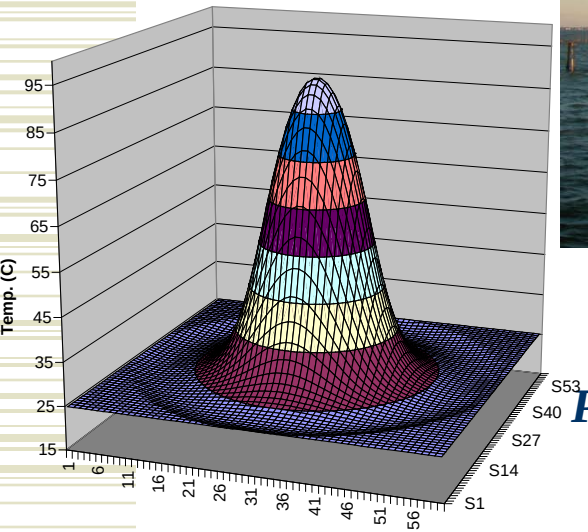
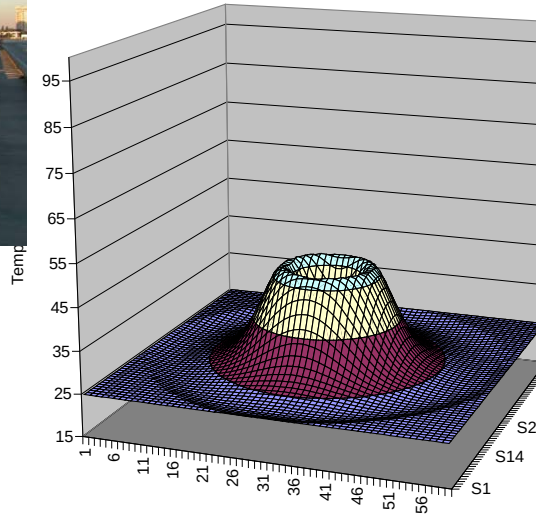
Attenuating Mass Concrete Effects in Drilled Shafts





Grip 2010

Presented by: Gray Mullins, Ph.D., P.E.

UNIVERSITY OF SOUTH FLORIDA

Civil & Environmental Engineering

Problem Statement

- Excessively high curing temperatures in mass concrete can affect long-term durability from Delayed Ettringite Formation (DEF).
- Differential Temperature in mass concrete has more immediate adverse effects in the form of cracking. . .
- Drilled shafts are susceptible to Mass Concrete issues.

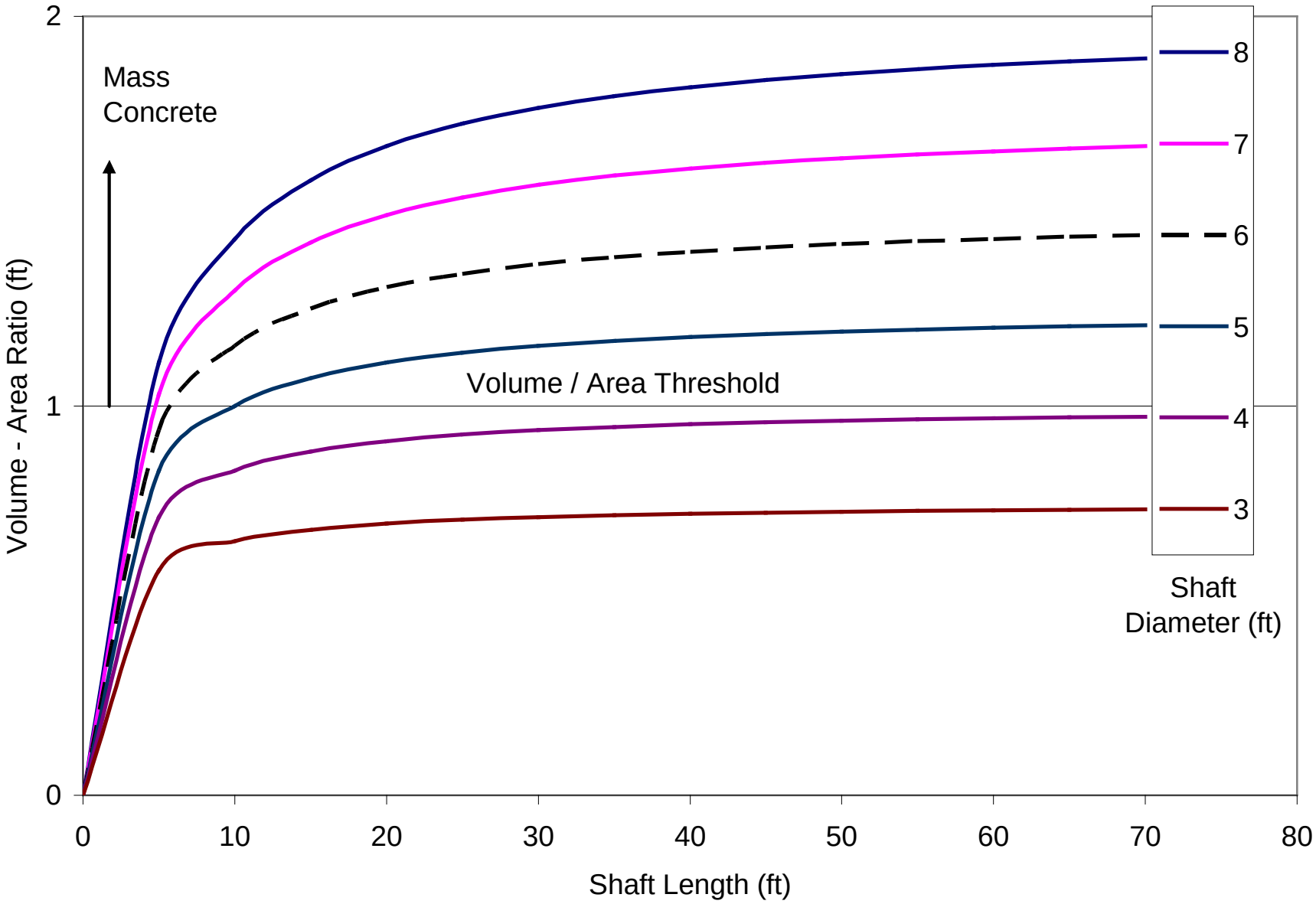
Project Tasks

- Construct Voided Shaft (monitor, model, etc)
- Collect Field Temperature Measurements of Mass Concrete / Shaft Elements (via thermocouple and integrity scans)
- Calibrate/Update Thermal Software

When is Concrete Mass?

- Guidelines
  - Mass Concrete Geometry Limit
  - Drilled Shaft Diameter Limit
- Performance Based Specification
  - Differential Temperature Limit
  - Peak Temperature Cut-off

Geometry Criterion Applied to Shafts



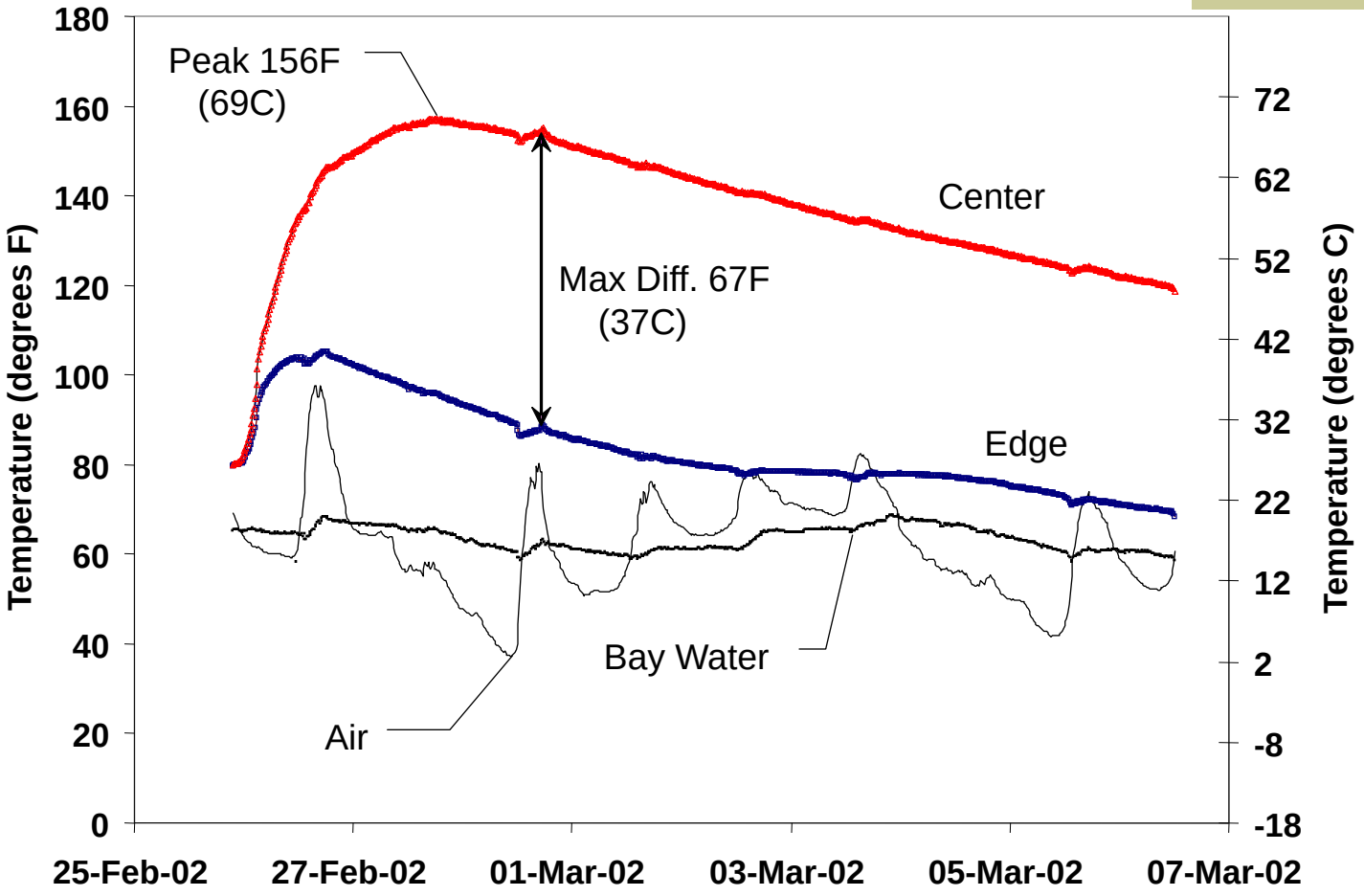
Case Studies: Hoover Dam

- Built 1932 - 1935
- More than 5 million yd^3 of concrete
- Equivalent to 2 lane road coast to coast (w/sidewalks)
- 600 miles of 1” steel cooling tubes
- 100 yr estimated cooling

Ringling Causeway Bridge

- Built 2001-2003
- 9 ft diameter shafts
- Standard FDOT shaft mix (4 ksi)
- Winter construction
- No cooling system

Ringling Causeway Bridge Shaft Curing Temperature



Predicting Mass Concrete Conditions

- 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)

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

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

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

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
Plant: Cemex Brooksville Cement
Location: Brooksville, FL
Production Date: 4/1/09 to 4/30/09

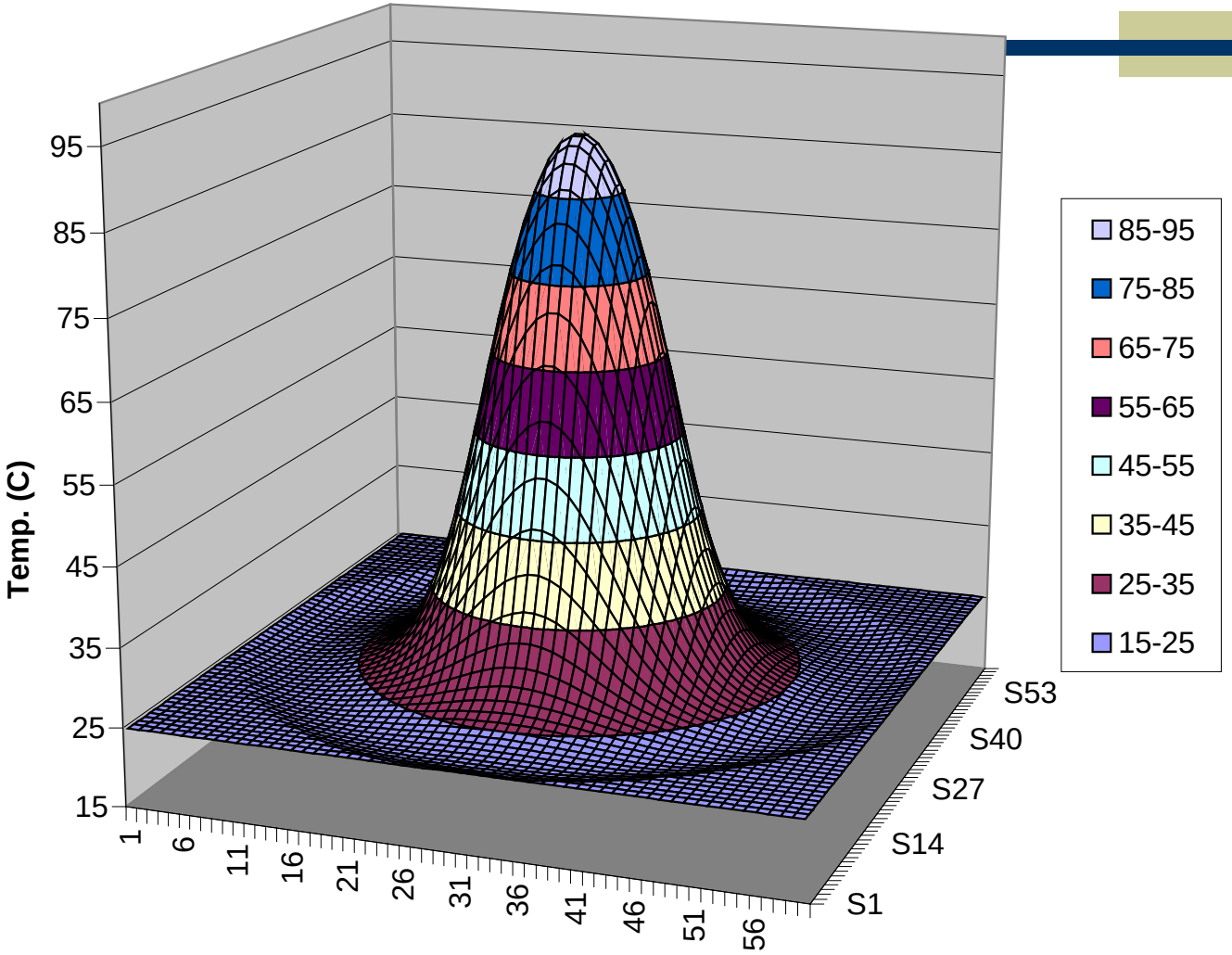
Date of Report: 5/4/09

Silo 1,2,5,10,15

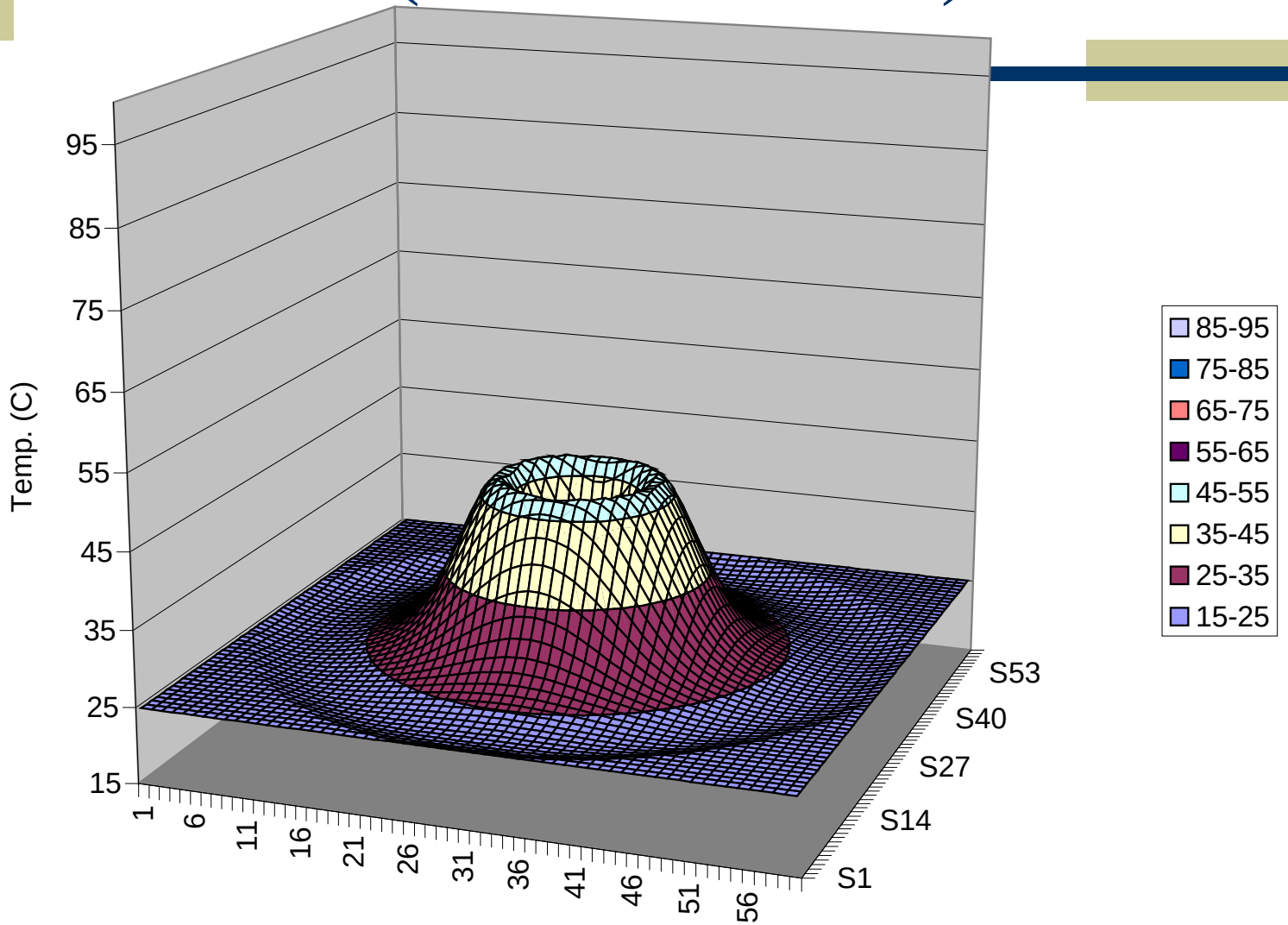
STANDARD CHEMICAL REQUIRMENTS (ASTM C114)	SPECIFICATIONS	ASTM C-150 TYPE I Low alkali	ASTM C-150 TYPE II Low alkali	ASTM C-1167 GU	AASHTO M-85 TYPE I Low alkali	AASHTO M-85 TYPE II Low alkali	TEST RESULTS
Silicon Dioxide (SiO2) %	Minimum	----	----	----	----	20.0	20.5
Aluminum Oxide (Al2O3) %	Maximum	----	6.0	----	----		4.8
Ferric Oxide (Fe2O3) %	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 (SO3) % **	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 (Na2O equivalent) %	Maximum	0.60	0.60	----	0.60	0.60	0.34
Carbon Dioxide in cement (CO2) %							0.80
Limestone % in cement (ASTM C150 A1)	Maximum	5	5		5	5	2.1
CaCO3 in limestone % (2.274 x %CO2 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 REQUIRMENTS							
(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)

(MgO) % — 0.6
(SO3) % — 2.8
(C3S) % — 58
(C2S) % — 15
(C3A) % — 6
(C4AF) % — 12
Blaine Fineness, — 3820

9 ft Diameter Shaft (Model simulation)



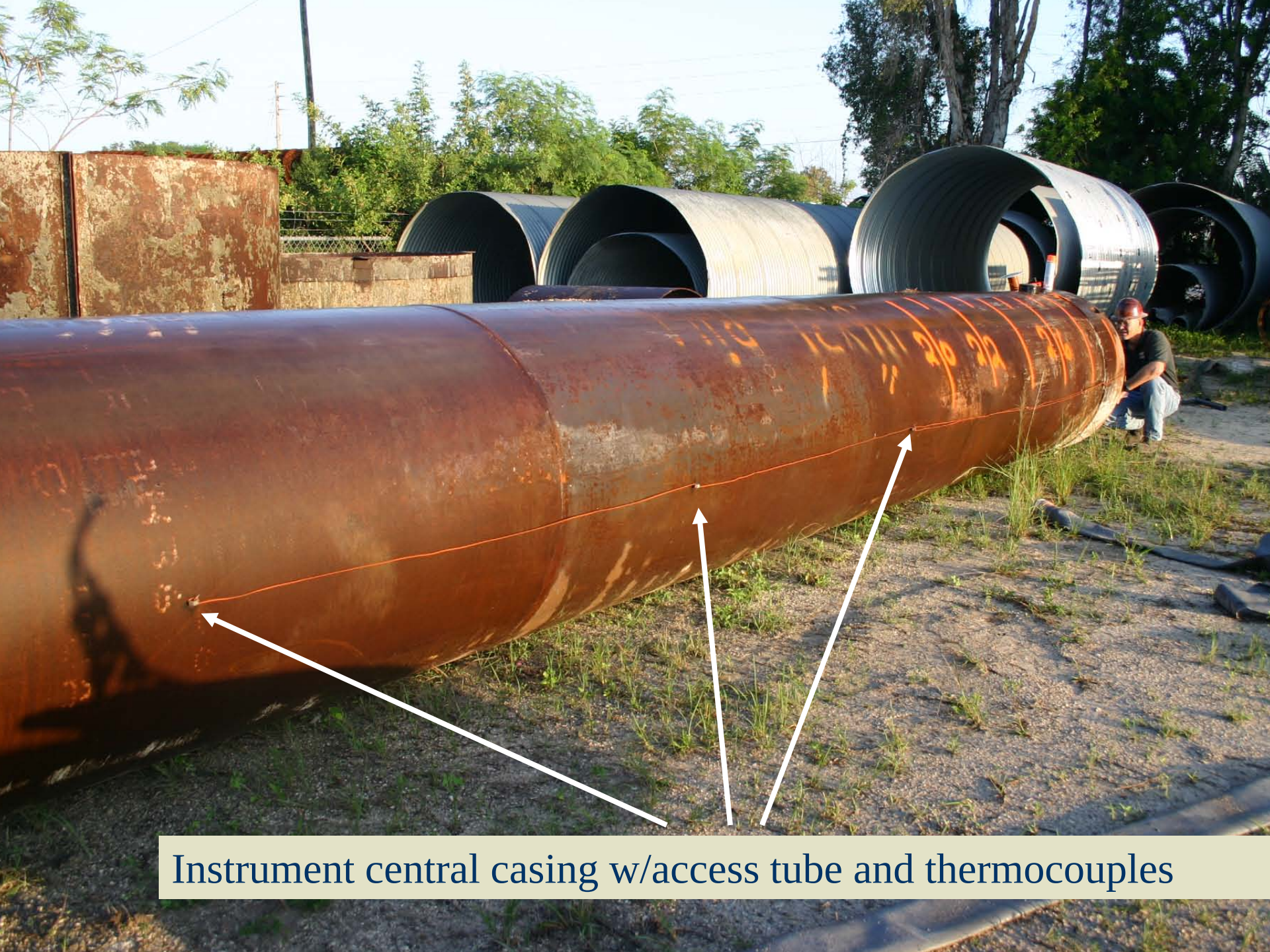
9 ft Diameter Voided Shaft (Model simulation)



