PCA

Concrete Technology and Codes

Thermal Control of Concrete

Overview

- Hot weather concreting
  - "External" influences
- Mass concrete
  - "Internal" influences

Hot Weather Concreting
ACI 305 Definition:

"Hot weather is any combination of:

- high air temperature
- high concrete temperature
- low relative humidity
- wind velocity
- solar radiation

…that tends to impair the quality of fresh or hardened concrete."

Questions You Ask Yourself During Hot Weather ?

- **What are the effects of *hot weather* on concrete ?**
  - Why are these effects important to the quality of the finished concrete product?

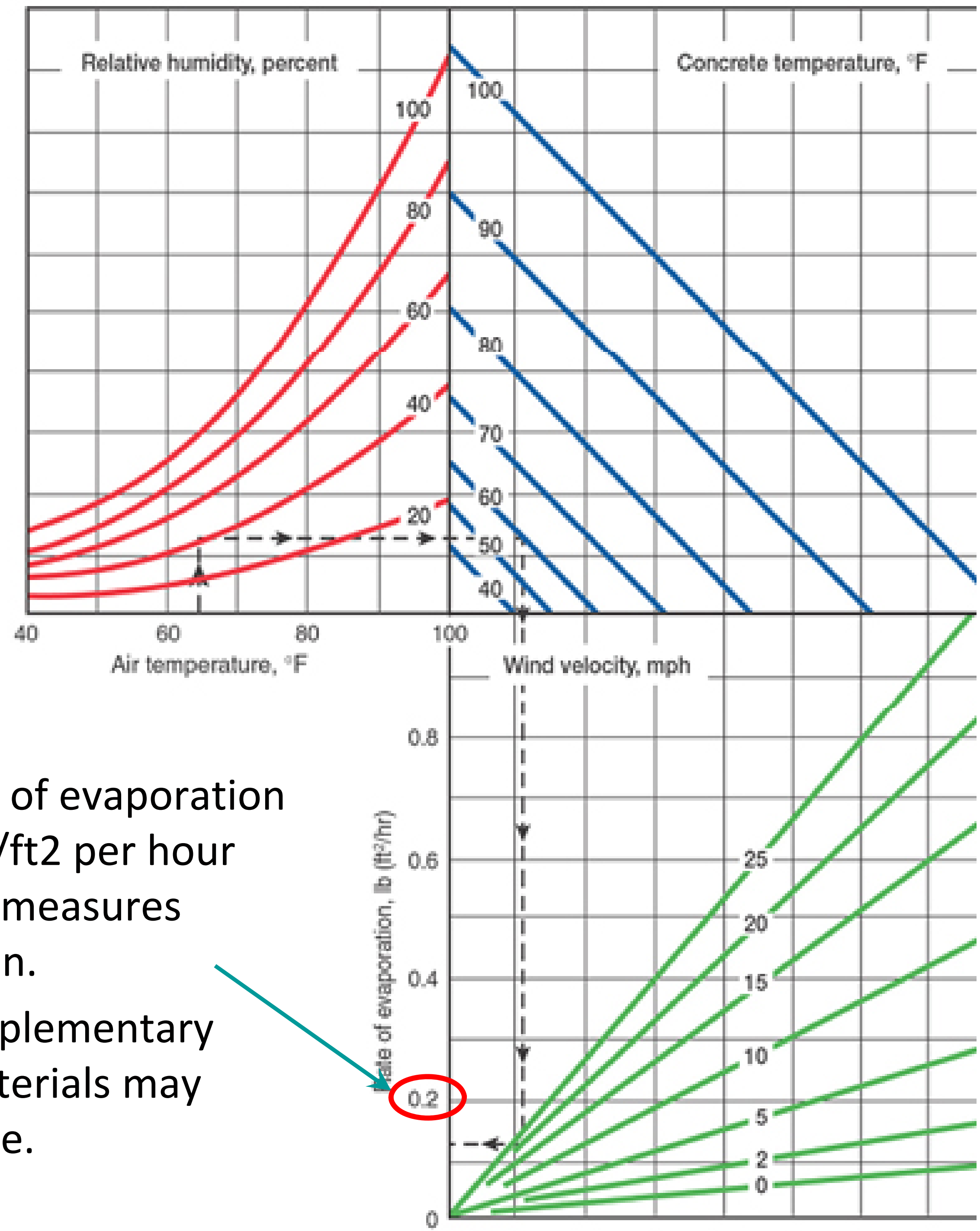
Hot Weather Concreting Problems – Fresh properties

- Increased Water Demand
- Accelerated Slump Loss
- Faster Set Times
- Rapid Water Evaporation
- Plastic Shrinkage
- Difficulties controlling entrained air
- Increased potential for thermal cracking

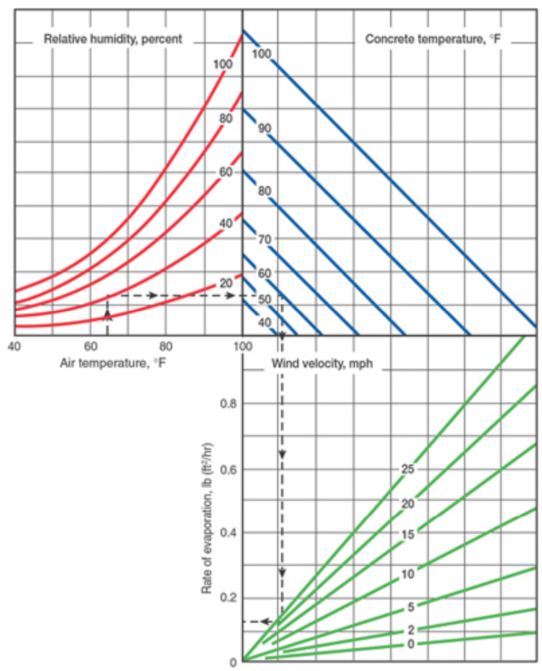
Hot Weather Concreting Problems – Hardened Properties

- Decreased strength
- Drying Shrinkage
- Decreased Durability
- Increased Permeability

Evaporation of Surface Moisture from Concrete



- When the rate of evaporation exceeds 0.2 lb/ft2 per hour precautionary measures should be taken.
- The use of supplementary cementing materials may lower this value.

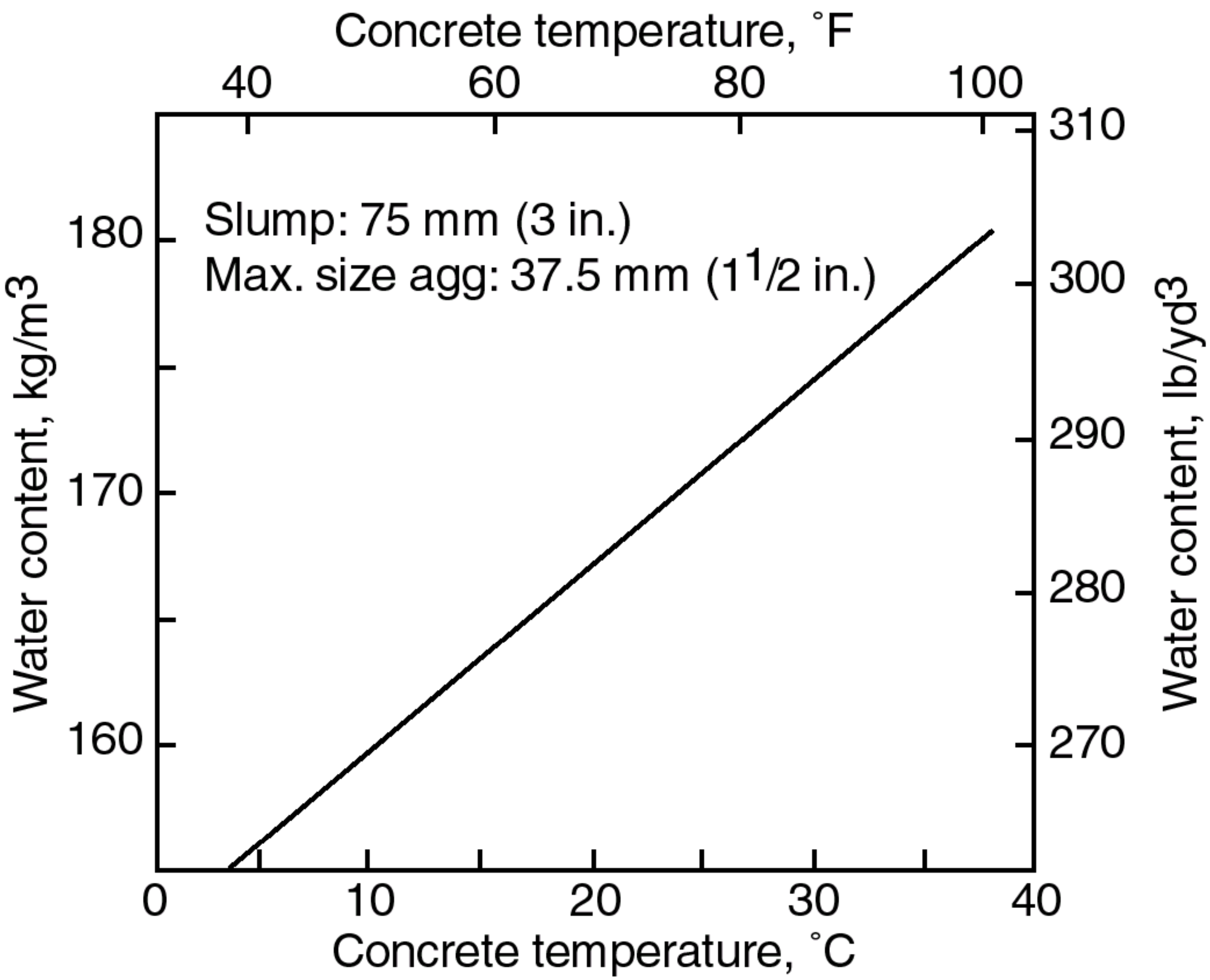


Relative humidity, percent
100
80
60
40
20
Concrete temperature, °F
100
90
80
70
60
50
40
40
60
80
100
Air temperature, °F
Wind velocity, mph
0.8
0.6
0.4
0.2
0
Rate of evaporation, lb (ft²/hr)
25
20
15
10
5
2
0

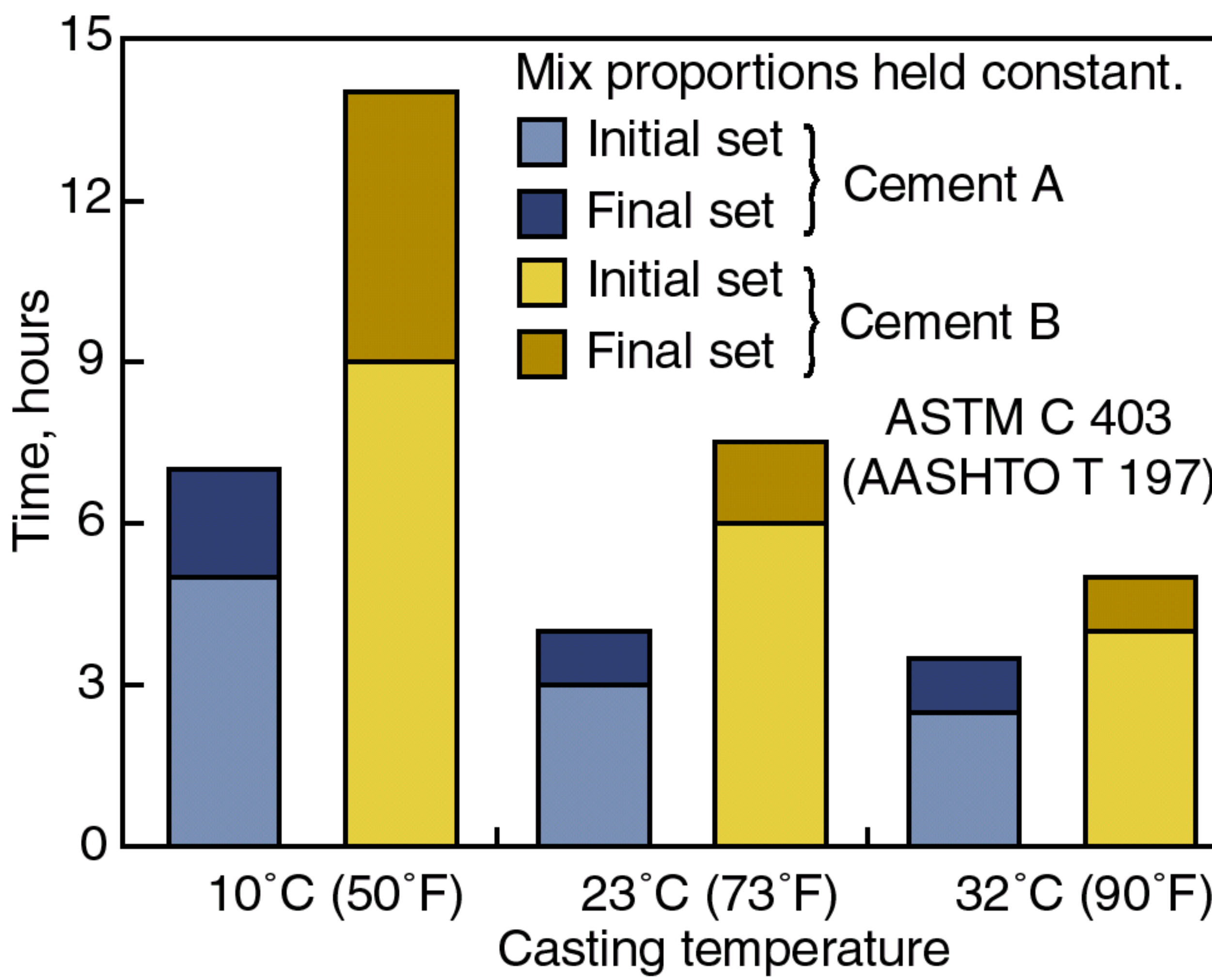
Concrete Temperature

- ACI 211.1 For every 100 lb Cement expect approximately 10-15^{o}F temperature rise from Heat of Hydration.
- Use tepid water for curing.
- After curing, let surface dry out **slowly** to reduce the possibility of crazing or cracking.

