PEM Seminar

Analysis of information collected during the curing process of materials used for underground coal mine seals.

08/27/2021

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Project Background

Why the requirement for Mine Seals?

Sealing of abandoned mines and or completed mined areas! MSHA / NIOSH

The requirements include:

- Seal strength, design, construction, maintenance and repair of **seals.**
- Monitoring and control of atmospheres behind **seals** in order to reduce the risk of explosions in abandoned areas of underground mines.
- It also addresses the level of overpressure for new **seals**.

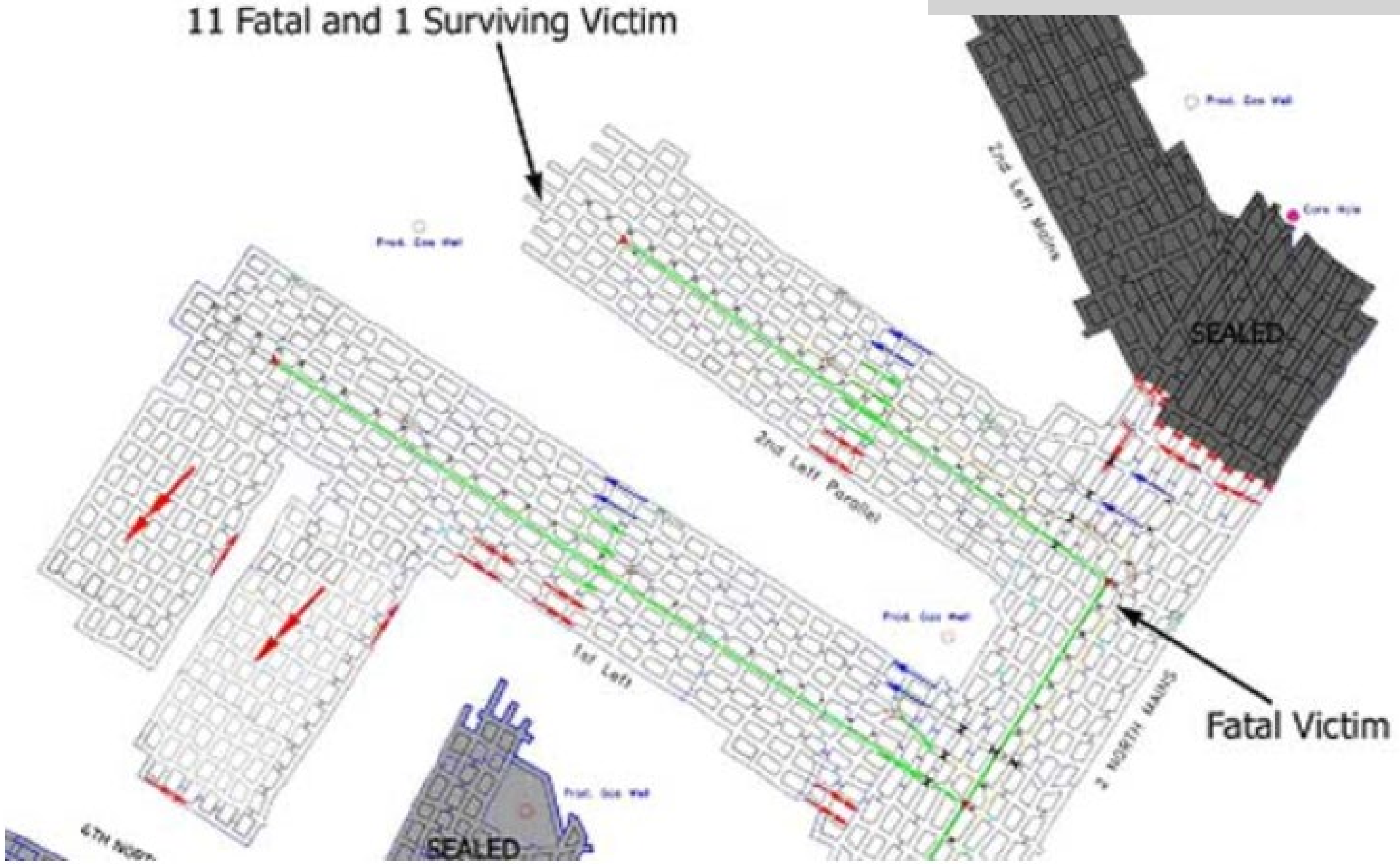
Coal Mine Seal Application

History and Track Record?

COAL MINE FATALITY - On Monday, January 2, 2006, at approximately 6:30 a.m., an underground explosion occurred resulting in the deaths of 12 miners and serious injury to one miner. Mine rescue teams rescued the surviving miner and recovered the remaining victims during the morning of January 4, 2006.

Ignition/Explosion of Gas/Dust - Underground - WV

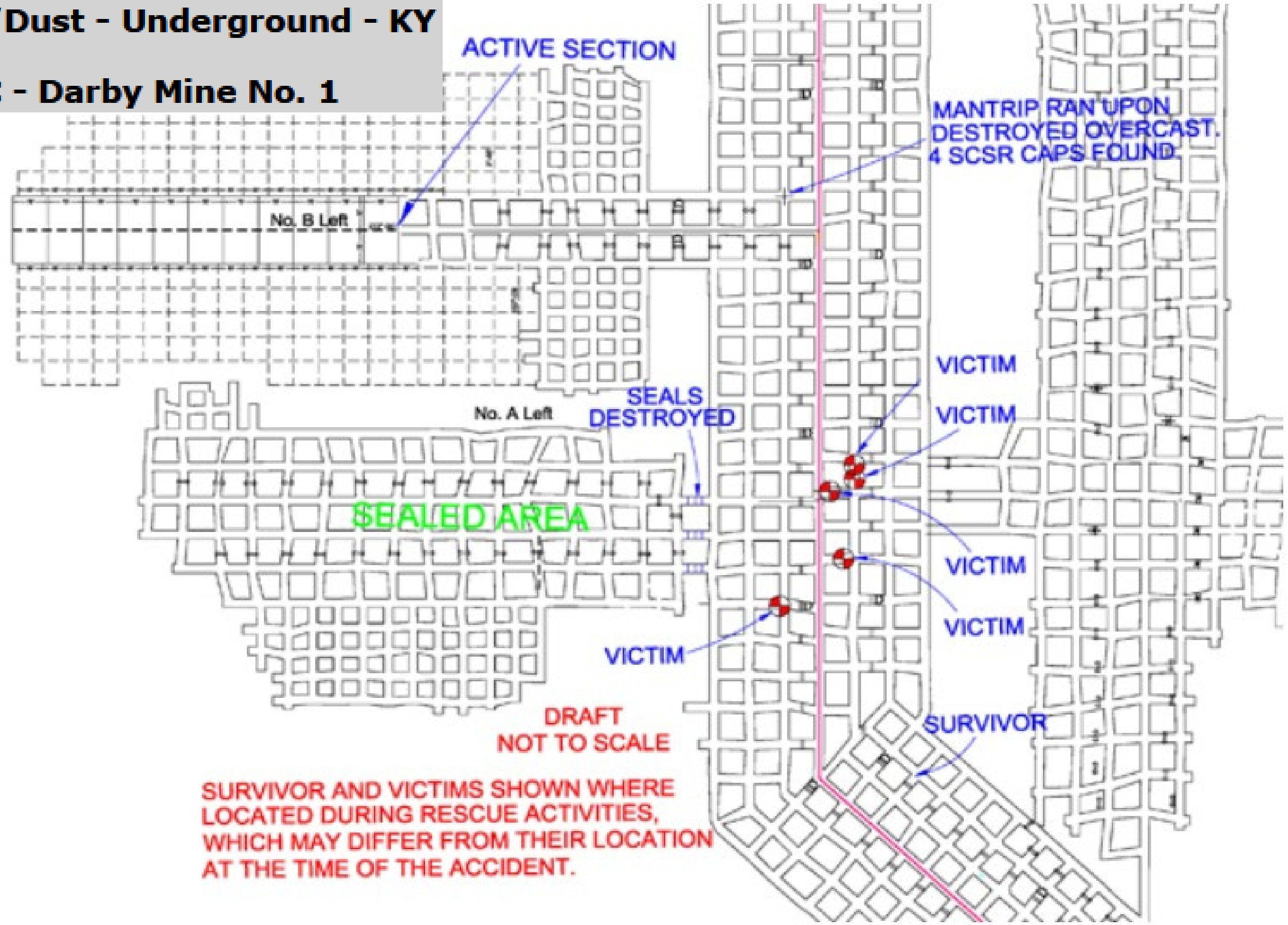
Anker West Virginia Mining Company Inc - Sago Mine



COAL MINE FATALITY - On Saturday, May 20, 2006, at about 1:00 a.m., an underground explosion occurred that resulted in the deaths of five miners and injury to one miner. The accident occurred at the start of the maintenance shift. Four of the six miners underground, including the survivor, were located in the active working section at the time of the explosion.