Voided Shaft Construction

- Install access tubes in soil around proposed excavation site
- Instrument 8 ft diameter cage / 4 ft central casing
- Construct Voided Shaft
- Monitor shaft and ground temperatures via thermocouples and integrity scans

Install ground access tubes
1/4D, 1/2D, 1D, and 2D
Instrument cage w/access tubes and thermocouples



Instrument central casing w/access tube and thermocouples

Instrument Central Casing

Excavation and Cleanout

Cage Placement
Manitex M2284
Access Tubes

Central Casing Installation

Secure??? Central Casing

Double Tremie

Concreting

Concrete level measurements

Surface Casing Extraction

Surface Casing Extraction

Finished Shaft

Cellular Antenna

Solar Panel

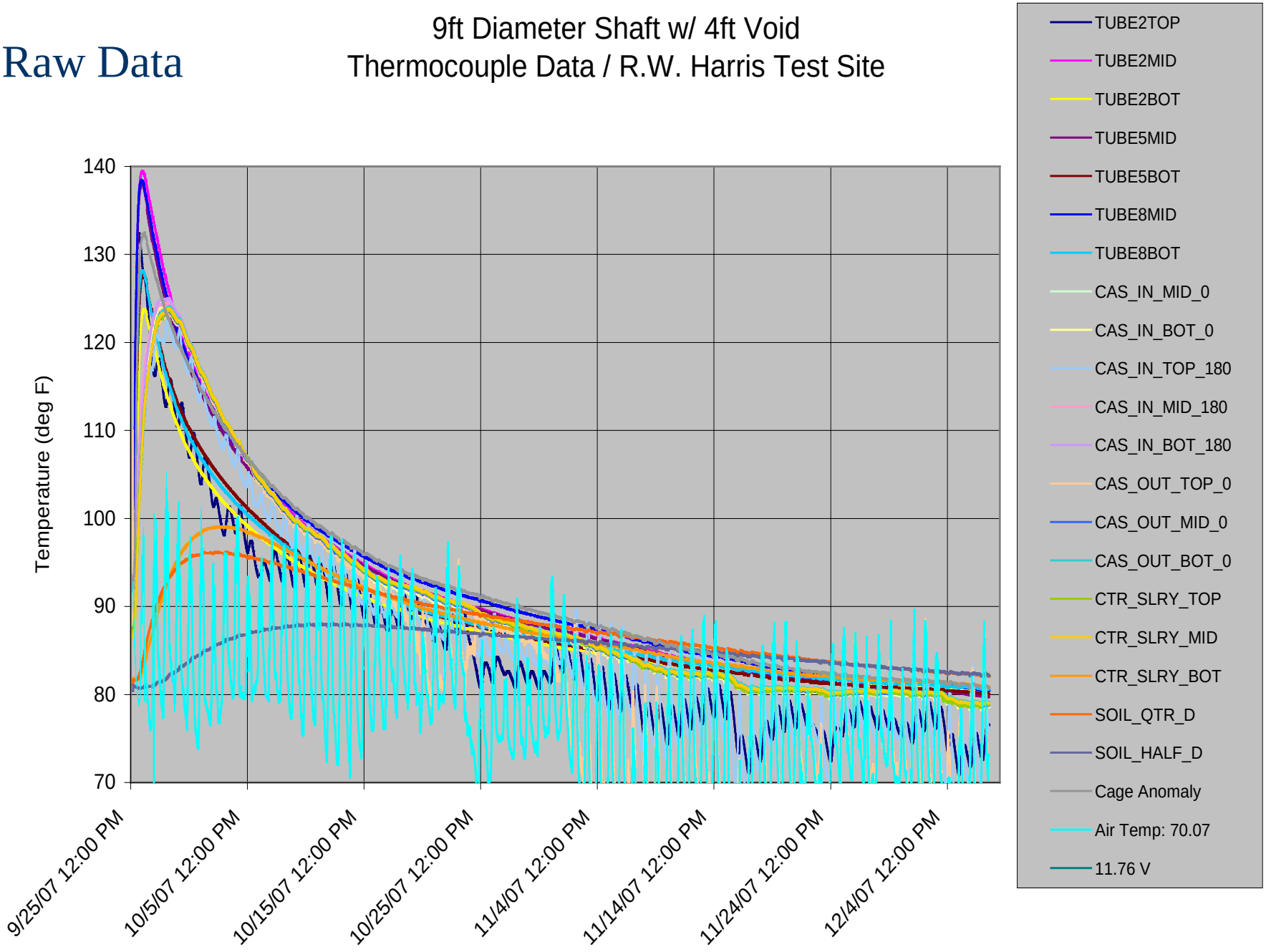
Data Logger

Thermocouple Wiring

Thermal Integrity Access Tubes

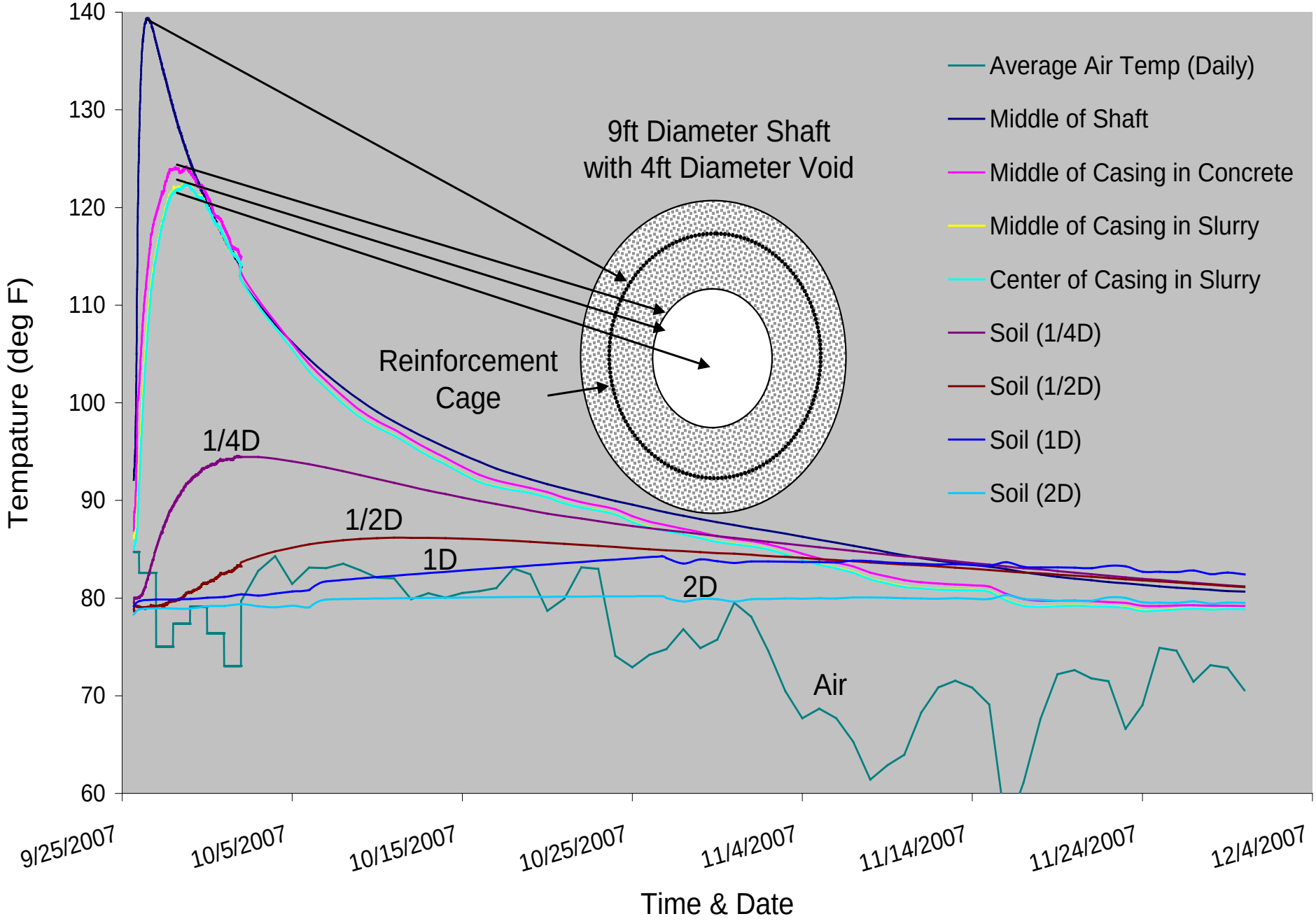
Raw Data

9ft Diameter Shaft w/ 4ft Void
Thermocouple Data / R.W. Harris Test Site



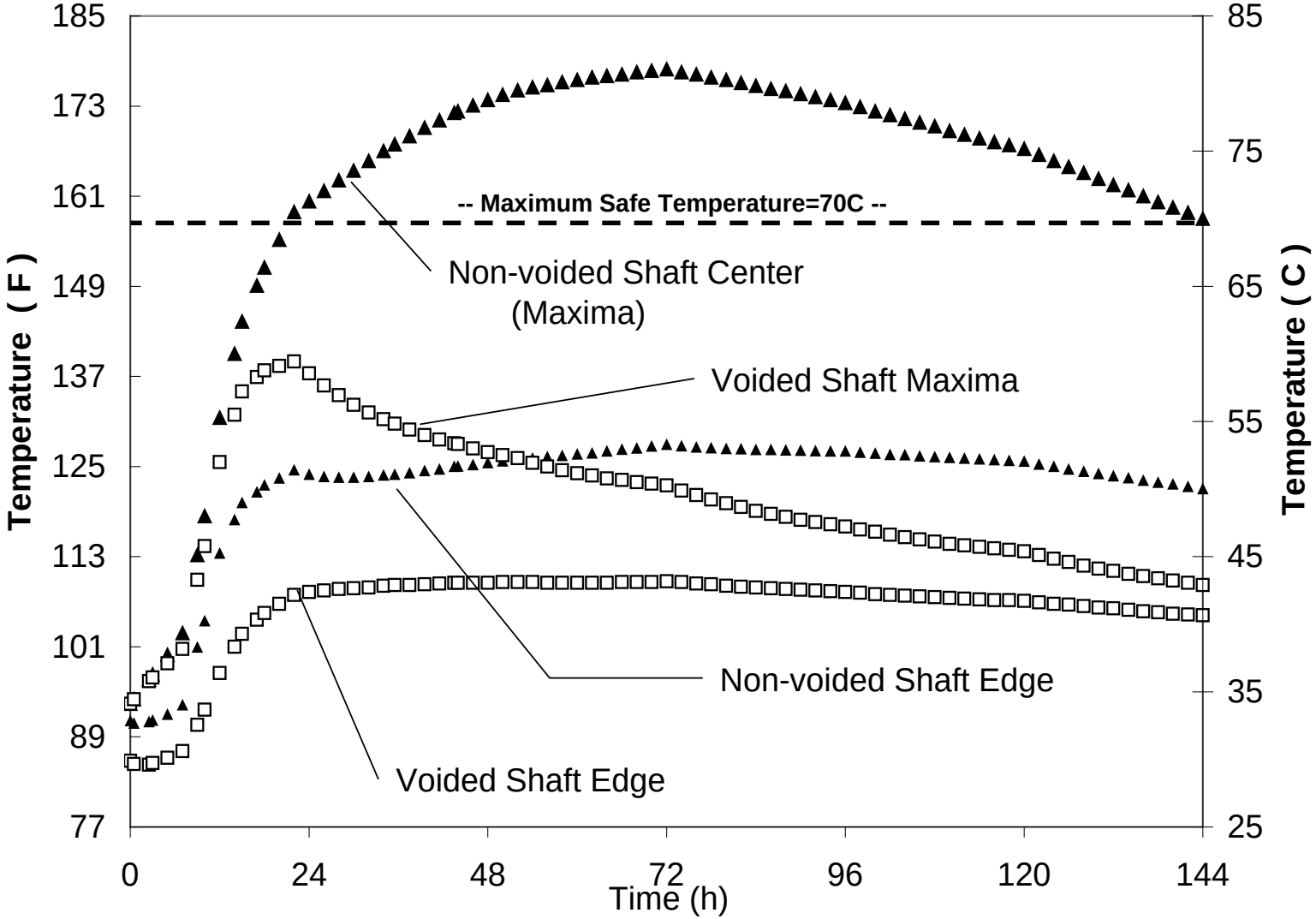
Note: You will need to *Refresh* to update graph this should be done every 15 minutes.

Annotated Data

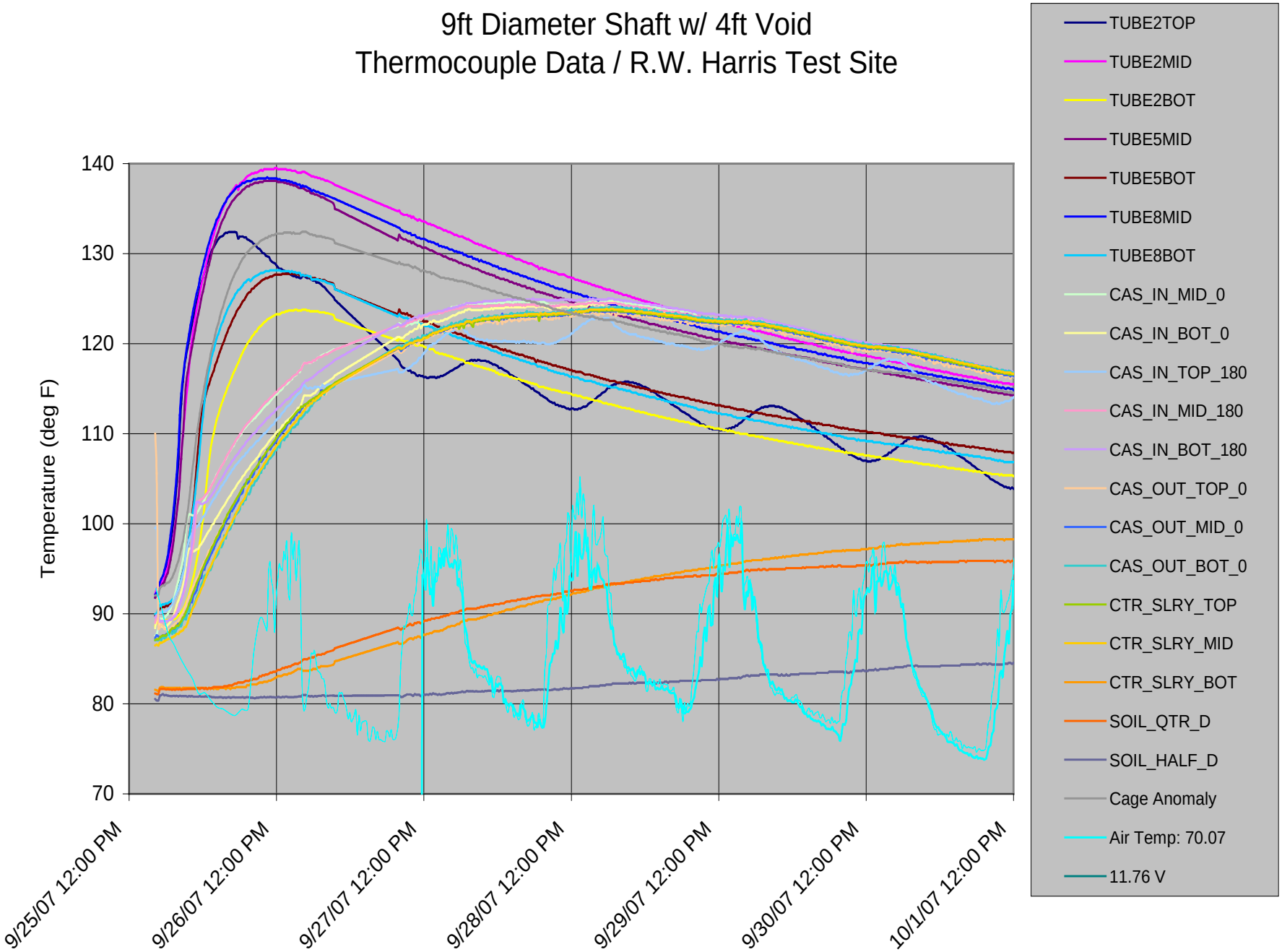


Modeled Temperature Predictions

Presented at GRIP 2007



9ft Diameter Shaft w/ 4ft Void
Thermocouple Data / R.W. Harris Test Site



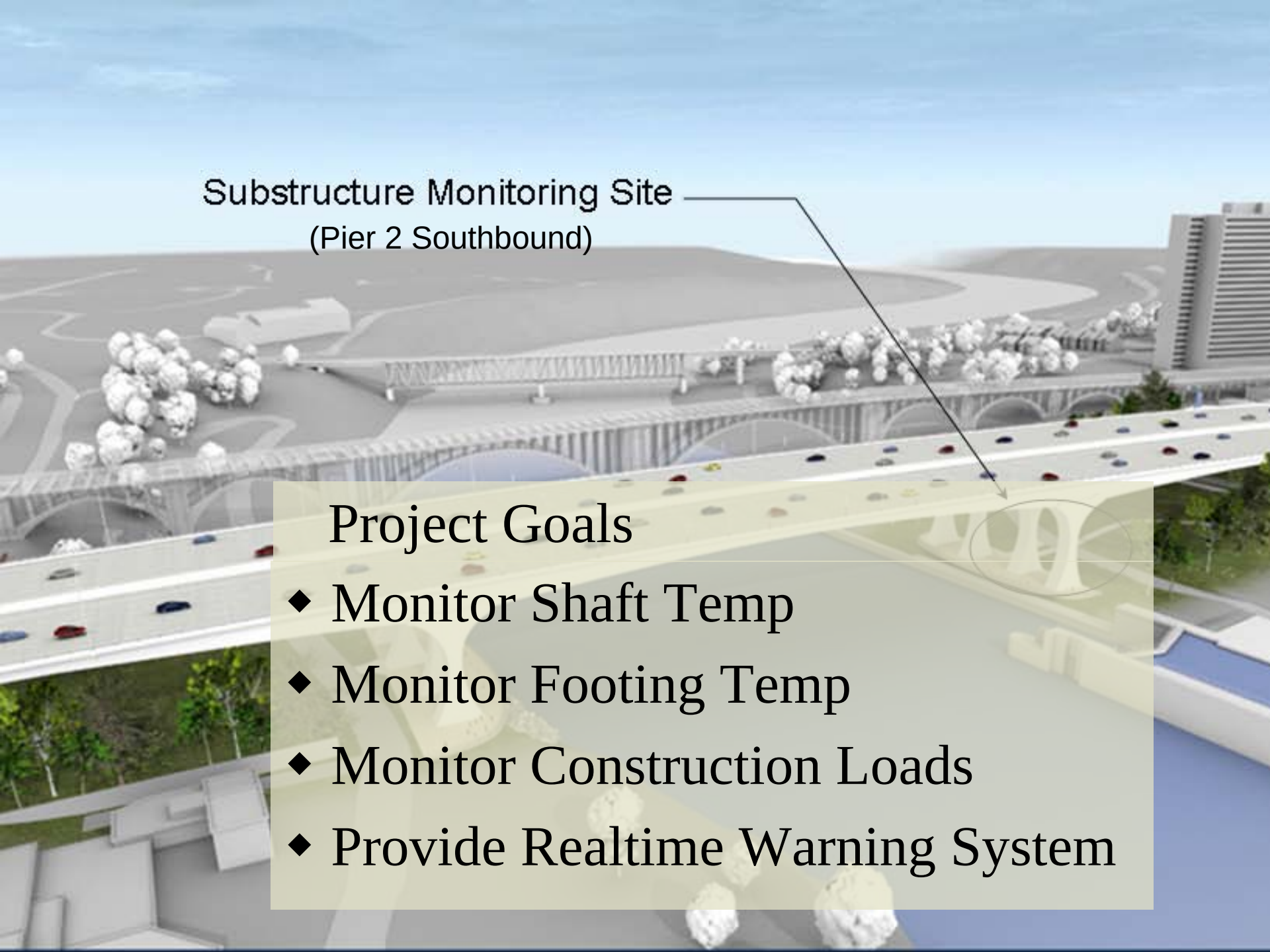
Note: You will need to *Refresh* to update graph this should be done every 15 minutes.