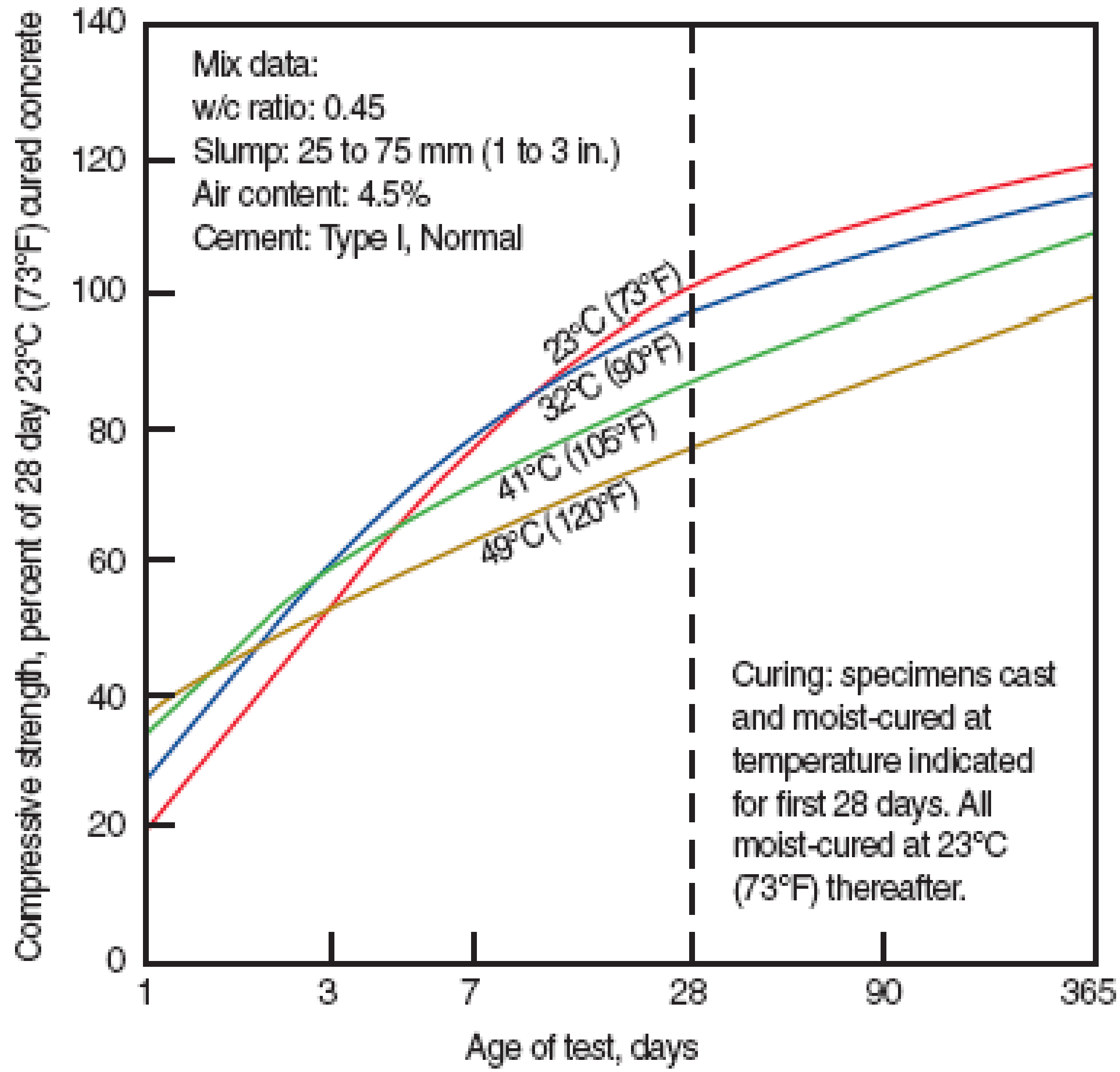
Effect of Concrete Temperature on Water Requirement



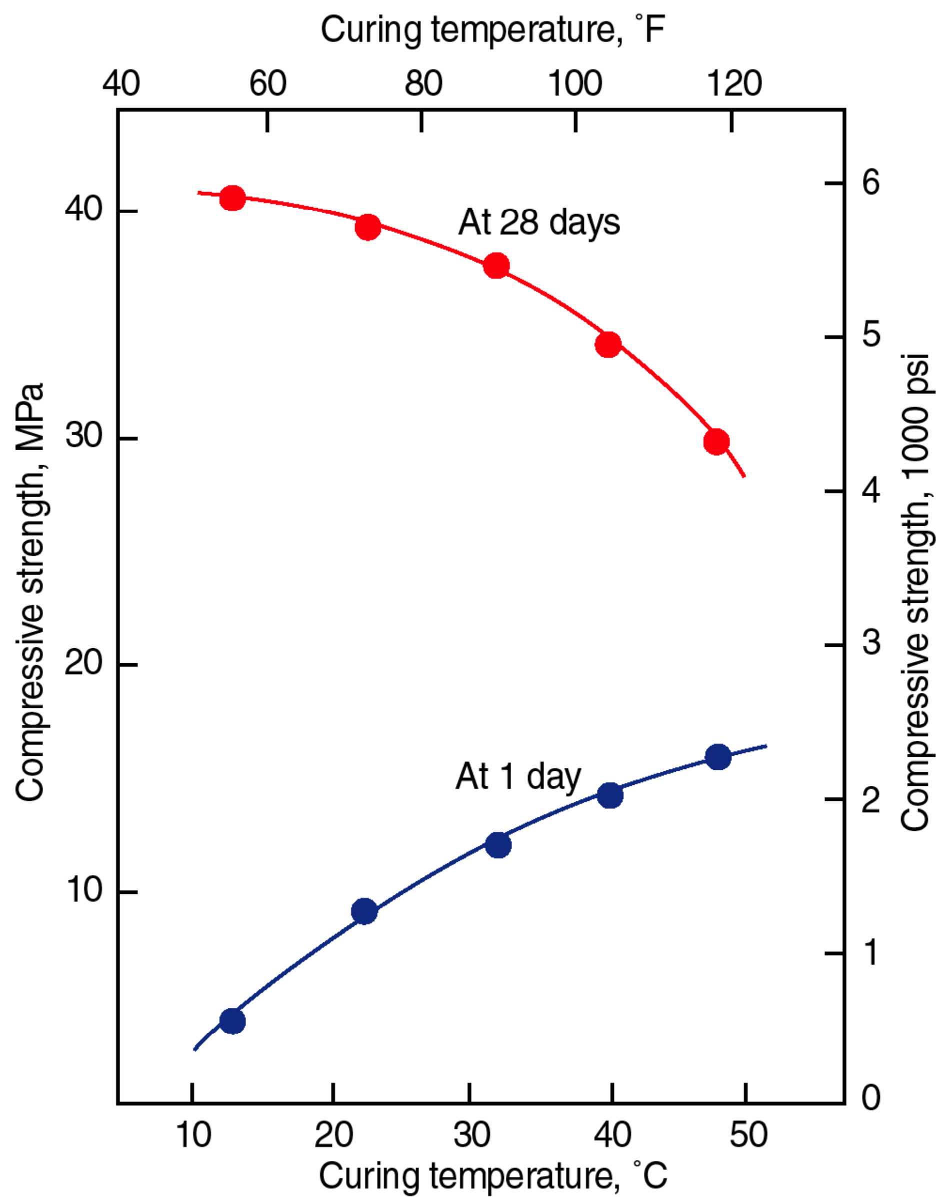
Effect of Concrete Temperature on Setting Time



Effect of Concrete Temperatures on Strength



Strength vs. Curing Temperature



Adjust the mix for Hot Weather

- Use of SCMs (fly ash, slag cement)

  (*Can be a double edged sword*)

- Retarders
- Cool concrete materials
- Moisten aggregates
- Cool concrete
- Add plastic fibers

Adjust Placement Practices

- Dampen subgrade
- Reduce the time of transport, placing and finishing
- Erect temporary windbreaks and sunshades
- Fog over the concrete immediately after placing
- Cover concrete

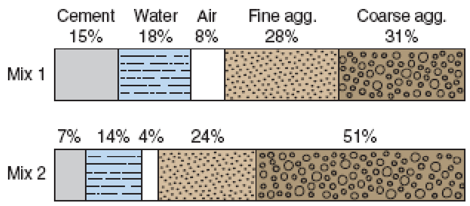
Effect of Temperature of Materials on Concrete Temperatures

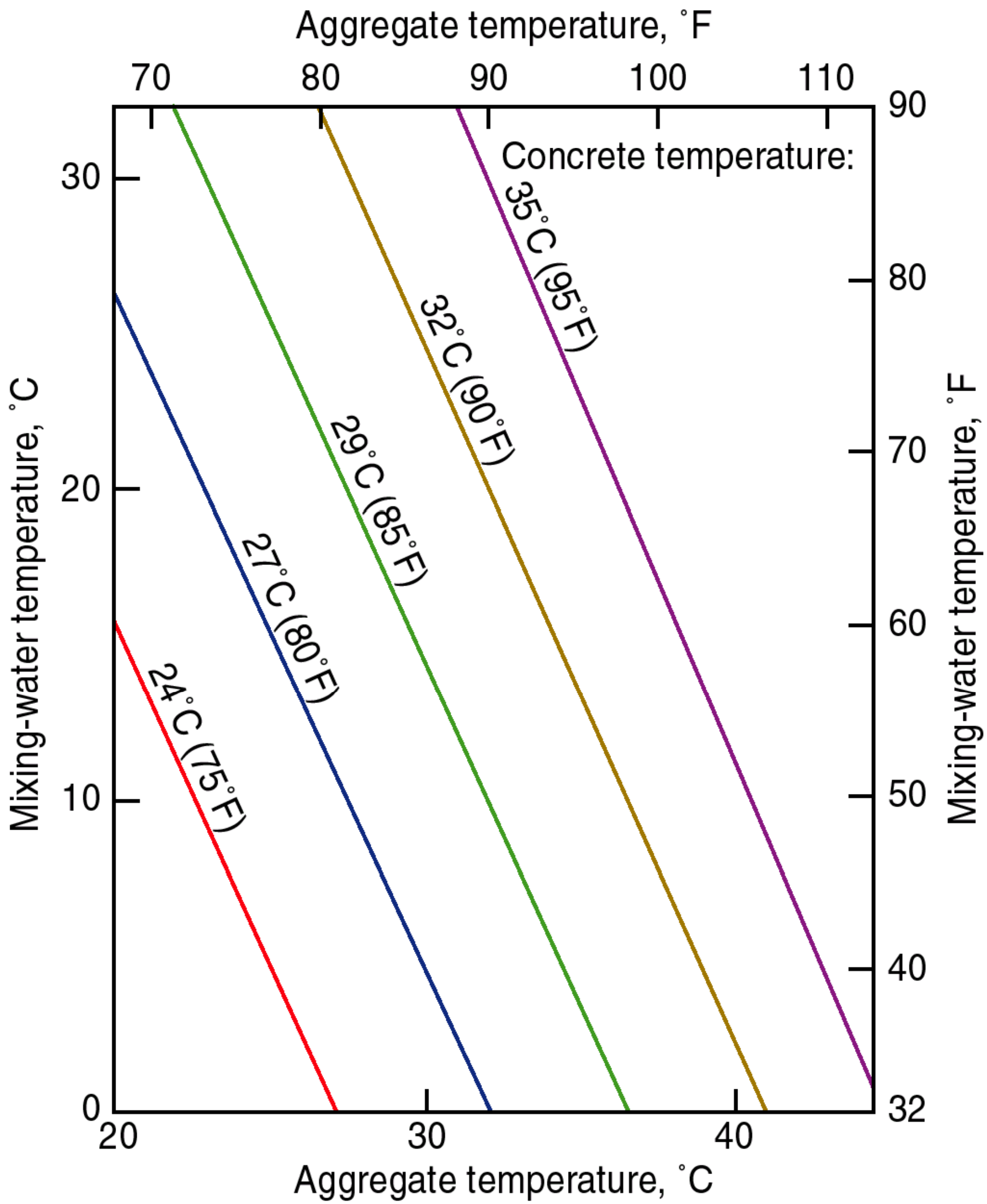
$$T = \frac{0.22(T_a M_a + T_c M_c) + T_w M_w + T_{wa} M_{wa}}{0.22(M_a + M_c) + M_w + M_{wa}}$$