Ignition/Explosion of Gas/Dust - Underground - KY

Kentucky Darby LLC - Darby Mine No. 1



Objectives

MSHA's final rule on mine, seals:

- Dictates several considerations of design requirements
  - Underground Seal Design Requirement – 50 psi for Inert Atmosphere (chemically inactive)
  - Underground Seal Design Requirement – 120 psi for Not Inert Atmosphere (chemically active)
- Maintenance requirements
- However, questions remain:
  - **Can micro and macro fractures originate or occur during the curing process,**
  - **or being created, as a consequence of, stress changes on the integrity and structural behavior of the mine seals?**

Objectives

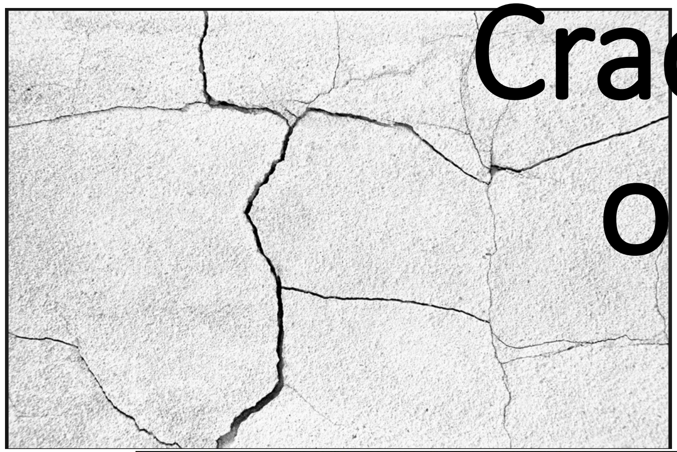
Reason for this Project:

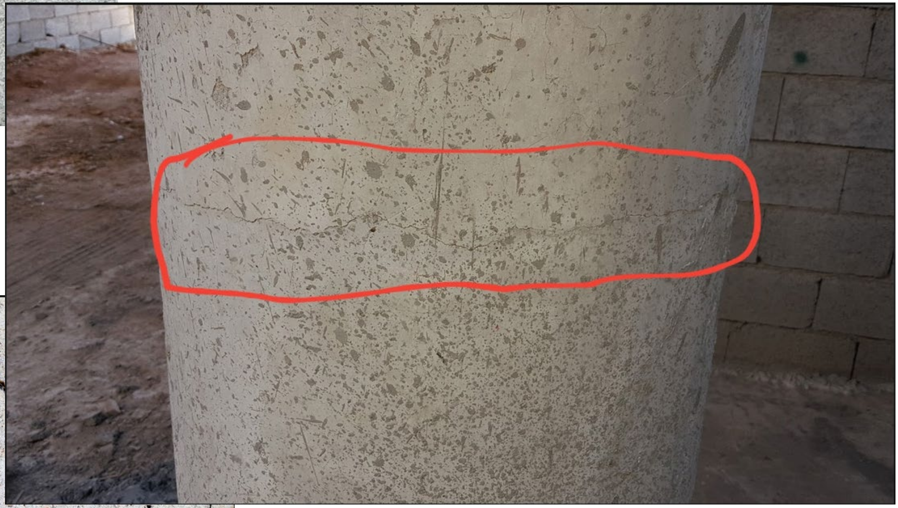
- **Can micro and macro fractures originate or occur during the curing process?**

What if answer is YES?

- How is the structural integrity being influenced and or compromised if yes?
- The analysis conducted and this presentation answers part of this question!

Cracks / Fractures in Slabs or Columns Not Seals





Structural Integrity

What does the word “Integrity” mean?

According to one definition:

“The condition of being unified, unimpaired, or sound in construction”

Cracks in Cementitious Materials

The reason for cracks forming:

- Is because these materials provides solutions with **Strength**, **Rigidity**, and **Resilience** from Deformation.
- These characteristics, result in concrete lacking the flexibility to move in response to environmental or volume change.
- Why: Due to volume changes and repeated loading
- Micro & Macro **Cracking,** is usually the first sign of distress in concrete.

Volume Change in Concrete

Reasons for Volume Change:

- Chemical Reaction of mixture
- Temperature Change
- Internal Strain
- Hydration
- Reinforced and or Unreinforced
- Aggregate inclusion Yes or No & Size of Aggregate

This all can have an influence on the early forming of Cracks & Fractures

Causes of Cracking

Why does cracking occur in these cementitious materials?

Some possible causes:

- Drying Shrinkage
- Thermal Stresses
- Chemical Reactions
- Poor Construction Practices

Cementitious Materials

Do we really understand Cementitious Materials: – Standard Concrete - versus - Only Powder Water Mixes?

- It's Behavior in general & under different conditions
- Alternative Compounds (**recognized industry suppliers**) – Behavior and Properties
- It's Different Applications
- Mixing Methods and change in behavior
- Properties – Content & Make-Up
- Why is this, one of the most researched topics in the civil and construction industry over decades?

Development?

What methods were used to collect the data and to do the analysis?

Timing – From Day 1 to Day 28

- Seal Samples - UCS Strength Testing on 7, 14, 28 Days
- Temperature Monitoring – Embedded Thermocouples
- Strain Monitoring – Embedded Strain Gauges
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- Testing and Parametric analysis

Scope: Seal Sample 4 x 4 x 4 ft

Table1.1

Sample Type	Pour Date	Sample QTY	Supplier	Specification
Mixture A	25 Feb '21	4 off	Comp 1	Standard of Supplier
Mixture B	25 Feb '21	4 off	Comp 1	Non-Conventional – Alternative 1
Mixture C	13 Apr '21	4 off	Comp 2	Standard of Supplier
Mixture A Repeat	10 Jun '21	1 off	Comp 1	Standard of Supplier
Mixture D	10 Jun '21	1 off	Comp 1	Non-Conventional – Alternative 2
Mixture E	13 Jun '21	1 off	Comp 2	Non-Conventional

(Note - Mixture A was repeated to gather Strain Gauge Data not collected in initial sample)

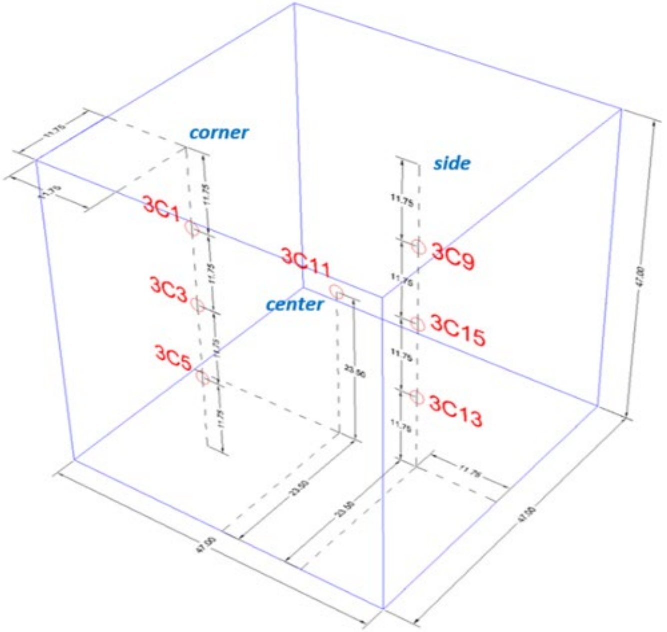

Figure 1.1 Sample Box with general instrumentation positions

Table 1.2

Sample Type	Sample QTY	Instrumentation Included & Data Collected
Mixture A	4 off	Thermocouples, Tracer Gas, Control Sample *2
Mixture B	4 off	Strain Gauges, Thermocouples, Tracer Gas, Control Sample
Mixture C	4 off	Strain Gauges, Thermocouples, Tracer Gas, Acoustic Emission
Mixture A (Repeat)	1 off	Strain Gauges, Thermocouples
Mixture D	1 off	Strain Gauges, Thermocouples, Acoustic Emission
Mixture E	1 off	Strain Gauges, Thermocouples

Through the support of two suppliers and changing the mixing ratios of powder to water, different out of specification mixtures were also tested.

Implementation

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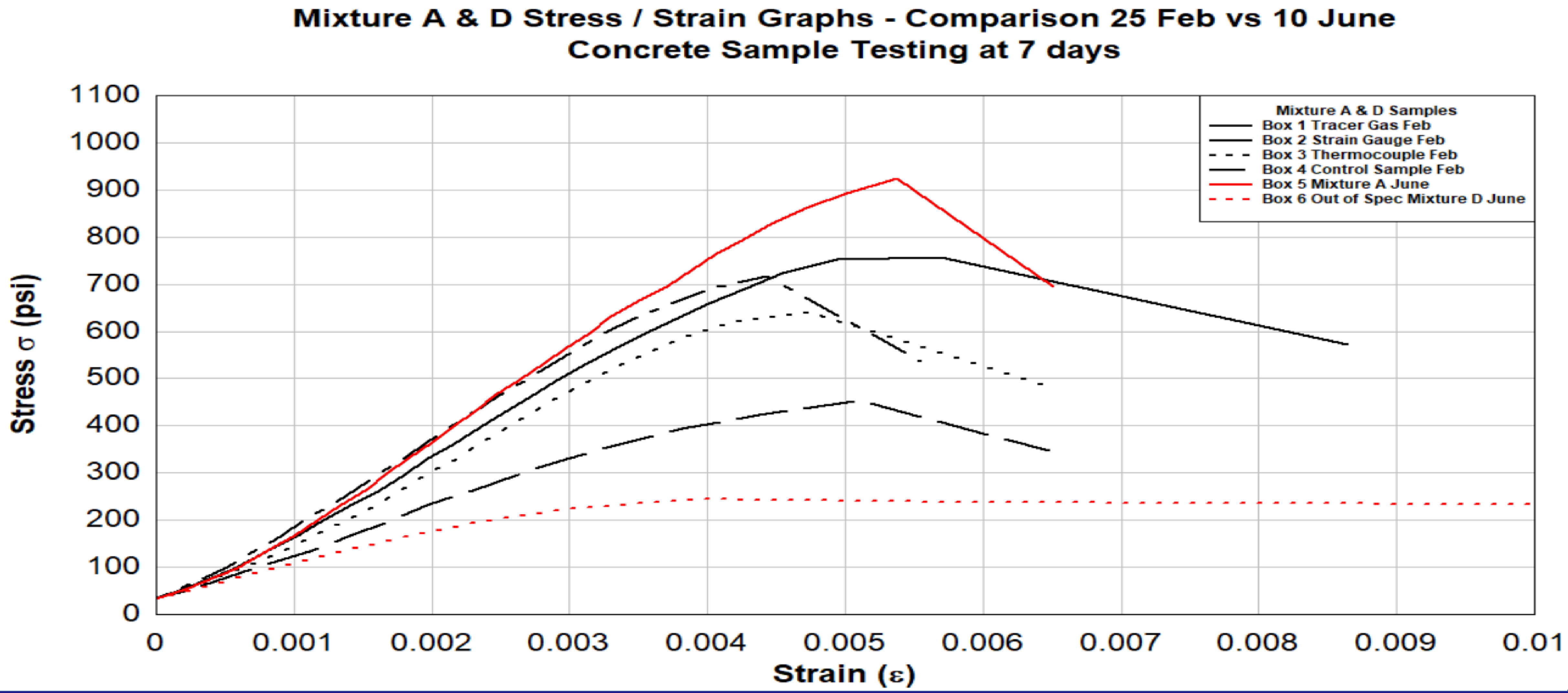
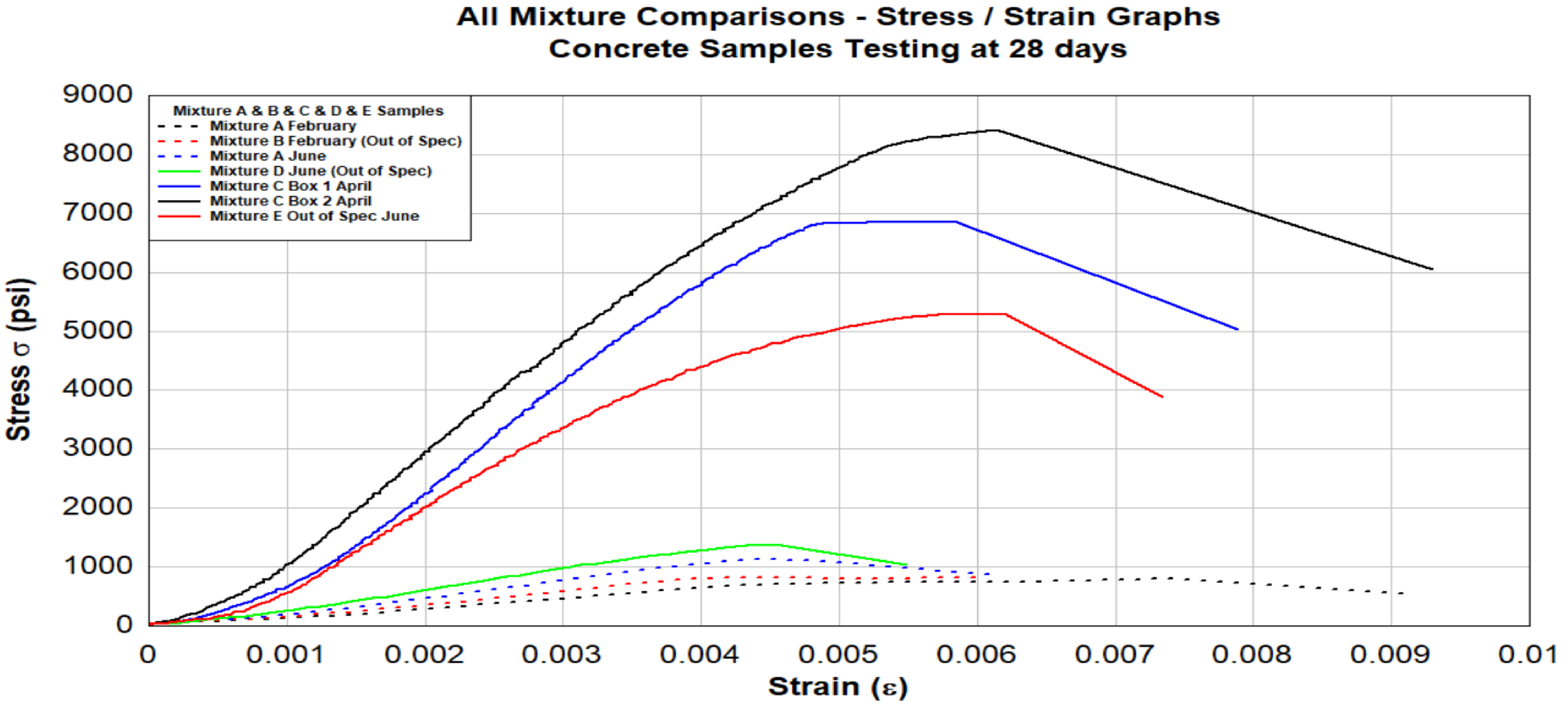
UCS Strength Testing at 7 Days