Collect Field Temperature Measurements

- Voided Shaft Monitoring (shafts)
- I-35W Bridge Replacement (shafts and footing)
- Marion County Courthouse (shafts)
- Lake Okeechobee Dike Remediation (cutoff wall)
- I-4, District 5 (shafts)

I35W St Anthony Falls Bridge Replacement

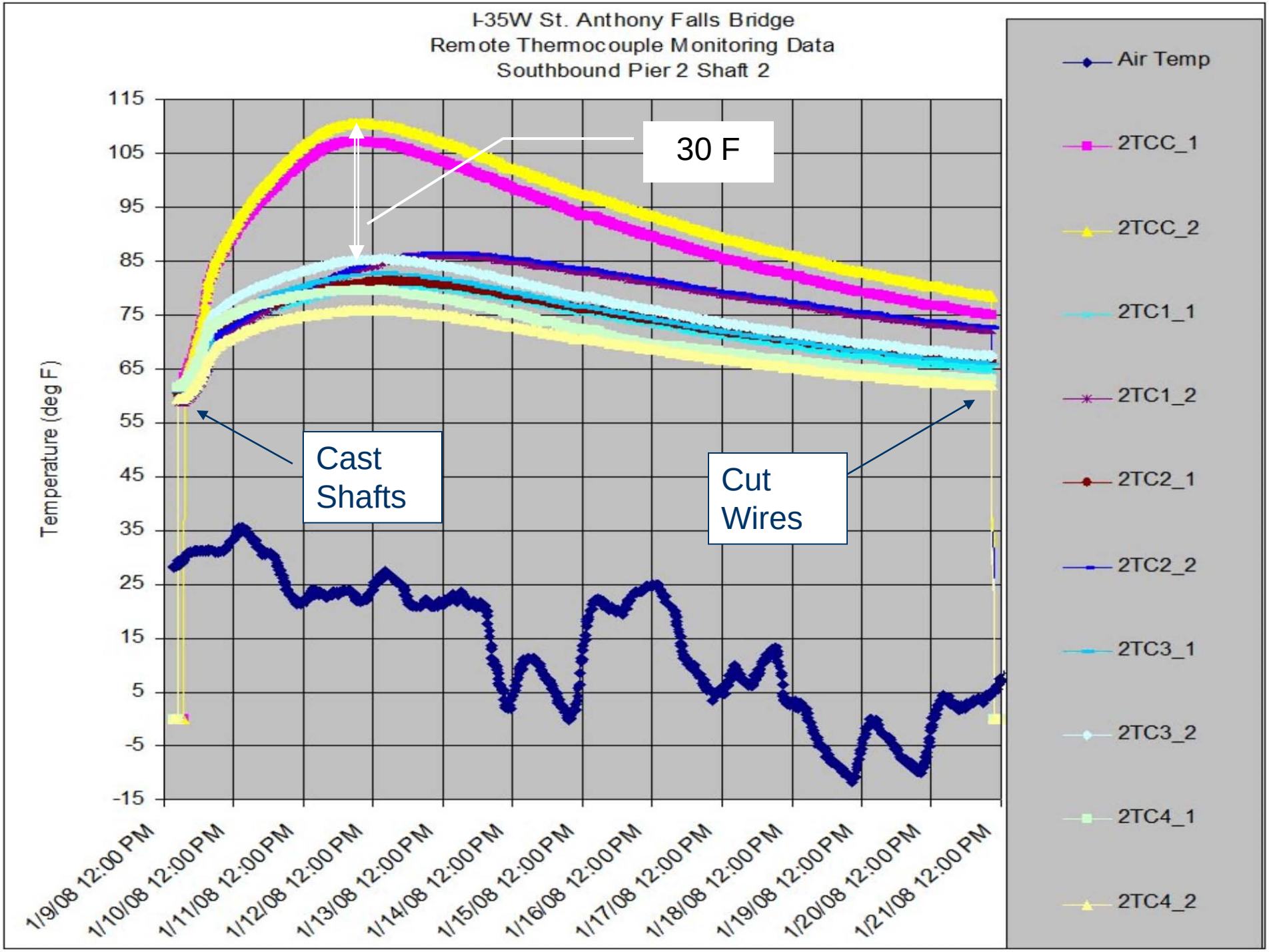
End
I35W

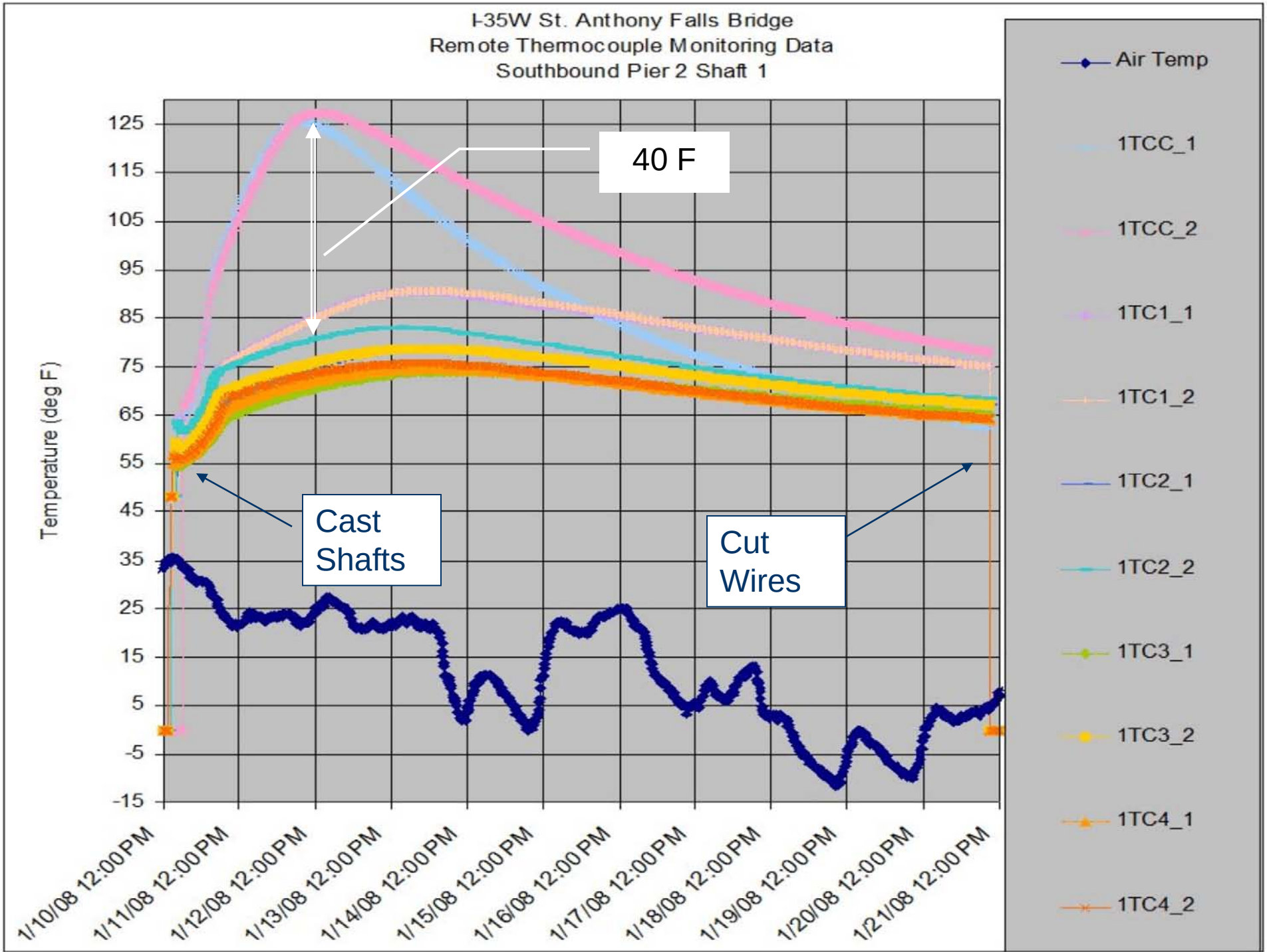


Project Goals

- Monitor Shaft Temp
- Monitor Footing Temp
- Monitor Construction Loads
- Provide Realtime Warning System

- Pier 2 Southbound Footing
- 40’ x 90’ x 12’ = 1600 yd^3
- 8 - 7 ft diameter shafts, 100 ft deep
- SCC shaft mix
- Thermocouples / Strain Gages

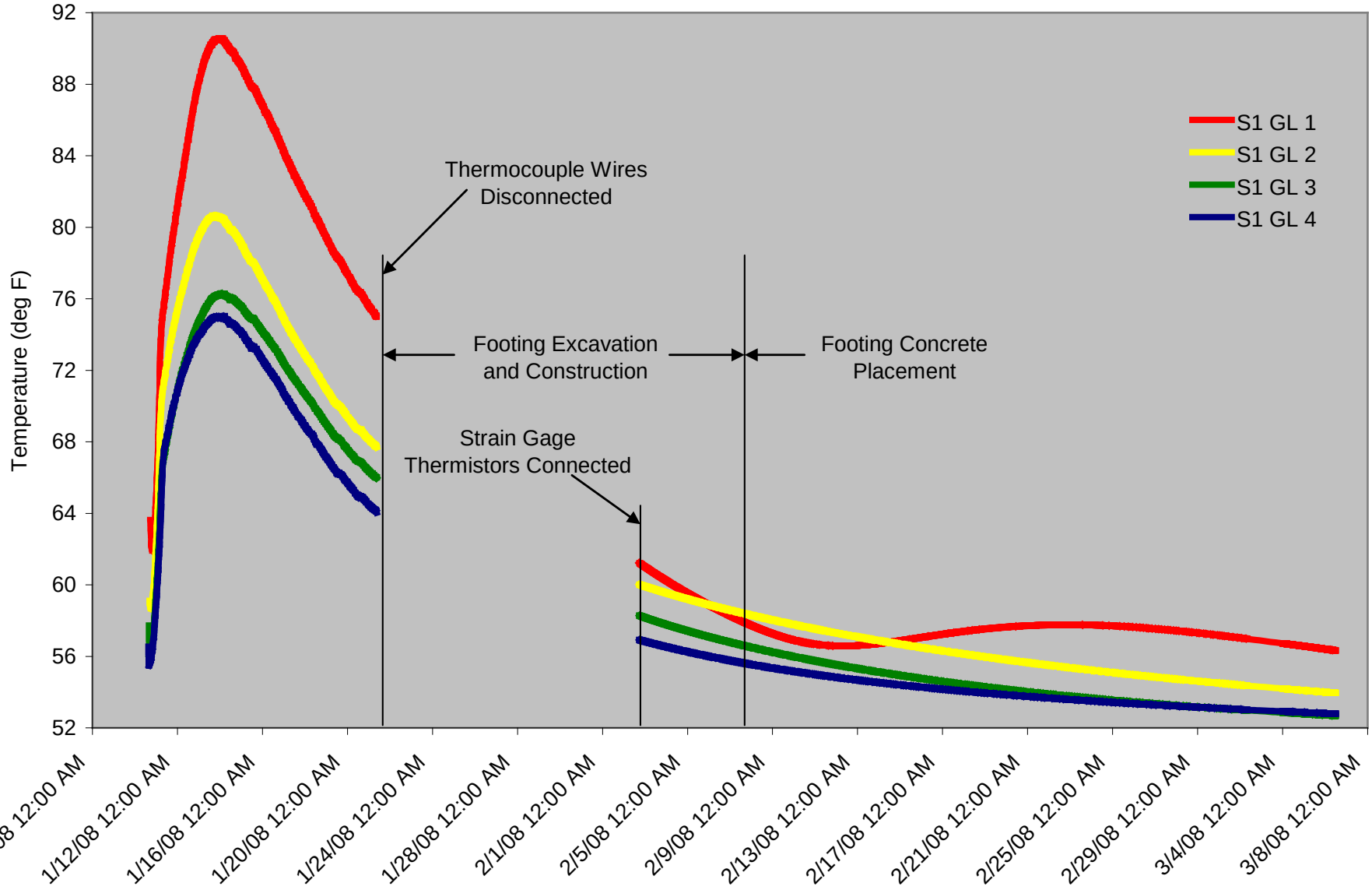

I-35W St. Anthony Falls Bridge
Remote Thermocouple Monitoring Data
Southbound Pier 2 Shaft 2
Temperature (deg F)
115
105
95
85
75
65
55
45
35
25
15
5
-5
-15
1/9/08 12:00 PM
1/10/08 12:00 PM
1/11/08 12:00 PM
1/12/08 12:00 PM
1/13/08 12:00 PM
1/14/08 12:00 PM
1/15/08 12:00 PM
1/16/08 12:00 PM
1/17/08 12:00 PM
1/18/08 12:00 PM
1/19/08 12:00 PM
1/20/08 12:00 PM
1/21/08 12:00 PM
30 F
Cast Shafts
Cut Wires
Air Temp
2TCC_1
2TCC_2
2TC1_1
2TC1_2
2TC2_1
2TC2_2
2TC3_1
2TC3_2
2TC4_1
2TC4_2


I-35W St. Anthony Falls Bridge
Remote Thermocouple Monitoring Data
Southbound Pier 2 Shaft 1
Temperature (deg F)
125
115
105
95
85
75
65
55
45
35
25
15
5
-5
-15
1/10/08 12:00 PM
1/11/08 12:00 PM
1/12/08 12:00 PM
1/13/08 12:00 PM
1/14/08 12:00 PM
1/15/08 12:00 PM
1/16/08 12:00 PM
1/17/08 12:00 PM
1/18/08 12:00 PM
1/19/08 12:00 PM
1/20/08 12:00 PM
1/21/08 12:00 PM
40 F
Cast Shafts
Cut Wires
Air Temp
1TCC_1
1TCC_2
1TC1_1
1TC1_2
1TC2_1
1TC2_2
1TC3_1
1TC3_2
1TC4_1
1TC4_2

Wiring Conduits to Data Collection System

*Thermal readings averaged per gage level
(2 thermocouples & 4 thermistors per level).

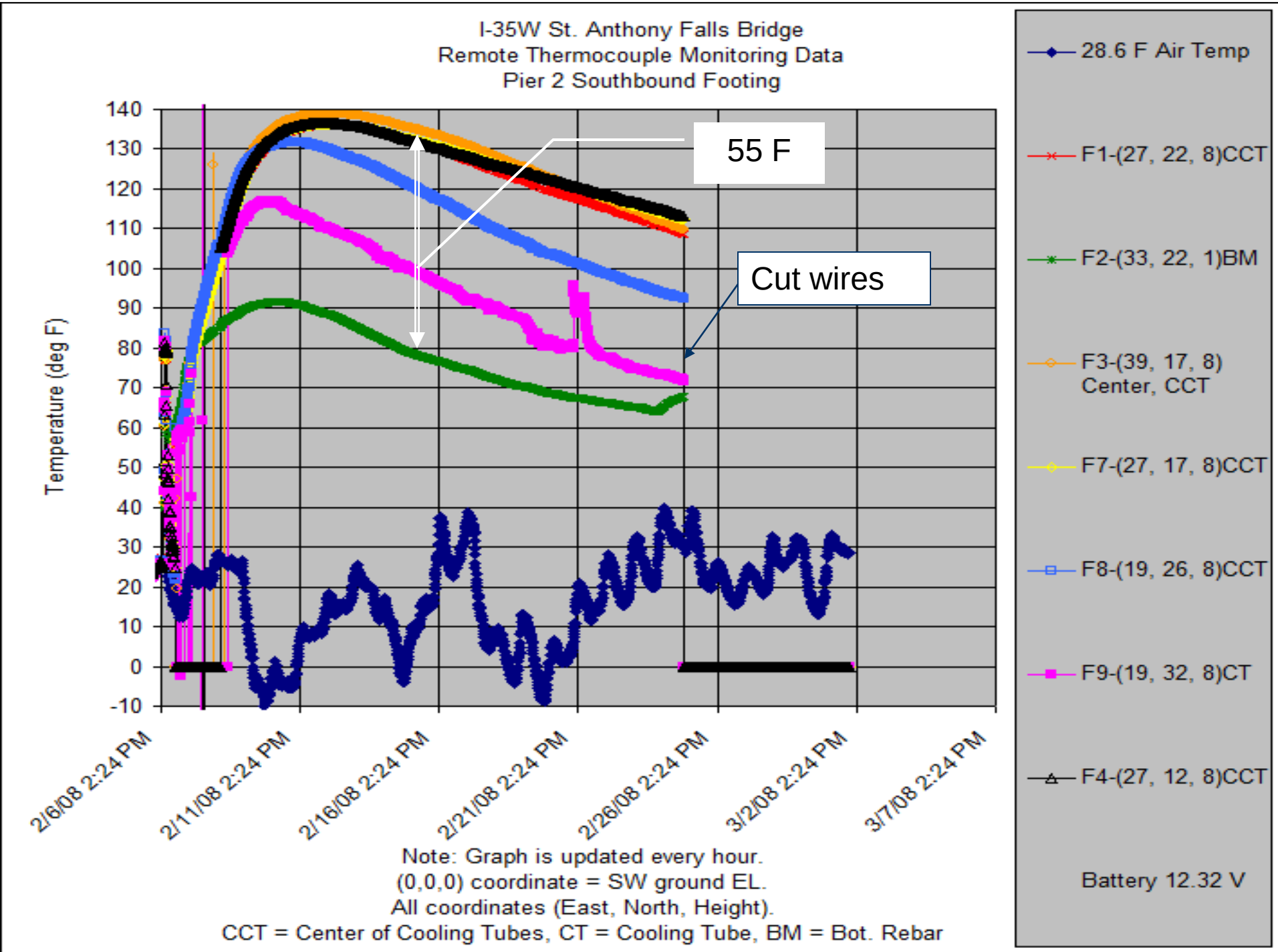
I-35 St. Anthony Falls Bridge
Shaft 1 Thermal Data



Footing Temperature Monitoring

Insulation Blankets to Maintain External Footing Temperature

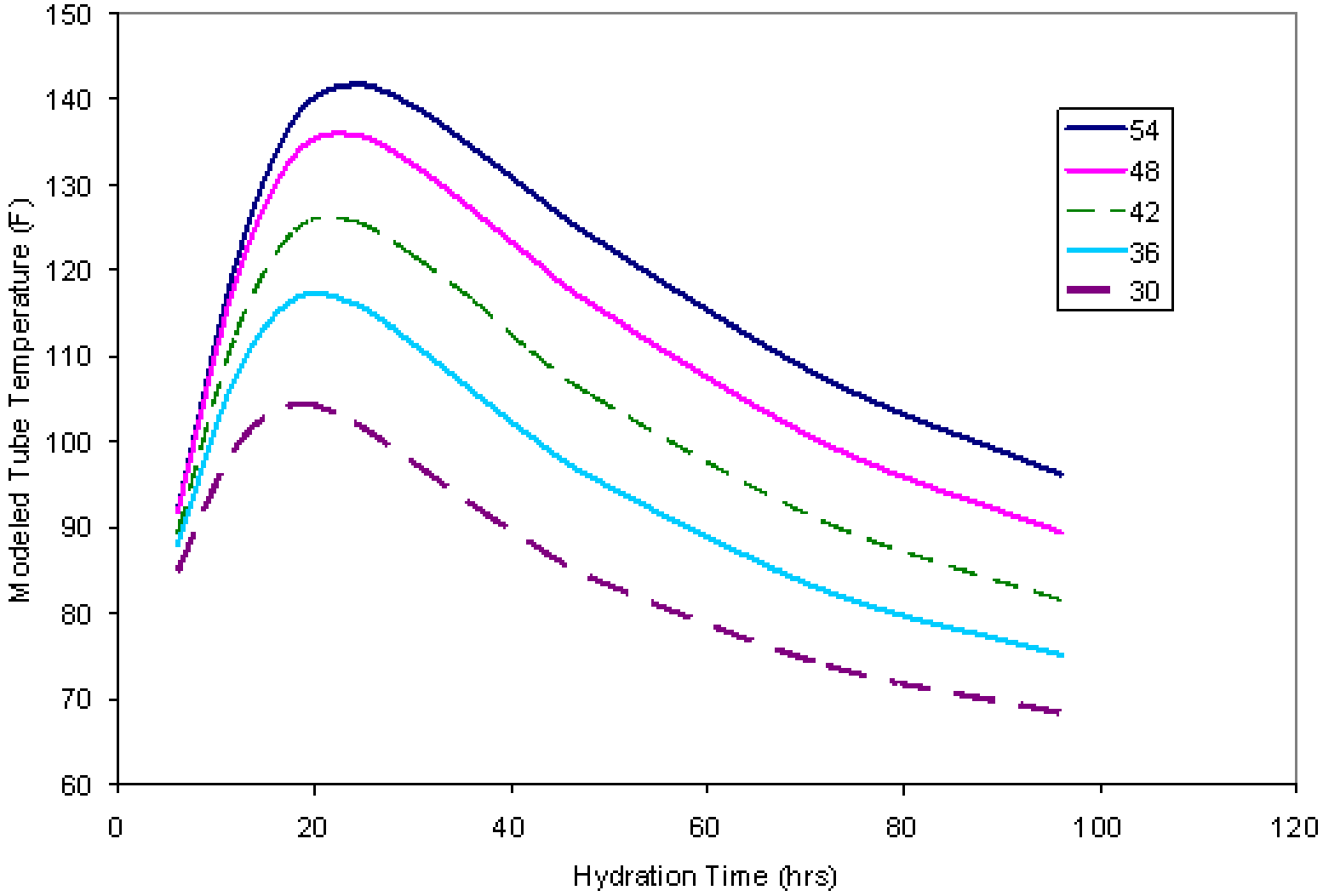
Network of cooling tubes

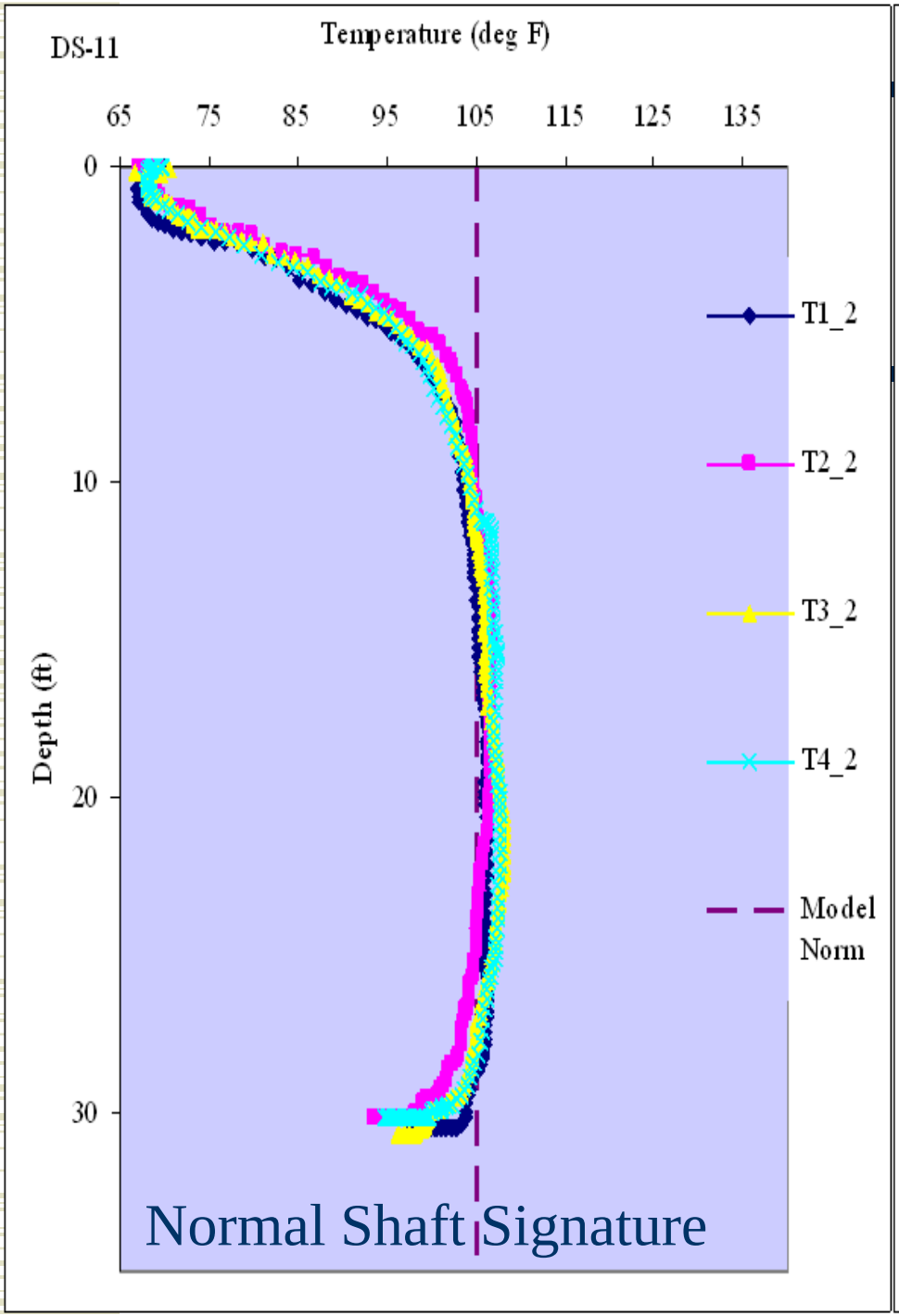

I-35W St. Anthony Falls Bridge
Remote Thermocouple Monitoring Data
Pier 2 Southbound Footing
Temperature (deg F)
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
55 F
Cut wires
2/6/08 2:24 PM
2/11/08 2:24 PM
2/16/08 2:24 PM
2/21/08 2:24 PM
2/26/08 2:24 PM
3/2/08 2:24 PM
3/7/08 2:24 PM
28.6 F Air Temp
F1-(27, 22, 8)CCT
F2-(33, 22, 1)BM
F3-(39, 17, 8) Center, CCT
F7-(27, 17, 8)CCT
F8-(19, 26, 8)CCT
F9-(19, 32, 8)CT
F4-(27, 12, 8)CCT
Battery 12.32 V
Note: Graph is updated every hour.
(0,0,0) coordinate = SW ground EL.
All coordinates (East, North, Height).
CCT = Center of Cooling Tubes, CT = Cooling Tube, BM = Bot. Rebar