T = temperature of the freshly mixed concrete, °C (°F)

T_a, T_c, T_w, and T_{wa} = temperature in °C (°F) of aggregates, cement, added mixing water, and free water on aggregates, respectively

M_a, M_c, M_w, and M_{wa} = mass, kg (lb), of aggregates, cementing materials, added mixing water, and free water on aggregates, respectively





Aggregate temperature, °F
70
80
90
100
110
Concrete temperature:
35°C (95°F)
32°C (90°F)
29°C (85°F)
27°C (80°F)
24°C (75°F)
Mixing-water temperature, °C
30
20
10
0
Mixing-water temperature, °F
90
80
70
60
50
40
32
20
30
40
Aggregate temperature, °C

Effect of Ice on Temperature of Concrete

$$T\ (^{\circ}C) = \frac{0.22(T_a M_a + T_c M_c) + T_w M_w + T_{wa} M_{wa} - 80 M_i}{0.22(M_a + M_c) + M_w + M_{wa} + M_i}$$

$$T\ (^{\circ}F) = \frac{0.22(T_a M_a + T_c M_c) + T_w M_w + T_{wa} M_{wa} - 112 M_i}{0.22(M_a + M_c) + M_w + M_{wa} + M_i}$$

Placing & Finishing Concrete in Hot Weather

- Cool equipment
- Dampen/ cool
  - subgrade
  - forms
  - rebar
- Scheduling: evening or night time construction
- Windbreaks
- Sunshades

Fogging

Questions on Hot Weather Concreting?

What is Mass Concrete?

What is Mass Concrete?

"Any volume of concrete with dimensions large enough to require that measures be taken to cope with generation of heat from hydration of the cement and attendant volume change, to minimize cracking." – American Concrete Institute (ACI)

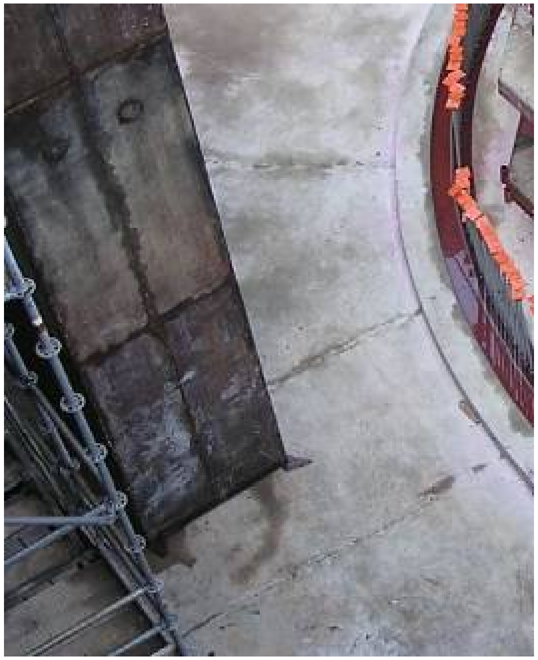
- Thick: Foundations, columns, radiation shielding, etc.
- Thin: High Performance (HPC), Self Consolidating Concrete (SCC), Grout, Patching material

Working Definition

- Minimum Dimension (Thickness)
  - No consensus (2½ ft to 7 ft)
  - ACI 301-09 will likely say ≥ 4 ft
- Cement Content
  - Usually not considered
  - ACI 301-09 will likely recommend a limit

Key Considerations

- Maximum temperature
  - Can reduce strength and durability
- Temperature difference
  - Can result in thermal cracking



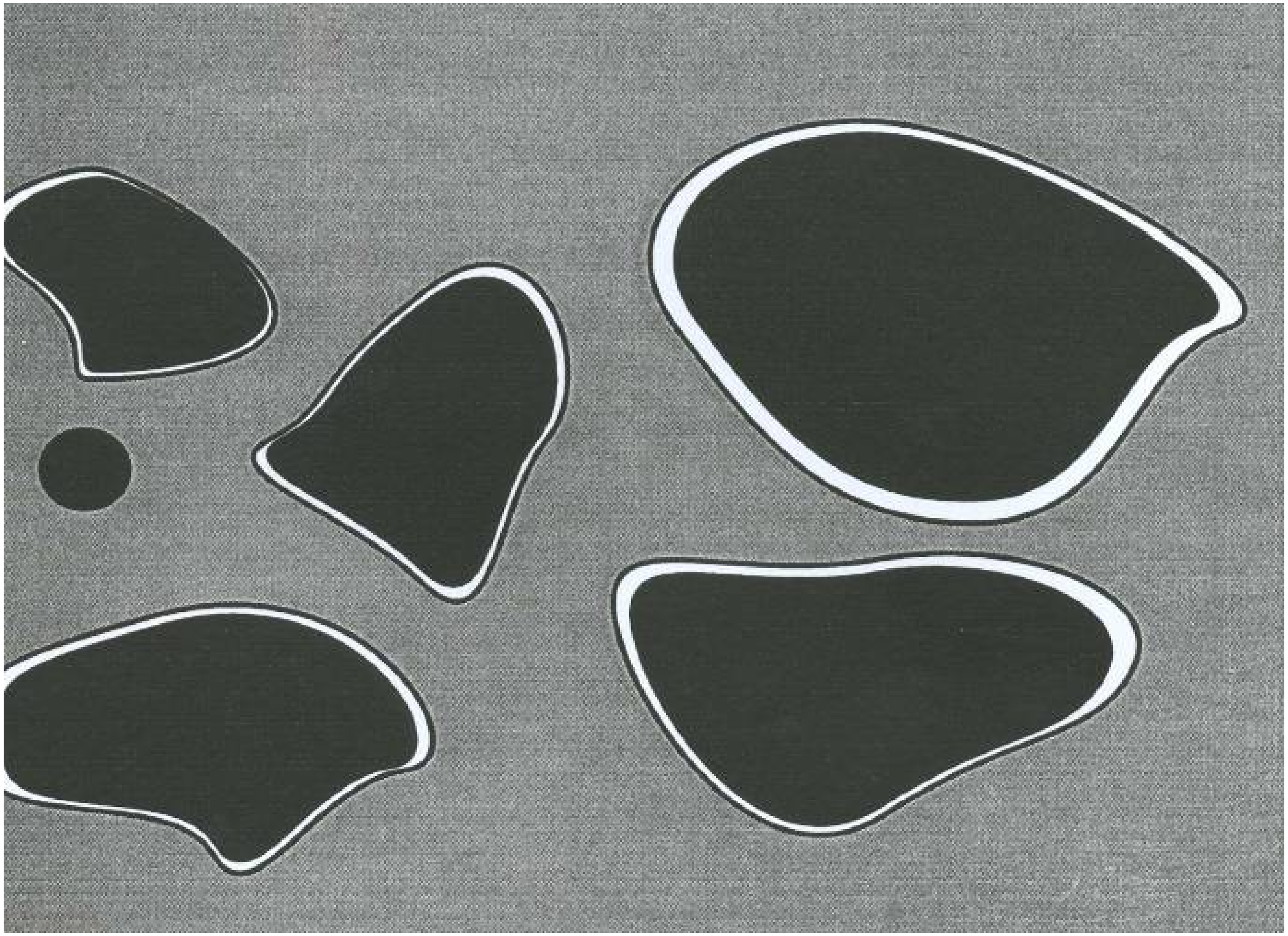
Maximum Temperature

- Often limited
  - No consensus between agencies
  - Safe limit: 160°F (70°C)
  - Delayed Ettringite Formation (DEF)
- Concrete mix design
  - Cement (type and quantity)
  - Pozzolans (type and percentage)

Delayed Ettringite Formation (DEF)

- Concrete cured at excessively high temperatures may develop DEF because ettringite decomposes – or does not form at high temperature.
- Later it forms/reforms after the concrete is hard, and may cause expansion.
- DEF is a term that is properly applied only to curing at elevated temperatures. It does not apply to ambient curing.

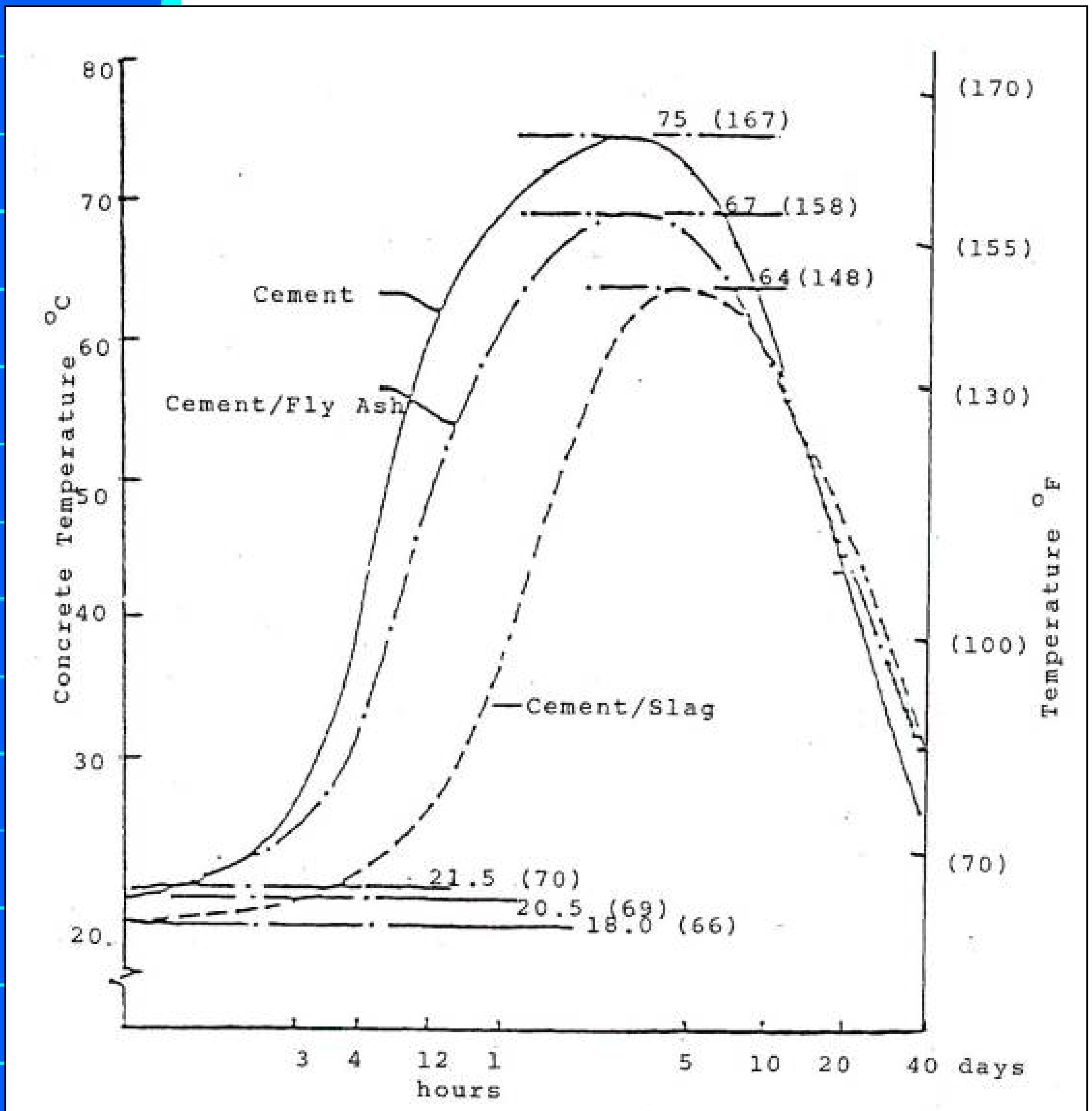
Expansion of Paste away from Aggregate



DEF potential?

- The heat of hydration of cement can raise the concrete temperature to above 160°F
- The critical temperature for DEF lies somewhere between 160°F and 195°F (depends on the cement)
- This is particularly true for cements with high fineness(> 400m^2/kg), high C_3S, high C_3A, and high alkali content. SO_3/Al_2O_3 ratio > 0.7

Maximum Temperature



- 100% Cement
- 70/30 Blend of Cement and Fly Ash
- 25/75 Blend of Cement and Slag

Maximum Temperature Estimation

Max. Temp. = Initial Temp. + Temp. Rise - Loss

- Initial Temperature
  - As low as economically practical (Payback of 1:1)
- Temperature rise depends on mix design
  - Equivalent cement content
- Loss (Early heat loss)
  - Minimal for placement >5 ft thick
  - 2-6 F per day, depends on R value, dimensions, etc.