UCS Strength Testing at 28 Days



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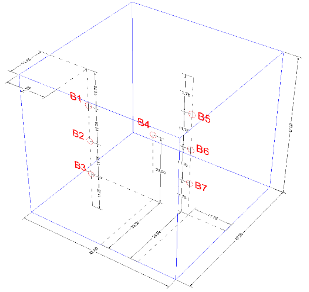
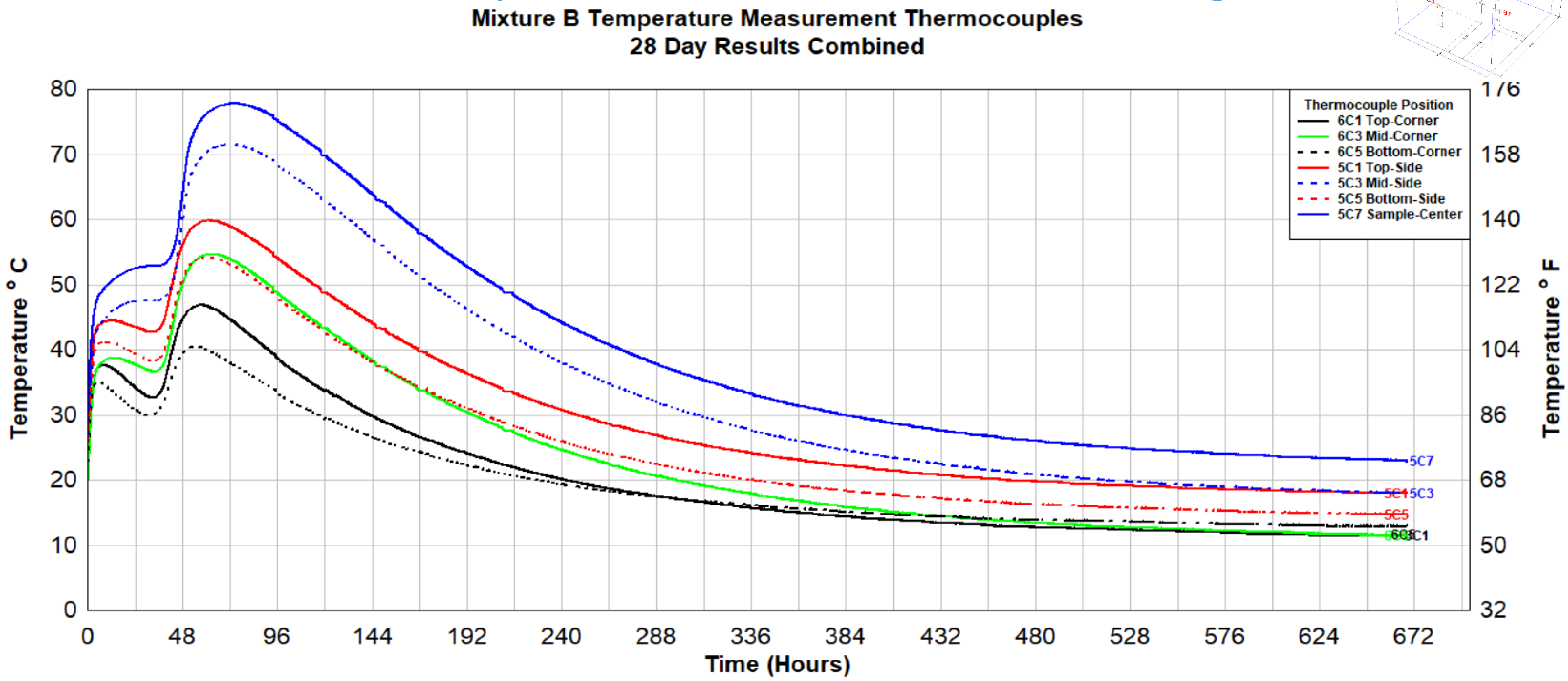
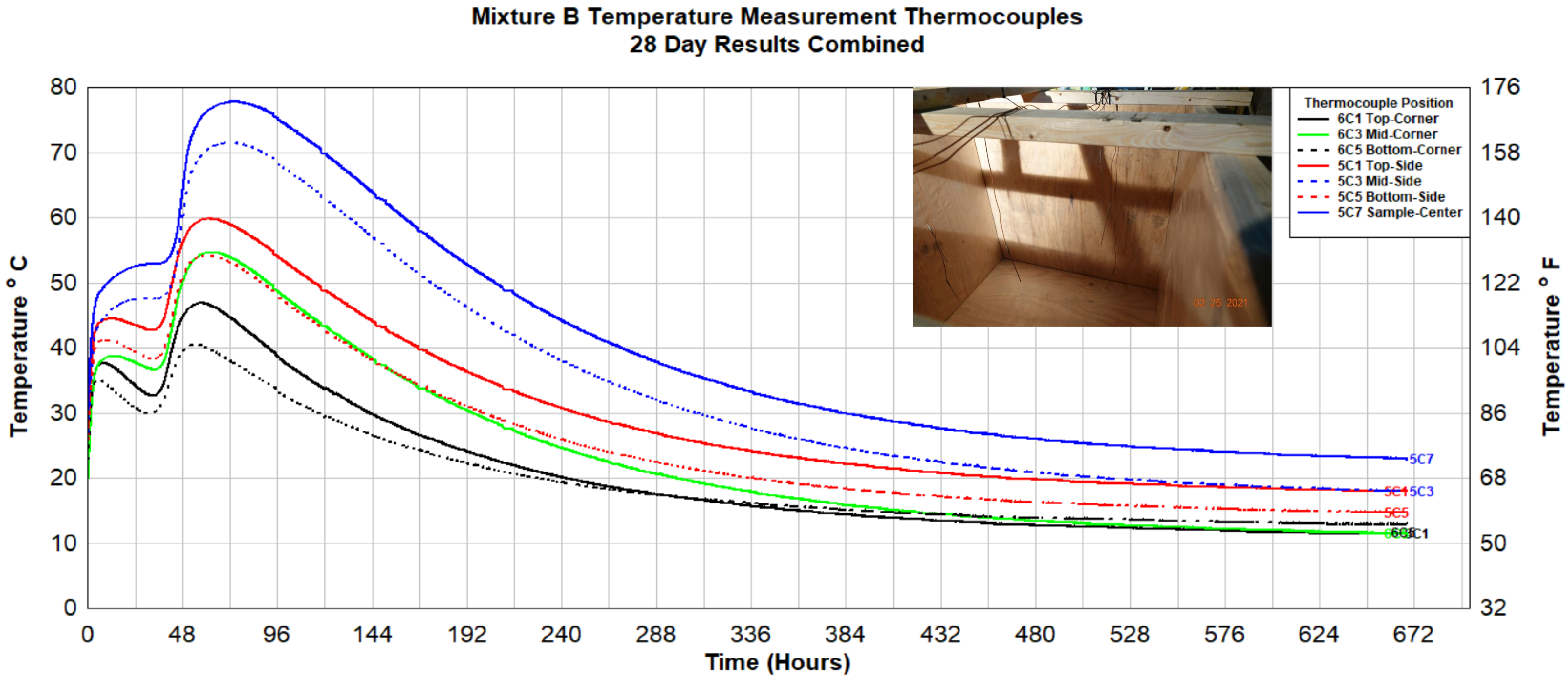
Temperature Monitoring

