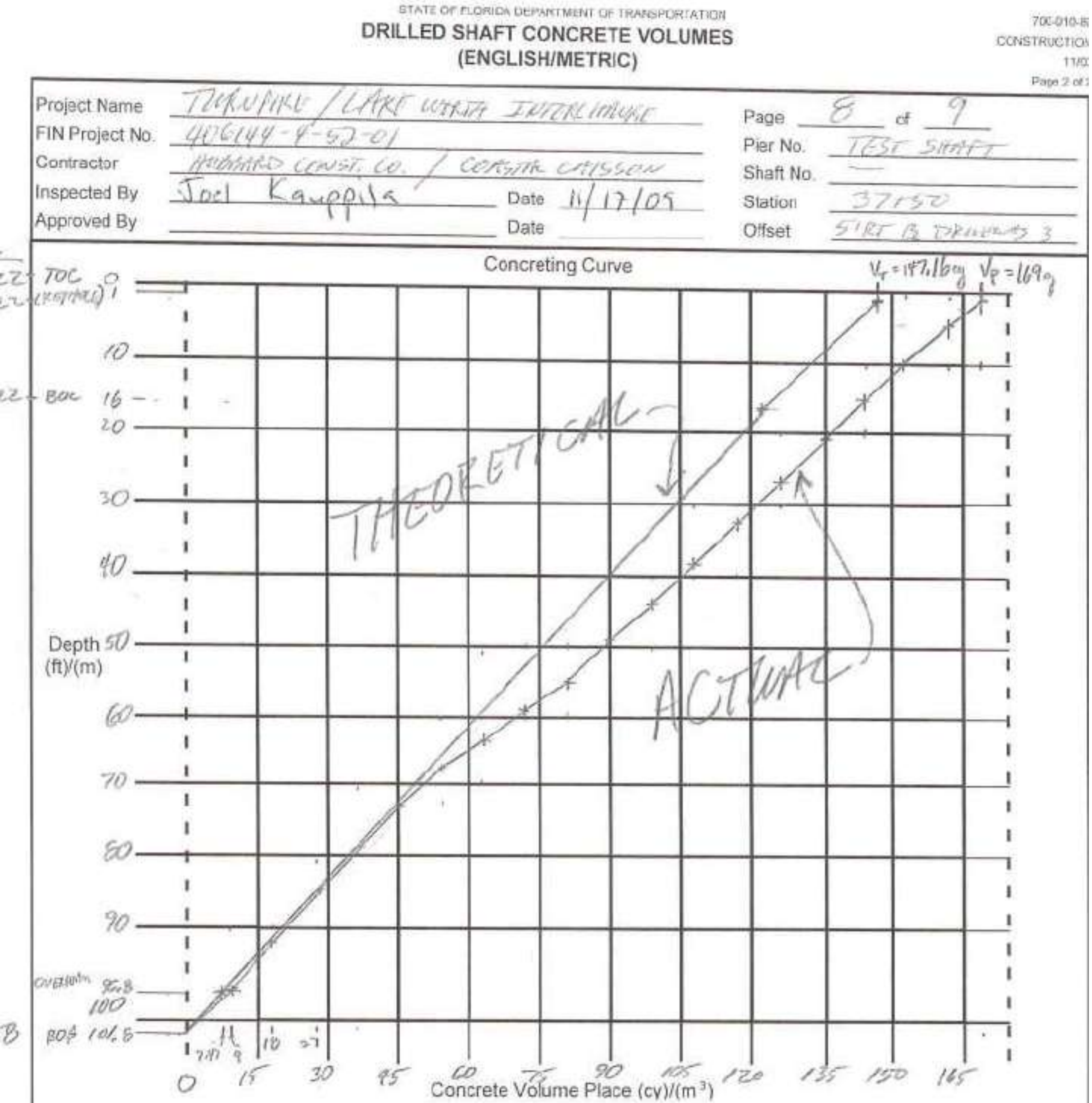
Level 1 Observations

- Cage misaligned *(tube temps vary across shaft)*
- Avg. shows shape
- Probable rock socket 75ft *(step in shaft temp; less eccentricity)*
- Clean top and toe signature
- Upper step / temporary casing at 14 ft
- Need Level 2 Information



Confirm Observations

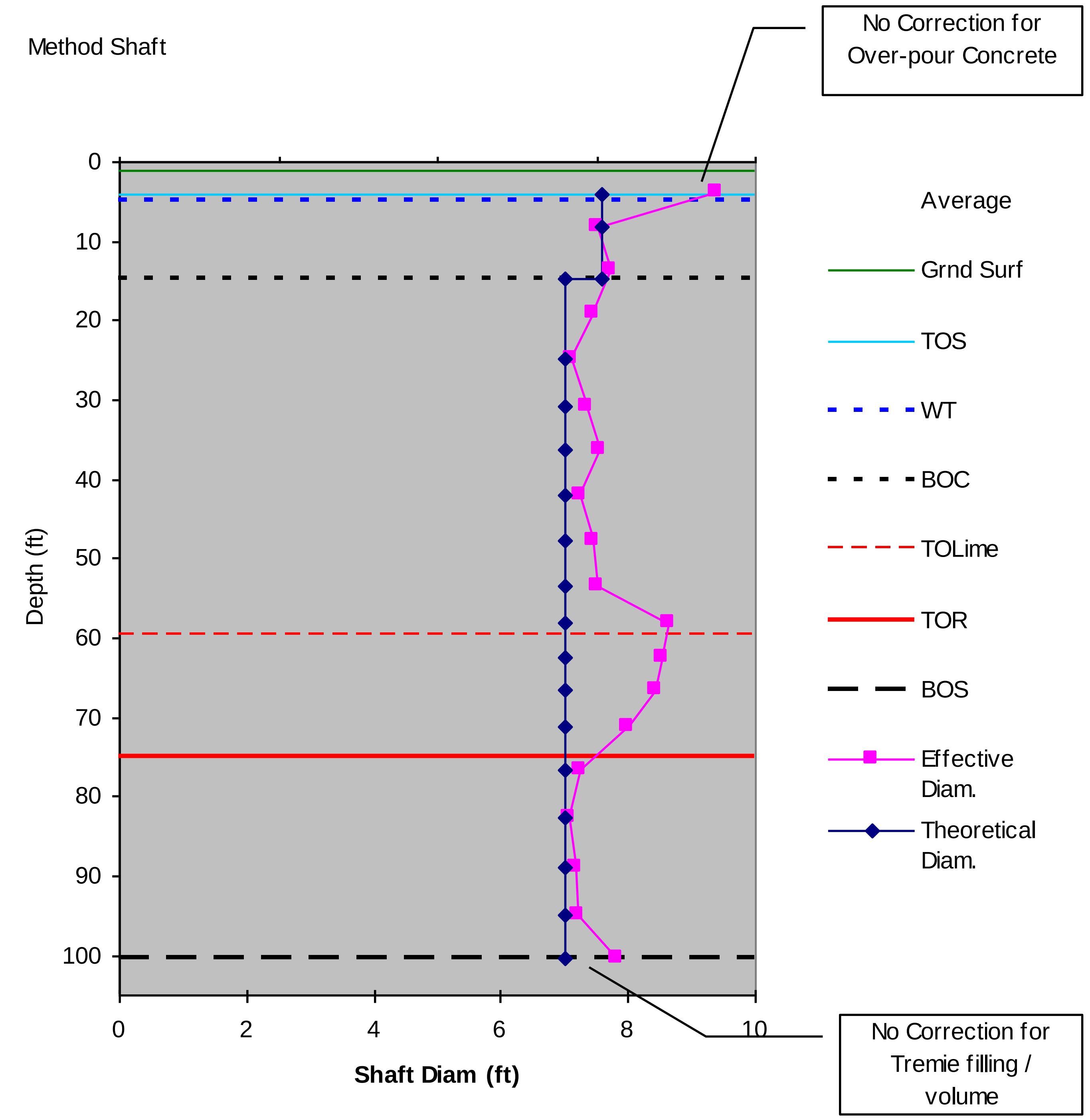
- Add const. log info
  - Top of shaft
  - Grnd surface
  - Water table
  - Bot of casing
  - Top of limestone
  - Top of good rock
  - Bot of shaft
- Add concrete yield information