Equivalent Cement Content

- 1lb/yd^3 of cement = 1 lb/yd^3 equiv. cement
- 1 lb/yd^3 of Class F ash = 0.5 lb/yd^3 equiv. cement
- 1 lb/yd^3 of Class C ash = 0.8 lb/yd^3 equiv. cement
- 1 lb/yd^3 of Slag (50%) = 0.9 lb/yd^3 equiv. cement
- 1 lb/yd^3 of Slab (75%) = 0.8 lb/yd^3 equiv. cement

- Temperature Rise in Concrete
  - 16°F per 100 lb/yd^3 equiv. cement

For example…

Concrete Foundation

- 400 lb/yd^3 cement and 200 lb/yd^3 class F fly ash
- 70°F delivered concrete
- 6 ft thick

Equivalent cement = 400 + 0.5*200 = 500 lb/yd^3

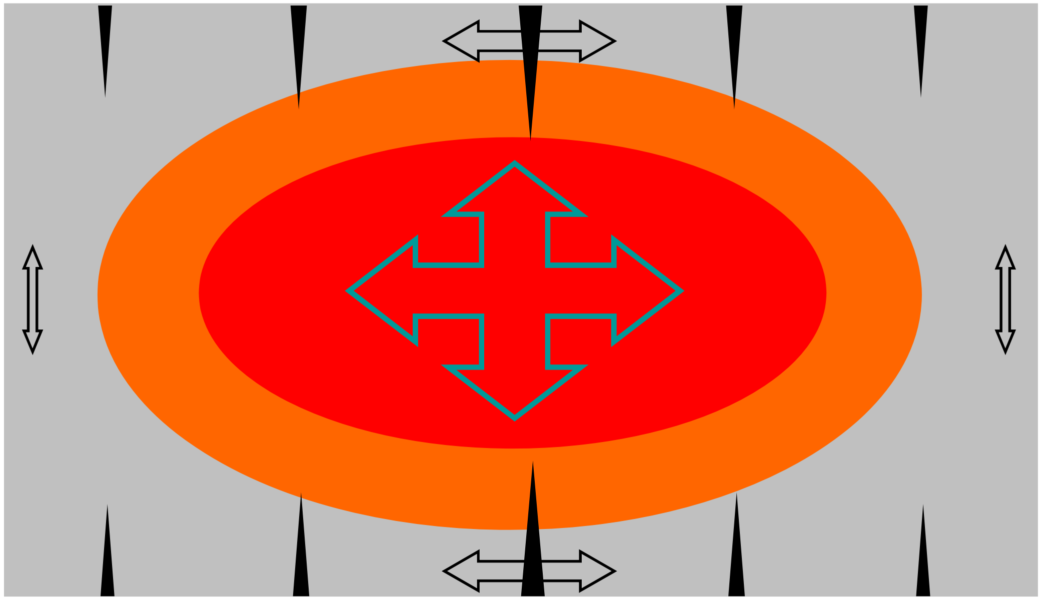
Temperature Rise = 500*16/100 = 80°F

Maximum Temperature = 80+70-0 = 150°F

Temperature Difference

Limited to minimize (or prevent) thermal cracking

Temperature difference between interior and surface



Crack width is a function of the temperature difference

Thermal Cracking

- Undesirable, but sometimes unavoidable
- Mostly a durability concern
- Severe can be a structural issue
- “Tolerable” limits in ACI 224R

Table 4.1—Guide to reasonable* crack widths, reinforced concrete under service loads

Exposure condition	Crack width, in.	Crack width, mm
Dry air or protective membrane	0.016	0.41
Humidity, moist air, soil	0.012	0.30
Deicing chemicals	0.007	0.18
Seawater and seawater spray, wetting and drying	0.006	0.15
Water-retaining structures†	0.004	0.10

* It should be expected that a portion of the cracks in the structure will exceed these values. With time, a significant portion can exceed these values. These are general guidelines for design to be used in conjunction with sound engineering judgement.
† Exclusing nonpressure pipes.

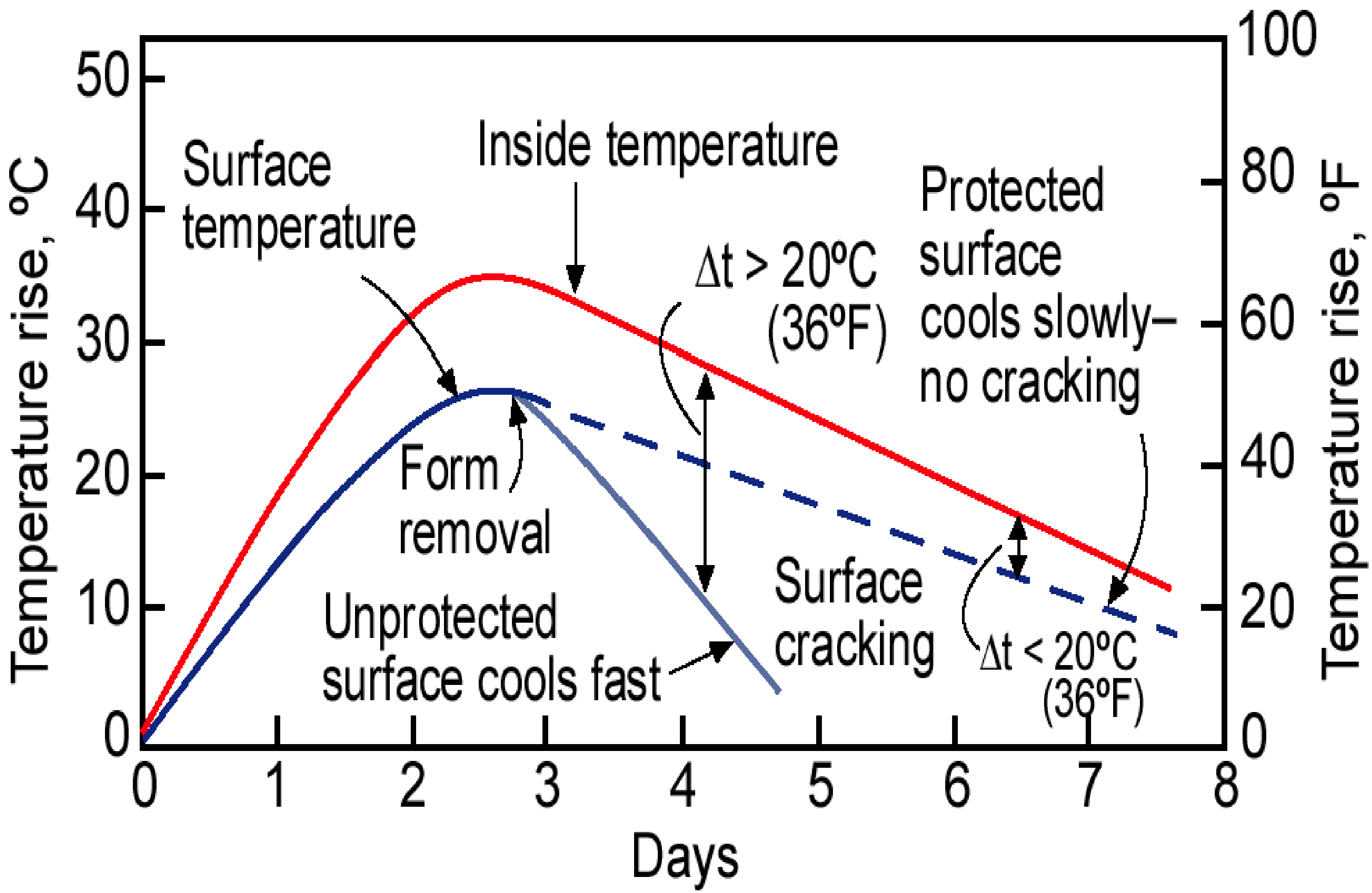
Extreme Thermal Cracking

More Extreme Thermal Cracking

Somewhat Extreme Thermal Cracking

Typical Thermal Cracking

More Typical Thermal Cracking



Temperature rise, °C
50
40
30
20
10
0
Surface temperature
Inside temperature
Δt > 20°C (36°F)
Protected surface cools slowly–no cracking
Form removal
Unprotected surface cools fast
Surface cracking
Δt < 20°C (36°F)
0
1
2
3
4
5
6
7
8
Days
100
80
60
40
20
0
Temperature rise, °F

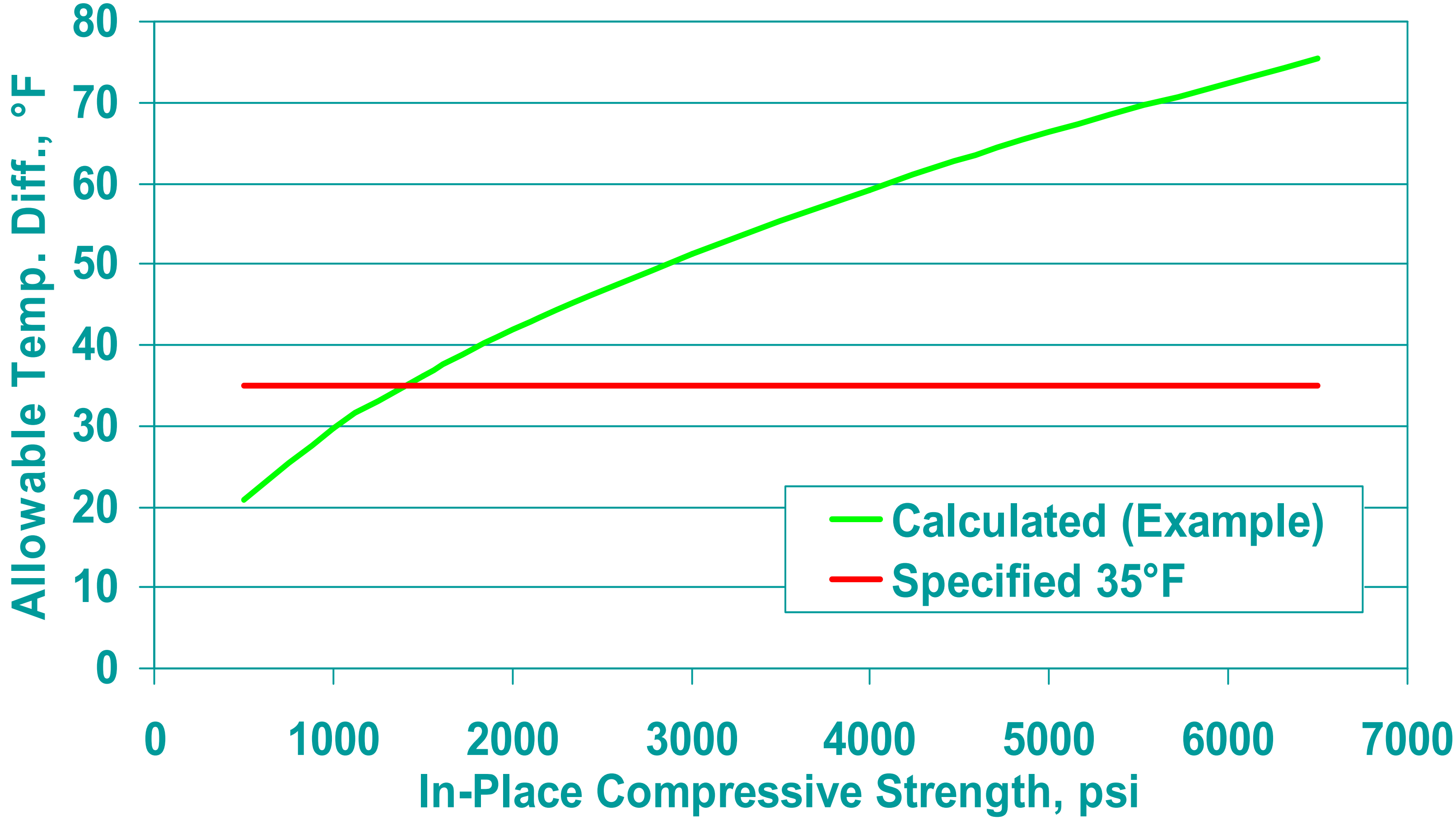
Temperature Difference Limits

- Often limited to a maximum of 35°F
  - Generalized “rule-of-thumb”
  - Worked for unreinforced dams in Europe 75+ years ago
  - May not prevent thermal cracking
  - Extends construction time
- Stepped limit
  - Steps up with age (35-45-60°F)
  - Shortens construction time
  - Can lead to thermal cracking
- Tailored limit