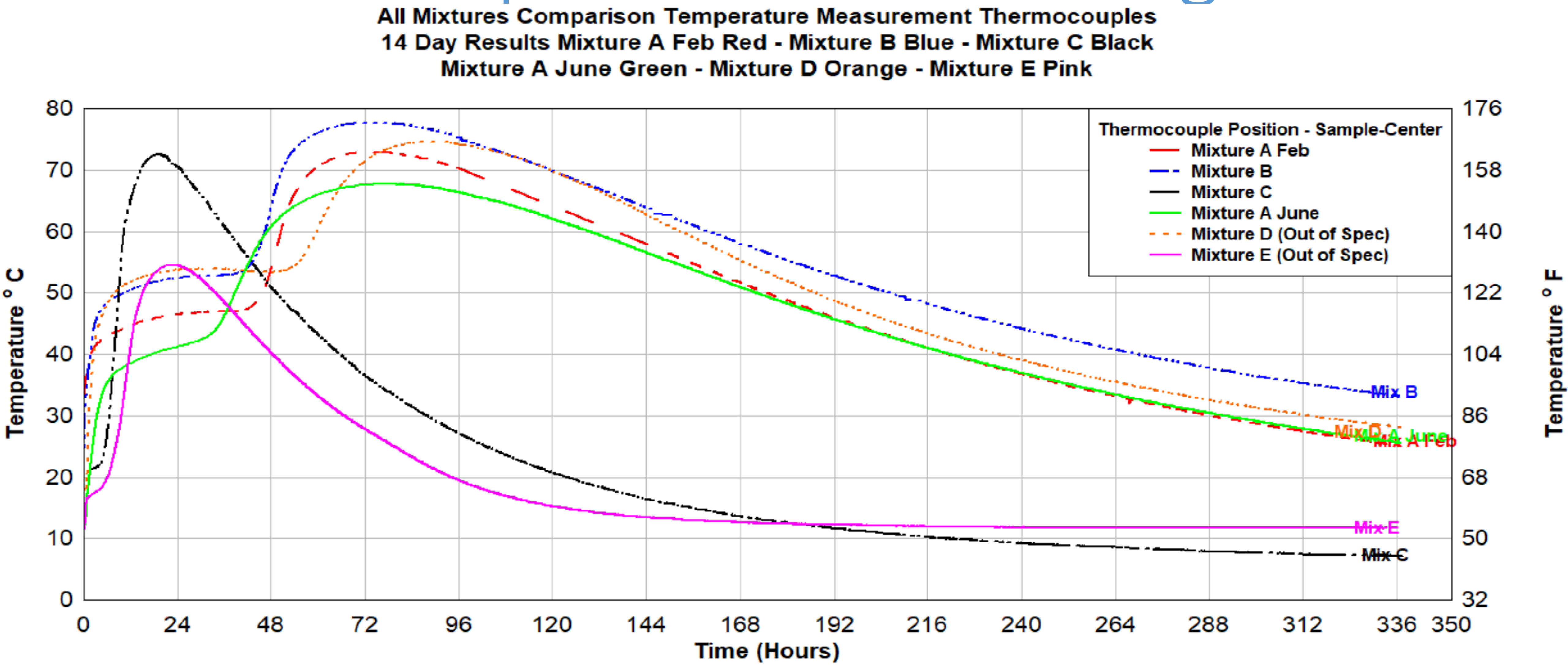




Temperature Monitoring



Temperature Monitoring



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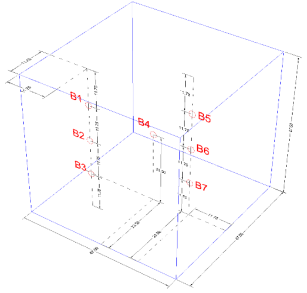
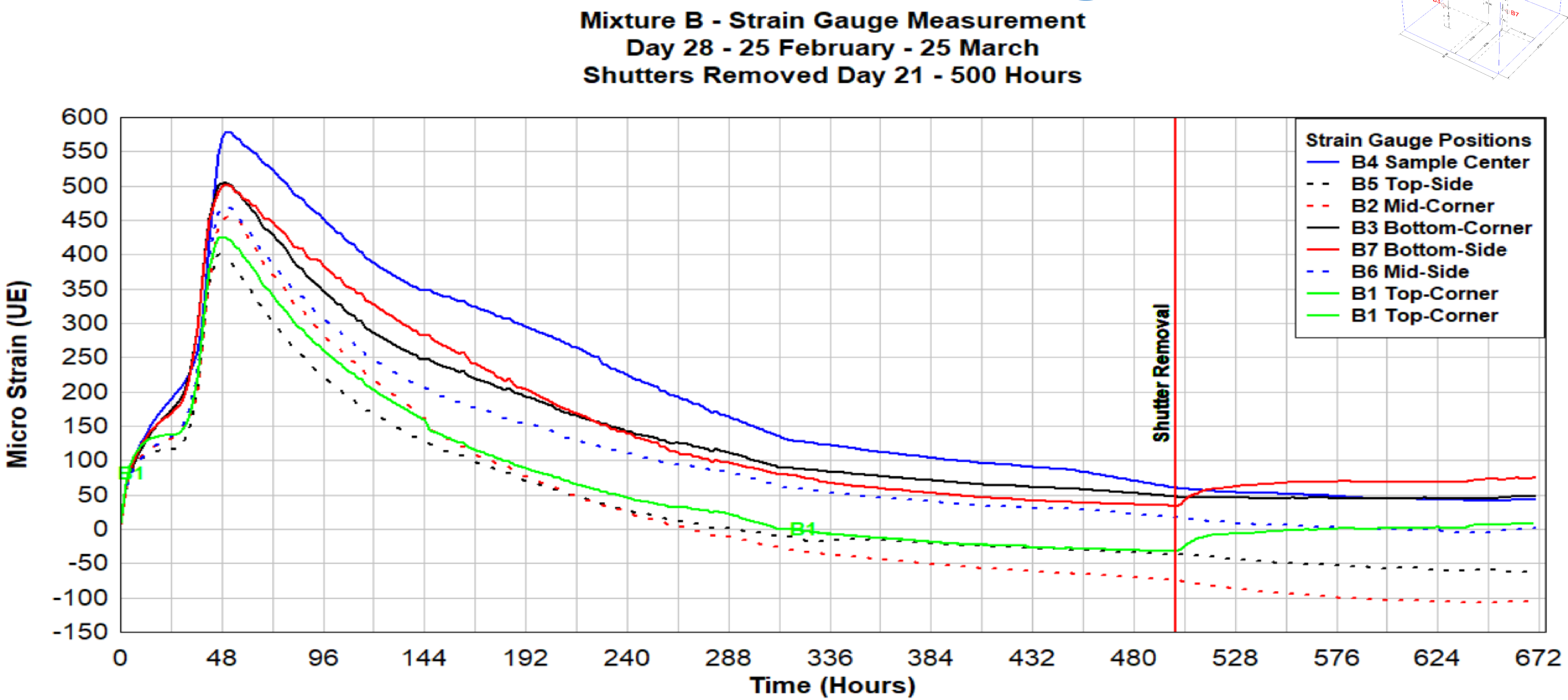
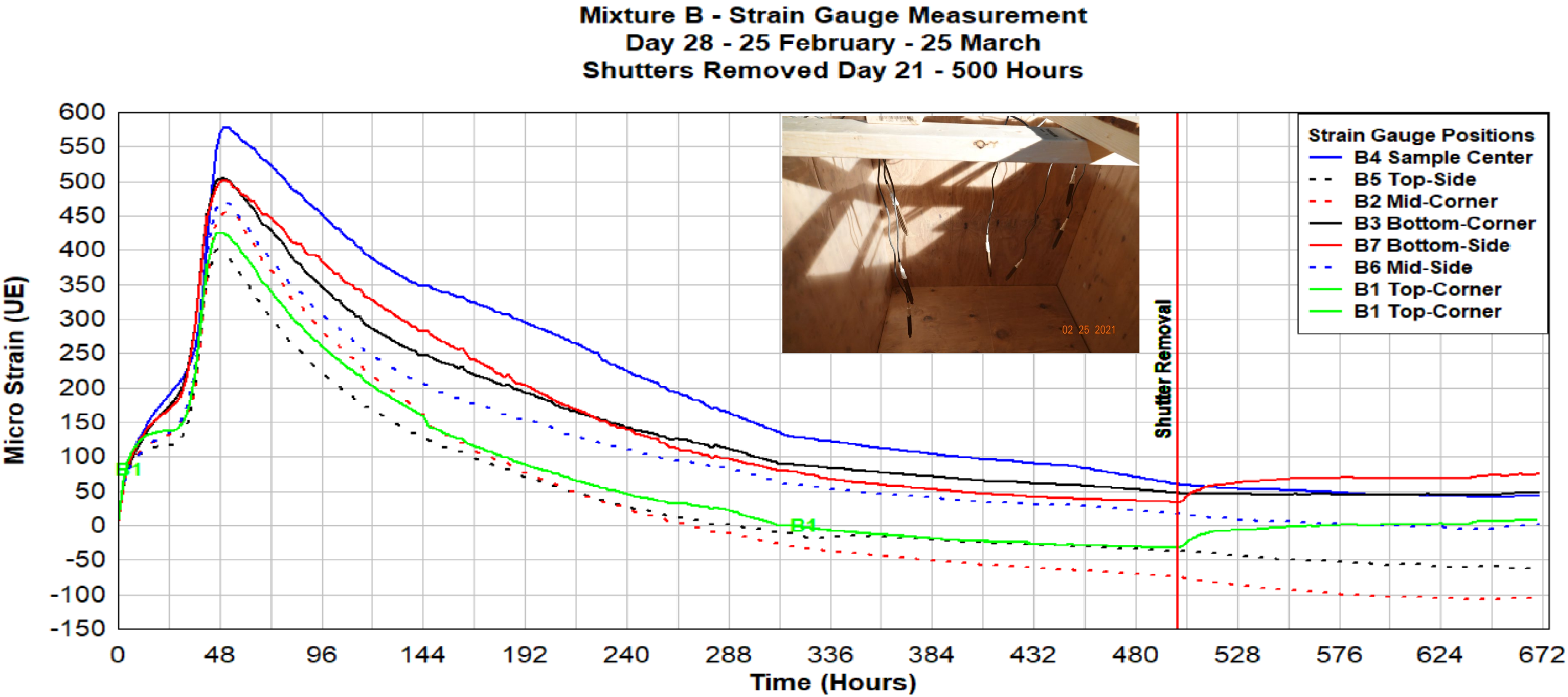
Strain Monitoring