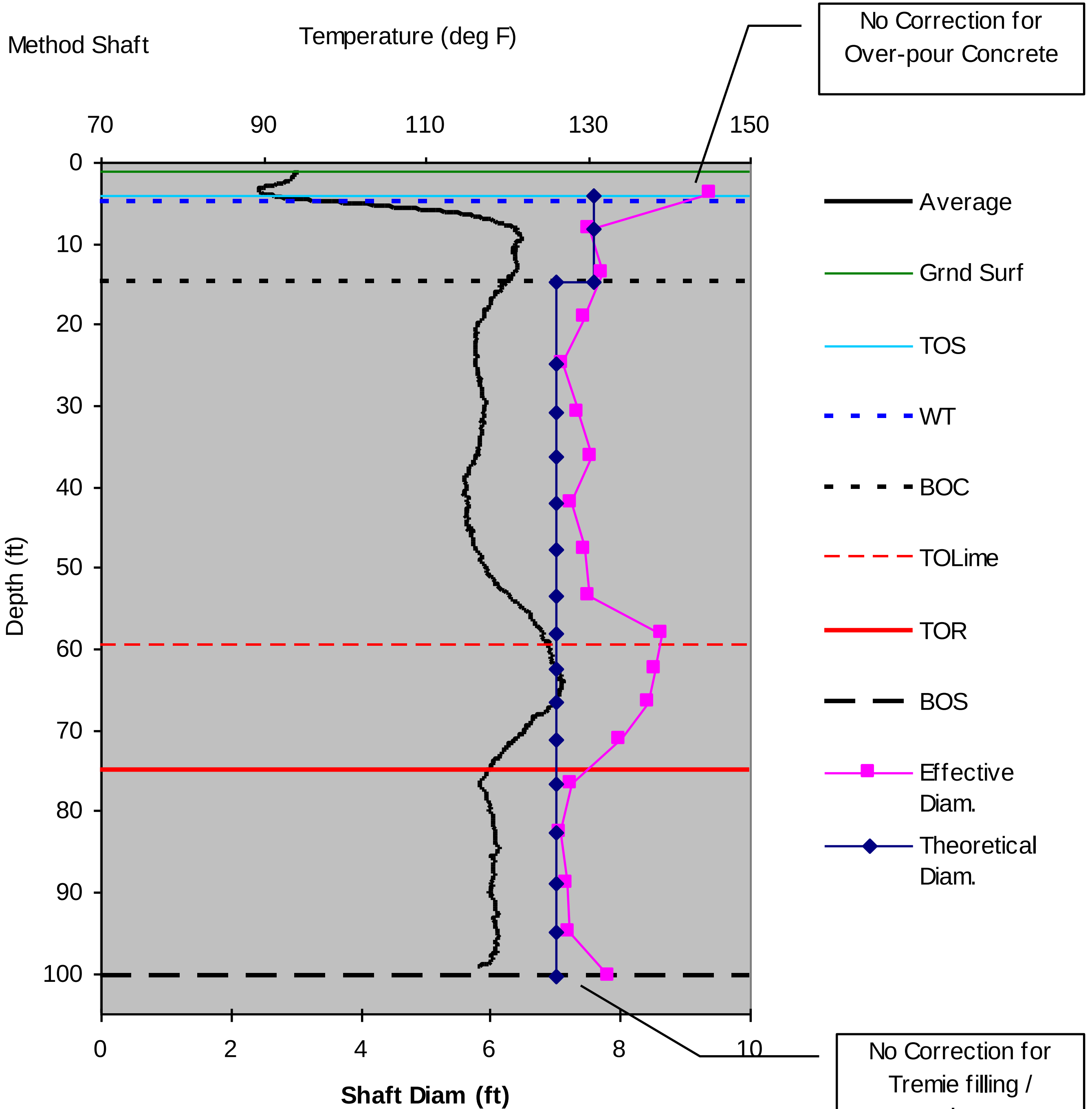
Concrete Yield Plots

- Depth change per truck
- Volume per truck
- Convert to avg diam or radius per truck

Concrete Yield to Diam Plot



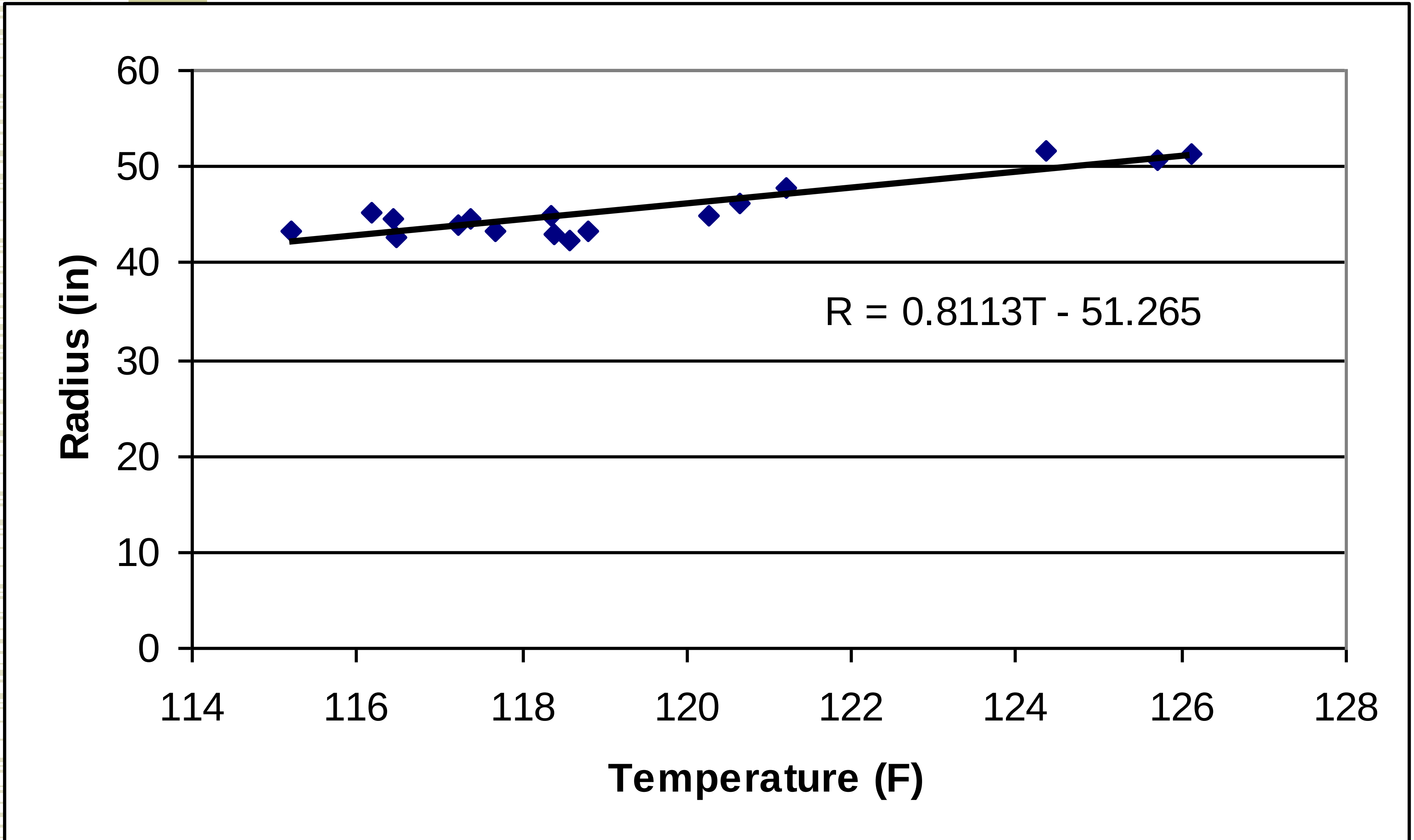
- Plot theoretical diam or radius
- Top and bottom truck weakest information