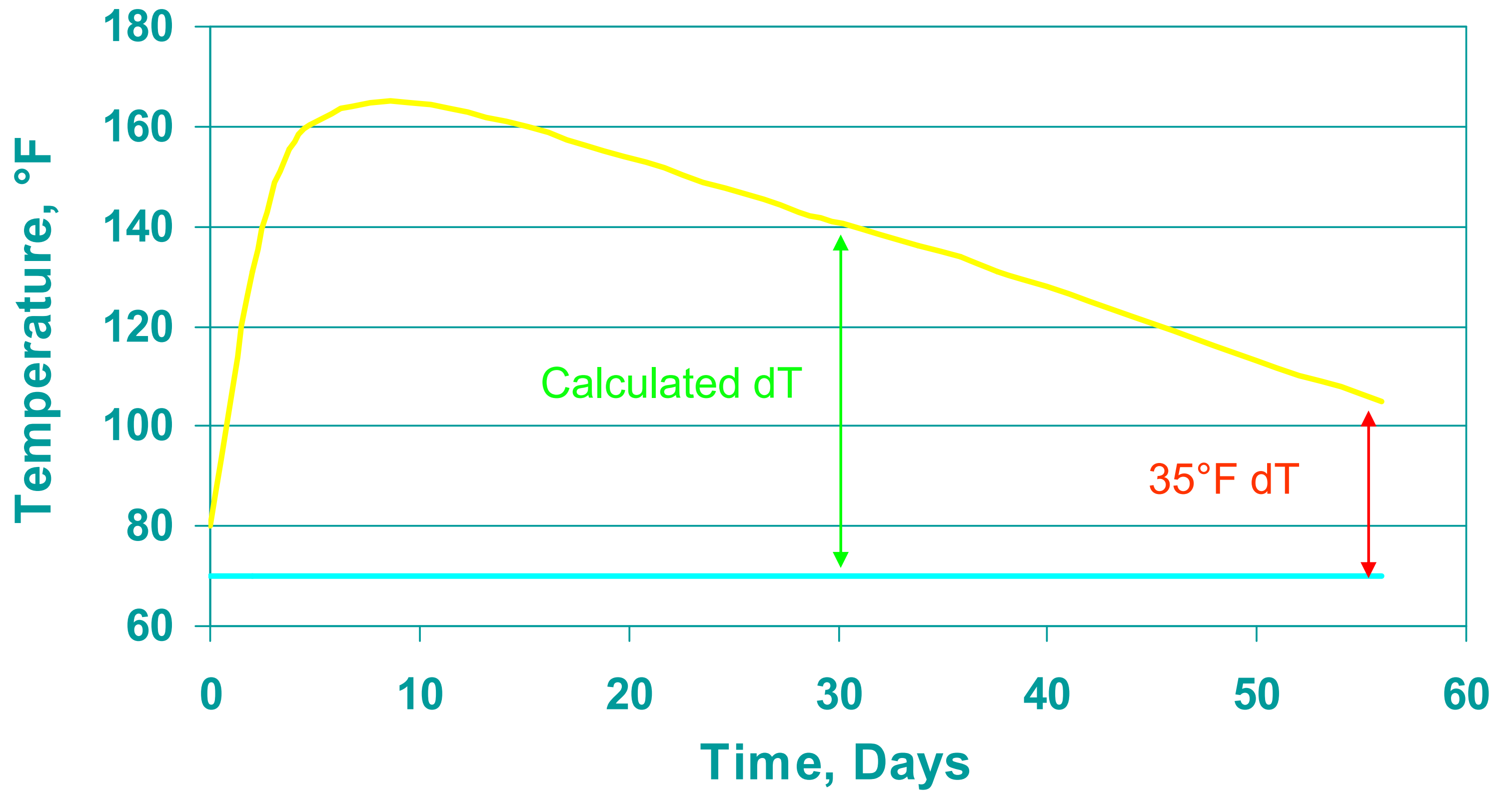
Tailored Temperature Difference

- Calculation based on ACI 207.2R
- Performance-based approach
- Accounts for concrete’s ability to withstand higher thermal stresses as in-place strength increases
- Based on concrete properties
- Based on structure and design
- Can be used to prevent cracking or limit crack widths

Temperature Difference (cont.)

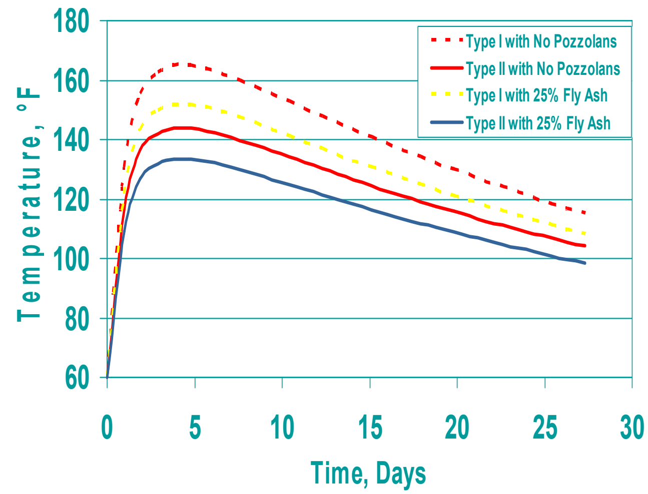


Temperature Difference and Time Savings



Temperature Control Strategies - *Use a Reduced Heat Concrete*

- Type I/II, II or V Cement
- Slag Cement
  - 50% to 75% replacement
- Fly Ash (Class F)
  - 25% to 40% replacement



Recall that:

1lb/yd^3 of cement = 1 lb/yd^3 equiv. cement
1 lb/yd^3 of Class F ash = 0.5 lb/yd^3 equiv. cement
1 lb/yd^3 of Class C ash = 0.8 lb/yd^3 equiv. cement
1 lb/yd^3 of Slag (50%) = 0.9 lb/yd^3 equiv. cement
1 lb/yd^3 of Slab (75%) = 0.8 lb/yd^3 equiv. cement

Temperature Control Strategies *– Place Concrete in Lifts*

- Thick placements take a long time to cool
- Multiple distinct placements
- Thin lifts allow early heat loss
  - Reduced maximum temperature
  - Faster cooling

Temperature Control Strategies – *Precool the Concrete*

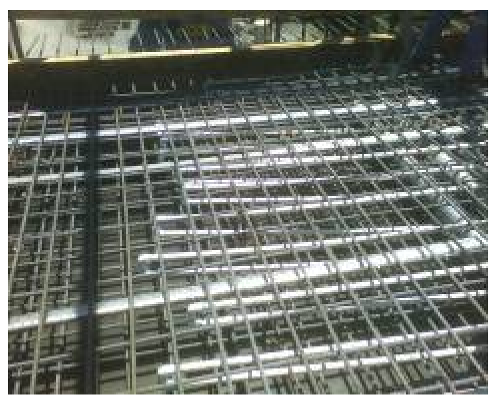
- Precool aggregates
  - Evaporative cooling is a very low cost solution
- Chilled mix water
  - Low cost (need chiller plant)
  - Max. reduction of about 5°F
- Substitute ice for mix water
  - More expensive
  - Can be labor intensive
  - Max. reduction of about 20°F

Temperature Control Strategies – *Precool the Concrete (Cont.)*

- Liquid Nitrogen (LN2)
  - Can re-cool concrete multiple times
  - Adds time and drum rotations
  - Cool onsite or at batch plant
  - Can be expensive
  - Can be dangerous

Temperature Control Strategies – *Cooling Pipes*

- Remove internal heat after concrete placed
- Reduces maximum temperature
- Reduces cooling time
- ¾” plastic cooling pipes
- Grouted afterwards



Temperature Control Strategies – *Cooling Pipes*

- Large supply of natural water (river, lake, ocean, ground water)
- Chiller

Temperature Control Strategies *– Insulation*

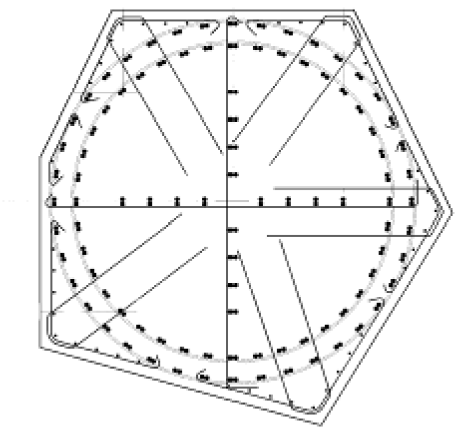
- Insulation retains surface heat to control the temperature difference
- Necessary in summer and winter

Things to Avoid

- Water Curing
- Improper Insulation
- Early Removal of Insulation

Example: 10 ft dia. column

- Performance specifications
  - 674 pcy minimum cementitious
  - 150°F maximum temperature
  - No thermal cracking
  - Tailored temperature difference

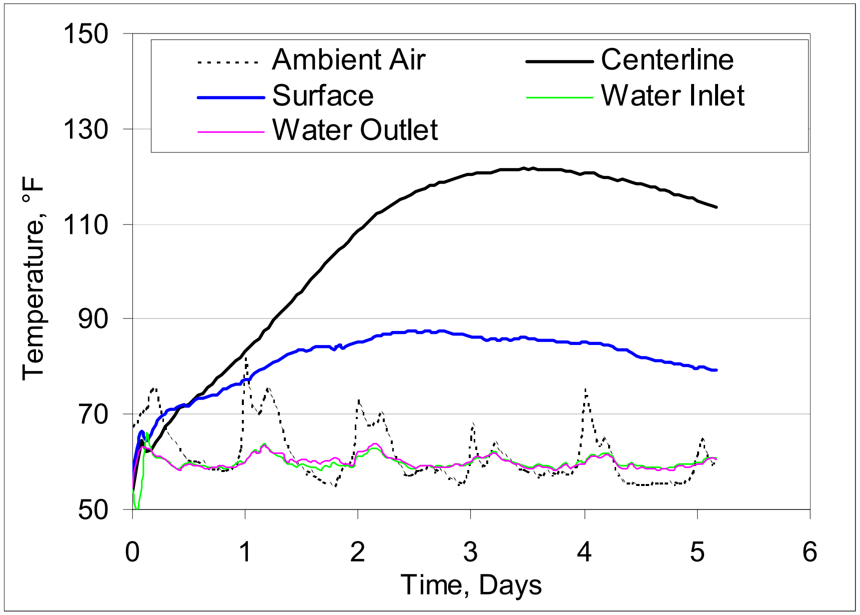


Example (cont.)

- Specially designed concrete
- Tight Schedule
- Used Cooling Pipes
- Used Maturity

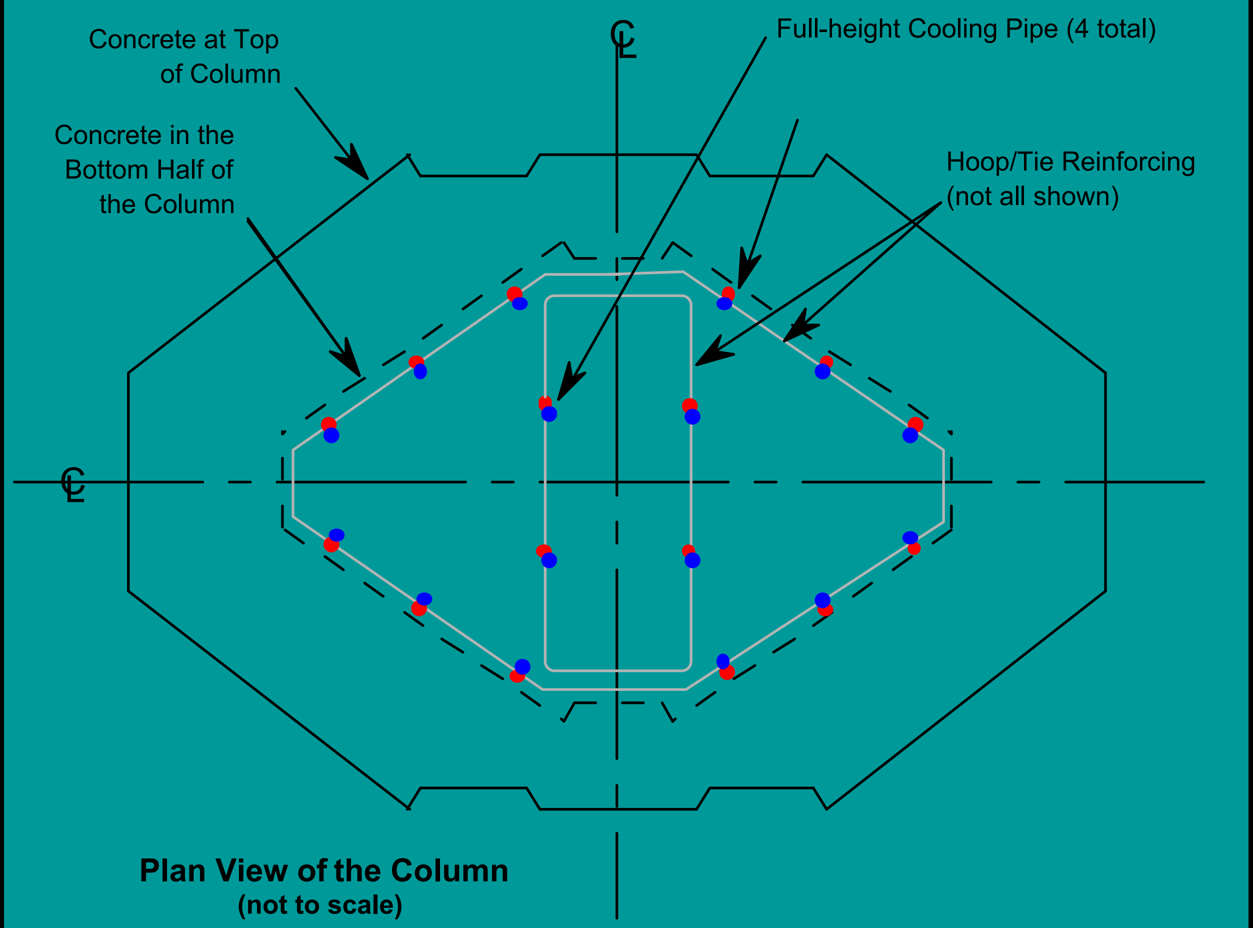
Example (cont.)