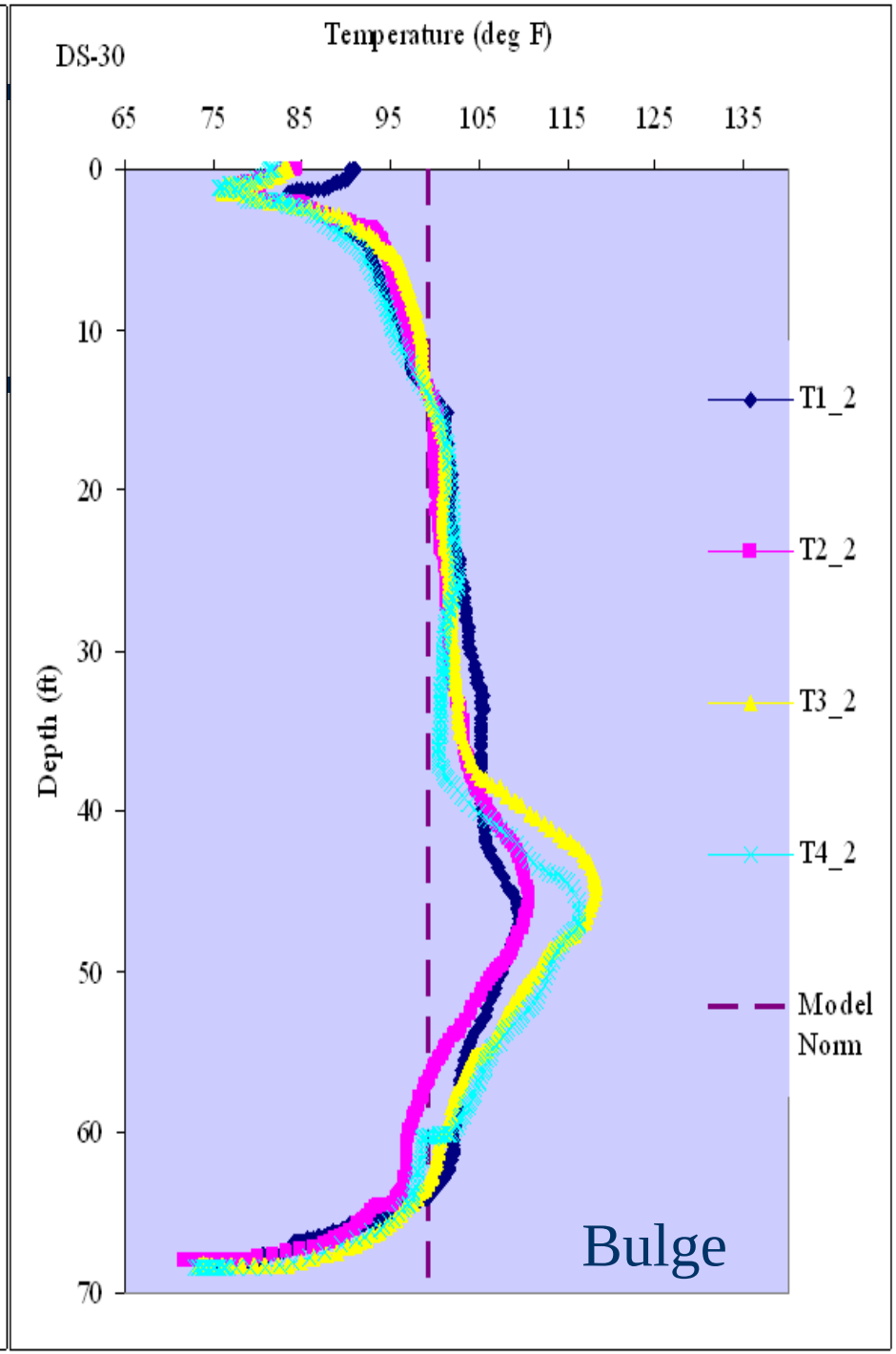
Thermal Integrity Scans

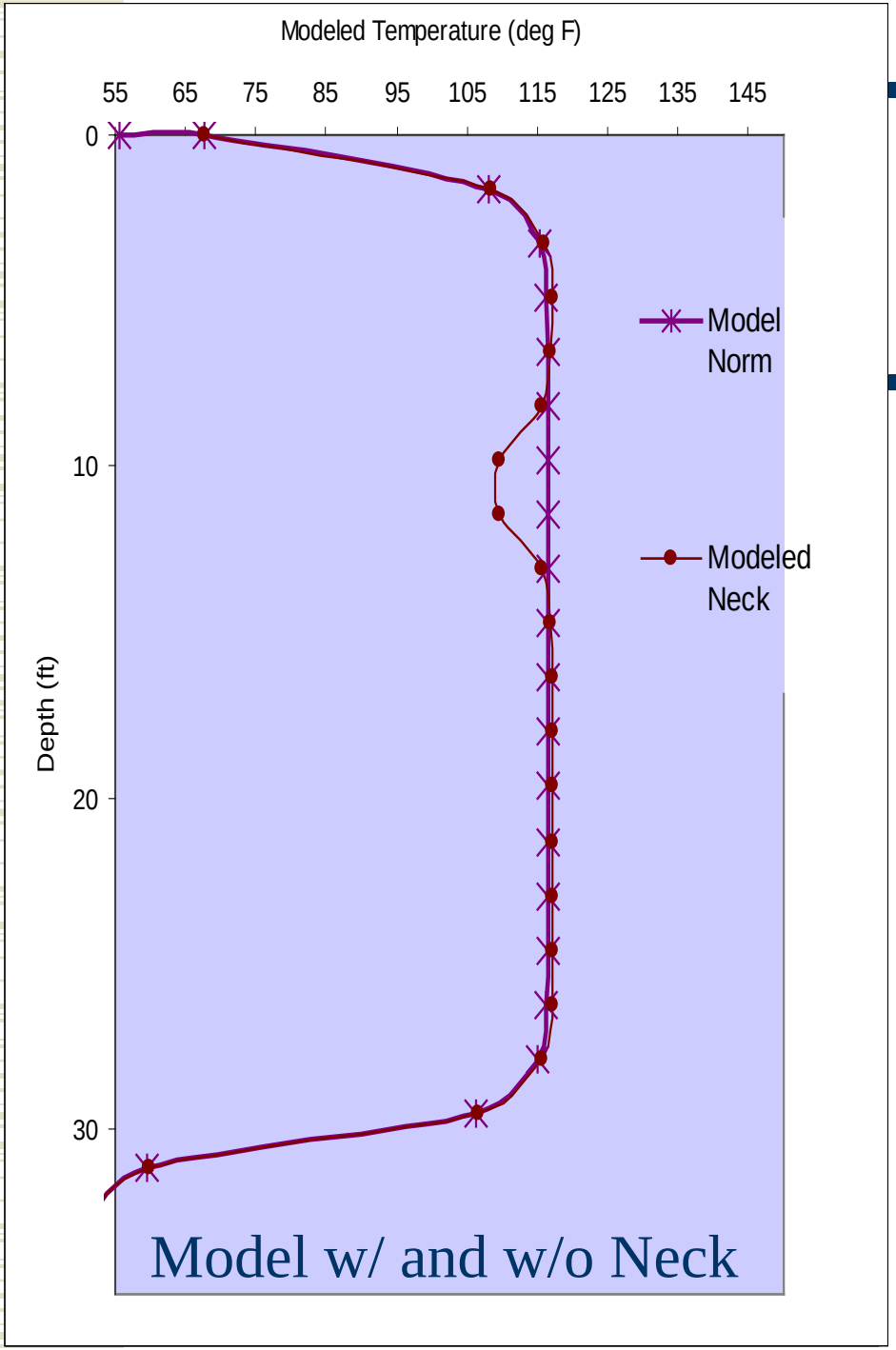
- Field Results / Model Predictions
- Bulging
- Necking
- Cage Alignment
- Concrete Maturation

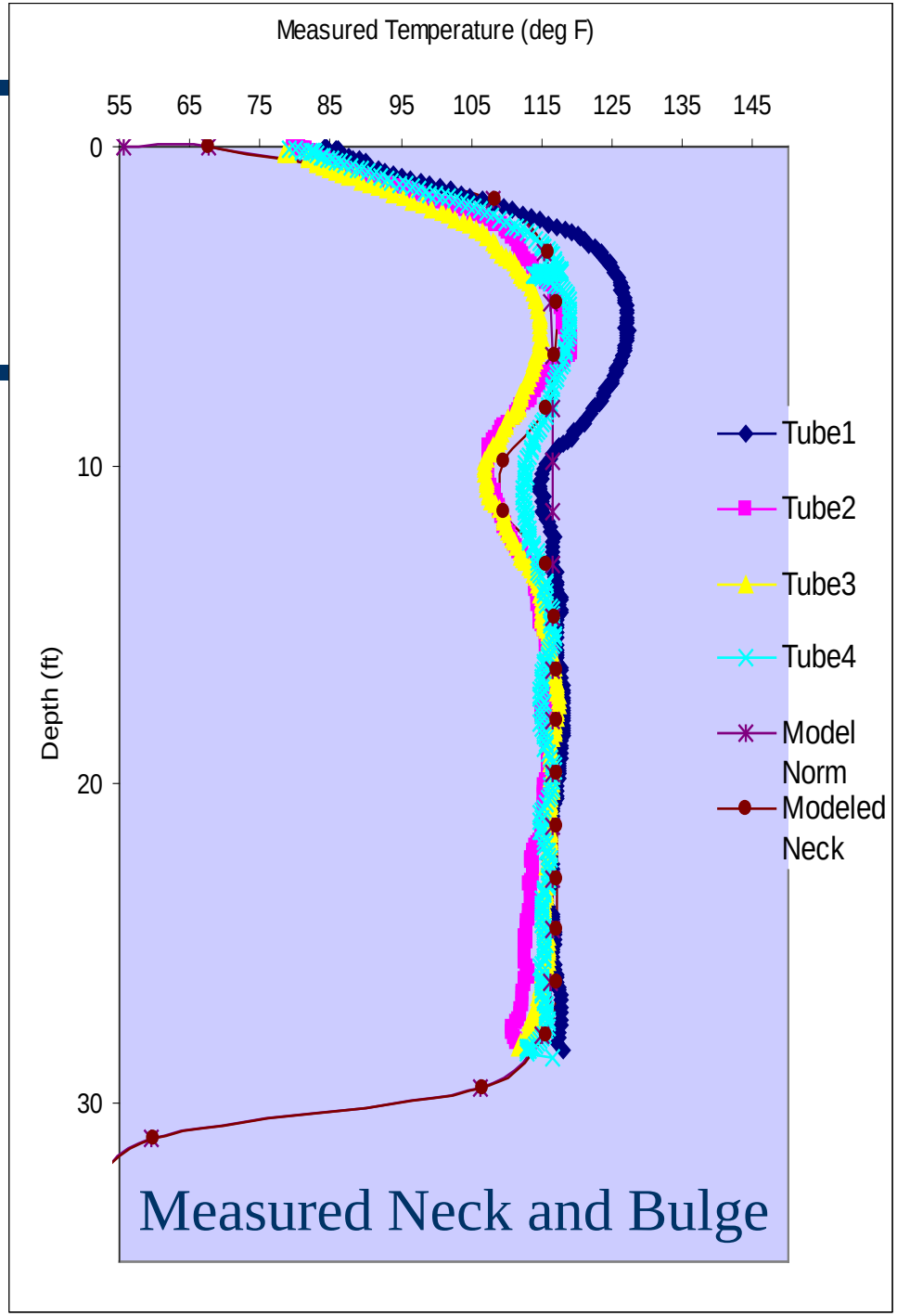
Normal Access Tube Temperatures for Courthouse Site



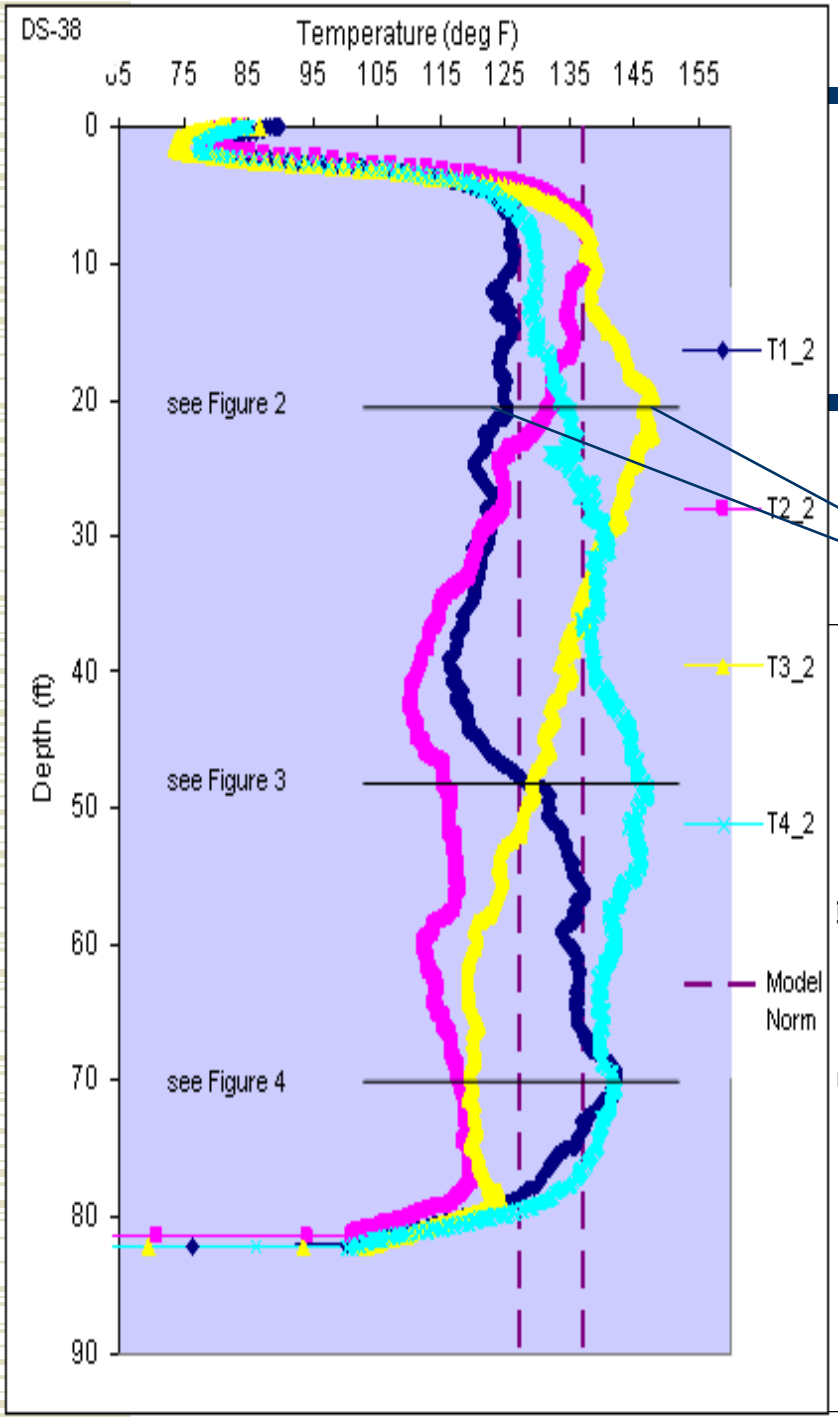

DS-11
Temperature (deg F)
65
75
85
95
105
115
125
135
0
10
20
30
Depth (ft)
T1_2
T2_2
T3_2
T4_2
Model Norm
Normal Shaft Signature

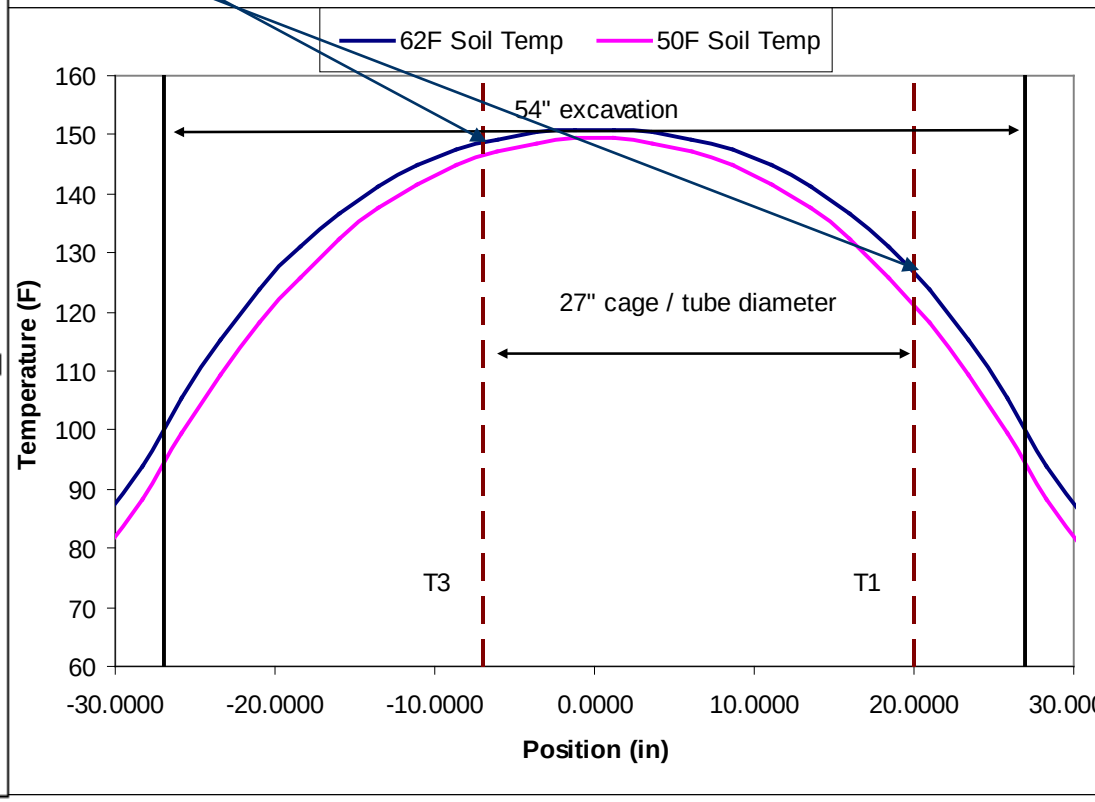

DS-30
Temperature (deg F)
65
75
85
95
105
115
125
135
0
10
20
30
40
50
60
70
Depth (ft)
T1_2
T2_2
T3_2
T4_2
Model Norm
Bulge

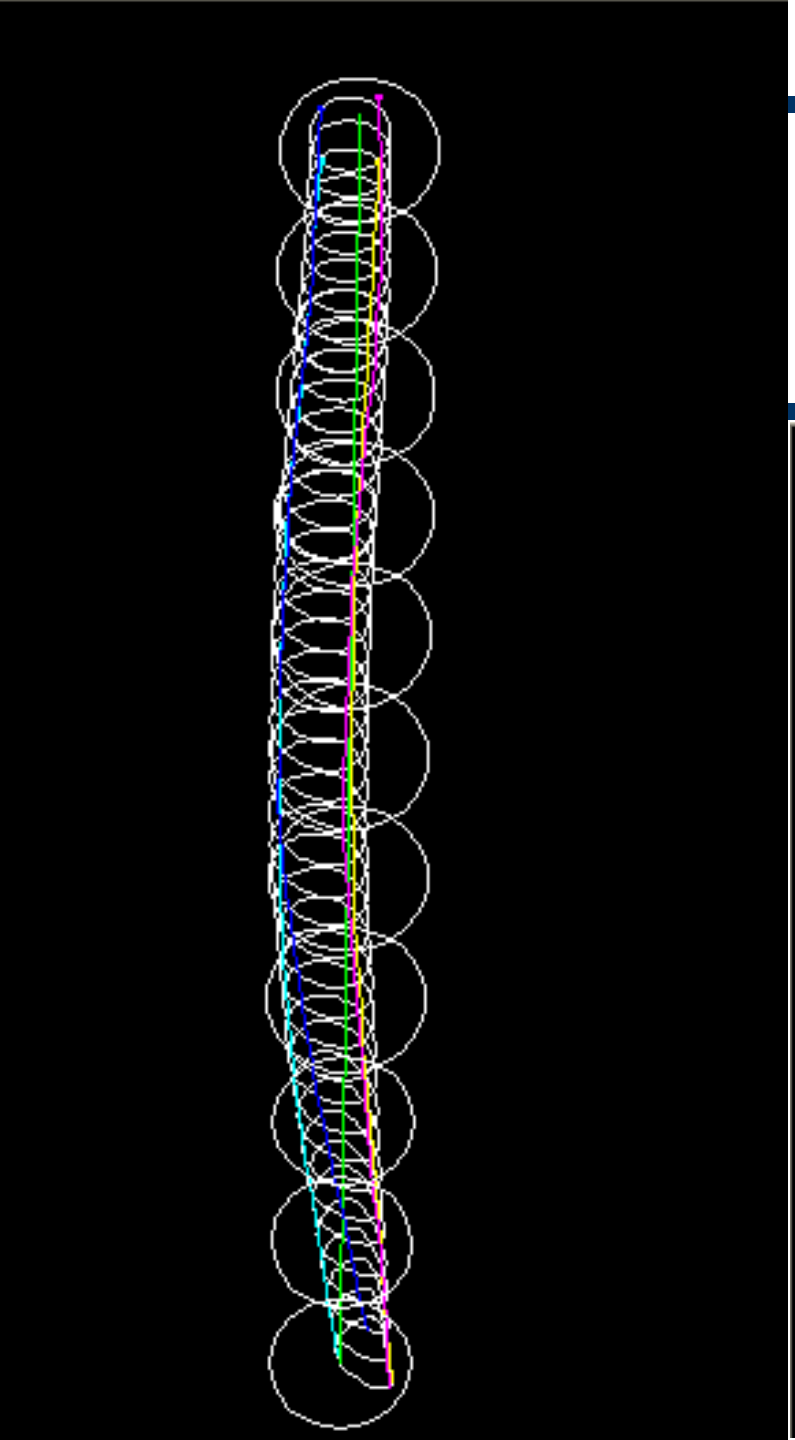

Modeled Temperature (deg F)
55
65
75
85
95
105
115
125
135
145
0
10
20
30
Depth (ft)
Model Norm
Modeled Neck
Model w/ and w/o Neck