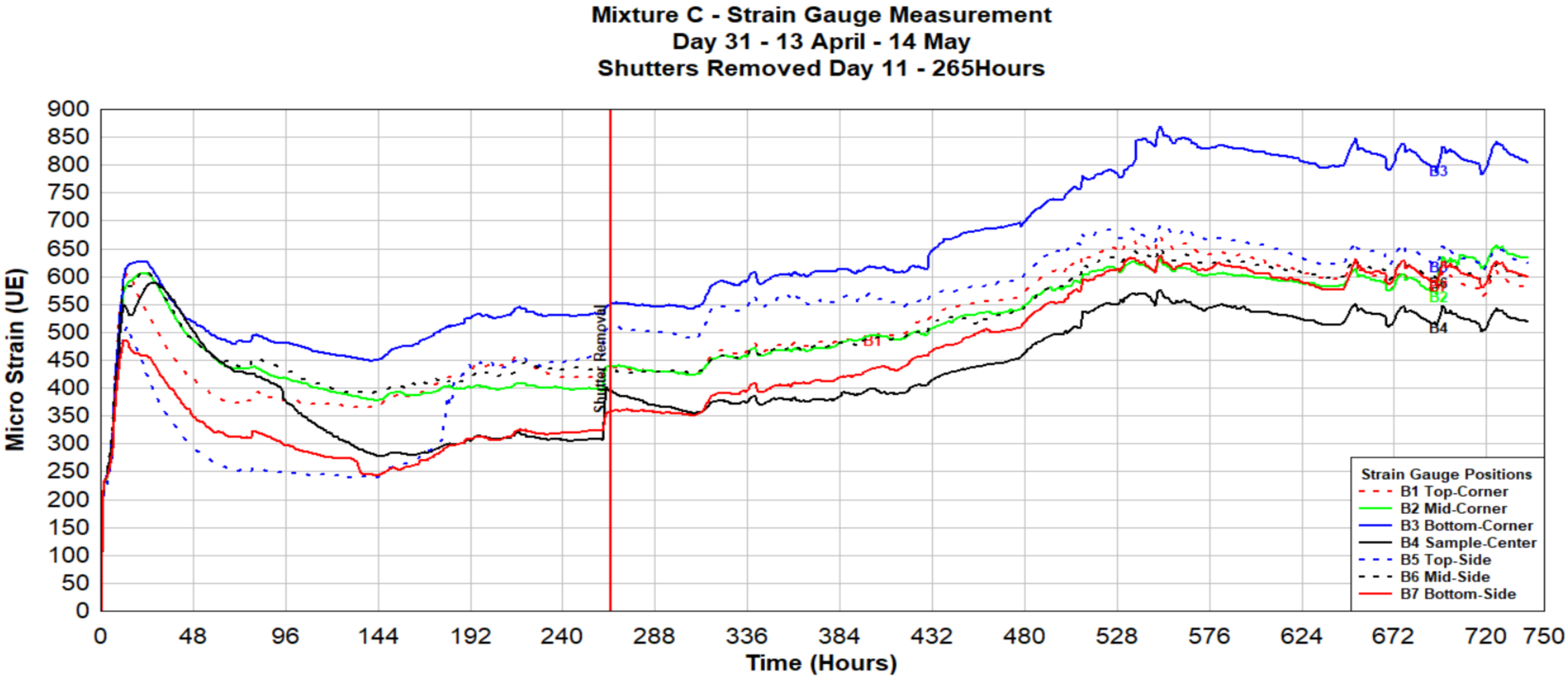




Strain Monitoring



Strain Monitoring



Implementation

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Tracer Gas – Sample Collection

Two unique Tracer Gases in two passive sources were embedded in each of the three seal samples:

- **Perfluoromethylcyclohexane (PMCH) and**
- **Perfluoromethylcyclopentane (PMCP).**

➢ Tracer Gas samples were collected from three seal samples (Mixture A, Mixture B, and Mixture C – representing 2 suppliers.

➢ A total of 37 tracer gas samples were collected.

➢ Preliminary results from the gas chromatography analysis shows the PMCH tracer gas present at low concentrations in the majority of 11 samples tested.

➢ Question: Did Tracer Gases move through the seal material itself or through fractures within the seal material?

➢ Note: Gas will move through path of least resistance!

Implementation

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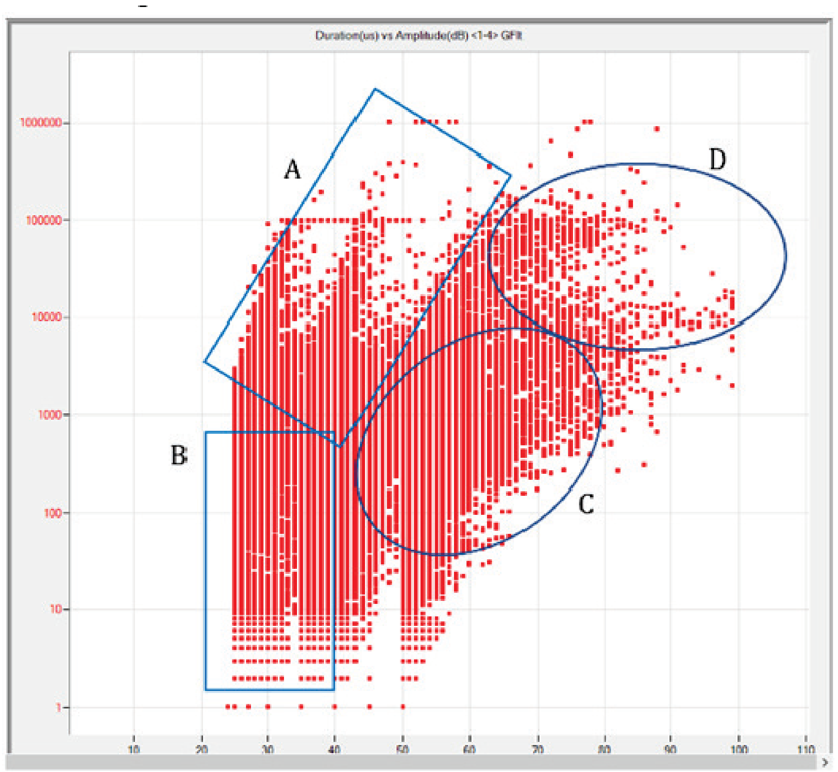
Acoustic Emissions – Data Capturing



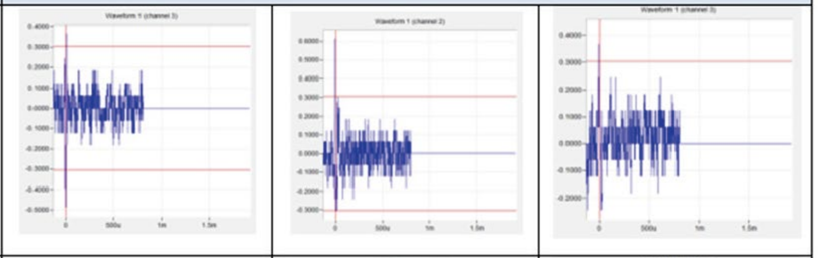
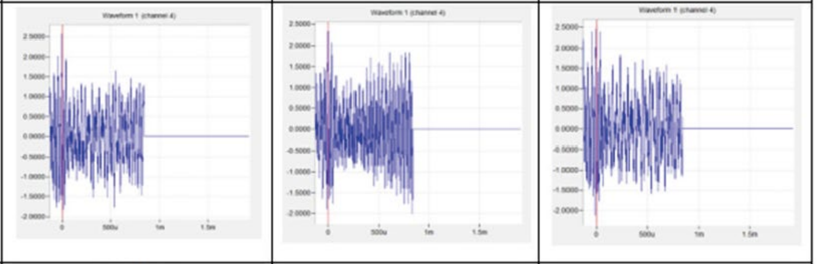
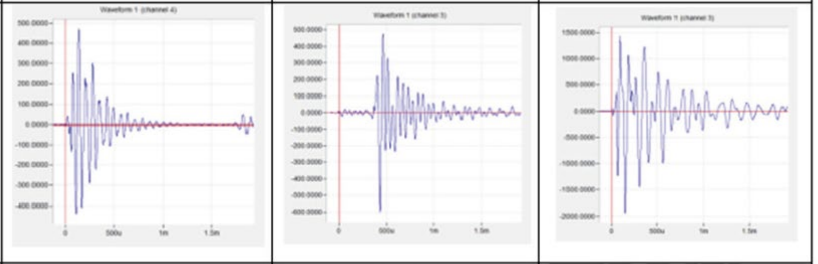
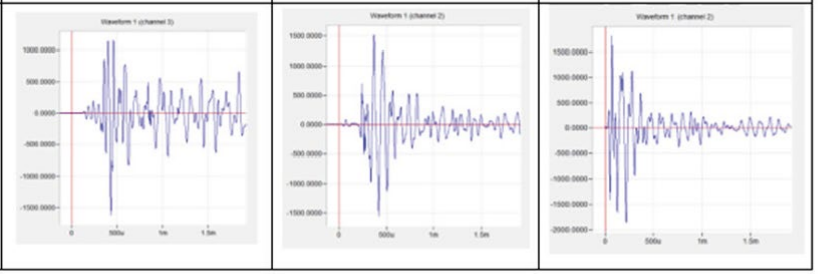
Region	Typical waveform
A	
B	
C	
D	

Figure Sensors installed on the sample of Mixture D.