- Using Calculated temp. difference, Columns sufficiently cool in 5 to 6 days

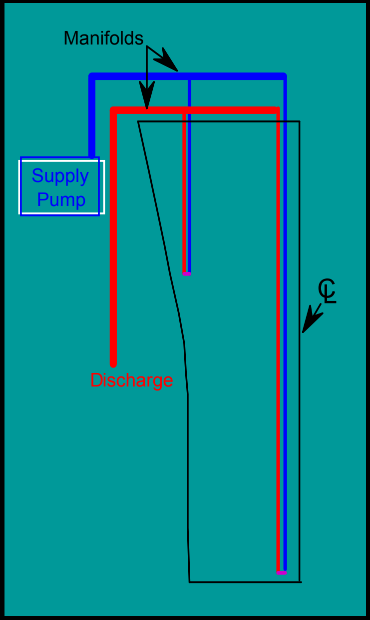


- If 20°C(35°F) temp differential specified…
  - cooling time increased by 50%
  - could not meet spec without cooling pipes

Example:
Column Analysis



Plan View of the Column
(not to scale)



Assumed Placement Conditions

Concrete Mix No. 1 with 330 pcy slag and 330 pcy cement

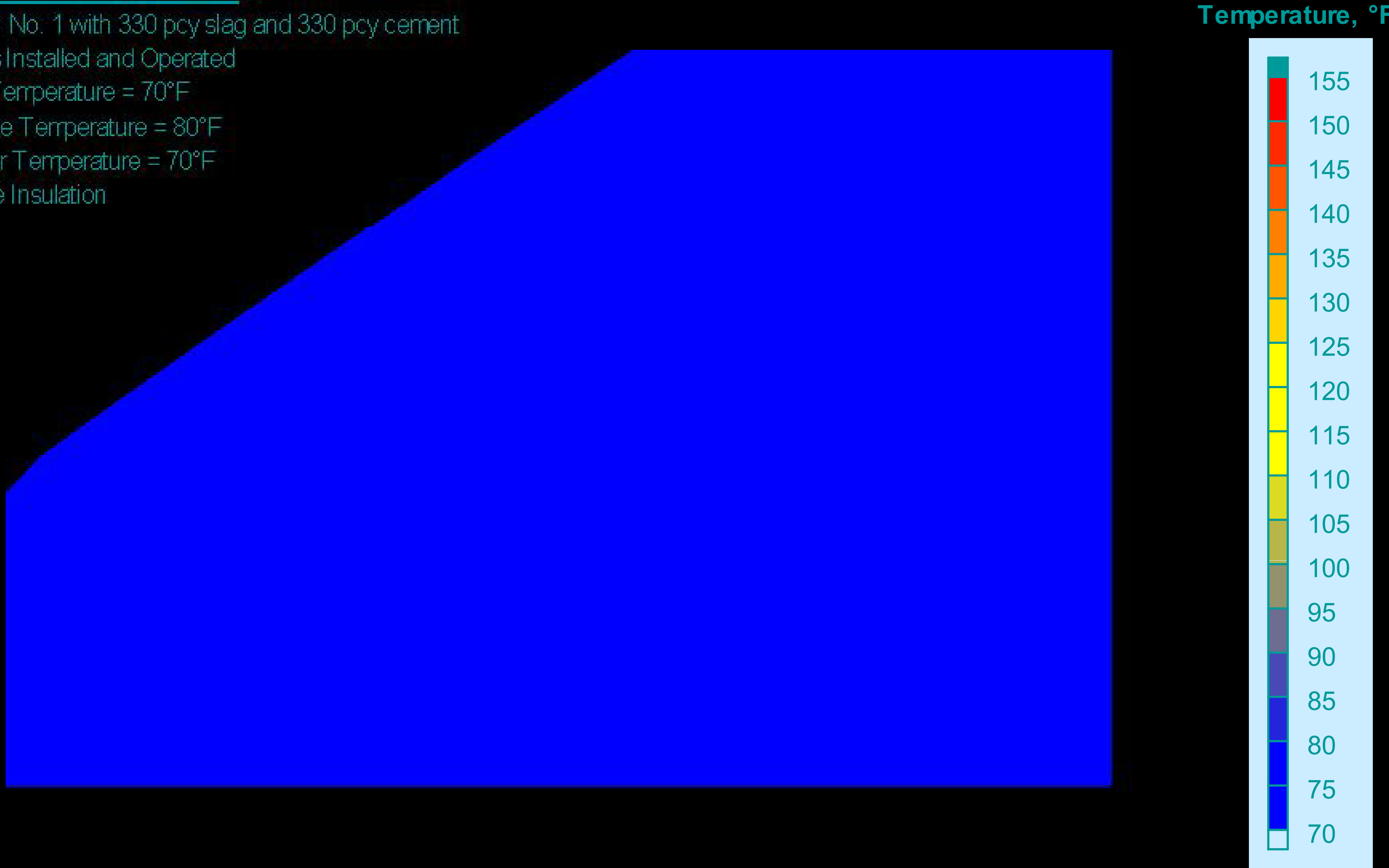
Cooling Pipes Installed and Operated

Average Air Temperature = 70°F

Initial Concrete Temperature = 80°F

Cooling Water Temperature = 70°F

R-2.8 Surface Insulation



Day = 0

Assumed Placement Conditions

Concrete Mix No. 1 with 330 pcy slag and 330 pcy cement

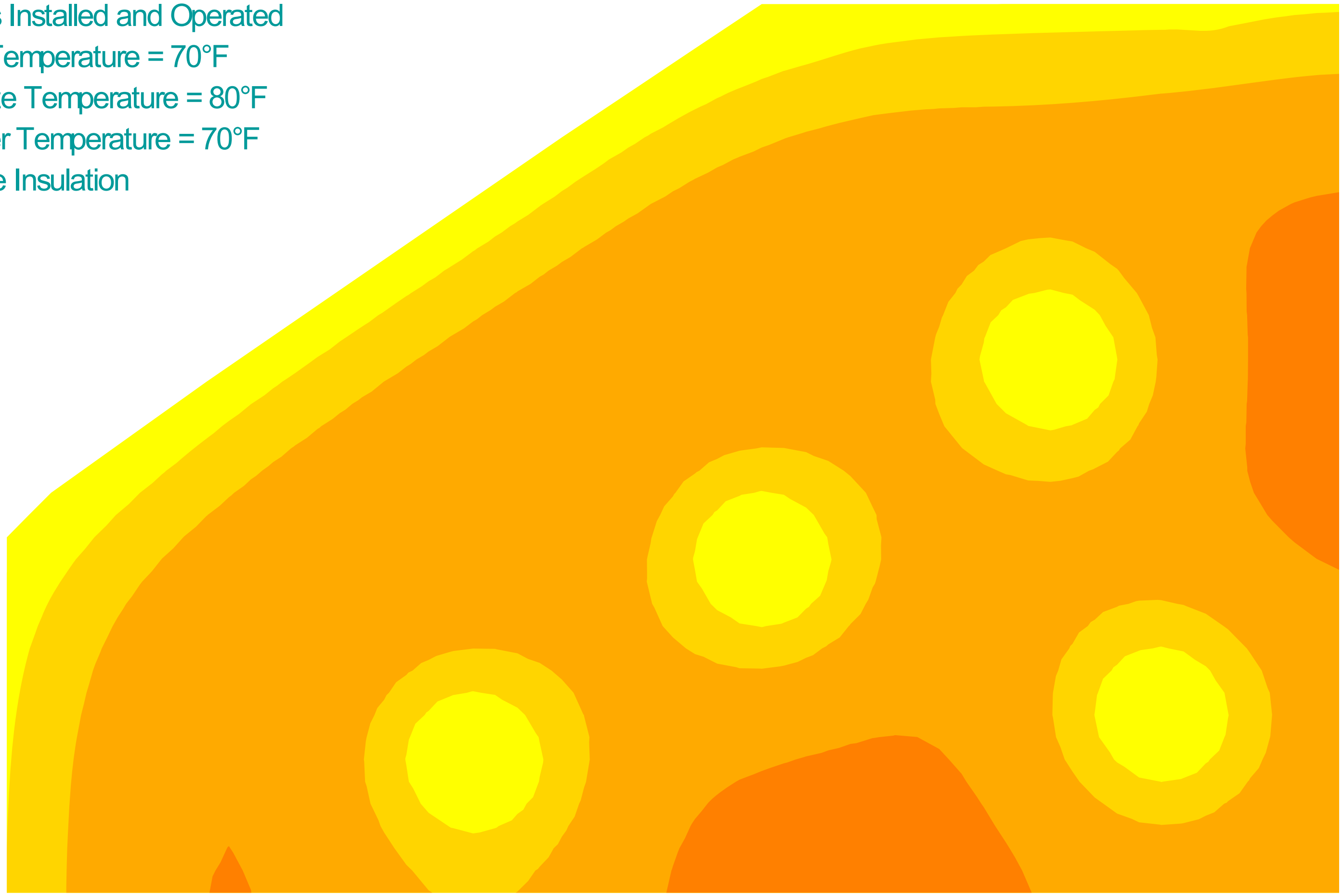
Cooling Pipes Installed and Operated

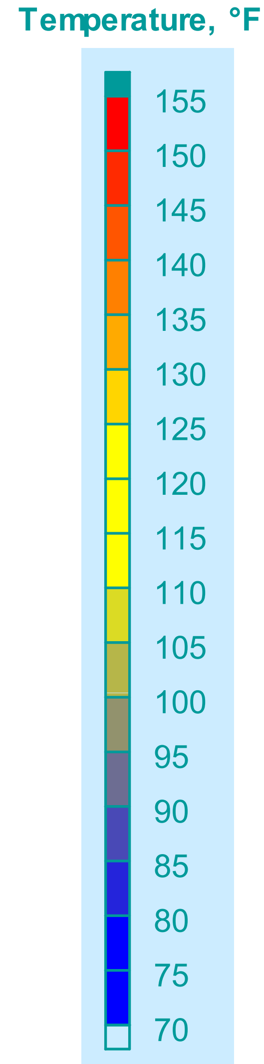
Average Air Temperature = 70°F

Initial Concrete Temperature = 80°F

Cooling Water Temperature = 70°F

R-2.8 Surface Insulation





Predicted Temperatures (See Drawing No. 3 for Thermocouple Locations)