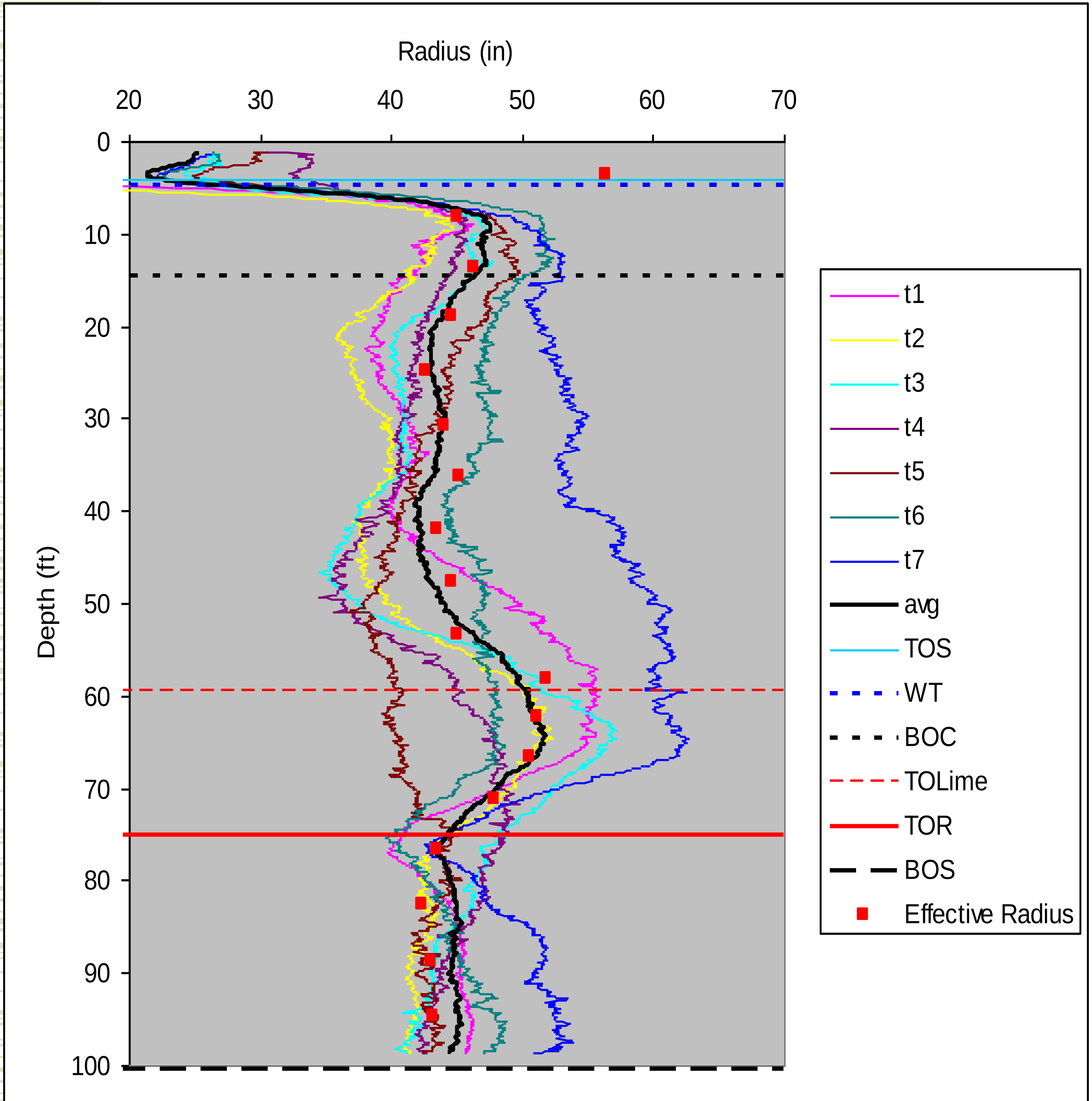


Temp / Diam Correlation

- Shape of avg. profile mimics diameter from concrete yield
- Average temp. is determined for a given truck yield (diam.)
- Results plotted to establish correlation