Measured Temperature (deg F)
55
65
75
85
95
105
115
125
135
145
0
10
20
30
Depth (ft)
Tube1
Tube2
Tube3
Tube4
Model Norm
Modeled Neck
Measured Neck and Bulge

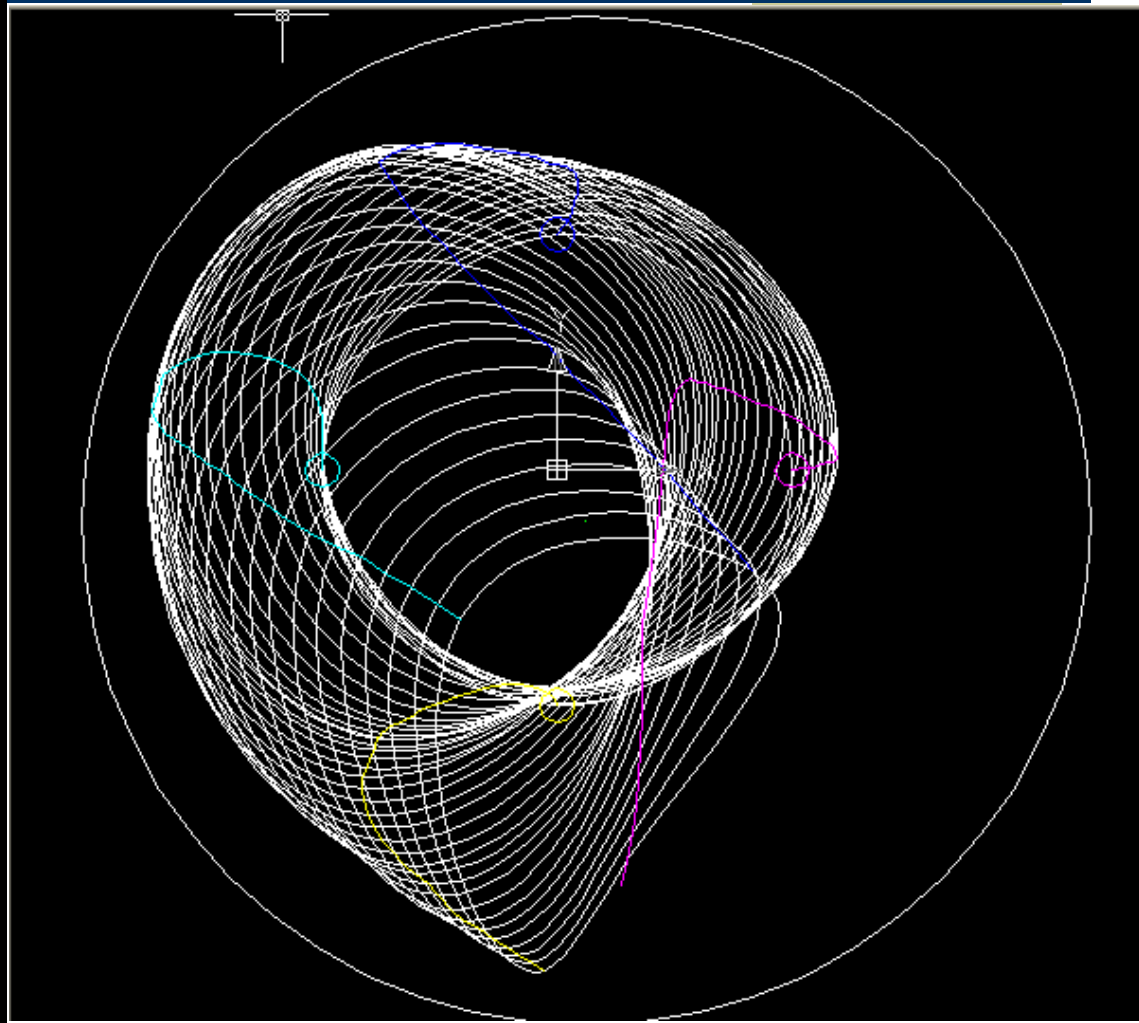
Cage Alignment







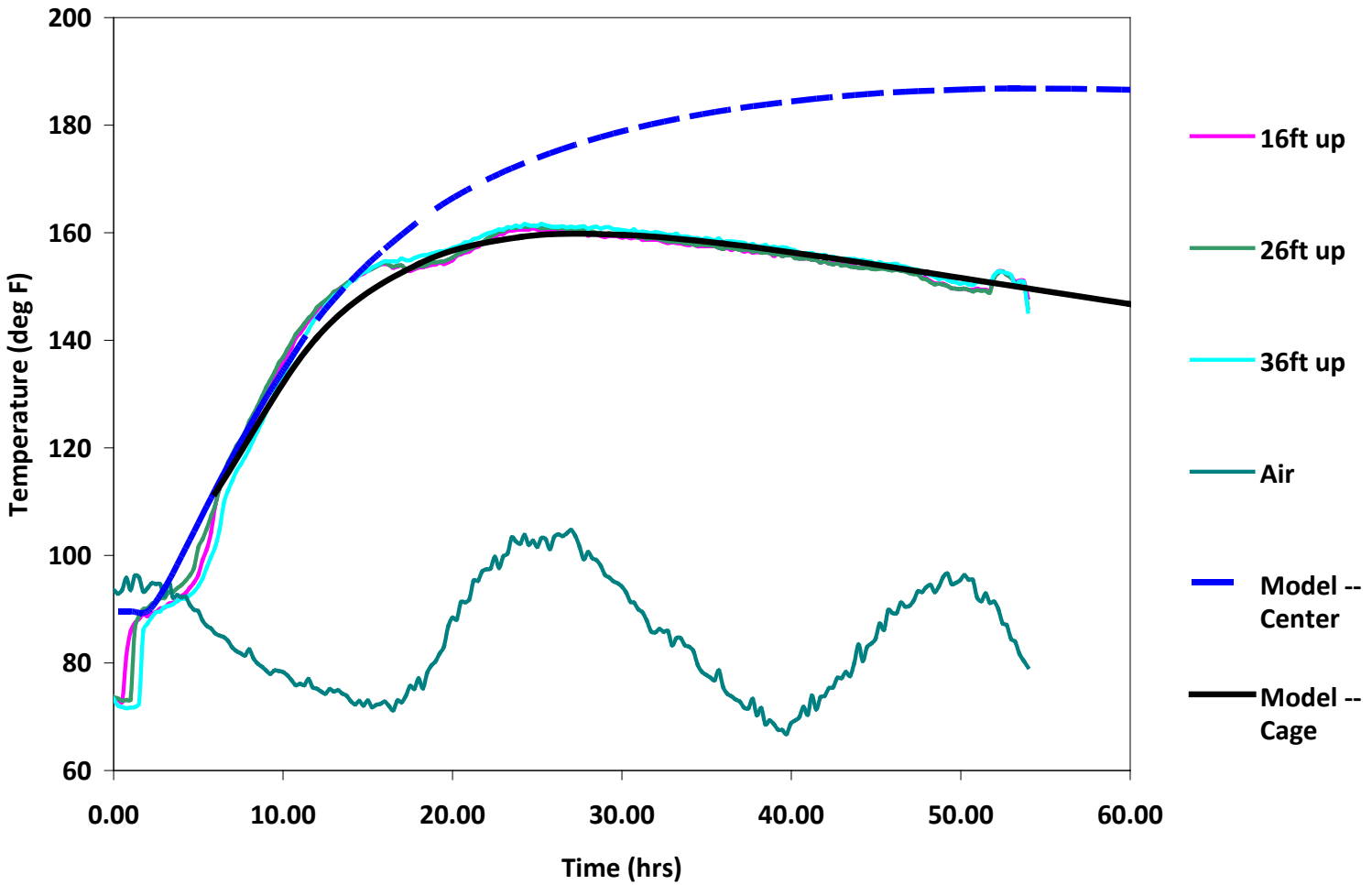
Cage Alignment

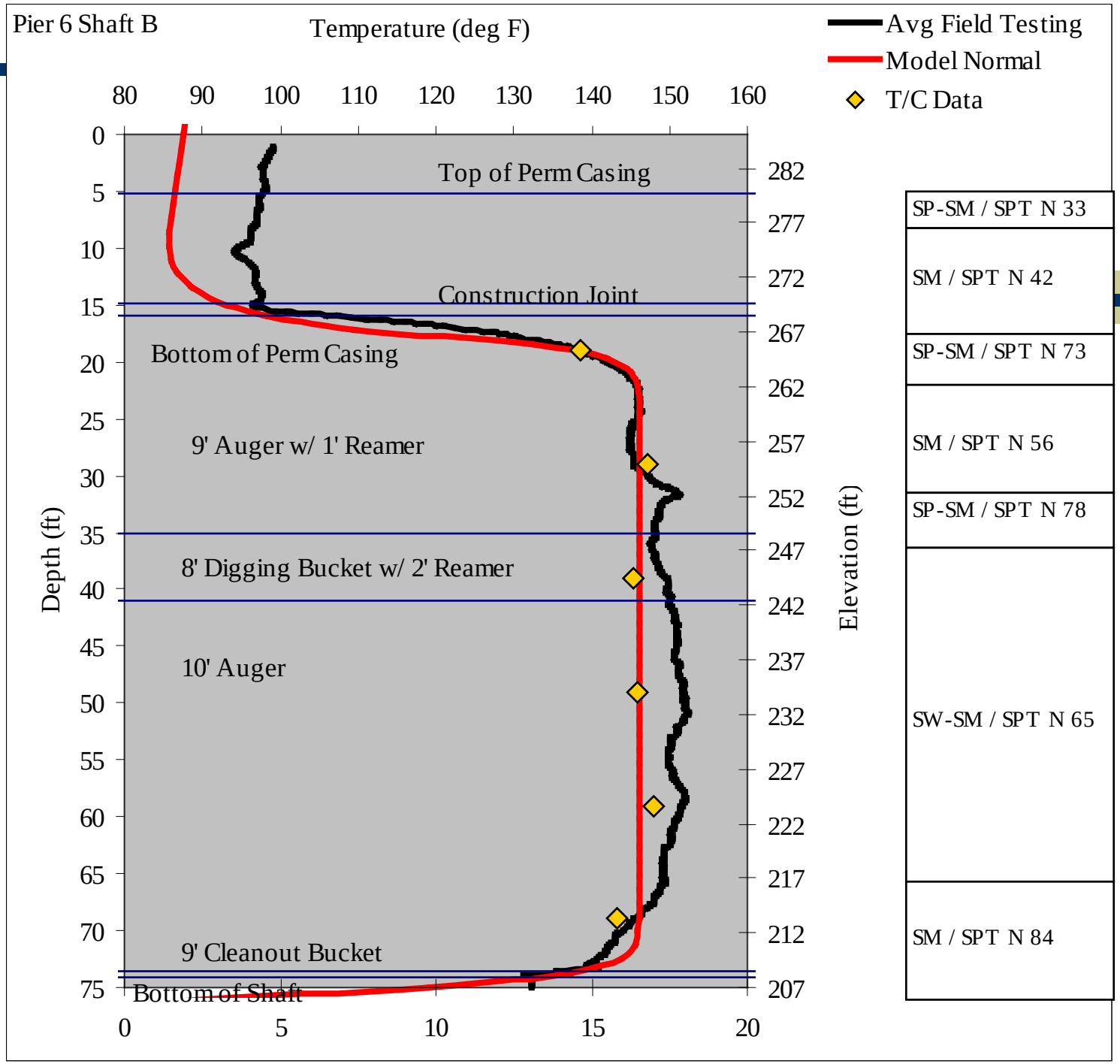


WSDOT Nalley Valley I-5/SR16

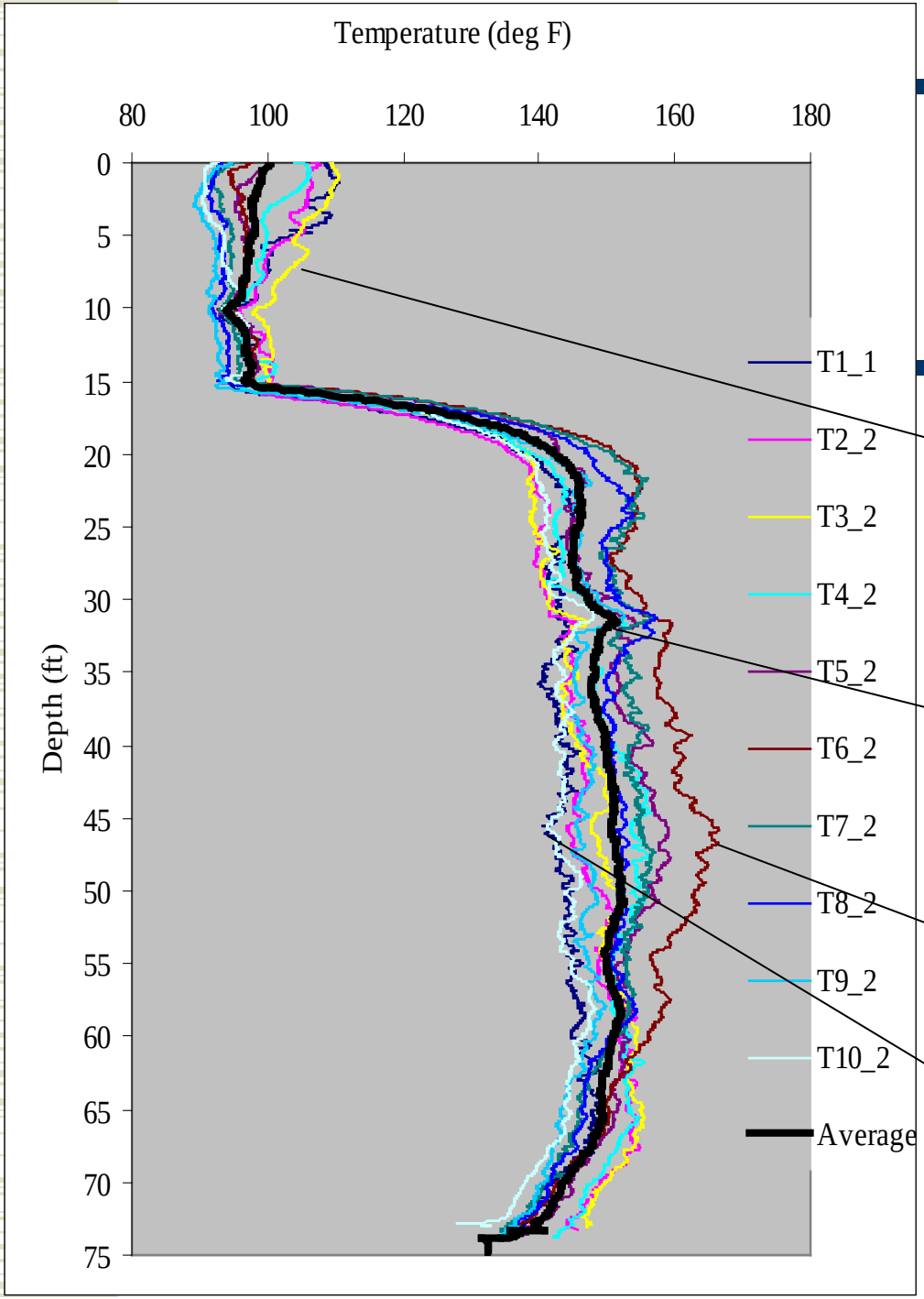
WSDOT Nalley Valley I-5/SR16

Modeled and Measured Core and Tube Temps




Pier 6 Shaft B
Temperature (deg F)
Avg Field Testing
Model Normal
T/C Data
80
90
100
110
120
130
140
150
160
Depth (ft)
Elevation (ft)
Top of Perm Casing
Construction Joint
Bottom of Perm Casing
9' Auger w/ 1' Reamer
8' Digging Bucket w/ 2' Reamer
10' Auger
9' Cleanout Bucket
Bottom of Shaft
SP-SM / SPT N 33
SM / SPT N 42
SP-SM / SPT N 73
SM / SPT N 56
SP-SM / SPT N 78
SW-SM / SPT N 65
SM / SPT N 84

Cage Alignment



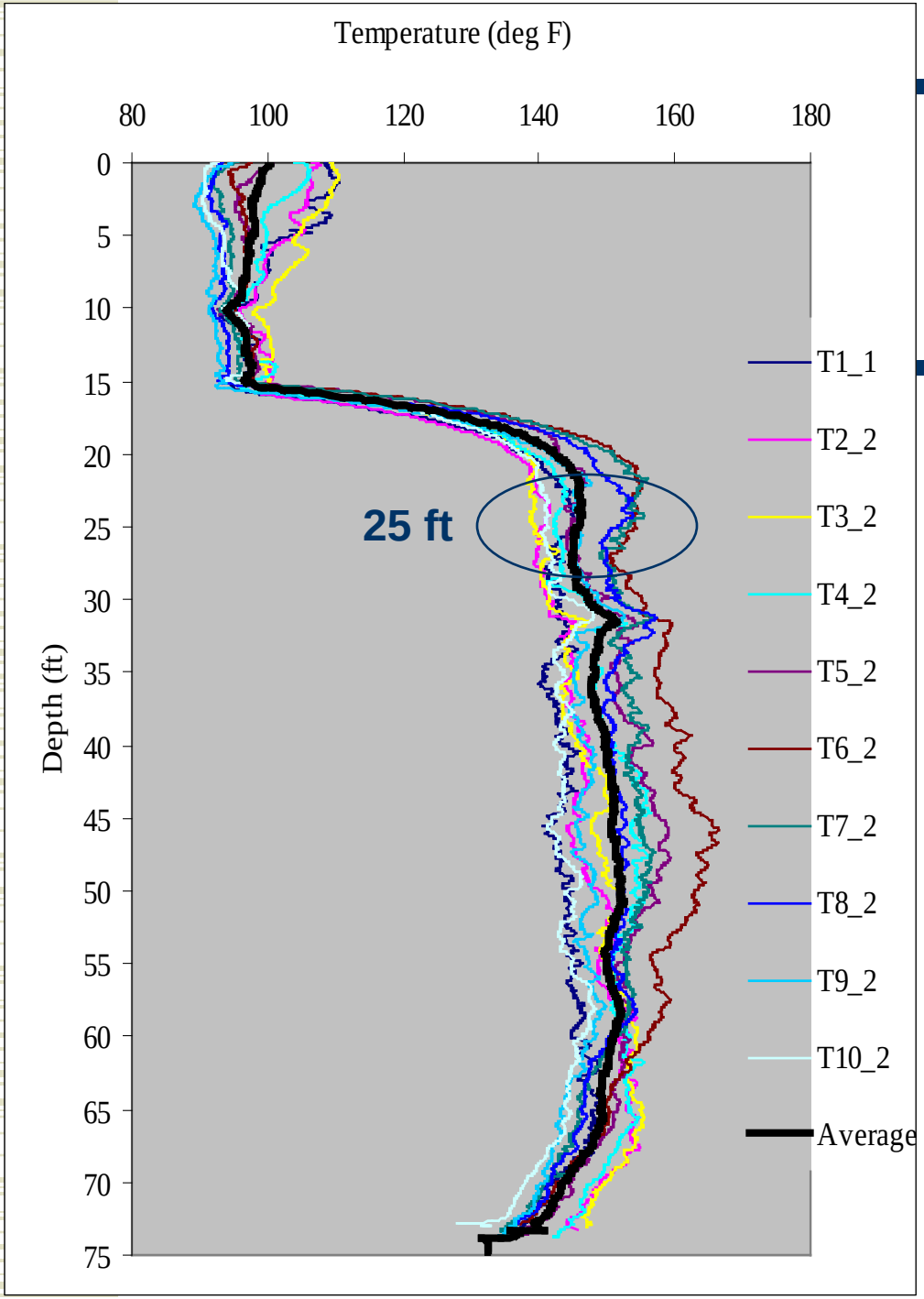
Tube Stickup

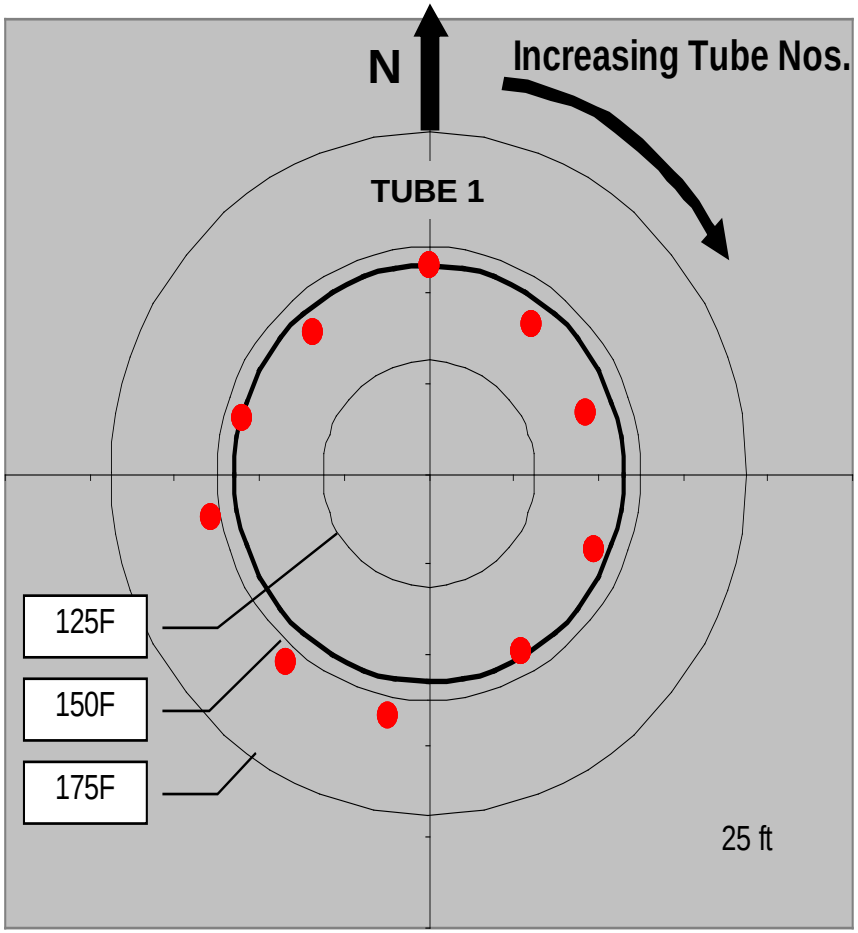
Water Table Sloughing

Tube No. 6

Tube No. 1

Cage Alignment





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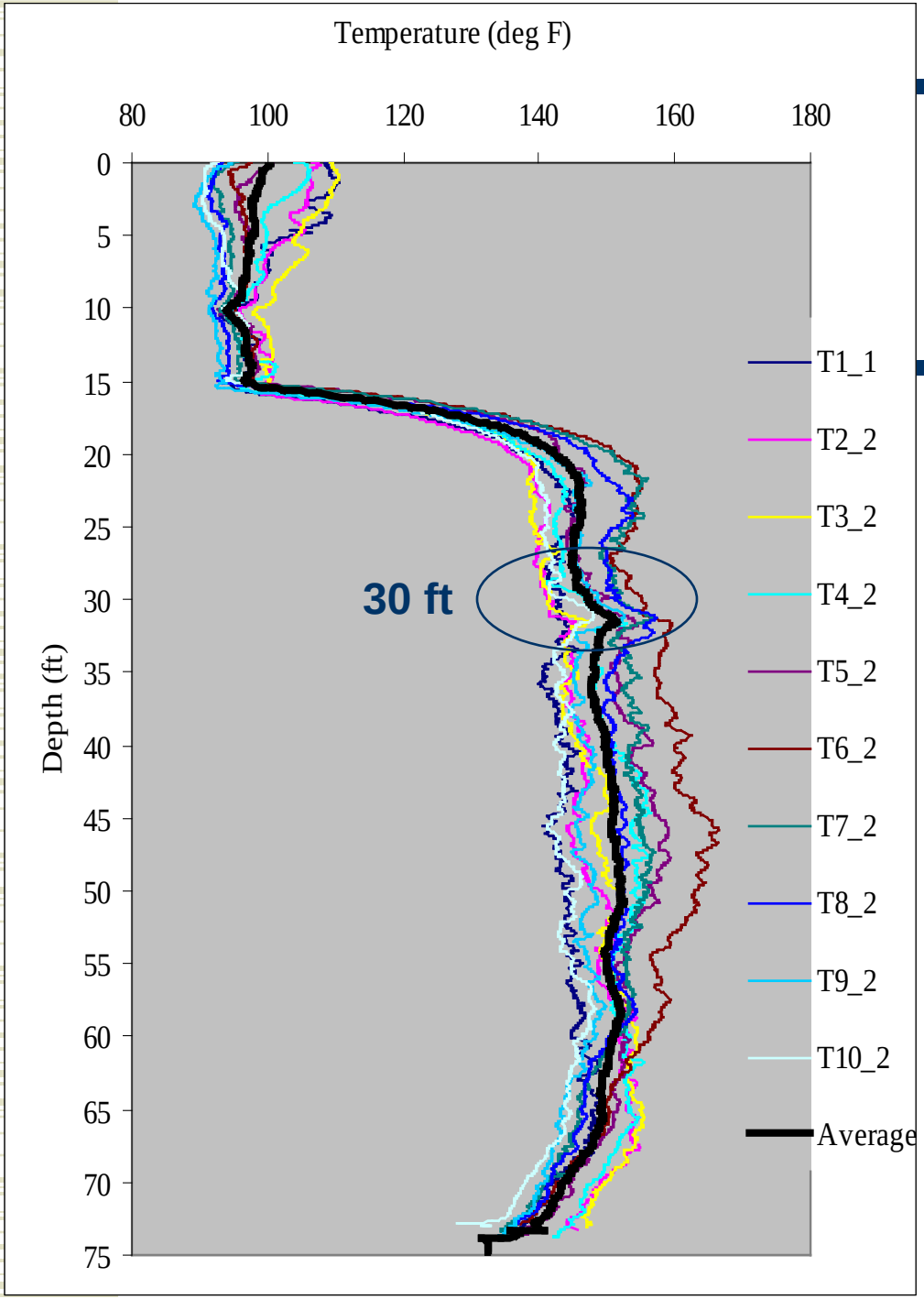