Center Thermocouple = 137°F

Surface Thermocouple = 123°F

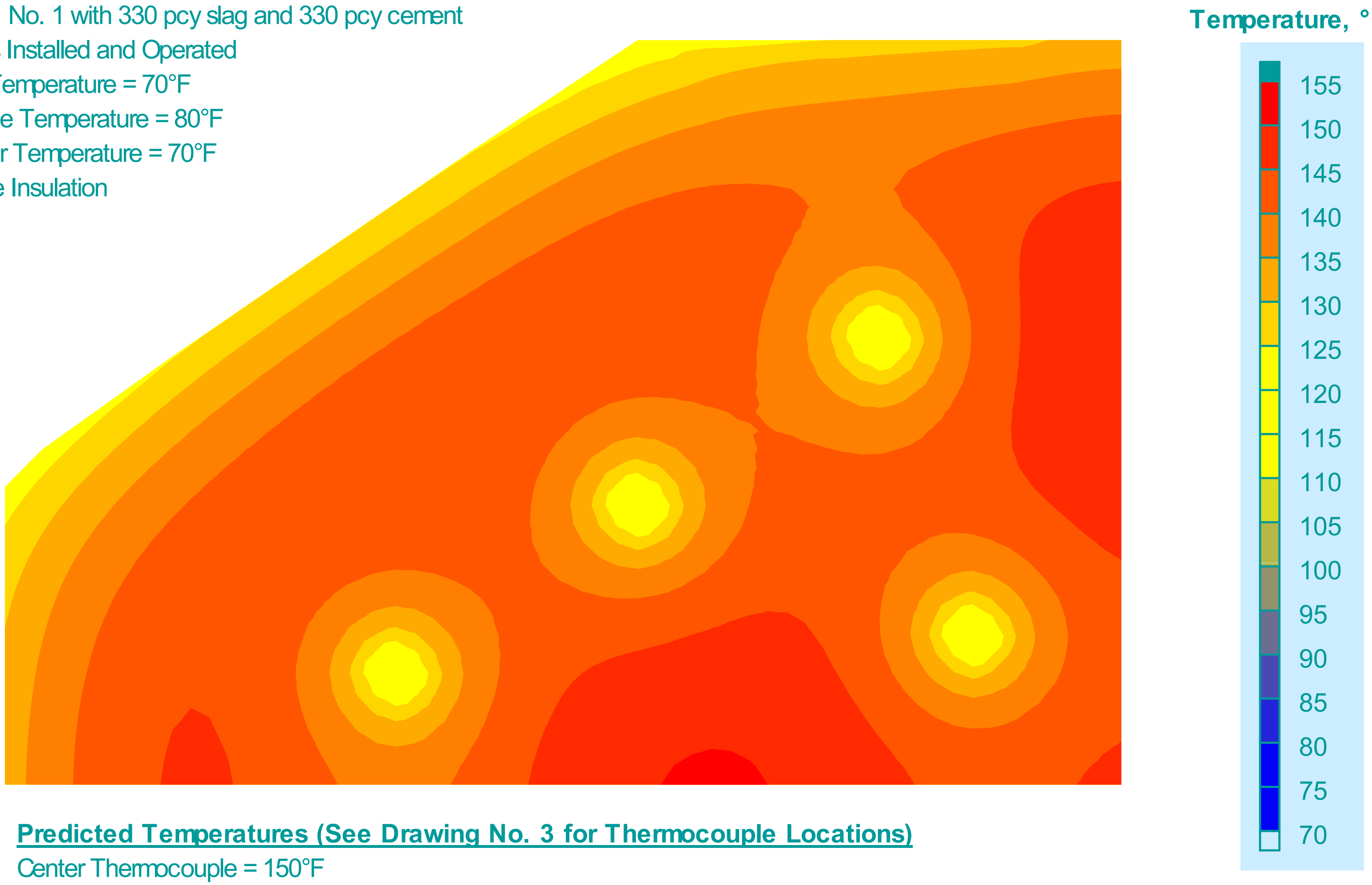
Pipe Thermocouple = 117°F

Largest Temp. Diff. = 20°F

Day = 1

Assumed Placement Conditions

Concrete Mix No. 1 with 330 pcy slag and 330 pcy cement
Cooling Pipes Installed and Operated
Average Air Temperature = 70°F
Initial Concrete Temperature = 80°F
Cooling Water Temperature = 70°F
R-2.8 Surface Insulation



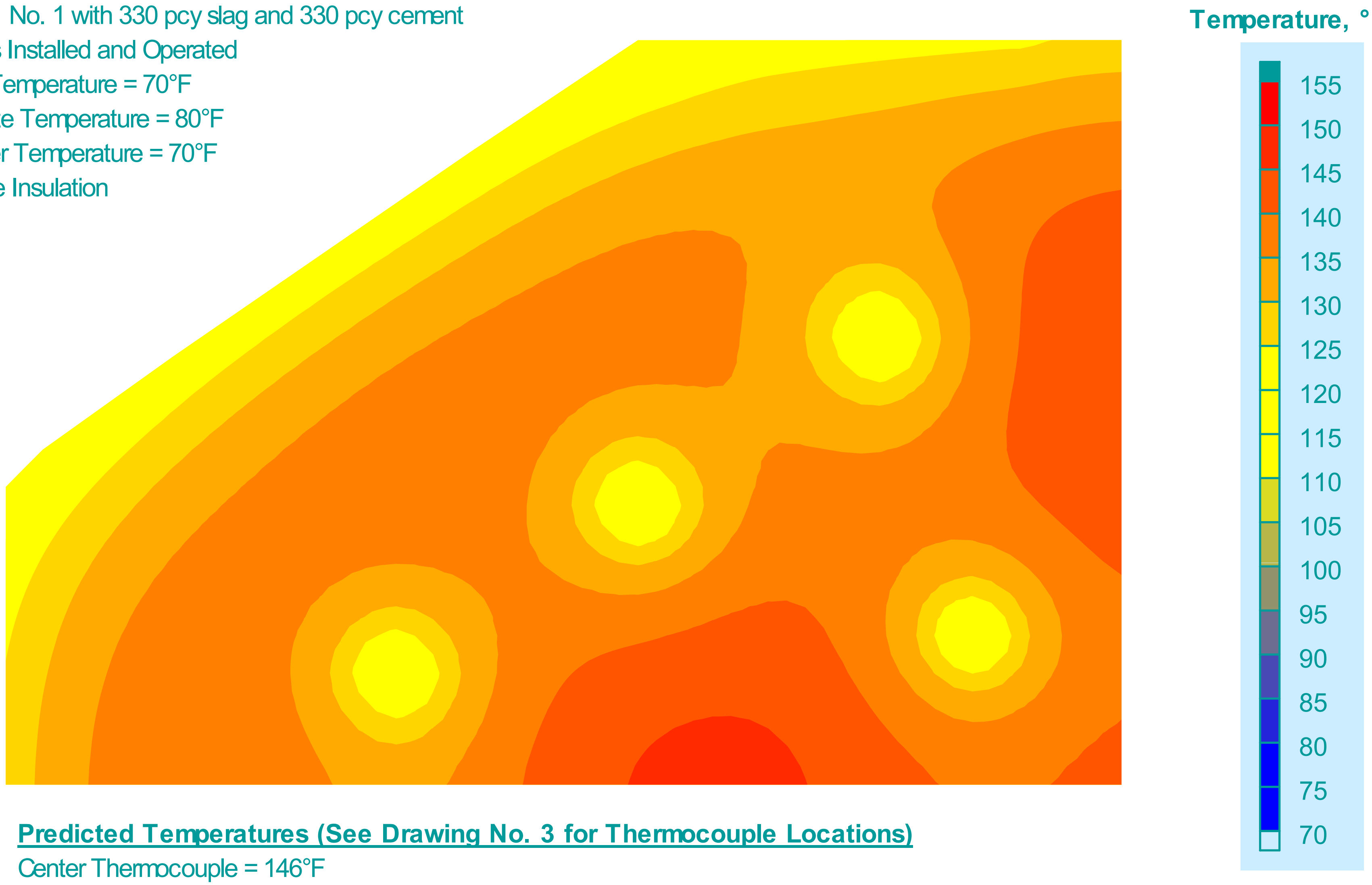
Predicted Temperatures (See Drawing No. 3 for Thermocouple Locations)

Center Thermocouple = 150°F
Surface Thermocouple = 129°F
Pipe Thermocouple = 124°F
Largest Temp. Diff. = 26°F

Day = 2

Assumed Placement Conditions

Concrete Mix No. 1 with 330 pcy slag and 330 pcy cement
Cooling Pipes Installed and Operated
Average Air Temperature = 70°F
Initial Concrete Temperature = 80°F
Cooling Water Temperature = 70°F
R-2.8 Surface Insulation



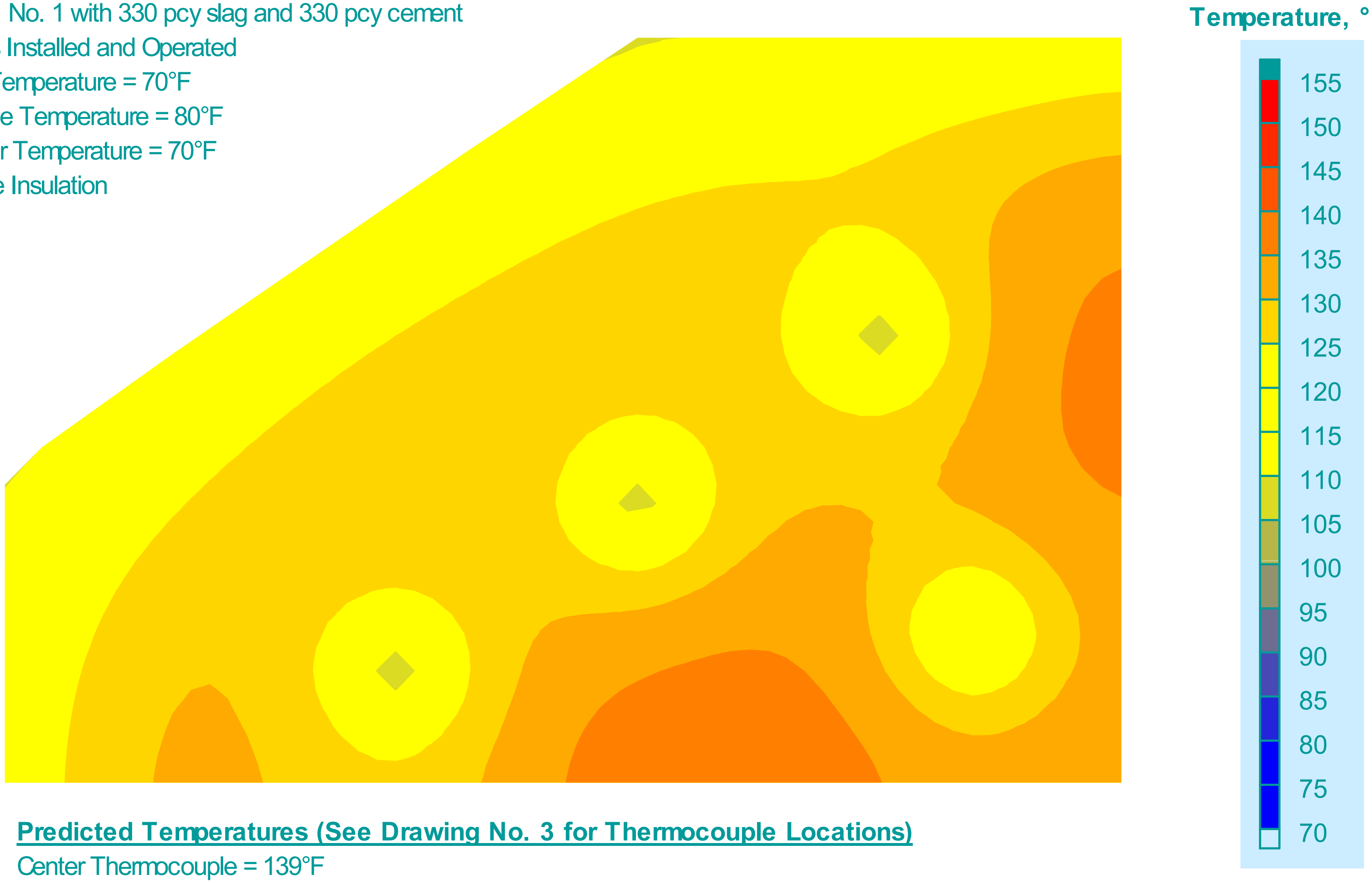
Predicted Temperatures (See Drawing No. 3 for Thermocouple Locations)

Center Thermocouple = 146°F
Surface Thermocouple = 123°F
Pipe Thermocouple = 121°F
Largest Temp. Diff. = 25°F

Day = 3

Assumed Placement Conditions

Concrete Mix No. 1 with 330 pcy slag and 330 pcy cement
Cooling Pipes Installed and Operated
Average Air Temperature = 70°F
Initial Concrete Temperature = 80°F
Cooling Water Temperature = 70°F
R-2.8 Surface Insulation



Predicted Temperatures (See Drawing No. 3 for Thermocouple Locations)

Center Thermocouple = 139°F
Surface Thermocouple = 116°F
Pipe Thermocouple = 116°F
Largest Temp. Diff. = 23°F

Day = 4

Assumed Placement Conditions

Concrete Mix No. 1 with 330 pcy slag and 330 pcy cement
Cooling Pipes Installed and Operated
Average Air Temperature = 70°F
Initial Concrete Temperature = 80°F
Cooling Water Temperature = 70°F
R-2.8 Surface Insulation

Predicted Temperatures (See Drawing No. 3 for Thermocouple Locations)

Center Thermocouple = 131°F
Surface Thermocouple = 109°F
Pipe Thermocouple = 111°F
Largest Temp. Diff. = 21°F