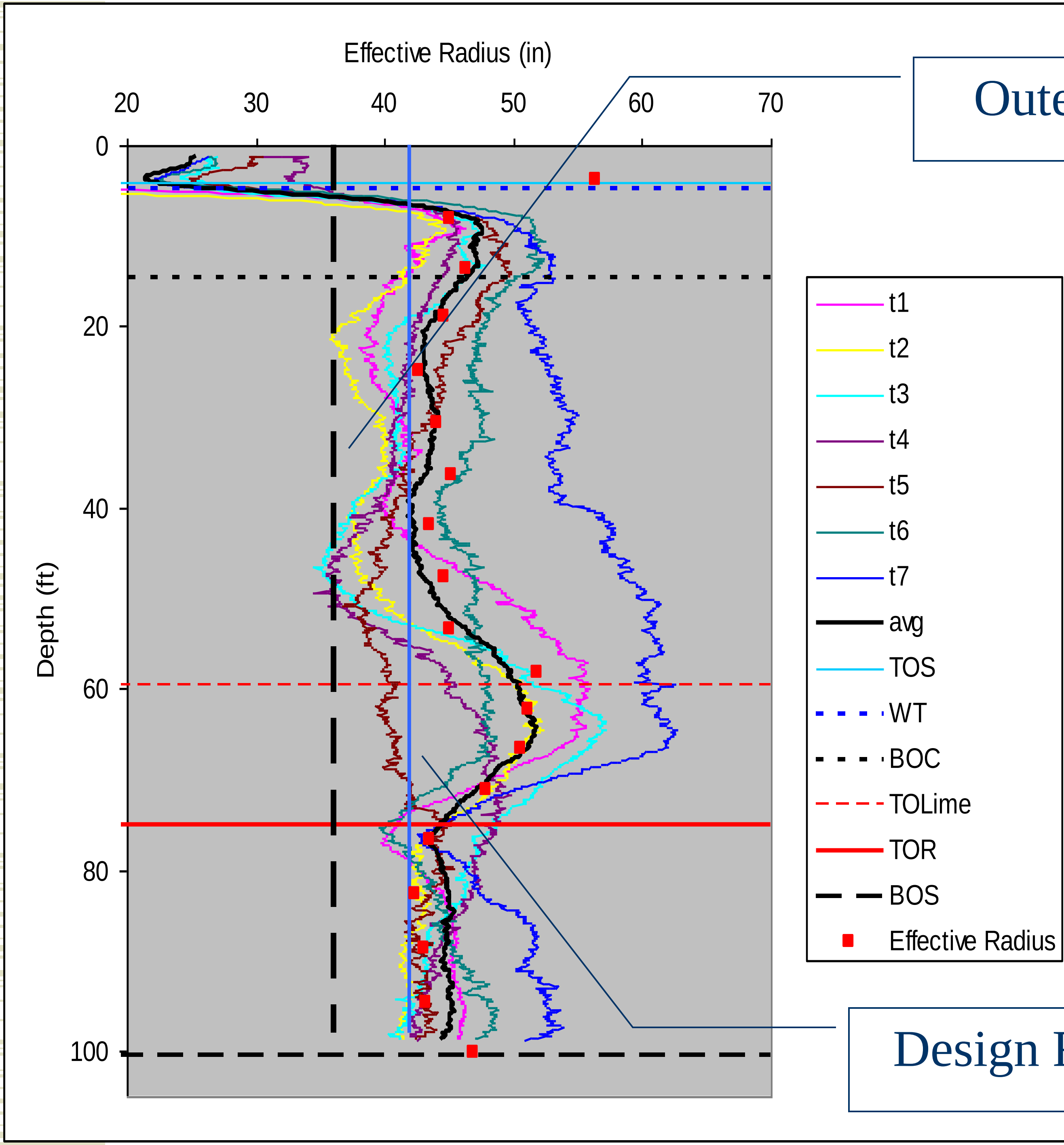
Temperature to Radius Conversion





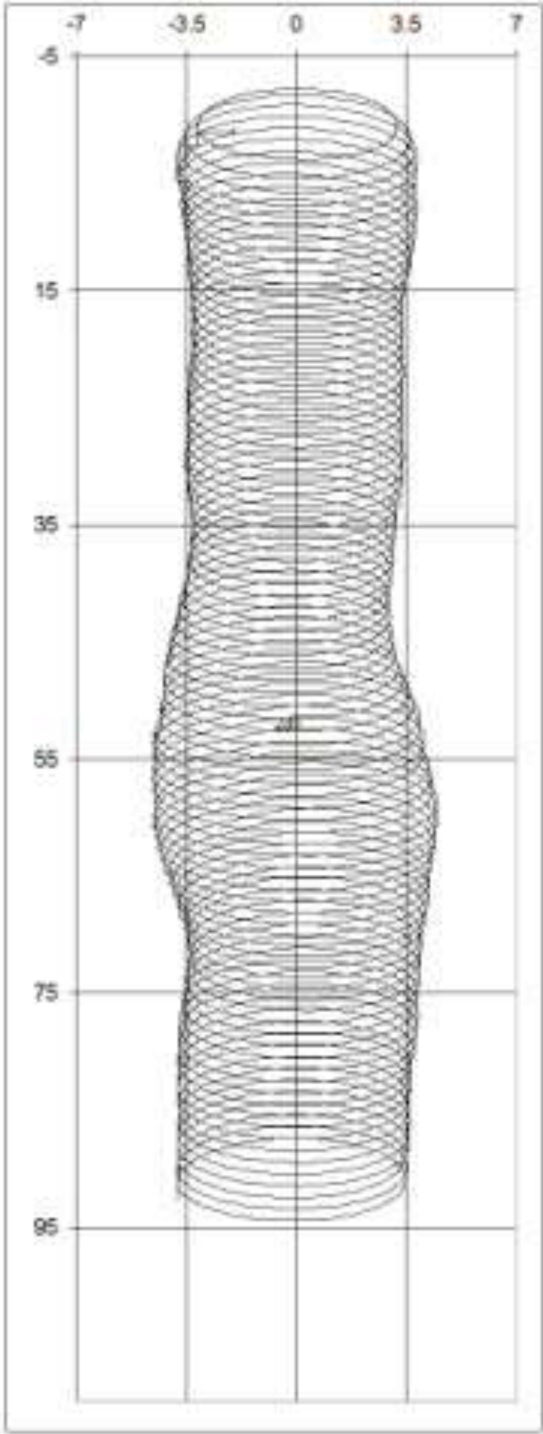
Individual Tube Positions

- Good agreement with yield plot information
- Check tube / cage cover

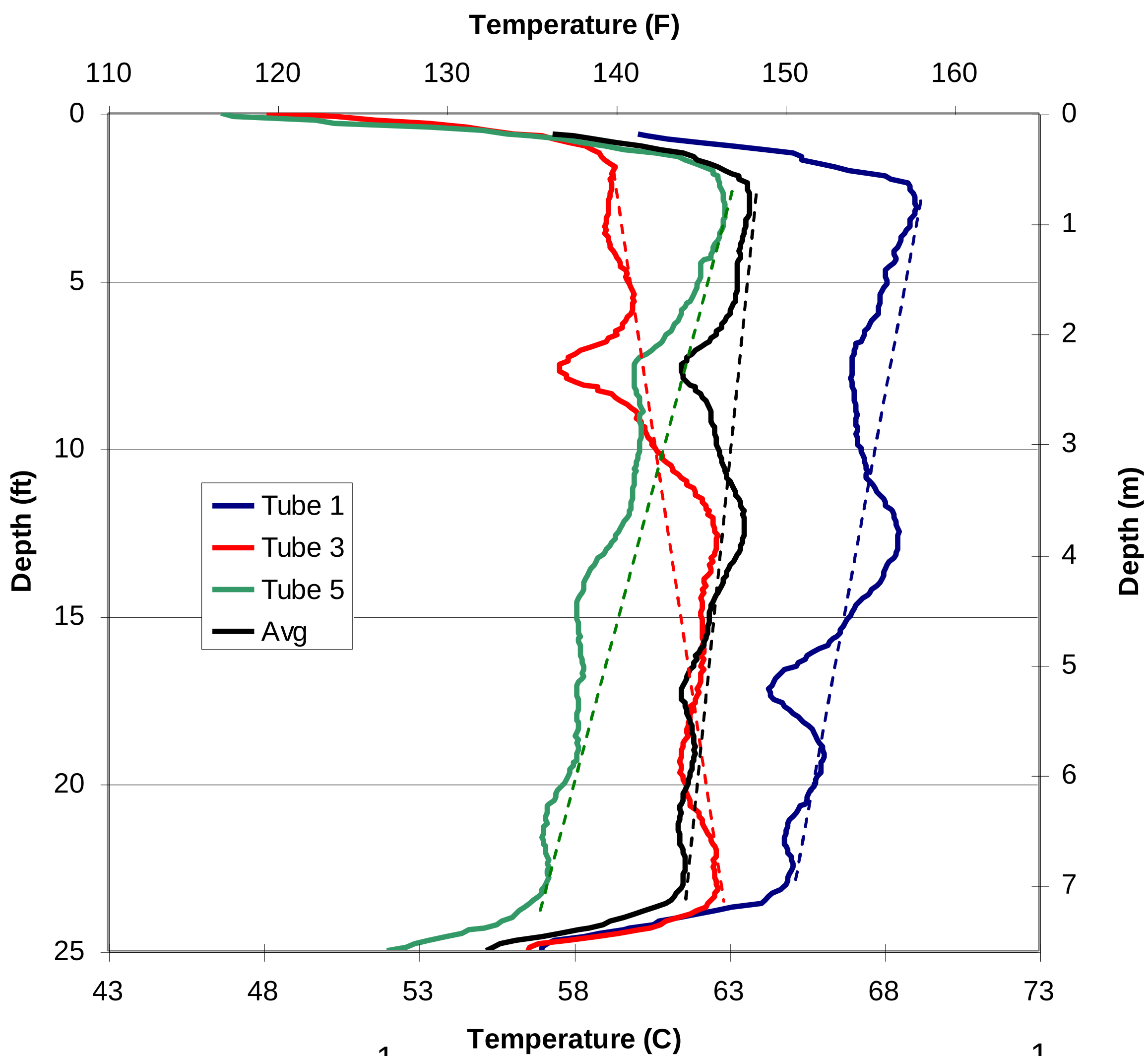


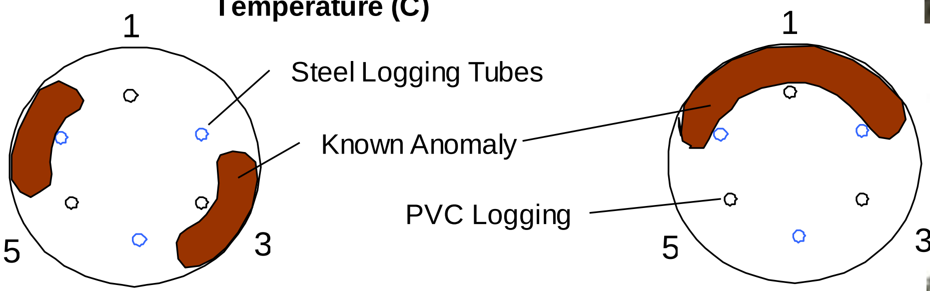
Individual Tube Positions

- Check tube / cage cover
- Three tubes touch side walls others with reduced cover



-7
-3.5
0
3.5
7
-5
15
35
55
75
95





Cross-Section A
Top Anomaly

Cross-Section B
Bottom Anomaly

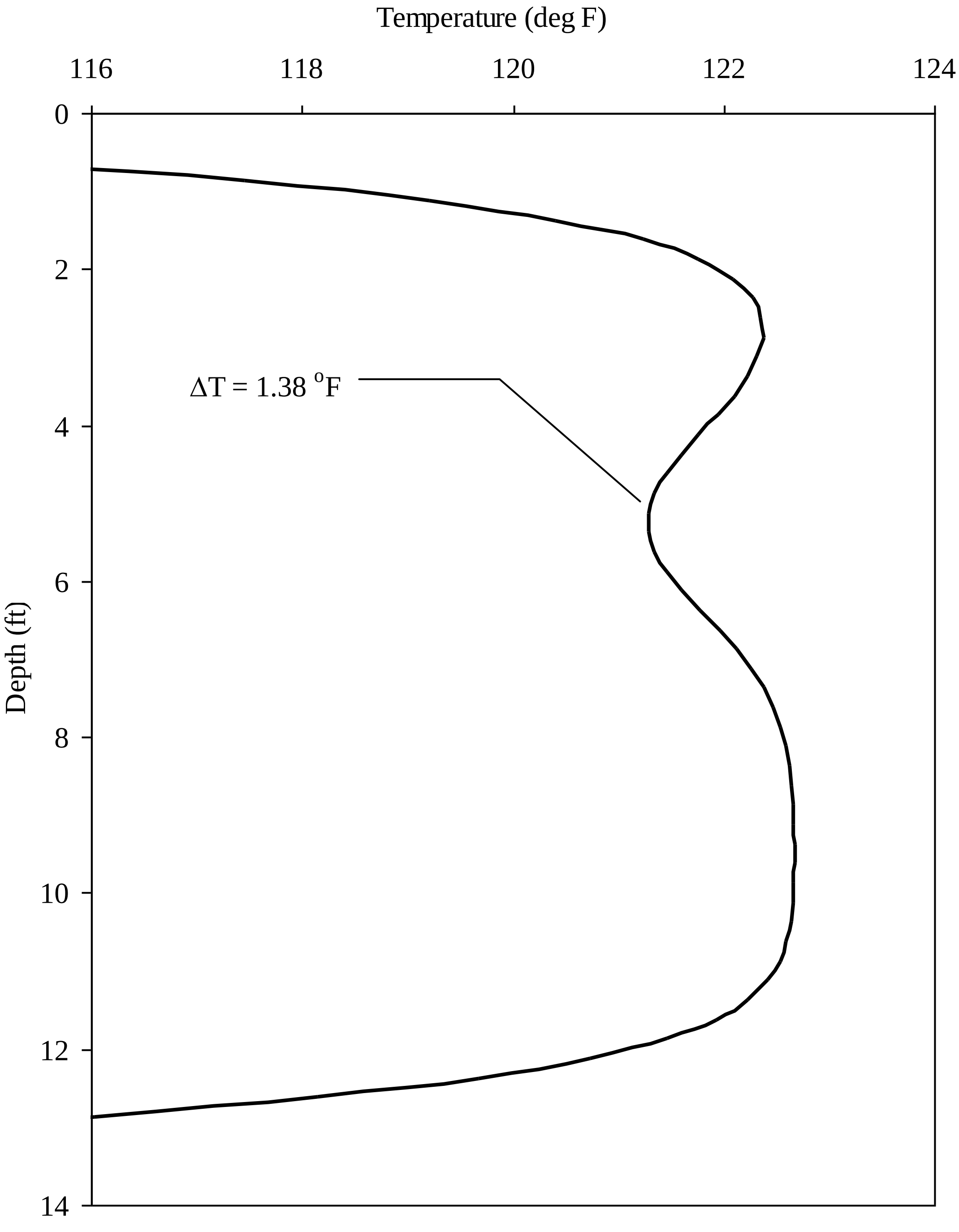
Summary

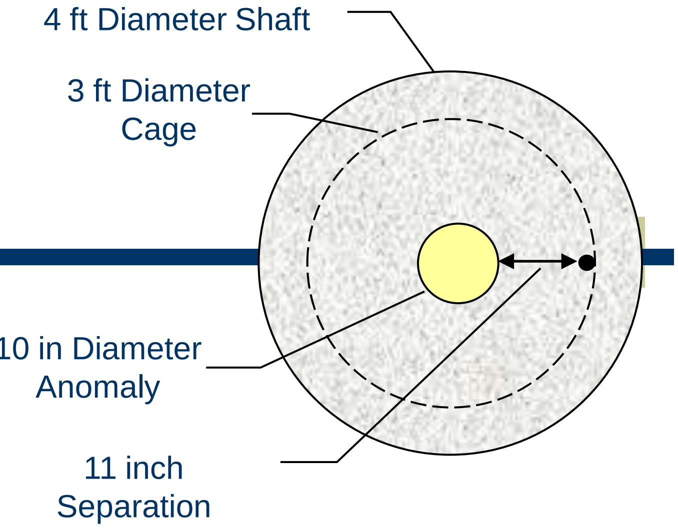
- Thermal profiling of shafts shows presence or absence of intact concrete both inside and outside reinforcement as well as confirmation of proper cover and cage alignment.
- Strong correlations between measured temperature and radius provide an as-built shape of the shaft.
- Testing is performed shortly after concreting expediting acceptance or rejection.