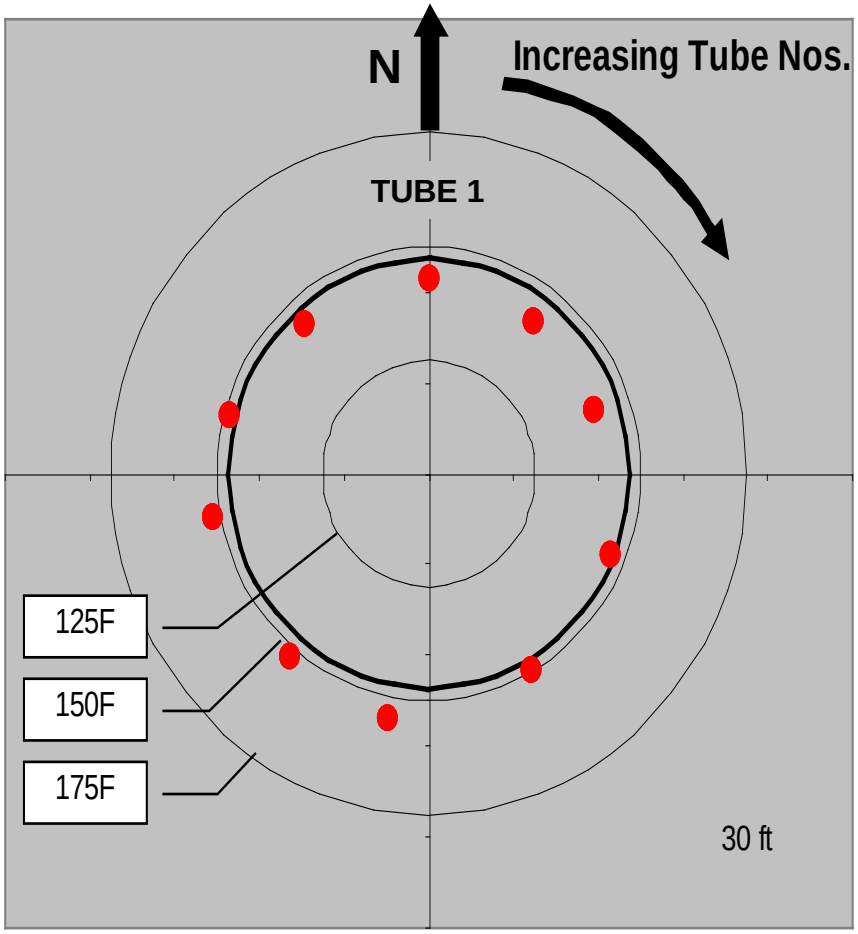

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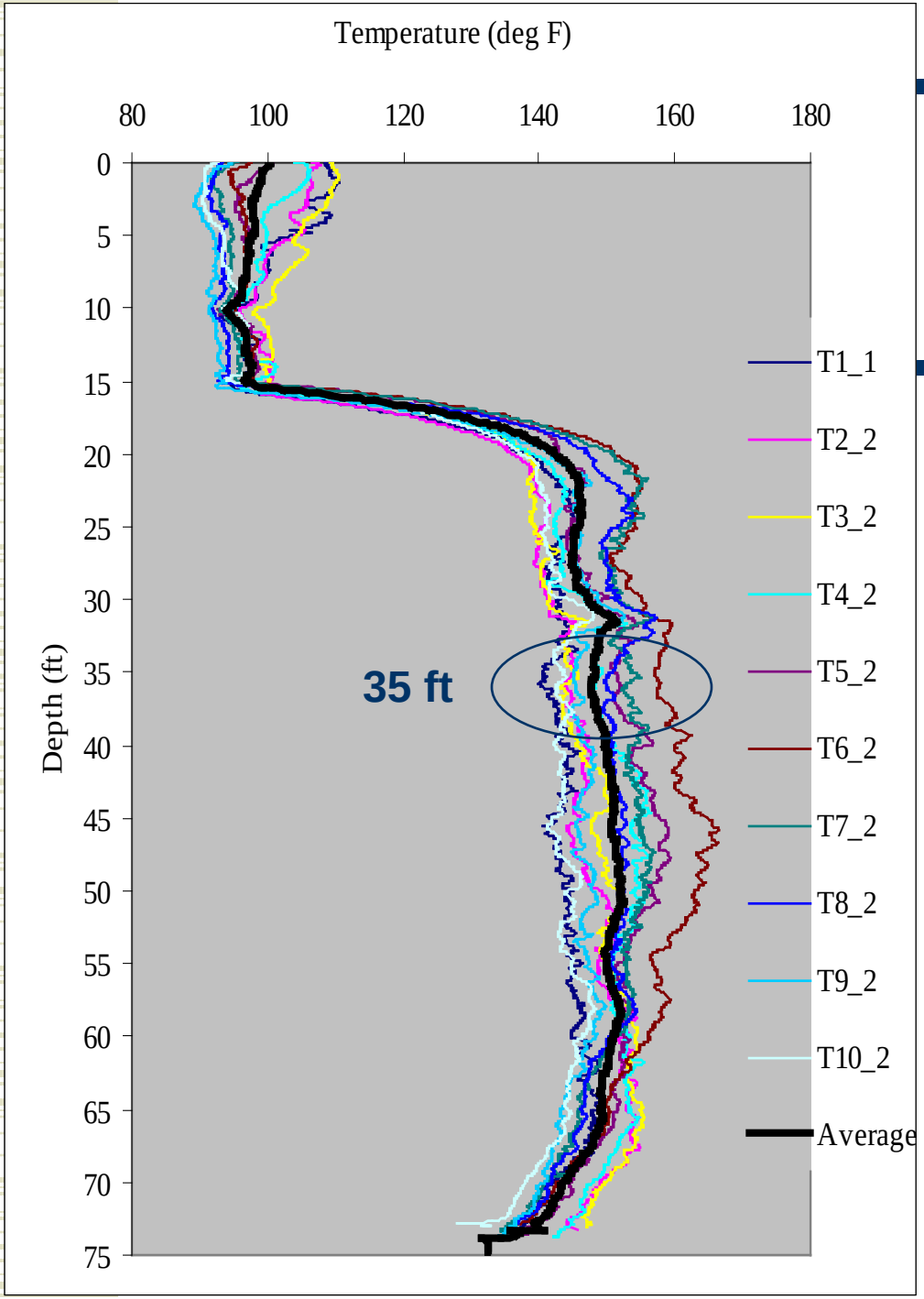

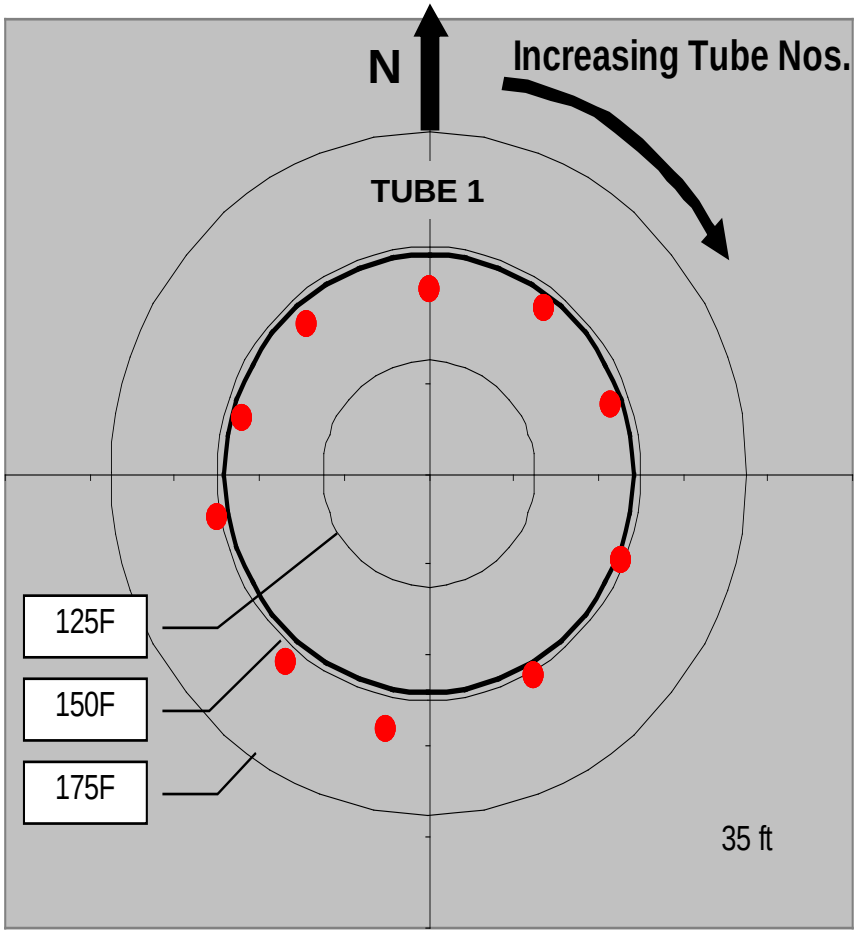

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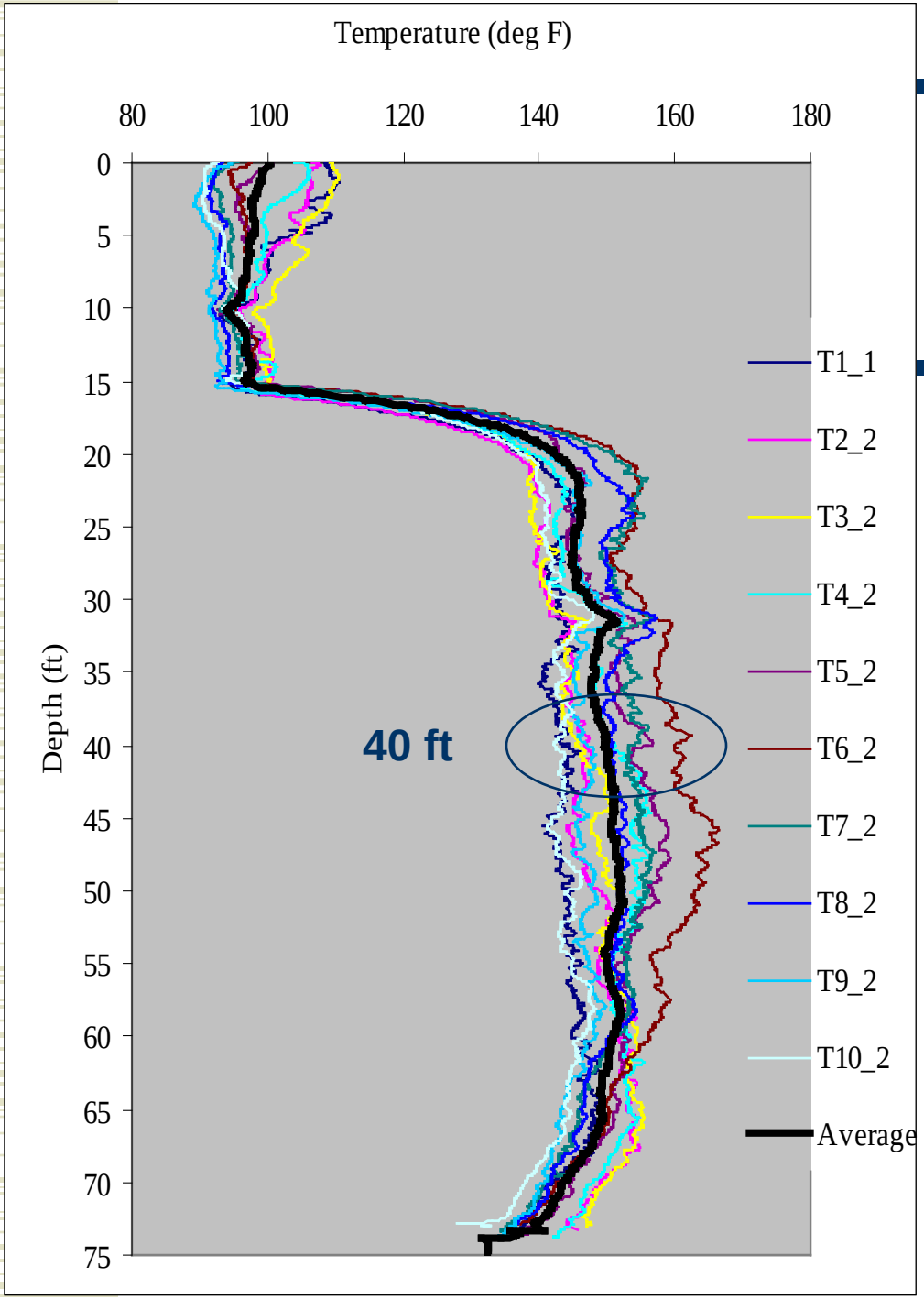

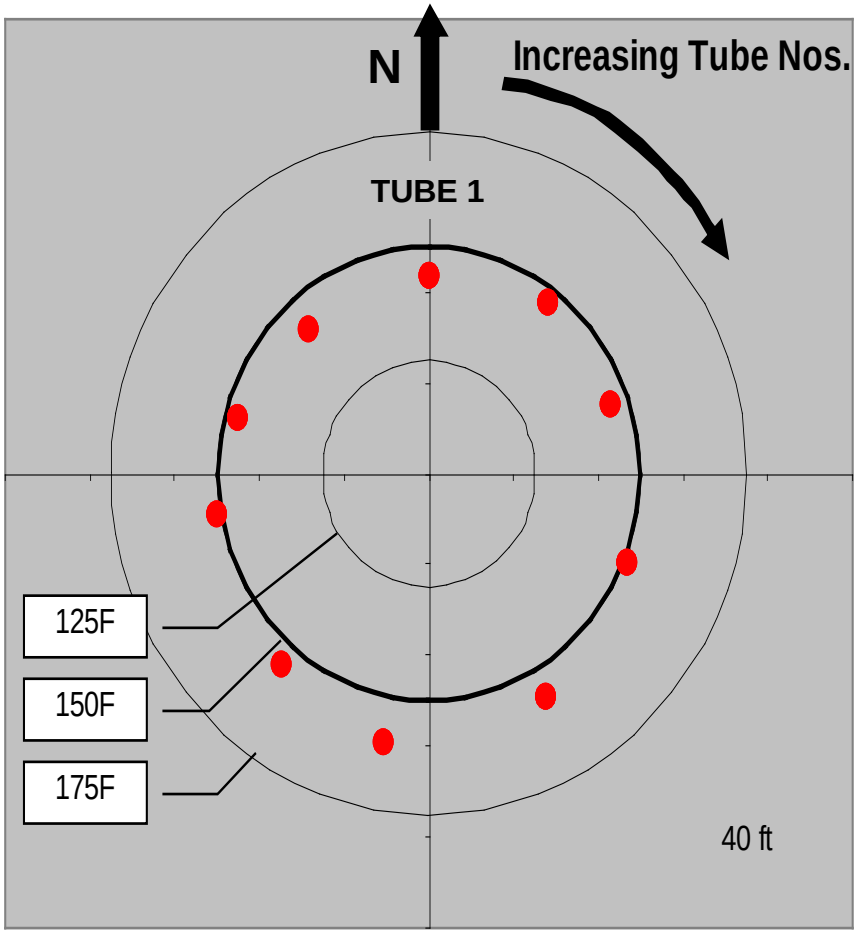

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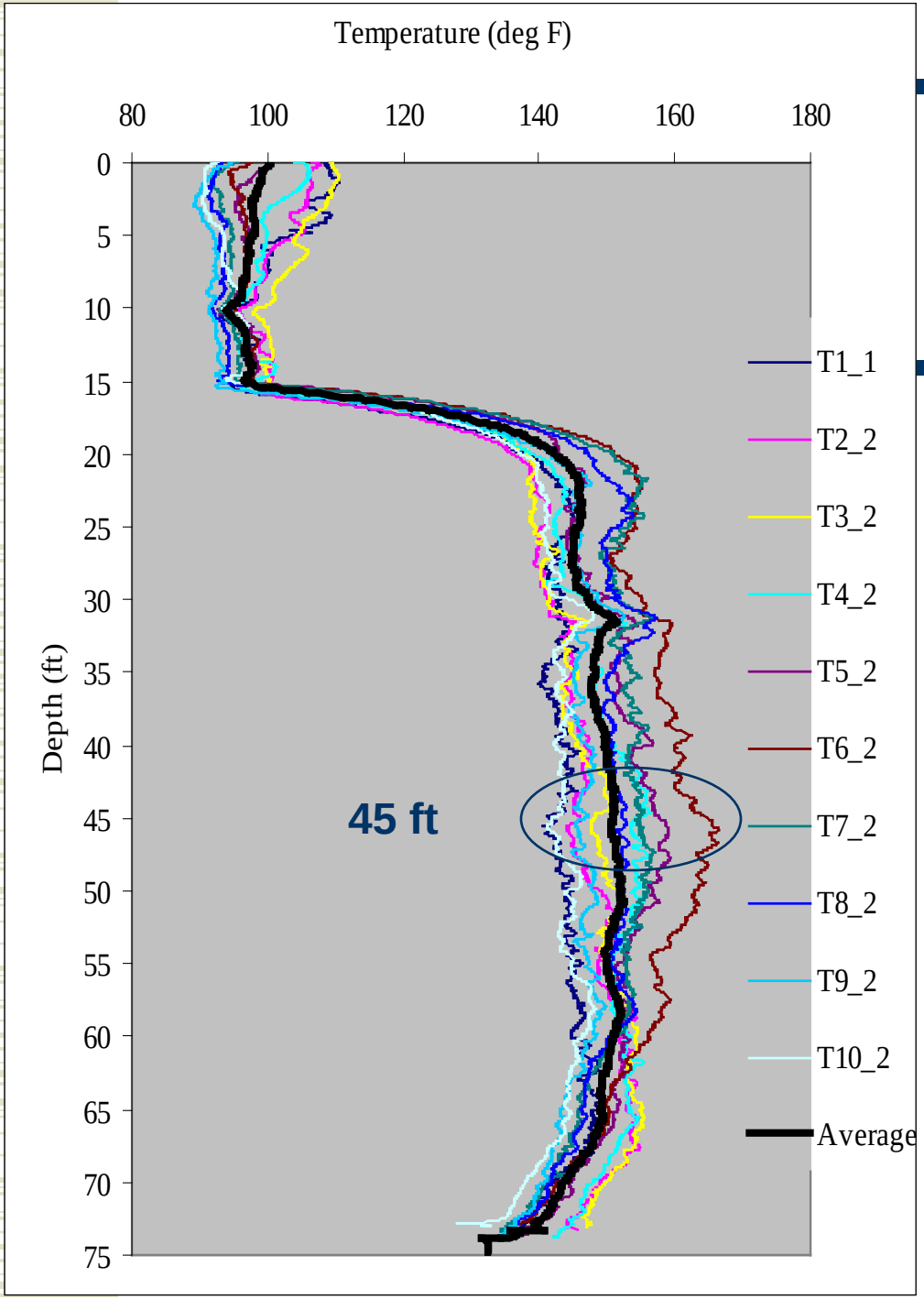