Day = 5

Assumed Placement Conditions

Concrete Mix No. 1 with 330 pcy slag and 330 pcy cement

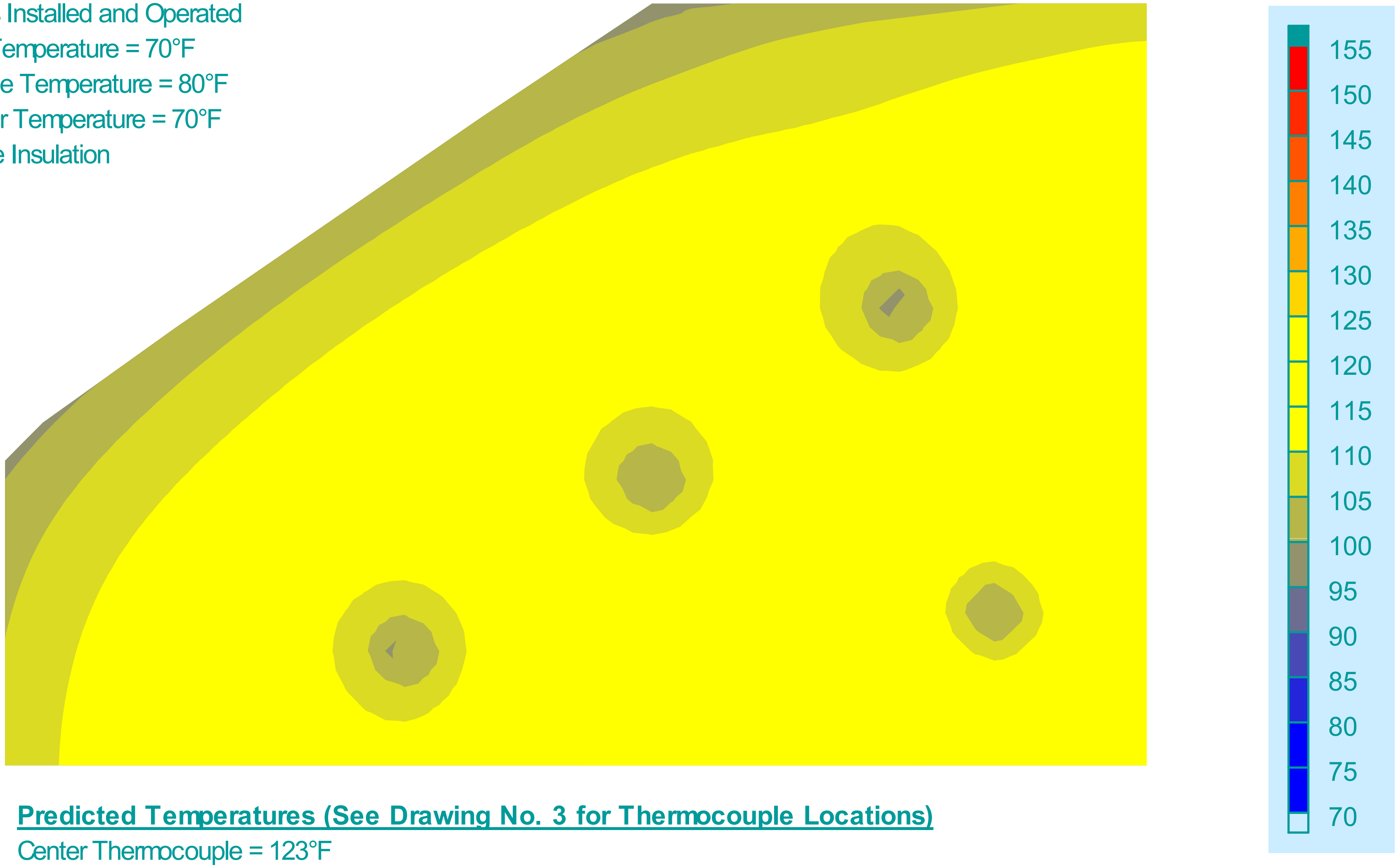
Cooling Pipes Installed and Operated

Average Air Temperature = 70°F

Initial Concrete Temperature = 80°F

Cooling Water Temperature = 70°F

R-2.8 Surface Insulation



Predicted Temperatures (See Drawing No. 3 for Thermocouple Locations)

Center Thermocouple = 123°F

Surface Thermocouple = 104°F

Pipe Thermocouple = 106°F

Largest Temp. Diff. = 19°F

Day = 6

Assumed Placement Conditions

Concrete Mix No. 1 with 330 pcy slag and 330 pcy cement

Cooling Pipes Installed and Operated

Average Air Temperature = 70°F

Initial Concrete Temperature = 80°F

Cooling Water Temperature = 70°F

R-2.8 Surface Insulation

Predicted Temperatures (See Drawing No. 3 for Thermocouple Locations)

Center Thermocouple = 116°F

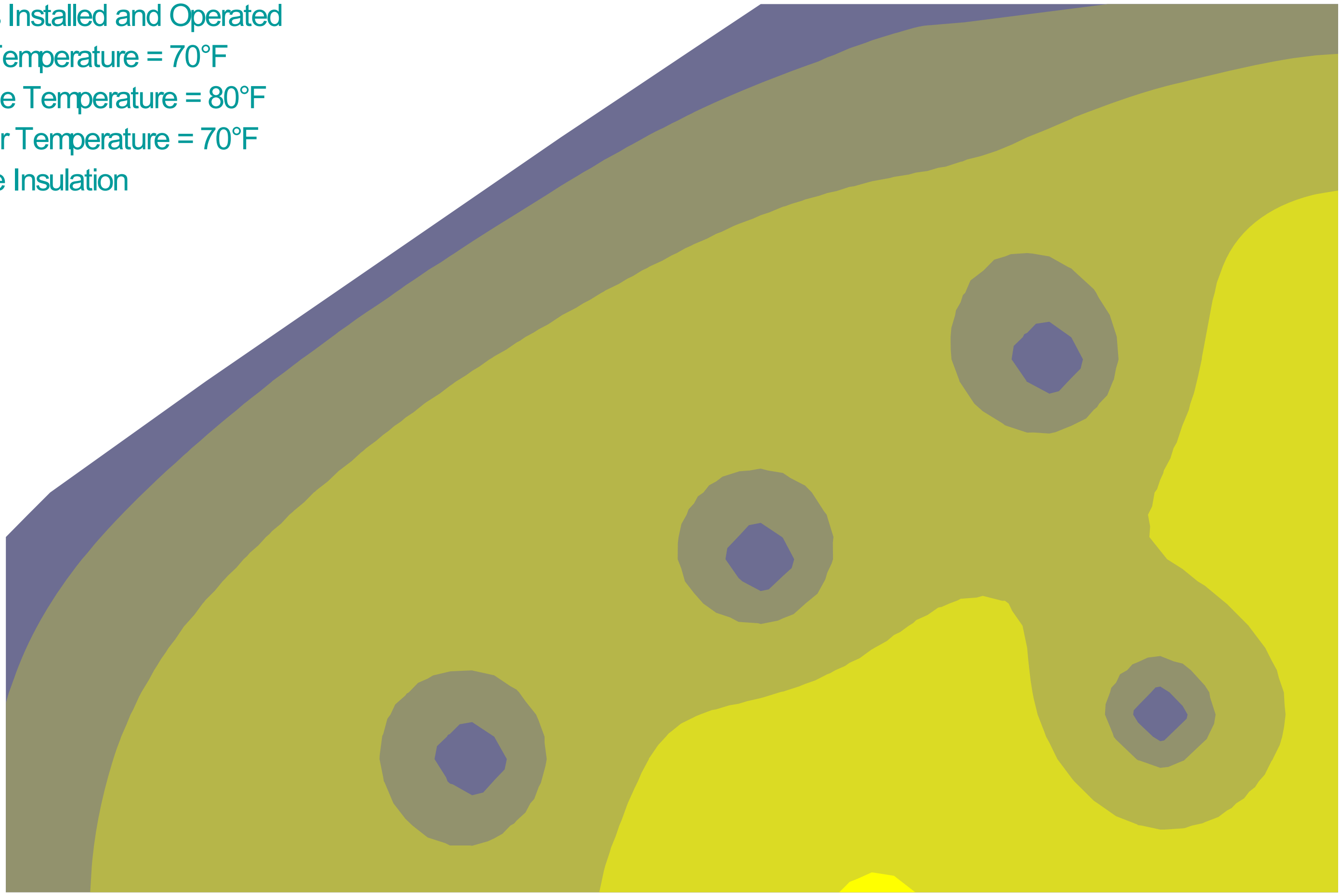
Surface Thermocouple = 99°F

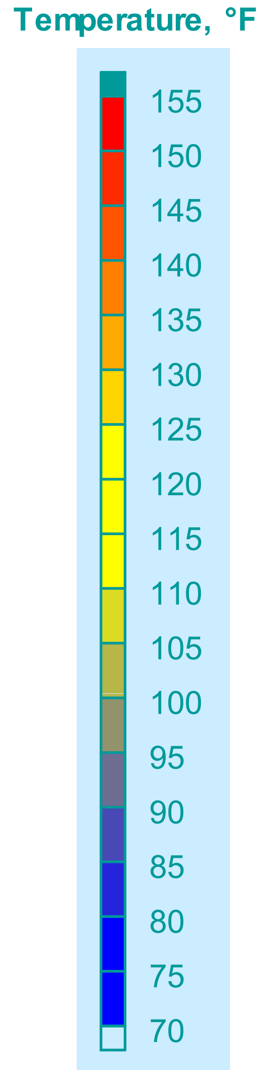
Pipe Thermocouple = 101°F

Largest Temp. Diff. = 17°F

Day = 7

Assumed Placement Conditions
Concrete Mix No. 1 with 330 pcy slag and 330 pcy cement
Cooling Pipes Installed and Operated
Average Air Temperature = 70°F
Initial Concrete Temperature = 80°F
Cooling Water Temperature = 70°F
R-2.8 Surface Insulation





Predicted Temperatures (See Drawing No. 3 for Thermocouple Locations)
Center Thermocouple = 110°F
Surface Thermocouple = 95°F
Pipe Thermocouple = 97°F
Largest Temp. Diff. = 15°F

Day = 8

Inspector's Guide to Mass Concrete – *Before Placement*

- Read contractor's thermal control plan
- Identify initial concrete temperature limit
- Identify other rejection criteria
- Verify cylinder storage area
- Verify placement equipment
- Schedule personnel and duties
- Verify installed temperature sensors
- Verify operation of cooling pipes (if used)

Thermal Control Plan (TCP)

- Submittal item
  - Must be approved before placement
- Demonstrates contractor's methods to
  - Comply with mass concrete specifications
  - Ensure maximum temperature under 160°F (or specified limit)
  - Minimize/prevent thermal cracking (states a temperature difference limit)
  - Ensure proper curing

Contents of a TCP

- Specification Requirements
- Concrete Placements covered by TCP
- Concrete Mix Design
- Predicted Temperatures in Placements
  - Assumptions used
  - Temperature ranges (air, concrete, etc).
  - Prediction method
  - Anticipated results

Contents of a TCP (cont.)

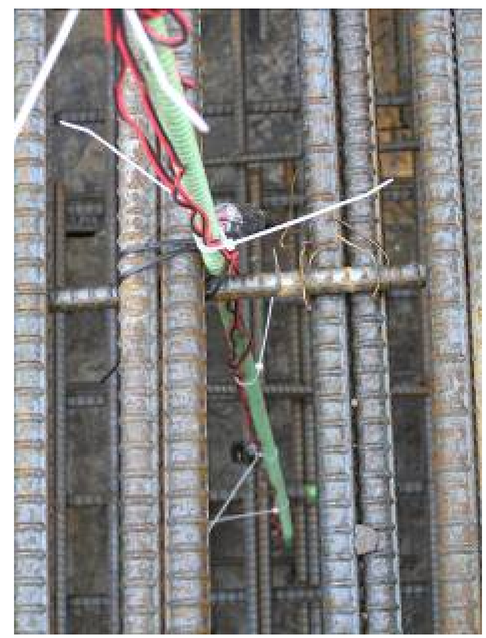
- Construction Practices
  - Placement method (pump, etc.)
  - Rejection temperature for delivered concrete
  - Curing method
  - Insulation (materials and installation)
  - Cooling pipe details (if used)
    - Materials
    - Installation
    - Operation

Contents of a TCP (cont.)

- Construction practices (cont.)
  - Temperature monitoring
    - Equipment
    - Frequency
    - Reporting
  - Corrective measures
- Completion criteria

Prepour Temperature Sensor Verification

- Correct equipment and locations
  - Per the thermal control plan
  - Typically at center of mass of placement
  - 2-3” below surface (top or side)
  - Away from pipes, piles, etc.
  - Backup sensors
- Functioning (good data)
- Wires protected



Prepour Cooling Pipe Verification

- Proper locations
  - Per the thermal control plan
  - Uniform layout
- Water flows through all pipes
- No leaks
- Flow rate

Inspector's Guide to Mass Concrete – *During Placement*

- Verify fresh properties
- Verify concrete temperature within limit
- Verify proper vibration
- Form pressure issues?
- Watch cooling pipes and temperature sensors
- Revibration
- Finishing
- Curing

Inspector's Guide to Mass Concrete – *During Thermal Control Period*

- Fully insulated concrete and formwork
- Cooling pipes operating properly
- All temperatures within limit
- Temperature differences within limit
- Contractor adjustments, if necessary

Inspector's Guide to Mass Concrete – *After Thermal Control is Complete*

- Cooling pipes grouted, cut below surface and patched
- No thermal cracking
- Repairs (if necessary)

Summary

- Concrete gets hot!!
- Extra measures are needed to prevent excessive temperatures and temperature differences.
- Many approaches to thermal control
- Insulation always needed
- Temperature sensors for verification of thermal control

Questions on Mass Concrete?