Implementation

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Visual – Photographic - Monitoring

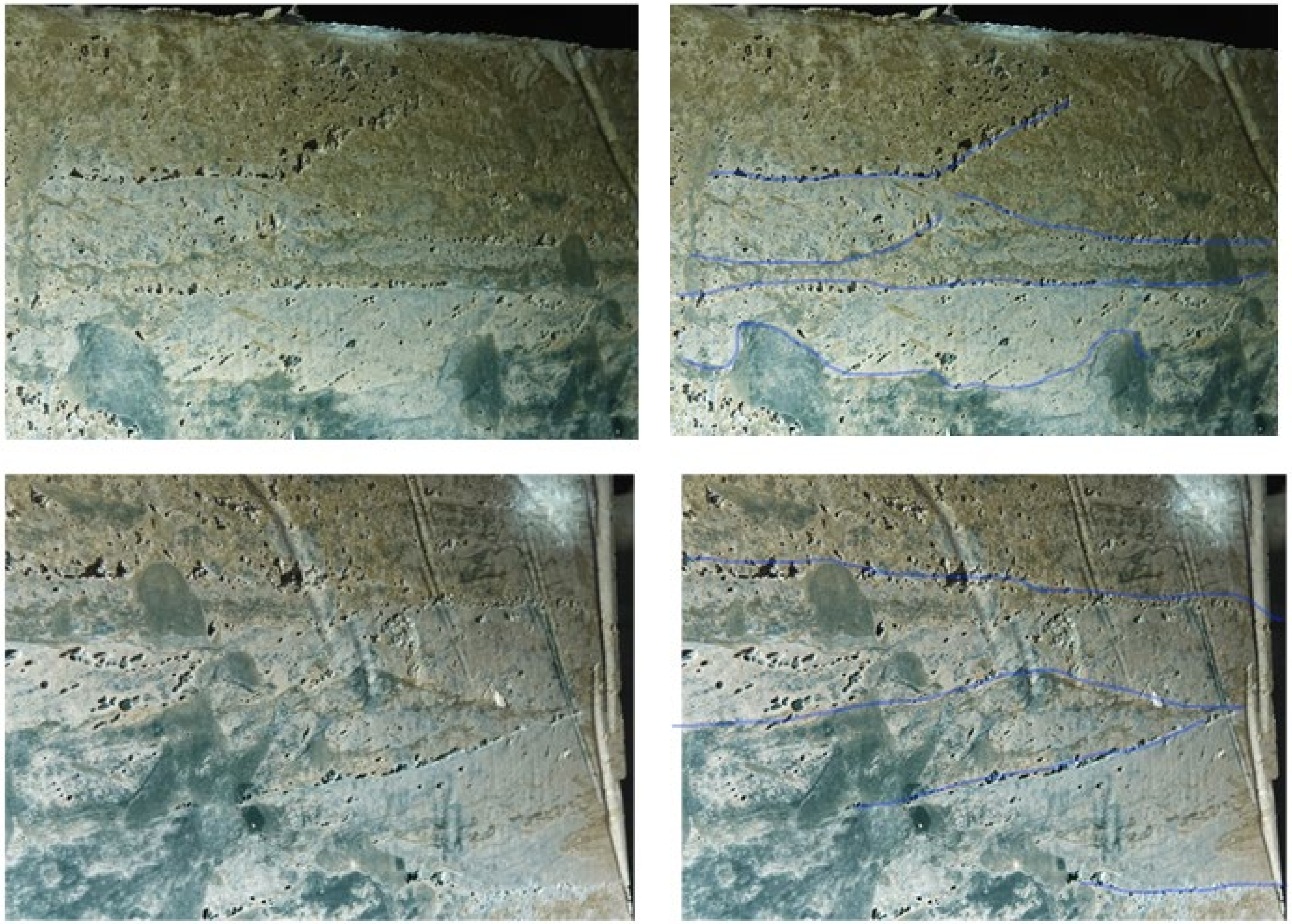


Figure | Visual inspection of samples for this project.

Implementation

What methods were used to collect the data and to do the analysis?

Timing – From Day 1 to Day 28

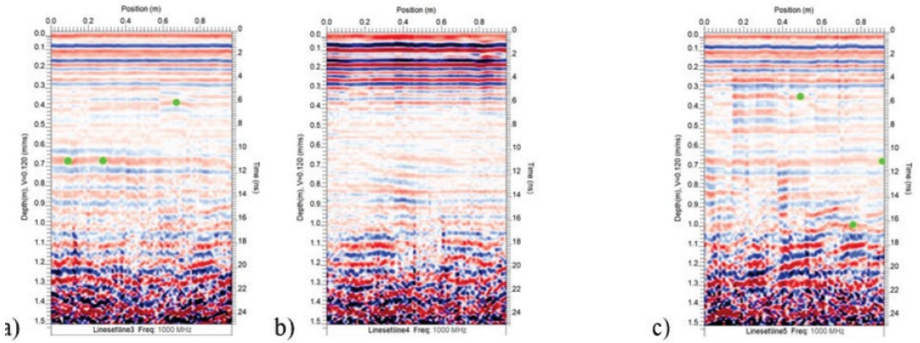
- Seal Samples - UCS Strength Testing on 7, 14, 28 Days
- Temperature Monitoring – Inserted Thermocouples
- Strain Monitoring – Inserted Strain Gauges
- Tracer Gas – Sample Collection – After Initial Setting
- Acoustic Emissions – Data Capturing – After Initial Setting
- Visual – Photographic – Monitoring with shutters removed
- Ground Penetration Radar (GPR)
- Testing and Parametric analysis.

Ground Penetration Radar (GPR)

Figure Collection of the GPR information.

Two Surveys Conducted:

1. Test, Calibration & Verification of Application.
2. Improved Methodology to Collect & Detect Macro Fractures.



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Testing & Parametric Analysis

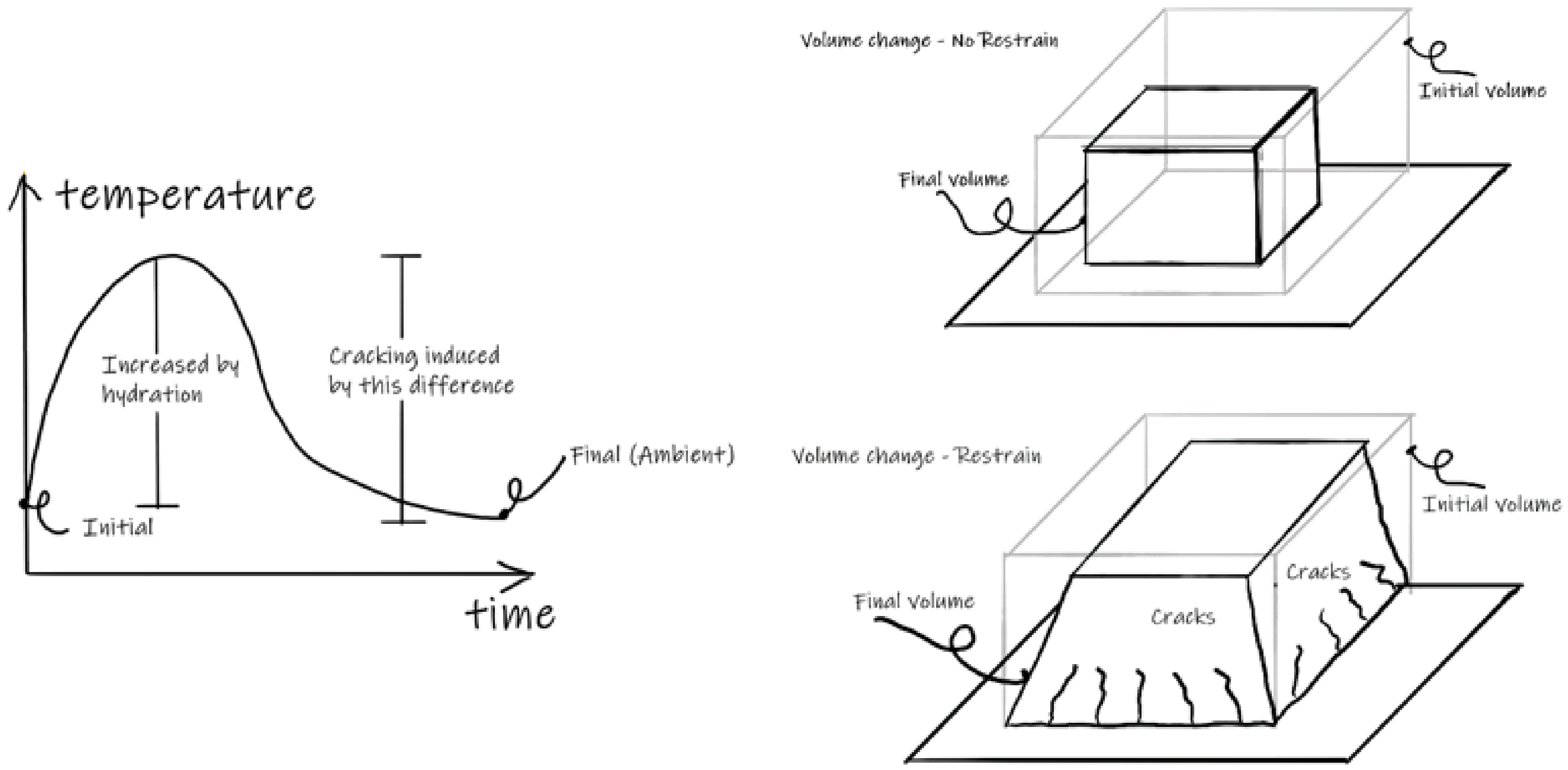
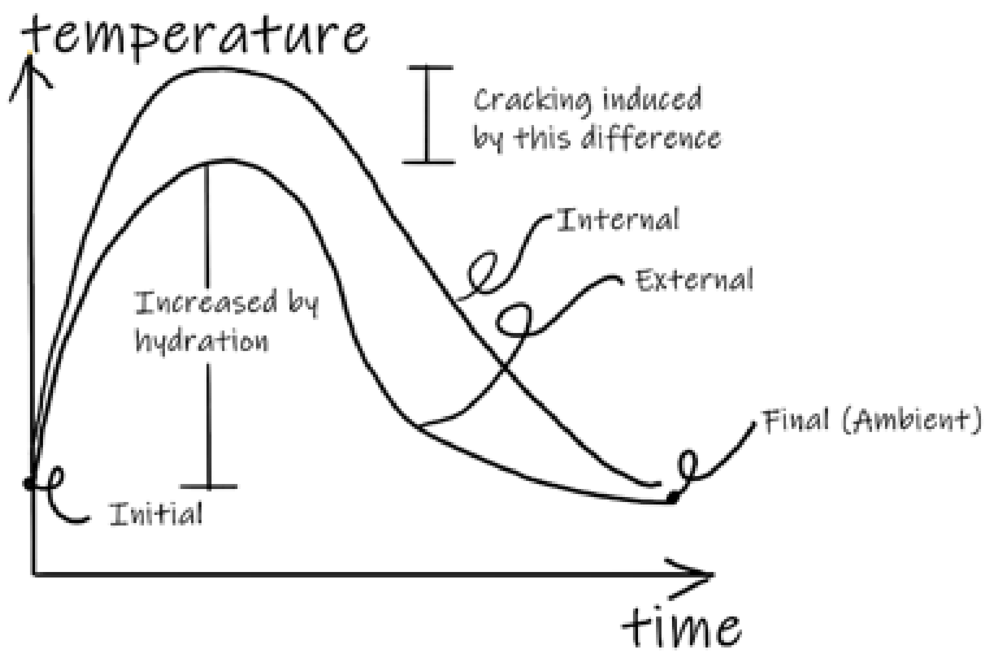