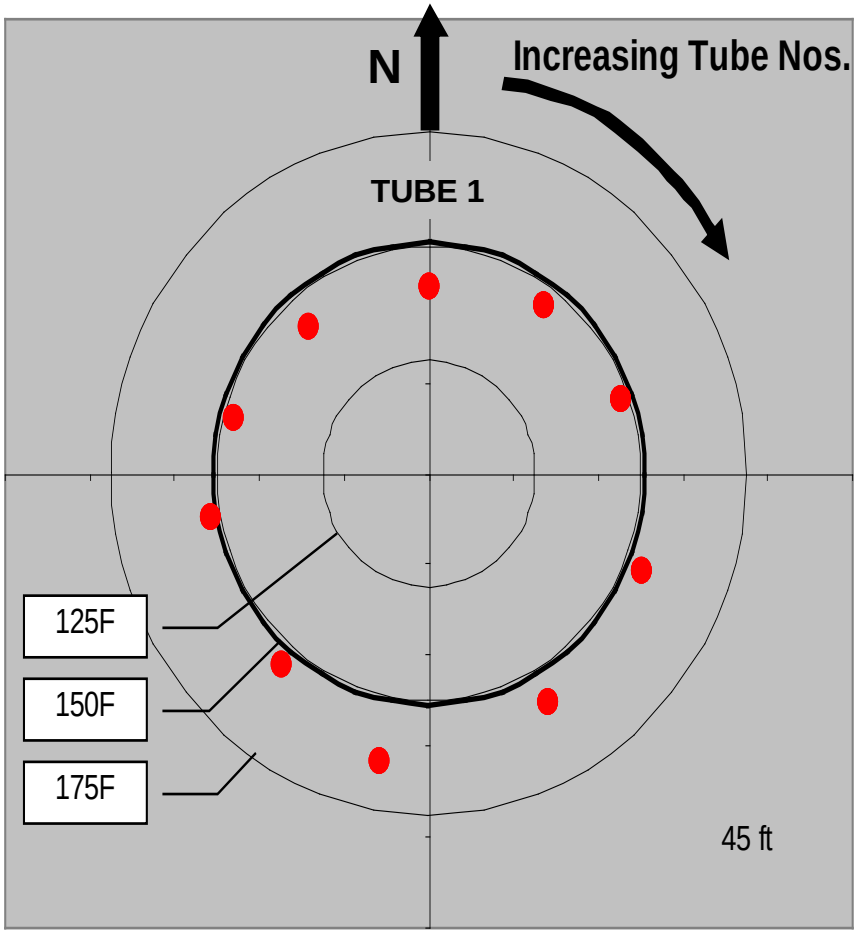

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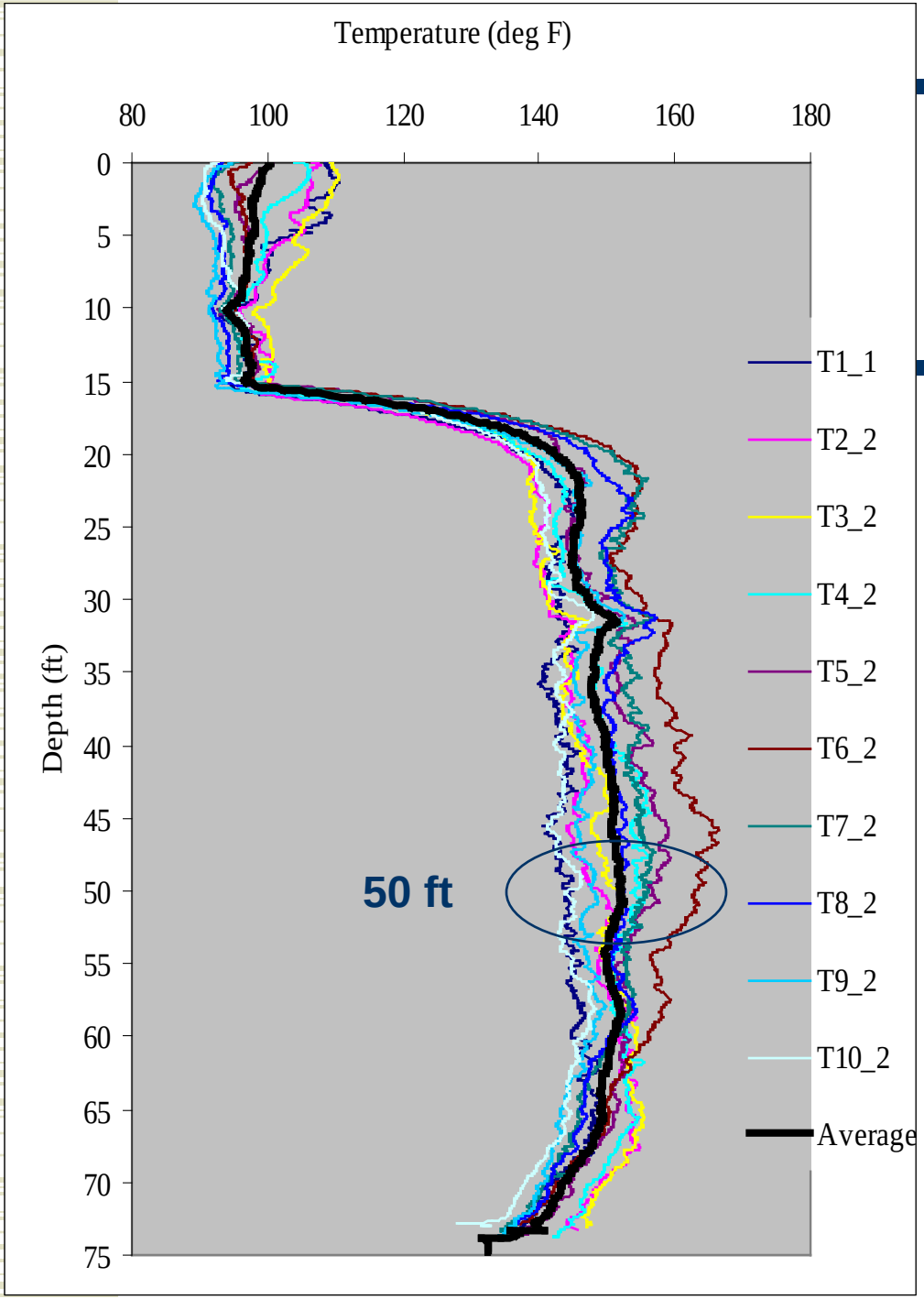

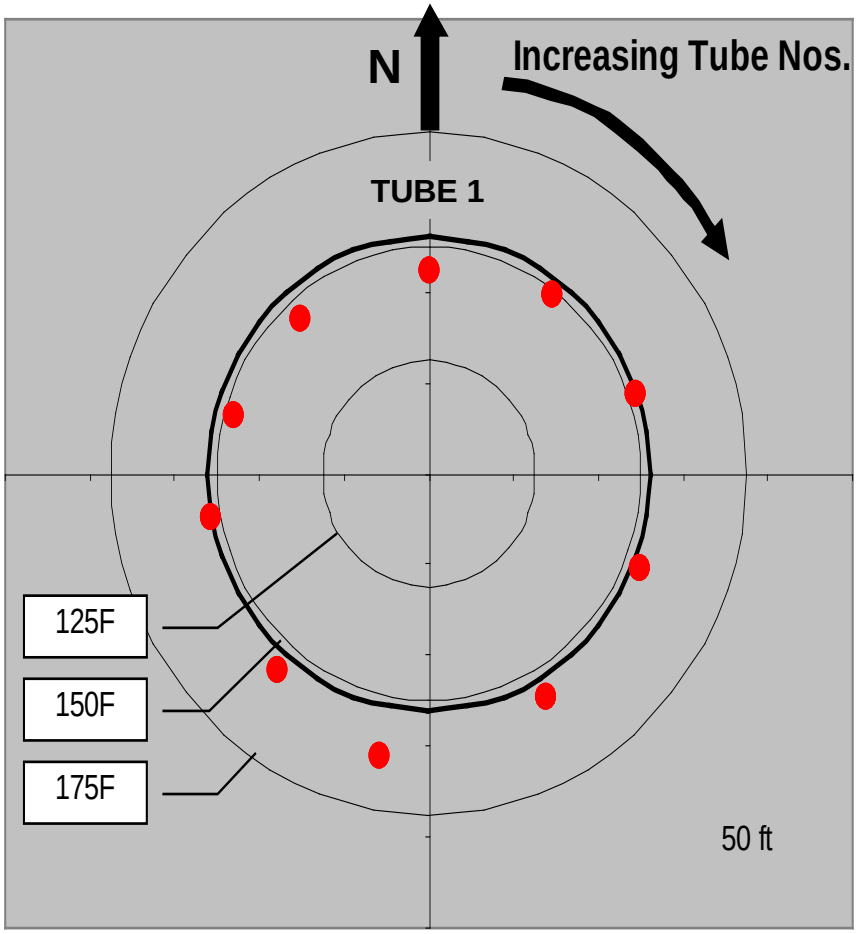

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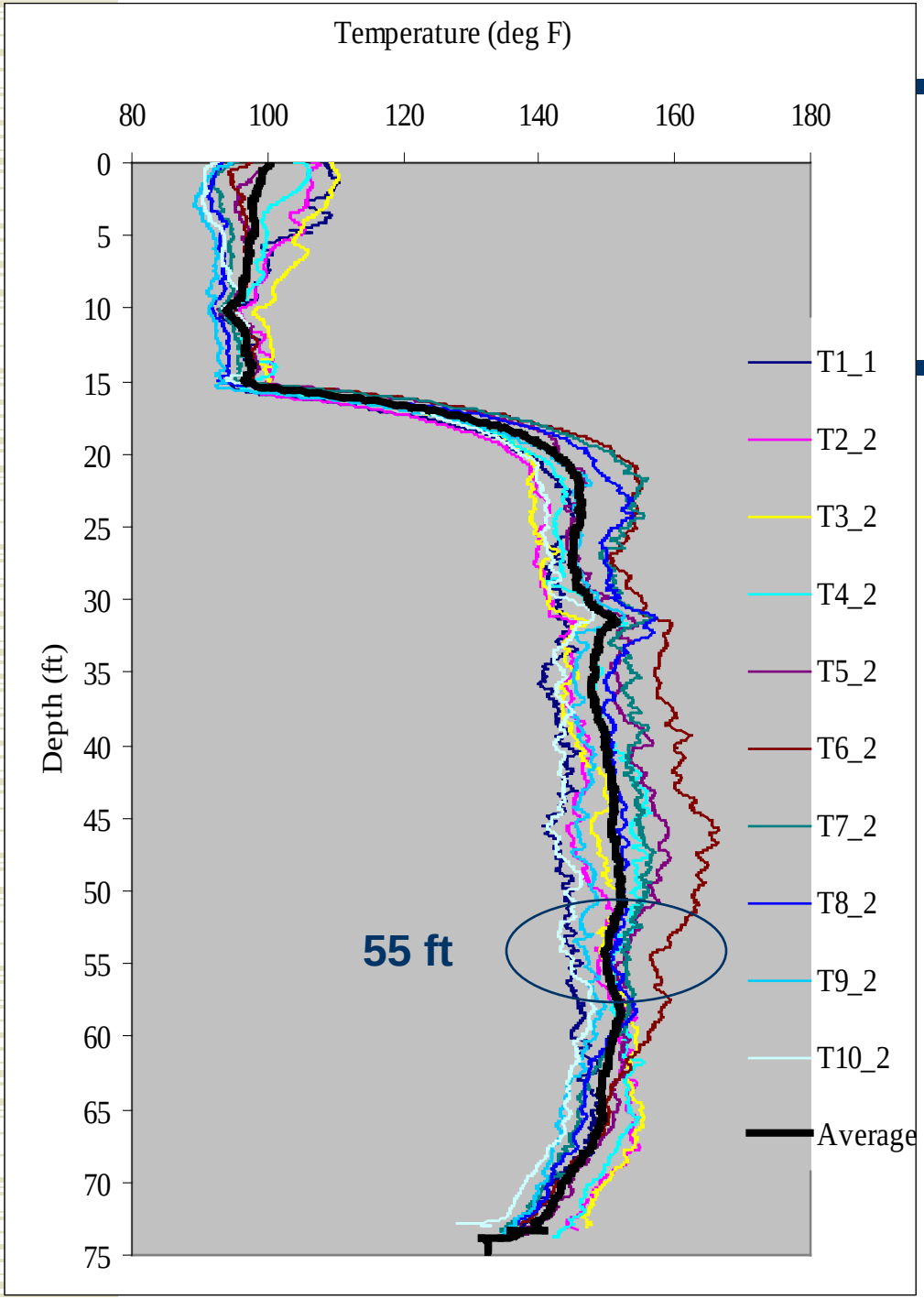

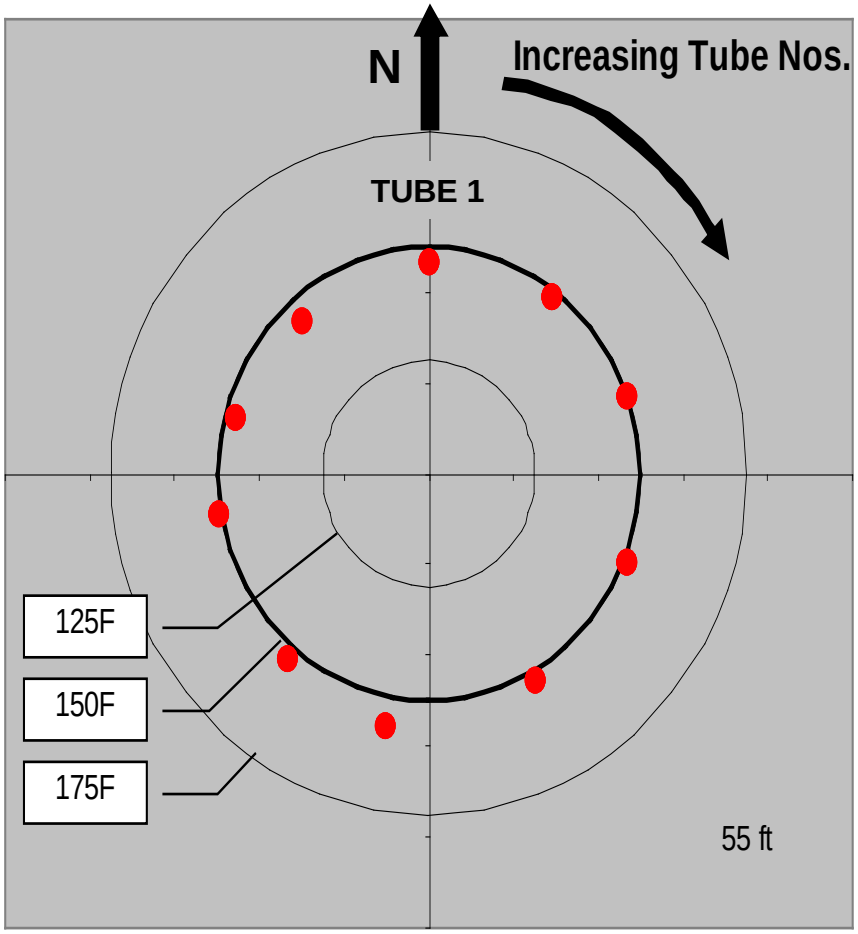

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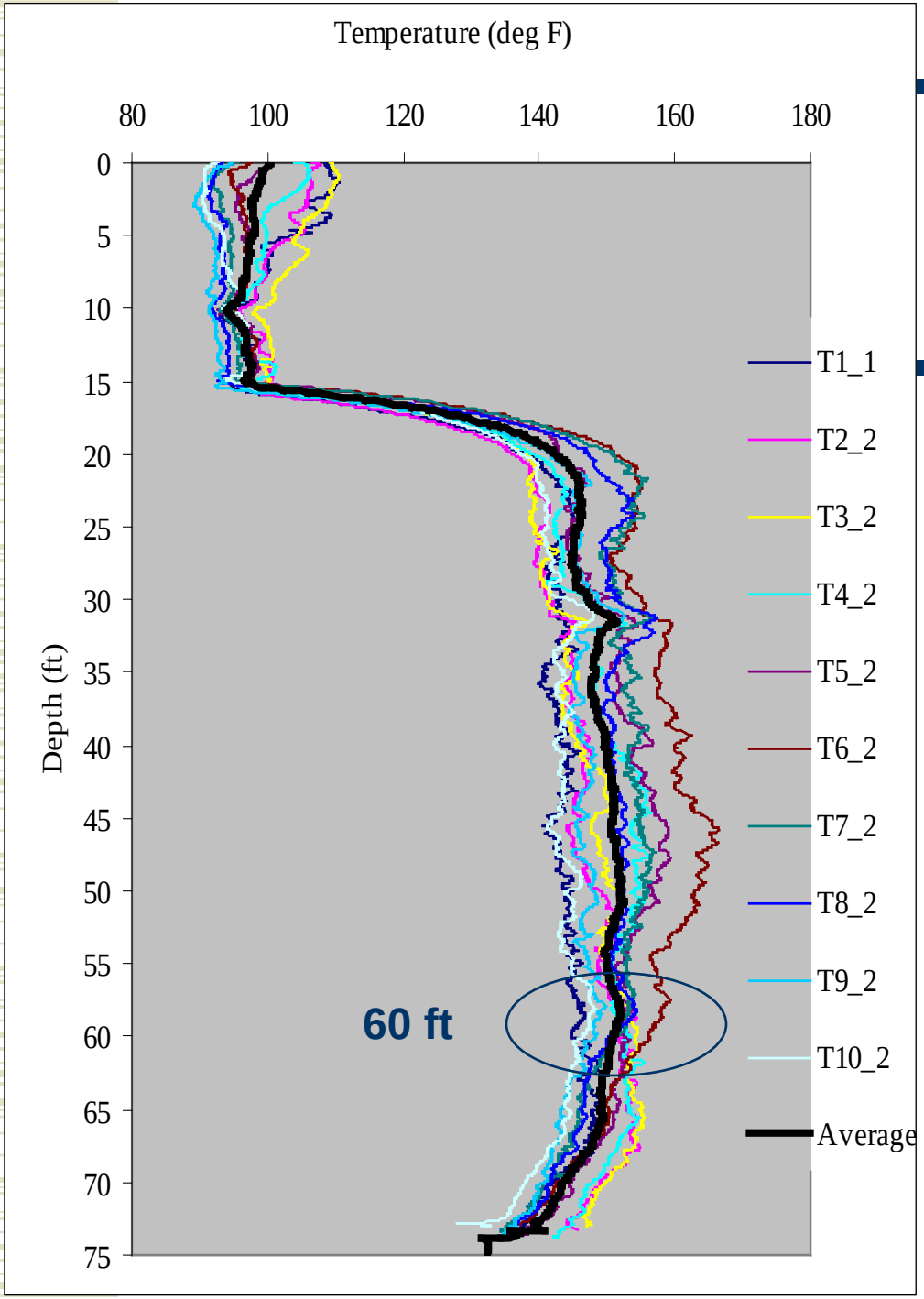

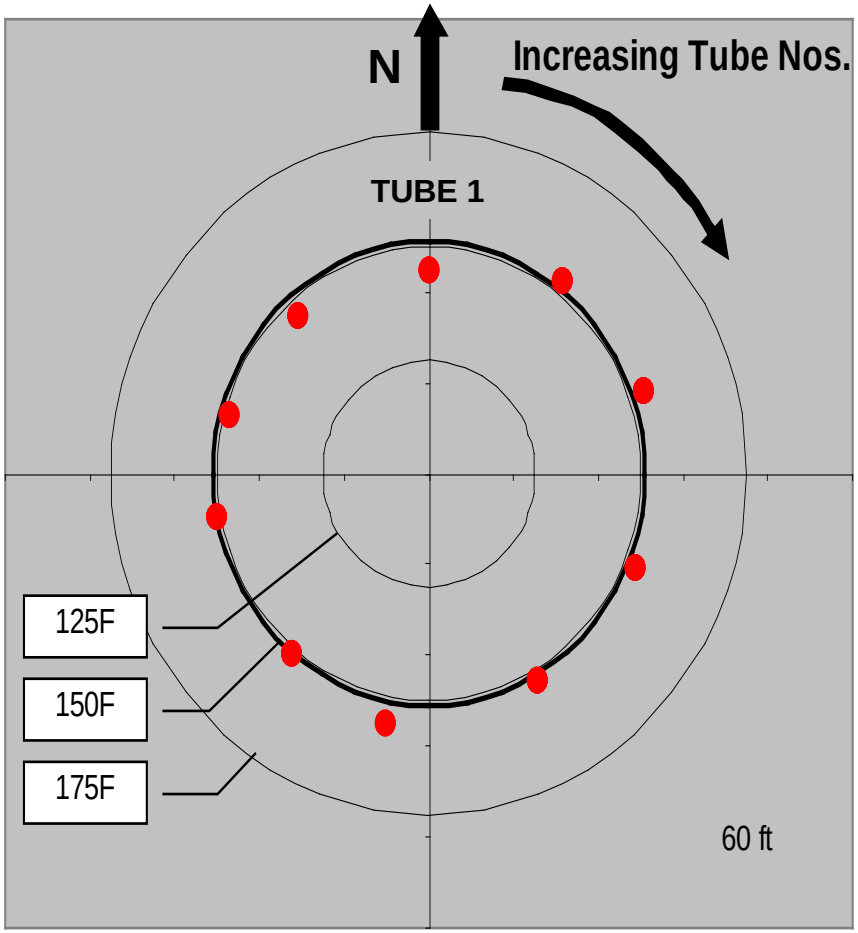

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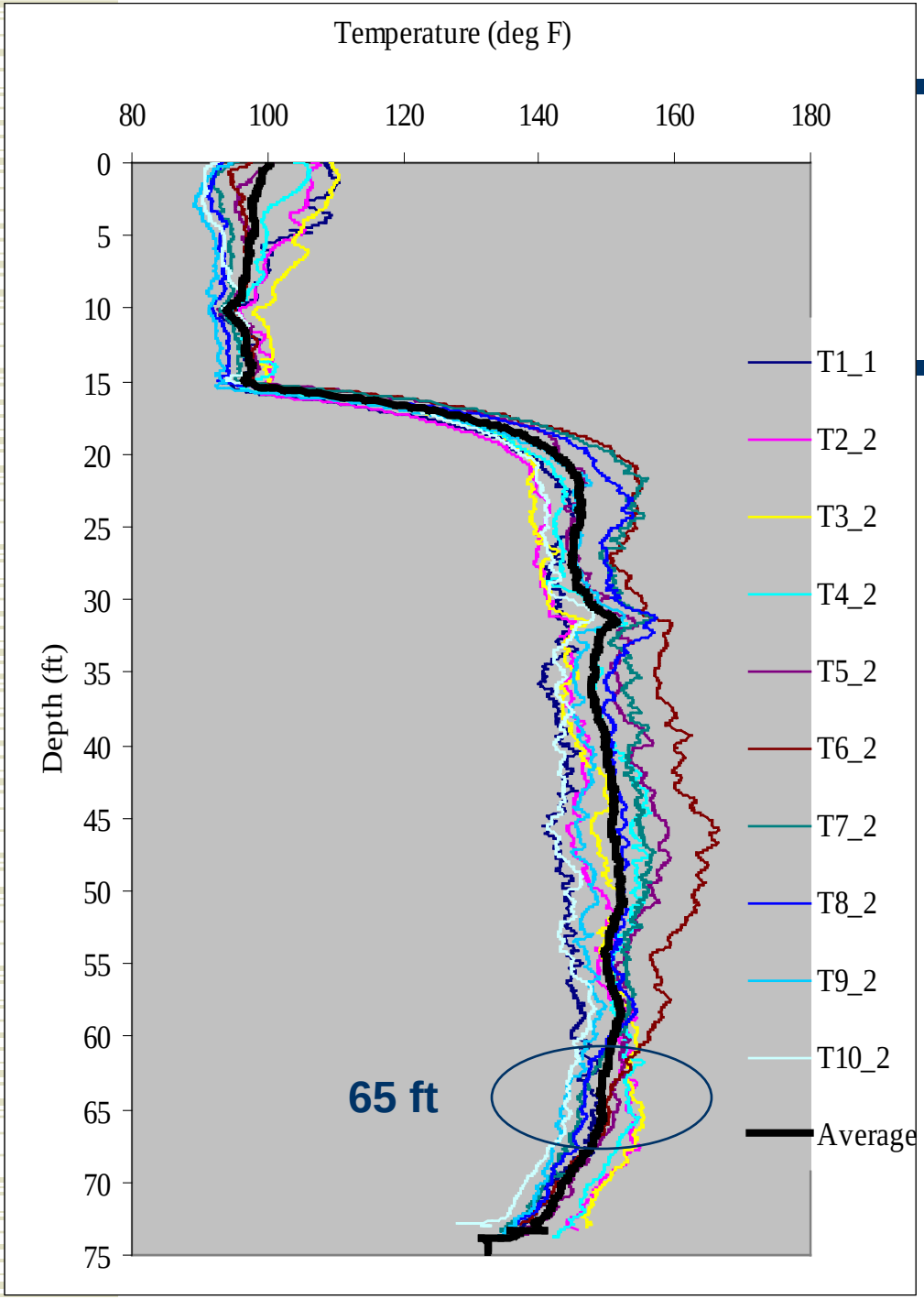