Sensitivity

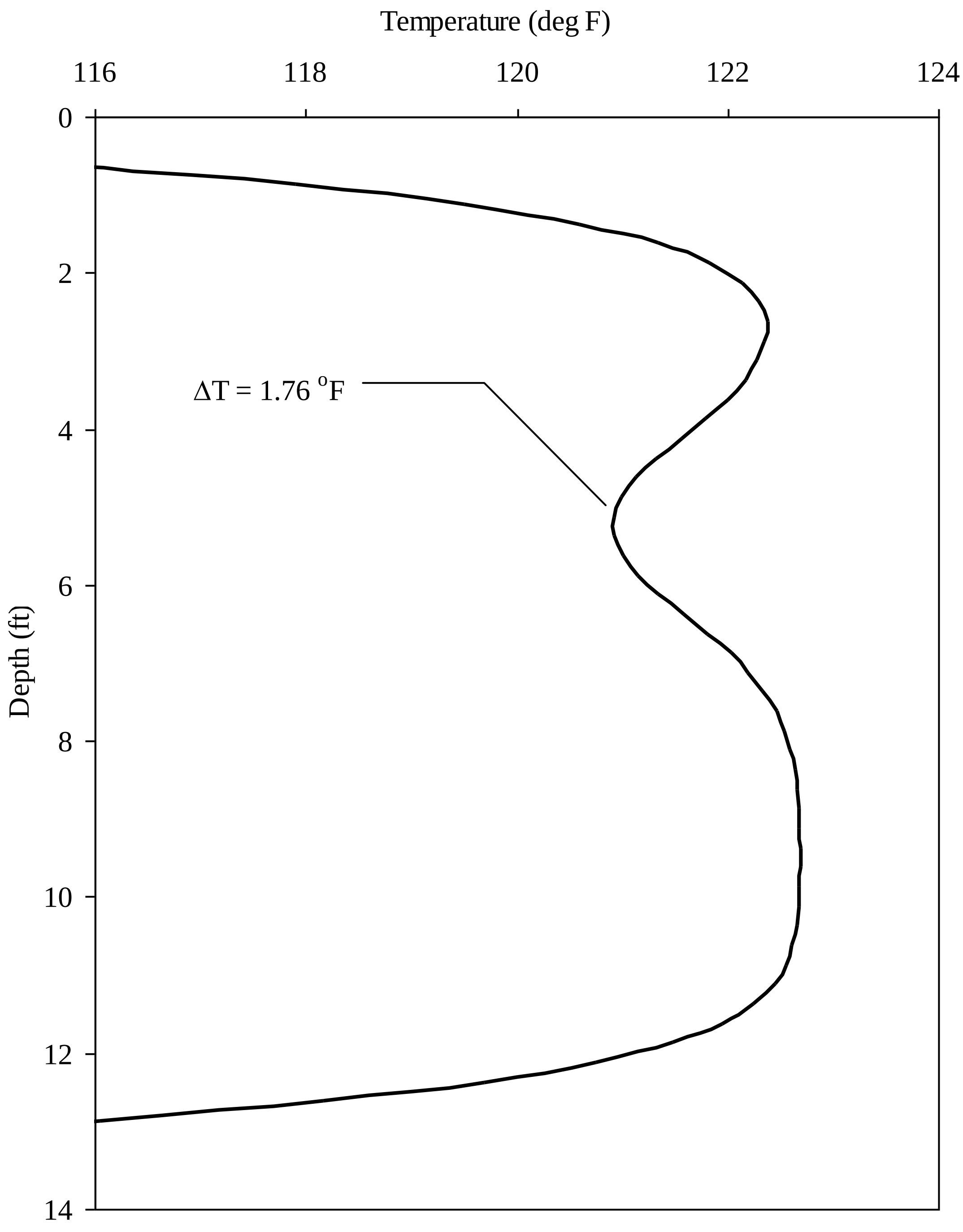
- Large anomalies are detected farther away
- Smaller anomalies must be closer to tubes
- Miniscule anomalies may not be detected but are of no importance.

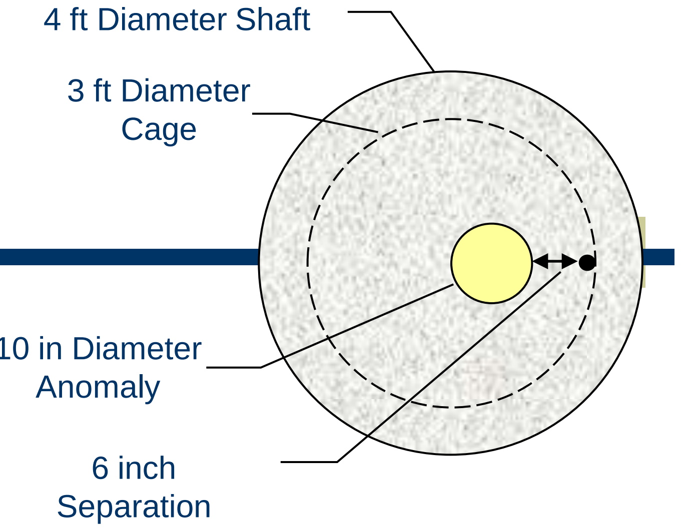
- Next three slides show a common tremie-induced anomaly in a 4ft diameter shaft.