Figure Crack formation due to external restrain (Source: Adapted from reference [4])

Testing & Parametric Analysis



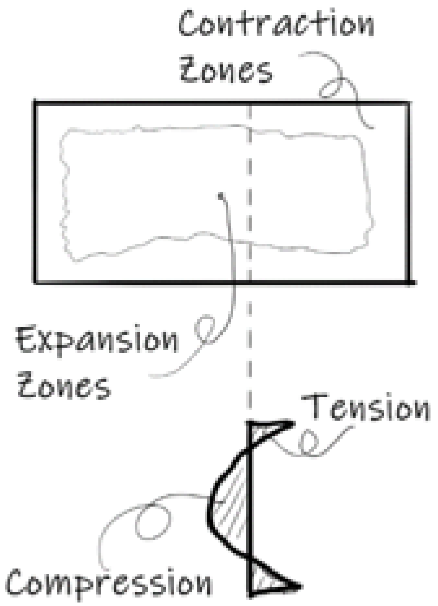
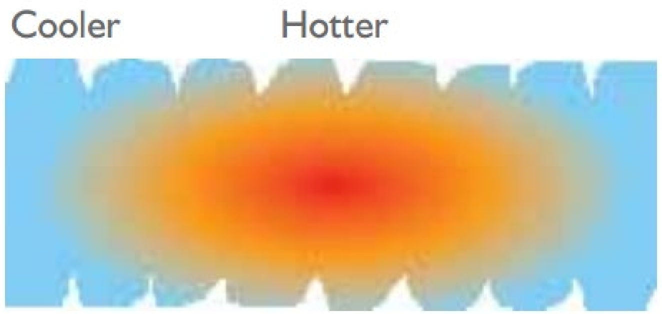


Figure Crack formation due to internal restrain (Source: Adapted from reference [4])



Testing & Parametric Analysis

$$I_{cr}(t) = \frac{f_{sp}(t)}{f_t(t)}$$

Eq. 2

Where:

$I_{cr}(t)$ =Crack index due to internal restrain at time t,

$f_{sp}(t)$ =tensile strength of the concrete at time t

$f_t(t)$ =maximum thermal stress at time t (can be analyzed using FEM)

Figure 3.19 shows the relationship between the probability of crack growth (occurrence) and the crack index.

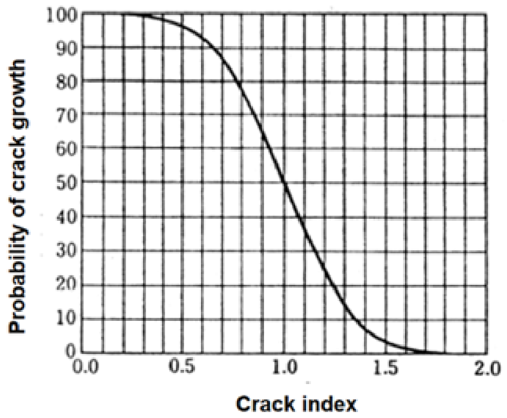


Figure Crack index and probability of crack growth (occurrence) (Source: Adapted from reference [11])

$$I_{crs}(i) = \frac{25}{\Delta T_{i-peak}}$$

Eq. 5

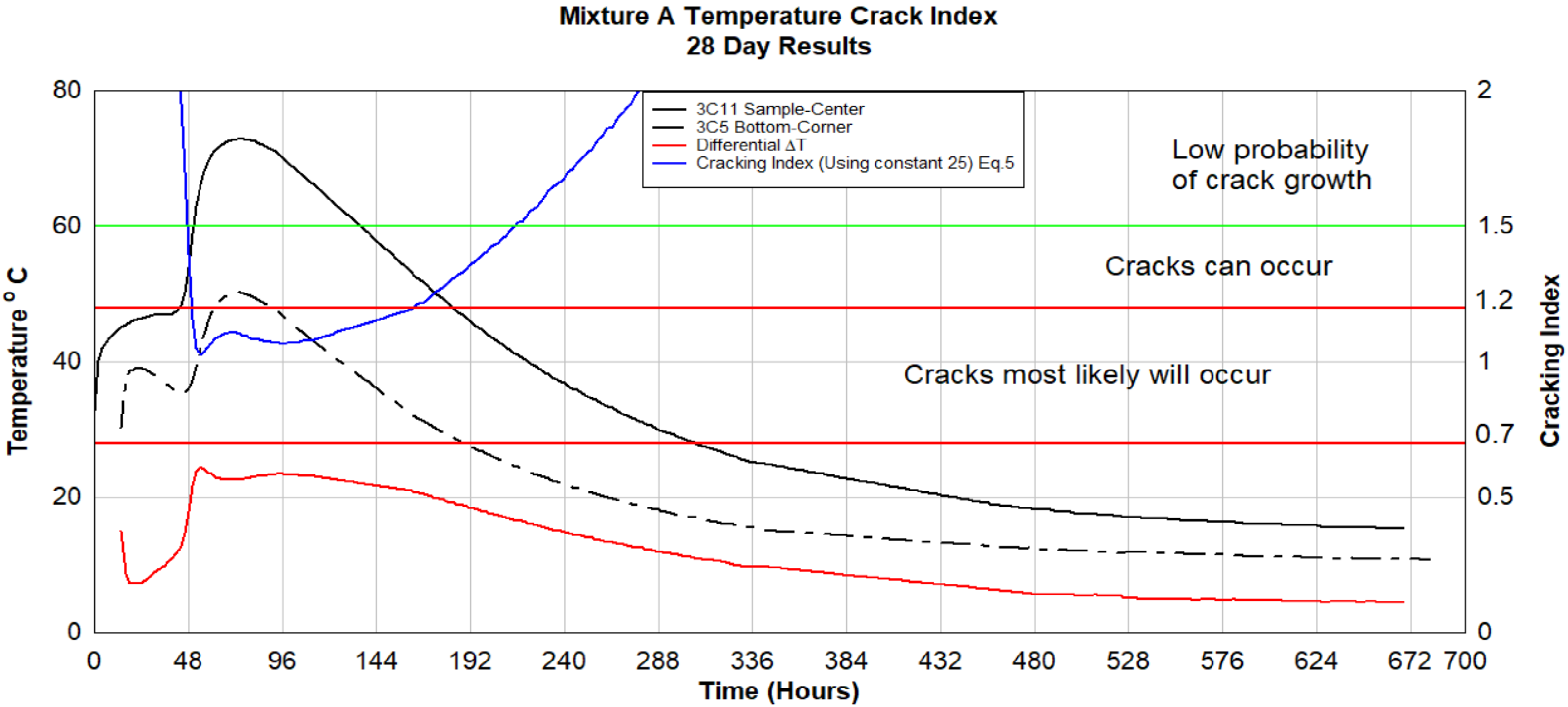
ΔT_{i-peak}= peak temperatures and hypo-elastic model

Using the crack index, the concrete engineer has a guideline to actions to be taken regarding cracking due to internal restrain. The actions are in the following table.

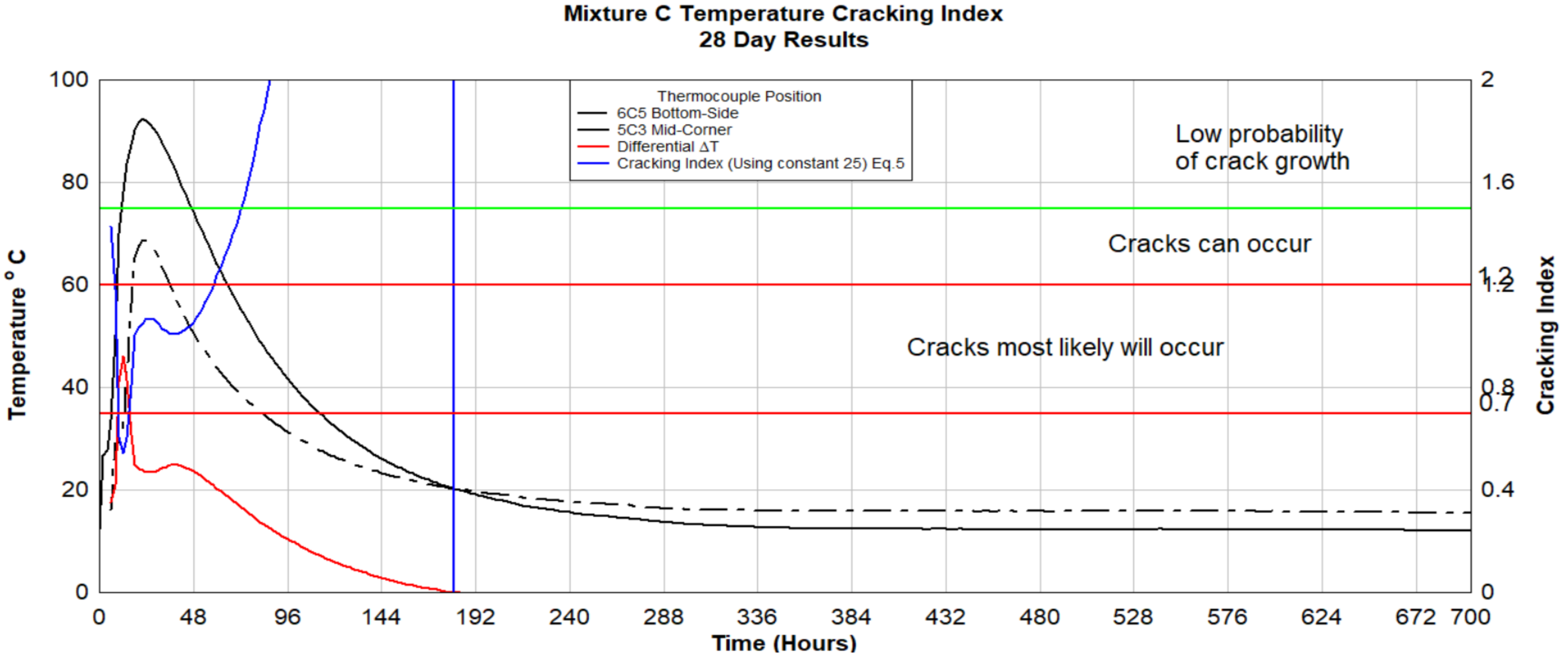
Table Thermal (internal restrain) crack criteria.