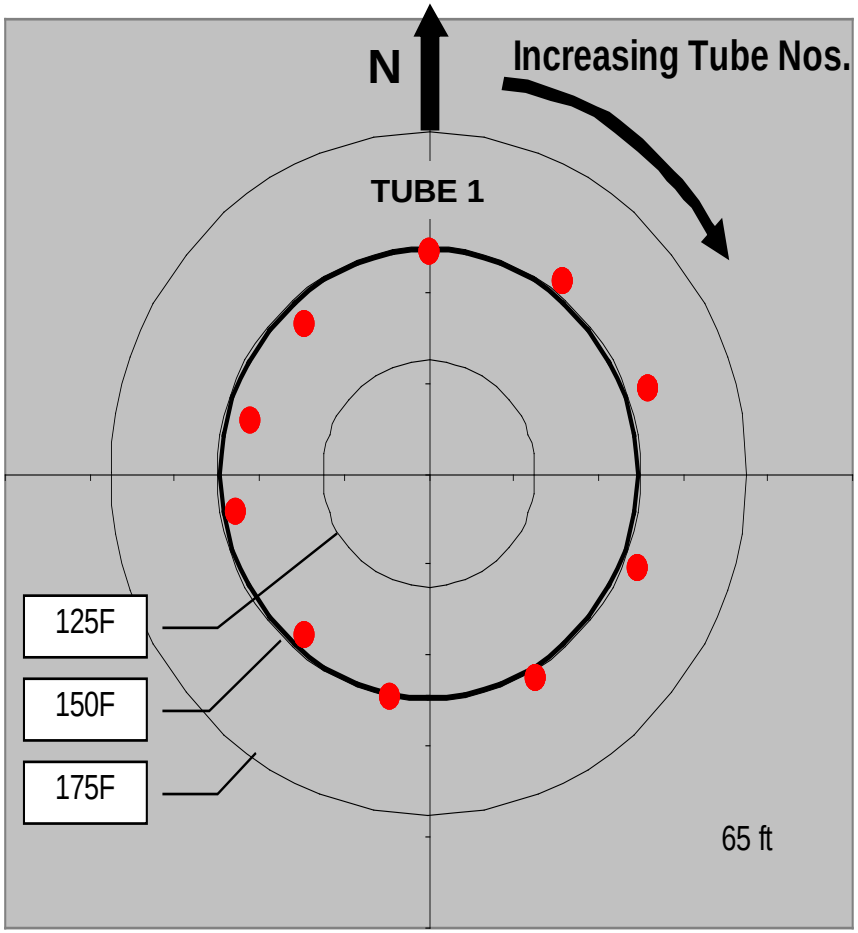

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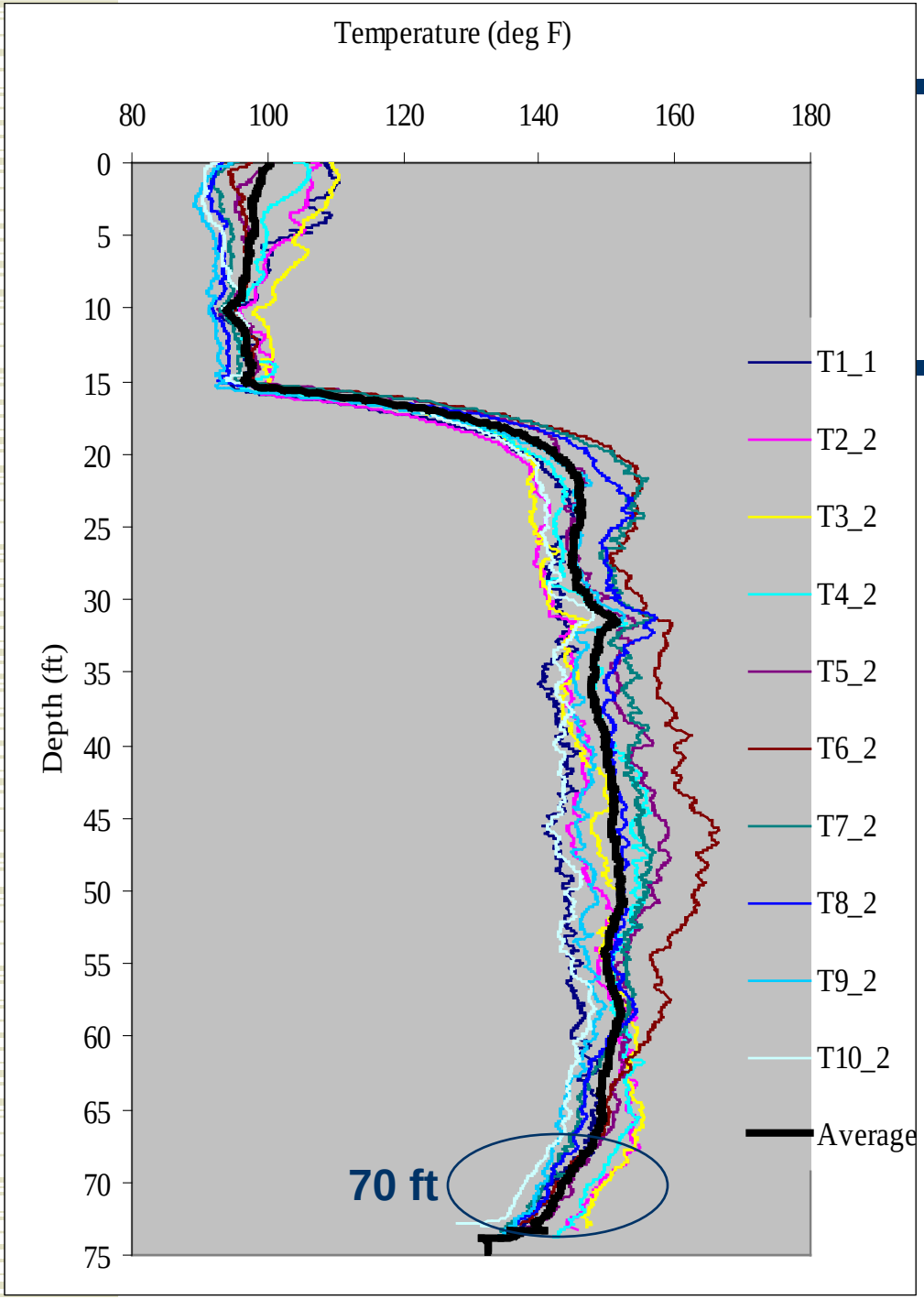
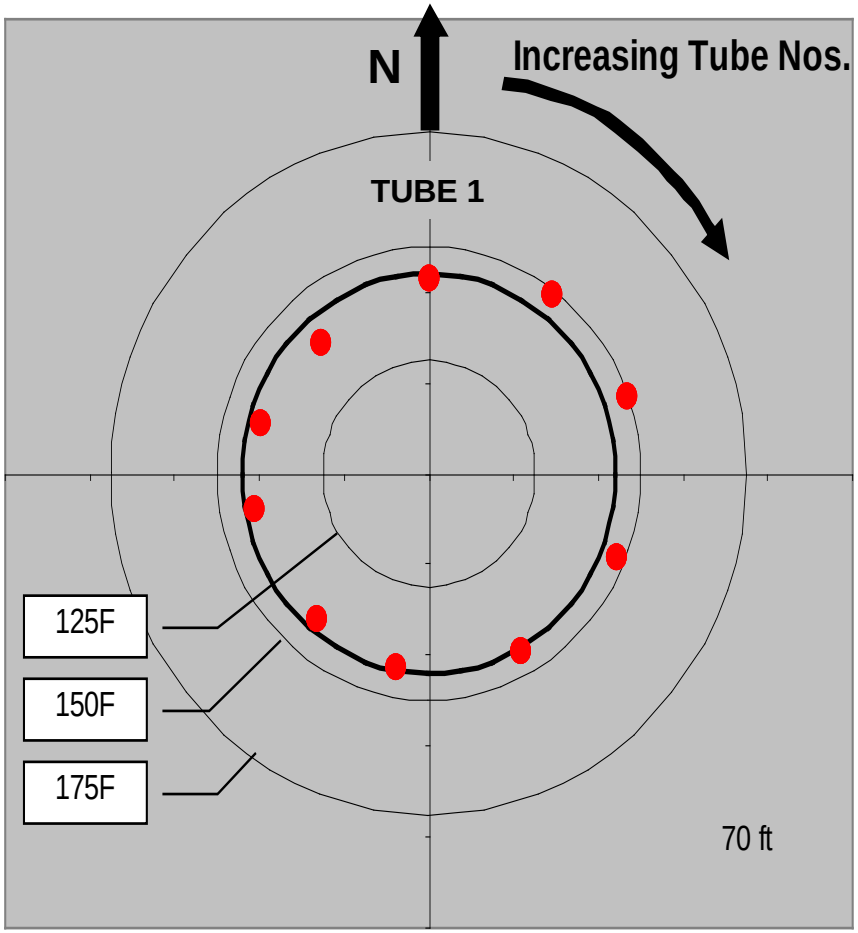
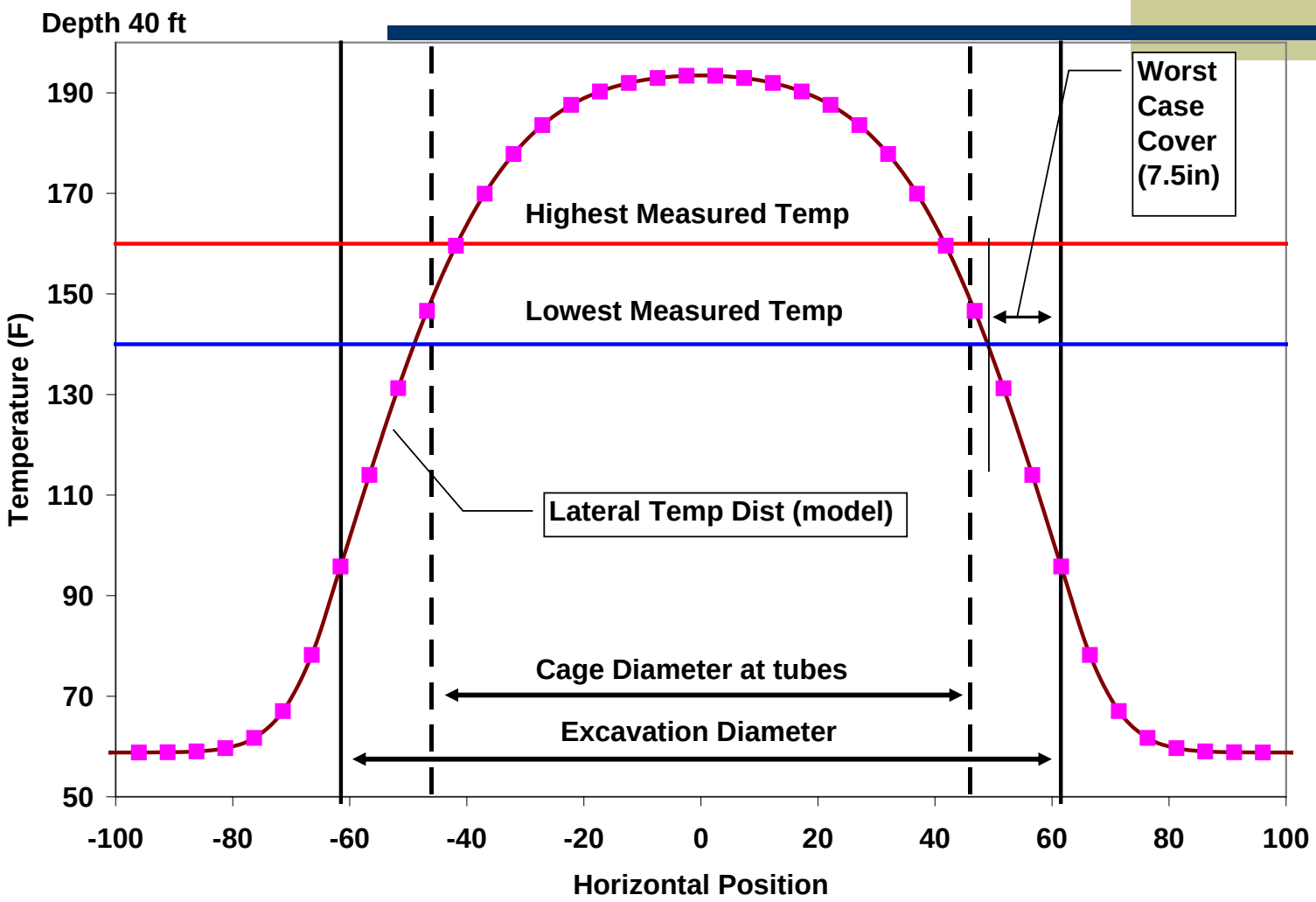
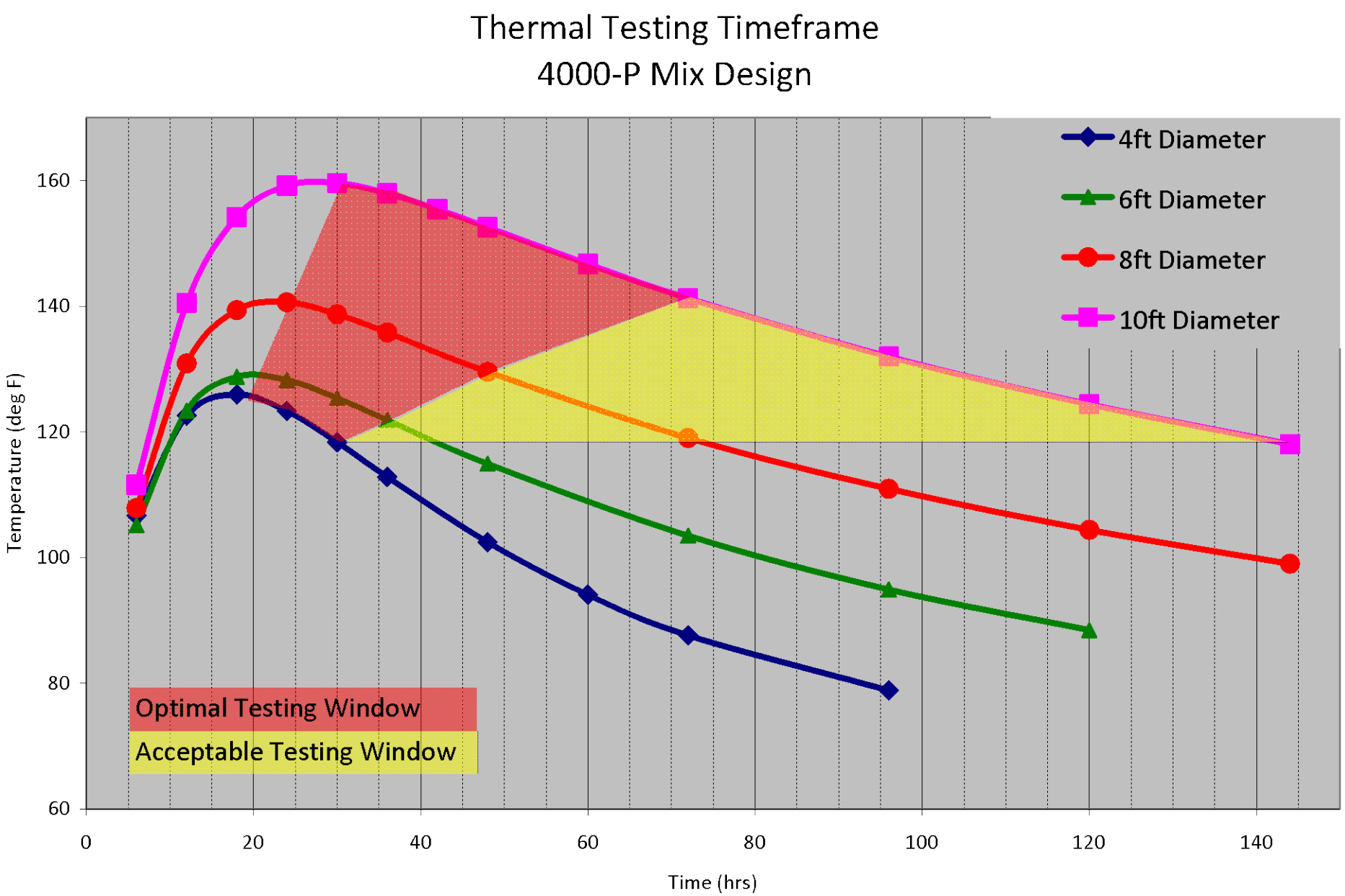




Cage Alignment
(at 40 ft)




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)
160
140
120
100
80
60
0
20
40
60
80
100
120
140

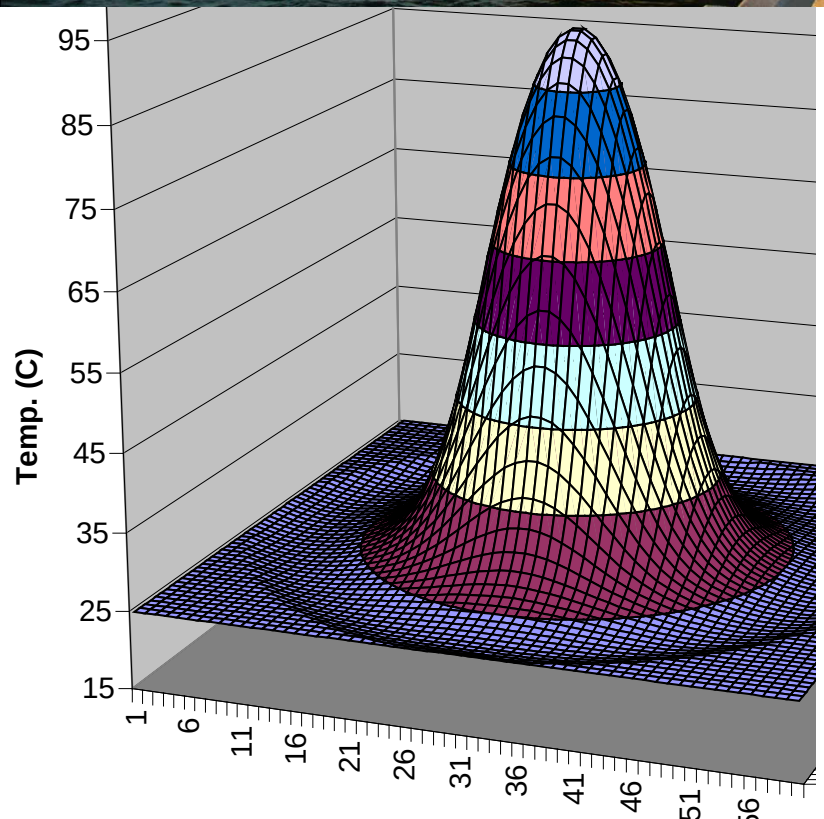
Conclusions

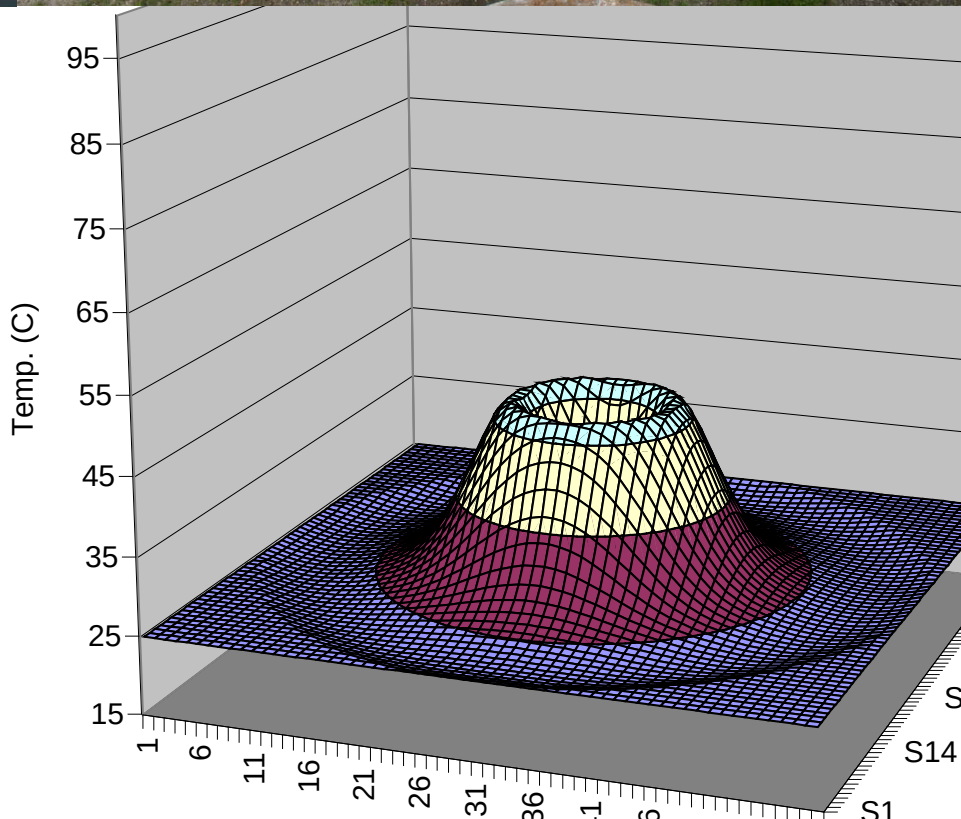
- Thermal modeling of shafts shows when concrete mix and environment will cause mass concrete conditions
- Large diameter shafts can be voided to alleviate mass concrete conditions
- Demonstration shaft showed constructability and verified temperature control (peak and differential)
- Measured temperatures were in close agreement with model predicted

Conclusions

- Thermal Integrity scans showed remarkable capability to detect anomalies in and outside the reinforcing cage (bulges and necks)
- Cage alignment and concrete cover can be verified.
- Timeframe for testing is dependent on shaft size and mix (e.g.1 – 3 days optimal).

The End


Temp. (C)
95
85
75
65
55
45
35
25
15
1
6
11
16
21
26
31
36
41
46
51


Temp. (C)
95
85
75
65
55
45
35
25
15
1
6
11
16
21
26
31
36
S14
S1