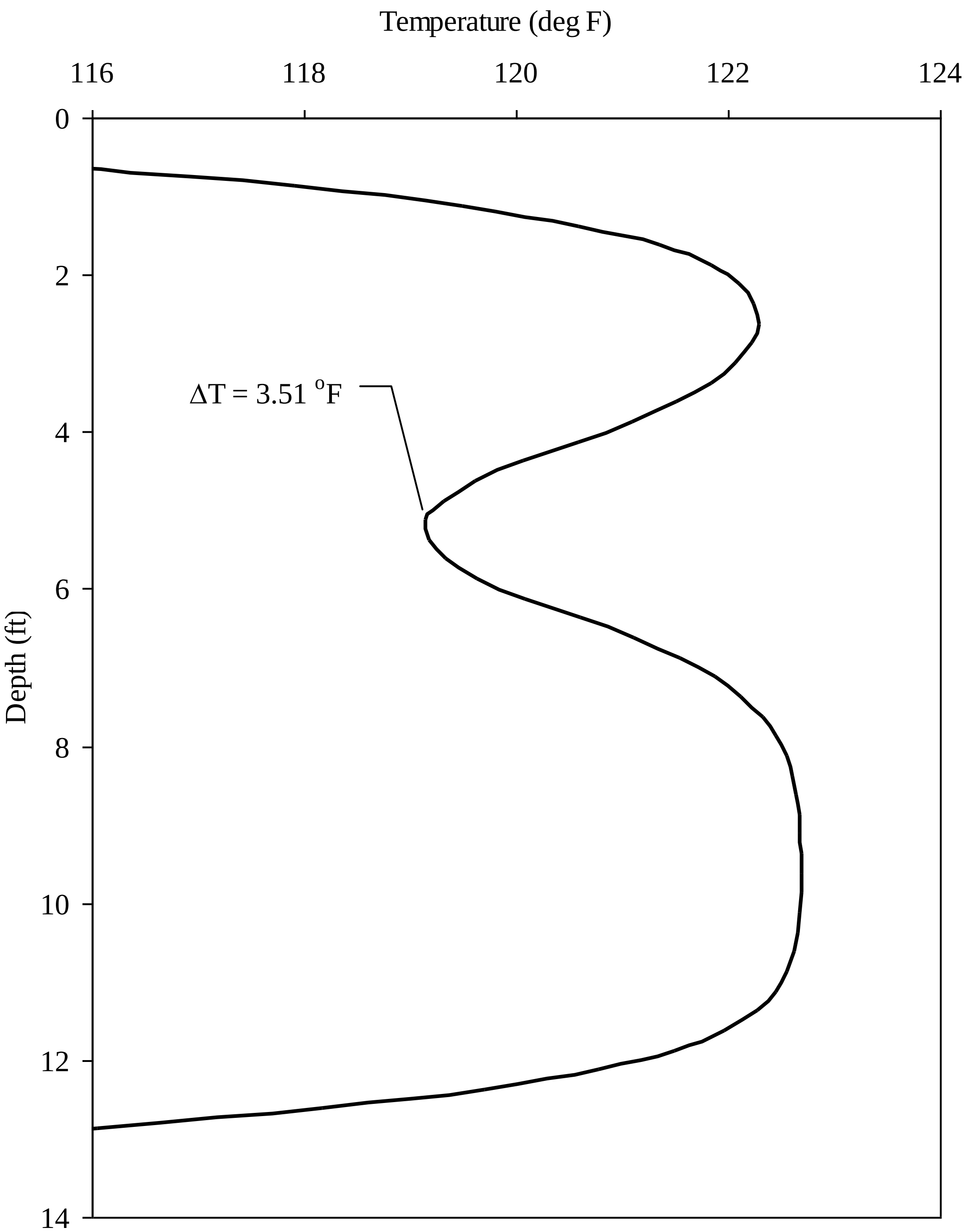


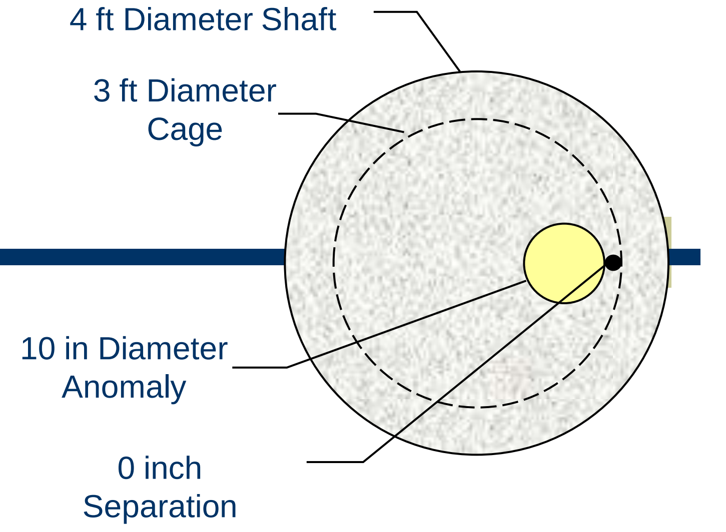
Anomaly in center of cage





Anomaly just off center





Anomaly adjacent tube

Level 3: 3-D Thermal Modeling

- Confirms Level 1 and Level 2
- Establishes the anticipated shaft temperature for a given size of shaft and time of testing.
- Verifies top and bottom roll-off distribution.
- Can be used to establish the field testing window.

Level 3: 3-D Thermal Modeling

Predicting Shaft Temperature

- Must know mix design with detailed cement and flyash reports (can change monthly)
- Must know geometry of shaft or other concrete element in question
- Must know environmental conditions (e.g. air temp, soil type, soil temp, etc.)

Hydration Energy
(Schindler, 2005)

Cement Energy Production

$$H_{cem} = 500p_{C_3S} + 260p_{C_2S} + 866p_{C_3A} + 420p_{C_4AF} +$$

$$624p_{SO_3} + 1186p_{FreeCaO} + 850p_{MgO}$$

Total Energy Production

$$H_u = H_{cem} \cdot p_{cem} + 461 \cdot p_{SLAG} + h_{FA} \cdot p_{FA}$$

Hydration Energy
(Schindler, 2005)

Degree of Hydration

$$\alpha(t_e) = \alpha_u \cdot \exp\left(-\left[\frac{\tau}{t_e}\right]^{\beta}\right)$$

Rate of Energy Production

$$Q_H(t) = H_u \cdot C_c \cdot \left(\frac{\tau}{t_e}\right)^{\beta} \cdot \left(\frac{\beta}{t_e}\right) \cdot \alpha(t_e) \cdot \frac{E}{R}\left(\frac{1}{273 + T_r} - \frac{1}{273 + T_c}\right)$$

Input Parameters
(from concrete supplier)

$$\alpha_u = \frac{1.031 \cdot w/cm}{0.194 + w/cm} + 0.50 \cdot p_{FA} + 0.30 \cdot p_{SLAG} \leq 1.0$$

$$\beta = 181.4 \cdot p_{C_3A}{}^{0.146} \cdot p_{C_3S}{}^{0.227} \cdot Blaine^{-0.535} \cdot p_{SO_3}{}^{0.558} \cdot \exp(-0.647 \cdot p_{SLAG})$$

$$\tau = 66.78 \cdot p_{C_3A}{}^{-0.154} \cdot p_{C_3S}{}^{-0.401} \cdot Blaine^{-0.804} \cdot (p_{SO_3}{}^{-0.758} \cdot \exp(2.187 \cdot p_{SLAG} + 9.50 \cdot p_{FA} \cdot p_{FA-CaO})$$

(MgO) %

(SO3) %

(C3S) %

(C2S) %

(C3A) %

(C4AF) %

Blaine Fineness,

Brooksville South Plant
10311 CEMENT PLANT ROAD
Brooksville, Fl 34601
Phone (352) 799-7881 / FAX (352) 799-6088

CEMENT MILL TEST REPORT

Cement Identified as: AASHTO M85; ASTM C150 TYPE I/II — Date of Report: 5/4/09

Plant: Cemex Brooksville Cement

Location: Brooksville, FL — Silo 1,2,5,10,15

Production Date: 4/1/09 to 4/30/09

STANDARD CHEMICAL REQUIREMENTS (ASTM C114)	SPECIFICATIONS	ASTM C-150 TYPE I Low alkali	ASTM C-150 TYPE II Low alkali	ASTM C-1157 GU	AASHTO M-85 TYPE I Low alkali	AASHTO M-85 TYPE II Low alkali	TEST RESULTS
Silicon Dioxide (SiO_2) %	Minimum	----	----	----	----	20.0	20.5
Aluminum Oxide (Al_2O_3) %	Maximum	----	6.0	----	----		4.8
Ferric Oxide (Fe_2O_3) %	Maximum	----	6.0	----	----	6.0	3.9
Calcium Oxide (CaO) %		----	----	----	----	----	64.8
Magnesium Oxide (MgO) %	Maximum	6.0	6.0	----	6.0	6.0	0.6
Sulfur Trioxide (SO_3) % **	Maximum	3.0	3.0	----	3.0	3.0	2.8
Loss on Ignition (LOI) %	Maximum	3	3	----	3	3	2.2
Insoluble Residue (IR) %	Maximum	0.75	0.75	----	0.75	0.75	0.73
Alkalies (Na_2O equivalent) %	Maximum	0.60	0.60	----	0.60	0.60	0.34
Carbon Dioxide in cement (CO_2) %							0.80
Limestone % in cement (ASTM C150 A1)	Maximum	5	5		5	5	2.1
$CaCO_3$ in limestone % (2.274 x %CO_2 LS)	Minimum	70	70		70	70	89
Tricalcium Silicate (C3S) %	Maximum	----	----	----	----	----	58
Dicalcium Silicate (C2S) %		----	----	----	----	----	15
Tricalcium Aluminate (C3A) %	Maximum	----	8	----	----	8	6
Tetracalcium Aluminoferrite (C4AF) %		----	----	----	----	----	12
(C3S + 4.75 C3A)	Maximum		100			100	87
(C4AF + 2C3A) or (C4AF + C2F) %	Maximum	----	----	----	----	----	24
PHYSICAL REQUIREMENTS							
(ASTM C204) Blaine Fineness, cm2/g	*Minimum*	2800	2800	----	2800	2800	3820
(ASTM C204) Blaine Fineness, cm2/g	Maximum		4200			4200	3820
(ASTM C430) -325 Mesh %		----	----	----	----	----	96.1
(ASTM C191) Time of Setting (Vicat)							
Initial Set, minutes	*Minimum*	45	45	45	45	45	86
Final Set, minutes	Maximum	375	375	420	375	375	188
(ASTM C185) Air Content of Mortar %	Maximum	12	12	----	12	12	6.9
(ASTM C151) Autoclave Expansion %	Maximum	0.80	0.80	0.80	0.80	0.80	-0.010
(ASTM C187) Normal Consistency %		----	----	----	----	----	24.9
(ASTM C1038) Expansion in Water %	Maximum	0.02	0.02	0.02	0.02	0.02	0.011
(ASTM C186) 7 day Heat of Hydration cal/g	Max. if specified					70	79
(ASTM C109) Compressive Strength, psi (Mpa)							
1 Day		----	----	----	----	----	2267 (15.6)
3 Days	*Minimum*	1740 (12.0)	1450 (10.0)	1450 (10.0)	1740 (12.0)	1450 (10.0)	4070 (28.1)
7 Days	*Minimum*	2760 (19.0)	2470 (17.0)	2465 (15.0)	2760 (19.0)	2470 (17.0)	5350 (36.9)
28 Days	*Minimum*	----	----	----	----	----	6585 (45.5)