Action	Intervals
Cracks have a low probability of growth (no action)	$I_{cr} \geq 1.5$
Cracks can occur, and actions are required to limit the growth	$1.2 \leq I_{cr} < 1.5$
Cracks most likely will appear and actions are required to avoid harmful cracking	$0.7 \leq I_{cr} < 1.2$

Testing & Parametric Analysis



Testing & Parametric Analysis



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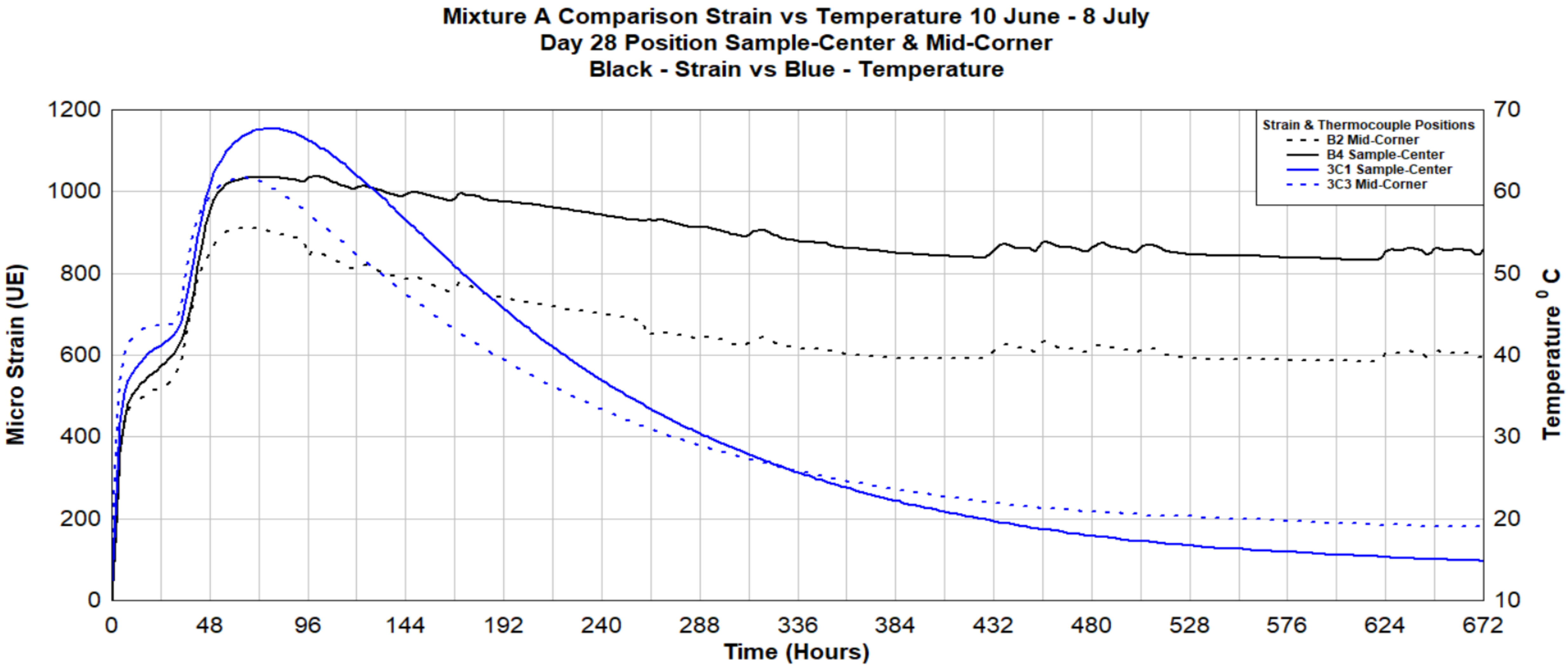
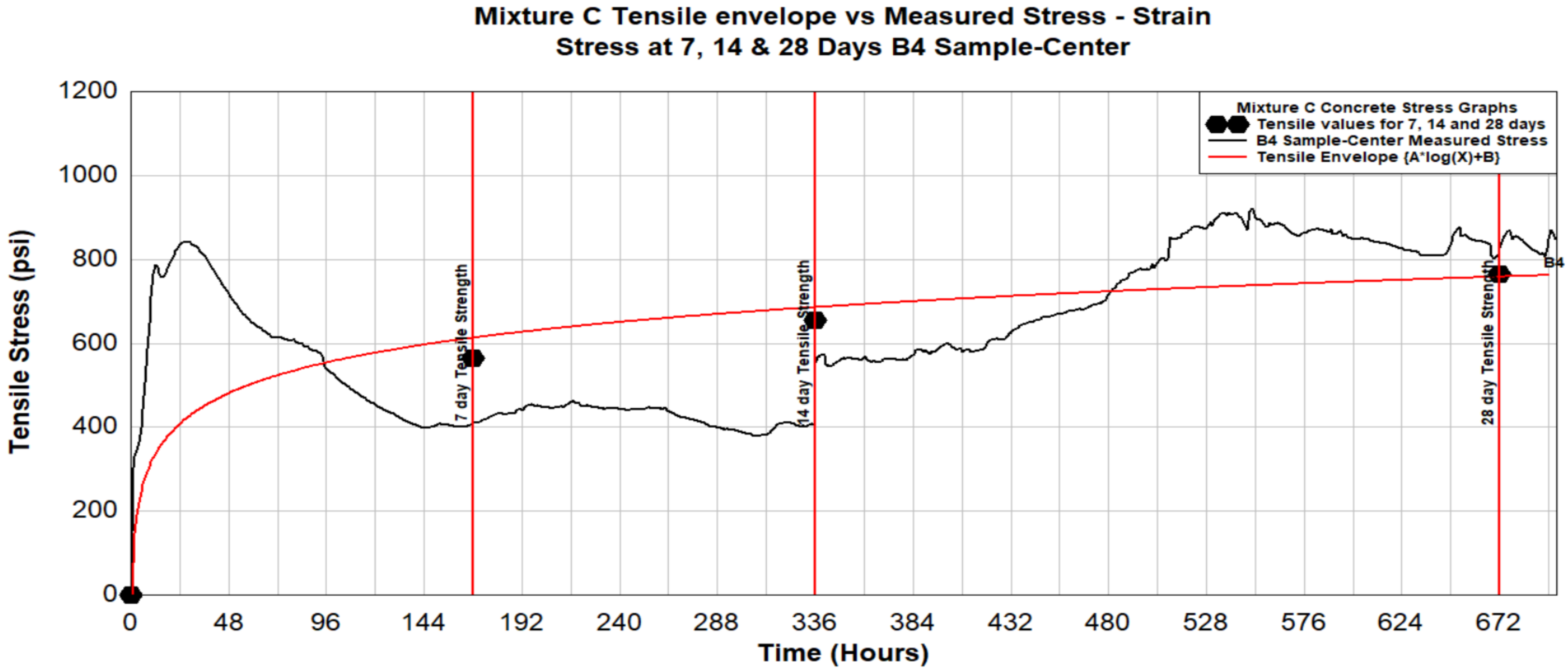


Testing & Parametric Analysis



Conclusion

- **To understand** the forming of micro and macro cracks, and the implications of these cracks, **the properties and behavior of concrete from the early stages**, under different conditions, from mixing to pouring to final curing **needs to be understood**.
- **Understanding your scope, application, constraints, and timing** related to the concrete product and outcome you require, will assist you, in making the right **decisions upfront**.
- The **curing** process of **cementitious materials** is a **complex phenomenon** given the chemical, physicochemical, and thermochemical reactions taking place in the solidification of a substance that initially is a fluid. This phenomenon is known as **hydration**.
- Every **cementitious material** has its **own hydration process**. In other words, the **heat evolution, and the probability of cracking changes between mixtures**, even for mixtures using the same material proportions.

Conclusion

- If the **proportions and standard procedures** developed by the company's providing materials for mine seals are followed, there is a **low probability** of having problems with the seals during the curing stage and there were **no evidence of macro cracks in any of the lab samples tested.**
- The **importance** of the **constructability**, **behavior**, and **quality control** during the **initial pouring and curing** of these seals was clearly demonstrated looking at **different behaviors** in **strength**, **temperature** and **strains** for similar mixtures and different mixtures, as well as similar and different construction methods. This is highlighted as a major factor that may affect the integrity and the performance of these seals at the early stages but also their life-time cycle when in use.
- Even though **no physical** and **clear micro** and or **macro cracks** were **visible** the **integrity** and **maintenance** of the seal's performance remain in question purely on what cannot be seen and if micro fractures exist which can lead to macro fractures in months and years to come. These micro fractures might remain in an invisible form which ultimately will only be effective if the seal sample can be tested to destruction, either introduced or during an explosion.

Acknowledgement:

Dr. Jhon Silva	University of Kentucky
Dr. Zach Agioutantis	University of Kentucky
Dr. Josh Calnan	University of Kentucky
Dr. Nino Ripepi	Virginia Tech
Cary Harwood	Virginia Tech
Dr. John Hole	Virginia Tech
Luis Velasquez	University of Kentucky
Dr Steve Tadolini	Minova USA Inc
Mike Fabio	Strata Worldwide

Thank You

Explosives Research Team

Questions?

Explosives Research Team