0.6

2.8

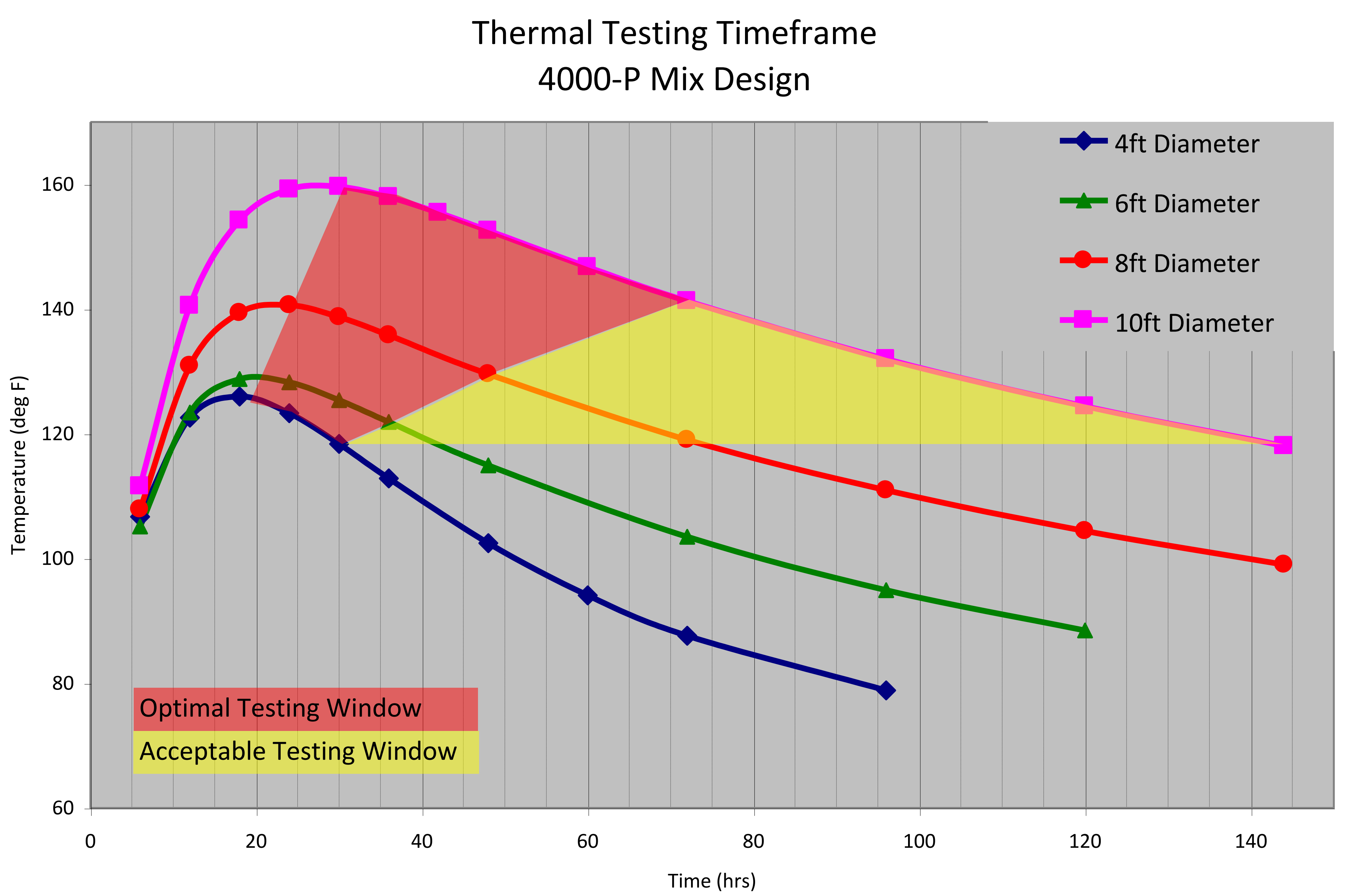
58

15

6

12

3820



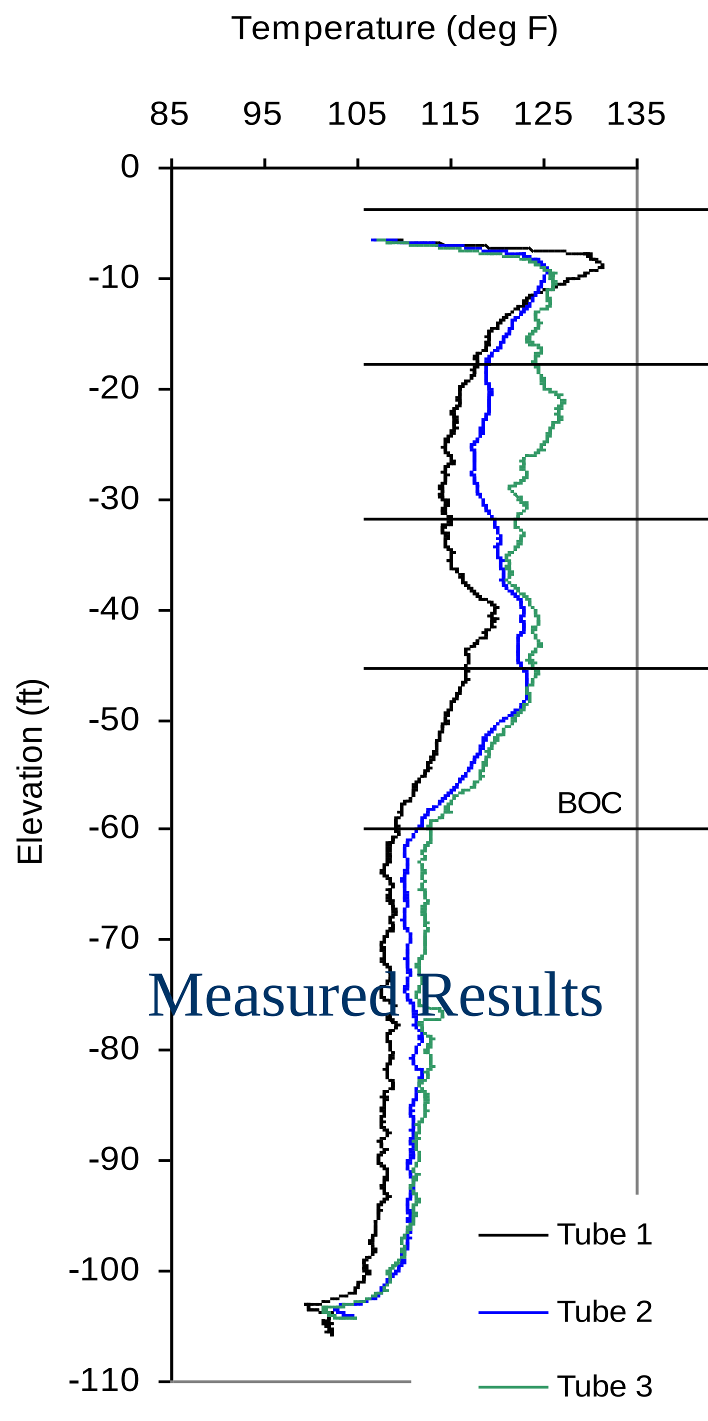
Thermal Testing Timeframe
4000-P Mix Design
4ft Diameter
6ft Diameter
8ft Diameter
10ft Diameter
Optimal Testing Window
Acceptable Testing Window
Temperature (deg F)
Time (hrs)
60
80
100
120
140
160
0
20
40
60
80
100
120
140

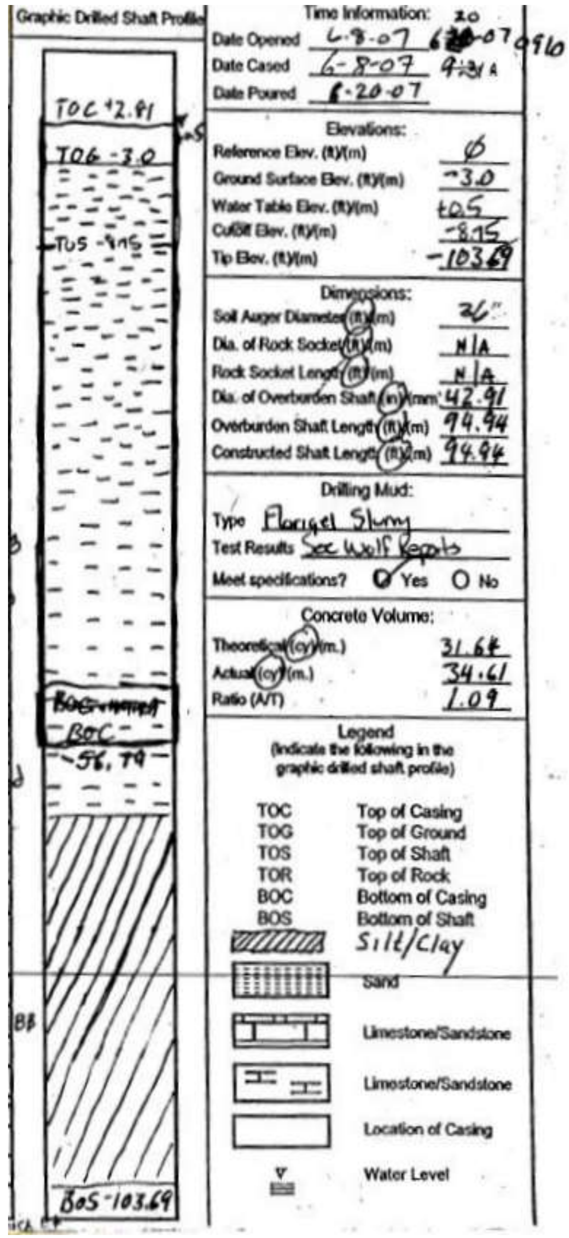
Level 4: Signal Matching

- Advanced 3-D modeling
- Variable soil strata
- Tailors the modeled shape of the shaft to match the field measured temperatures
- Variable climatic inputs

St. Augustine Bridge of Lions


Bridge of Lions
Pier 25 – Shaft 3
3ft diameter





Time Information:

Date Opened	6-8-07	6-20-07
Date Cased	6-8-07	9:31 A
Date Poured	6-20-07	

Elevations:

Reference Elev. (ft)/(m)	Ø
Ground Surface Elev. (ft)/(m)	-3.0
Water Table Elev. (ft)/(m)	+0.5
Cutoff Elev. (ft)/(m)	-8.15
Tip Elev. (ft)/(m)	-103.69

Dimensions:

Soil Auger Diameter (ft)/(m)	36"
Dia. of Rock Socket (ft)/(m)	N/A
Rock Socket Length (ft)/(m)	N/A
Dia. of Overburden Shaft (in)/(mm)	42.91
Overburden Shaft Length (ft)/(m)	94.94
Constructed Shaft Length (ft)/(m)	94.94

Drilling Mud:

Type: Florigel Slurry

Test Results: See Wolf Reports

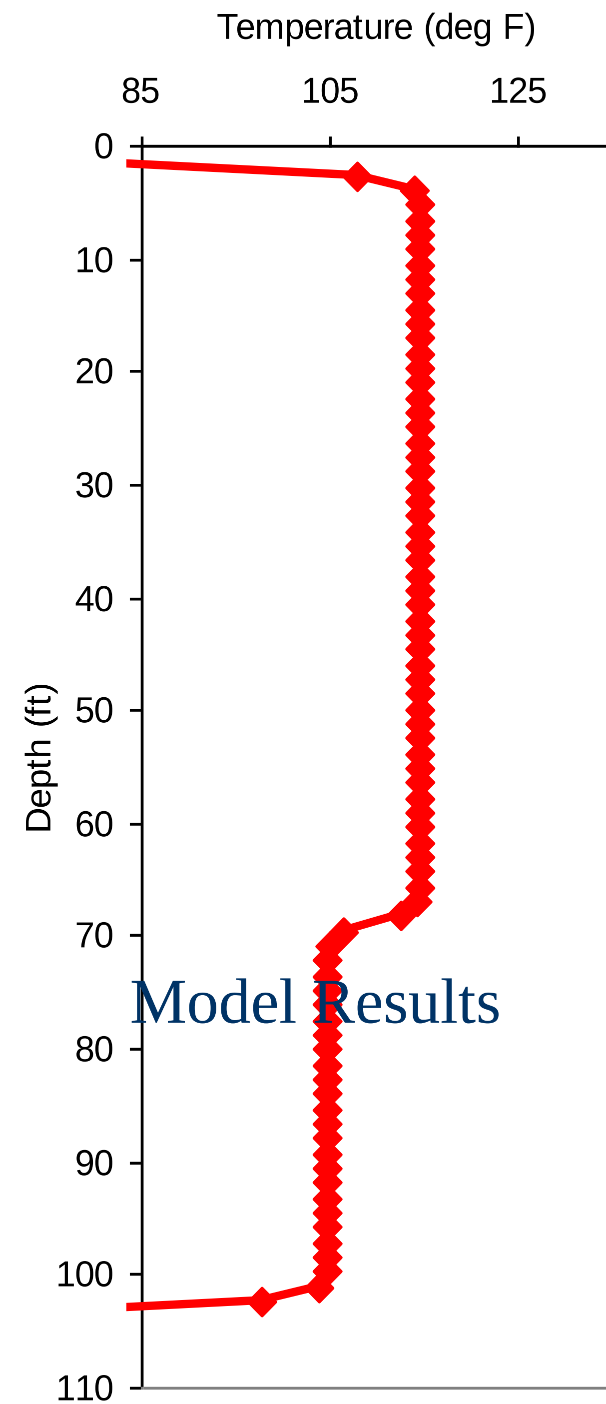
Meet specifications? ☑ Yes ○ No

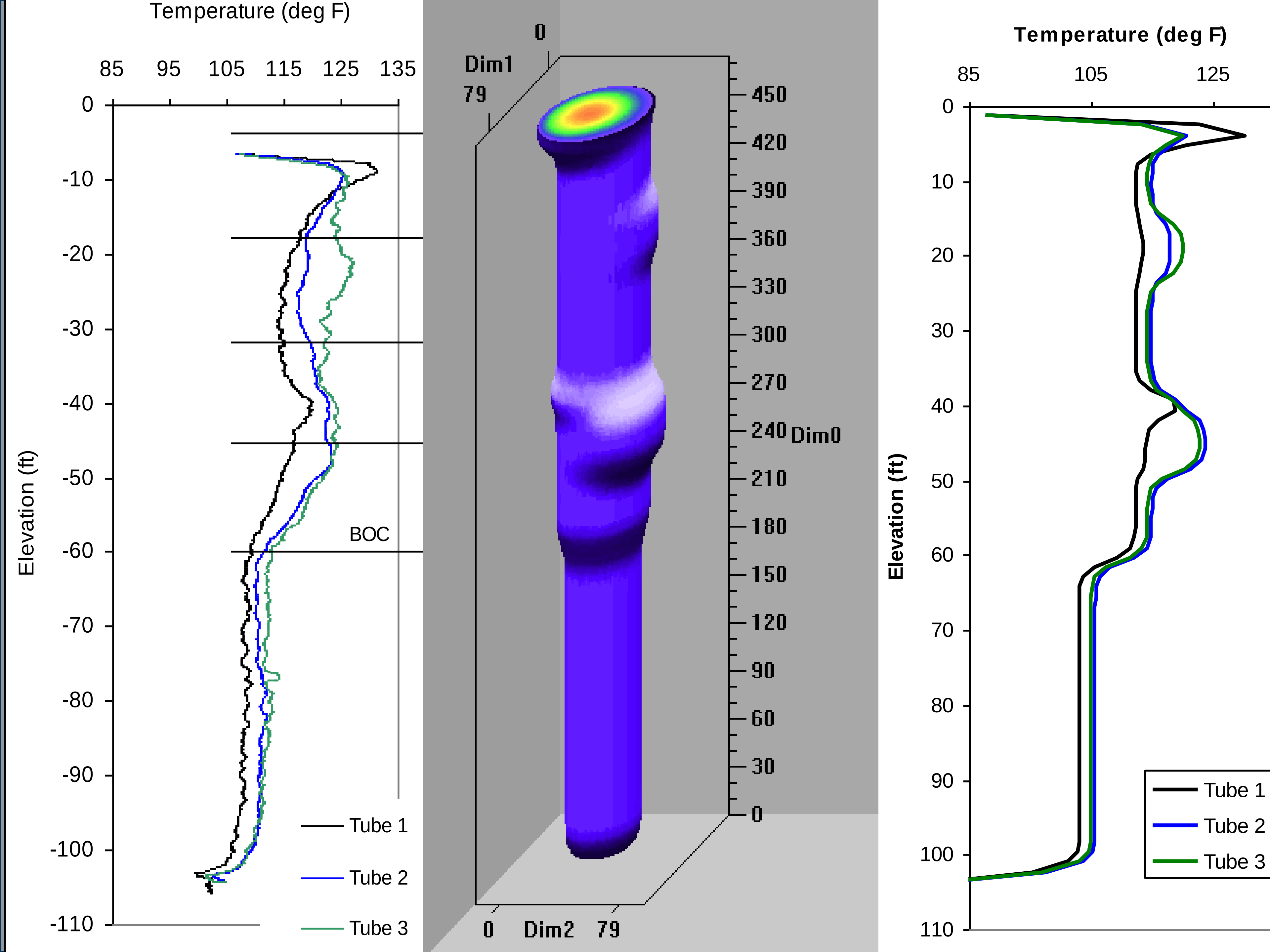
Concrete Volume:

Theoretical (cy)/(m.)	31.64
Actual (cy)/(m.)	34.61
Ratio (A/T)	1.09

Legend
(indicate the following in the graphic drilled shaft profile)

TOC	Top of Casing
TOG	Top of Ground
TOS	Top of Shaft
TOR	Top of Rock
BOC	Bottom of Casing
BOS	Bottom of Shaft
[hatched]	Silt/Clay
[dotted]	Sand
[block]	Limestone/Sandstone
[block]	Limestone/Sandstone
[box]	Location of Casing
[symbol]	Water Level




Temperature (deg F)
85
95
105
115
125
135
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
Elevation (ft)
BOC
Tube 1
Tube 2
Tube 3
0
Dim1
79
450
420
390
360
330
300
270
240
Dim0
210
180
150
120
90
60
30
0
0
Dim2
79
Temperature (deg F)
85
105
125
0
10
20
30
40
50
60
70
80
90
100
110
Elevation (ft)
Tube 1
Tube 2
Tube 3