Section 1
Overview of the Unsuppressed and Suppressed Multiple Fuel Fire Tests with Verdagent (MFF Test)
Boeing MPS Chamber April and May 2023

Rachel Darr and Wes Quigley

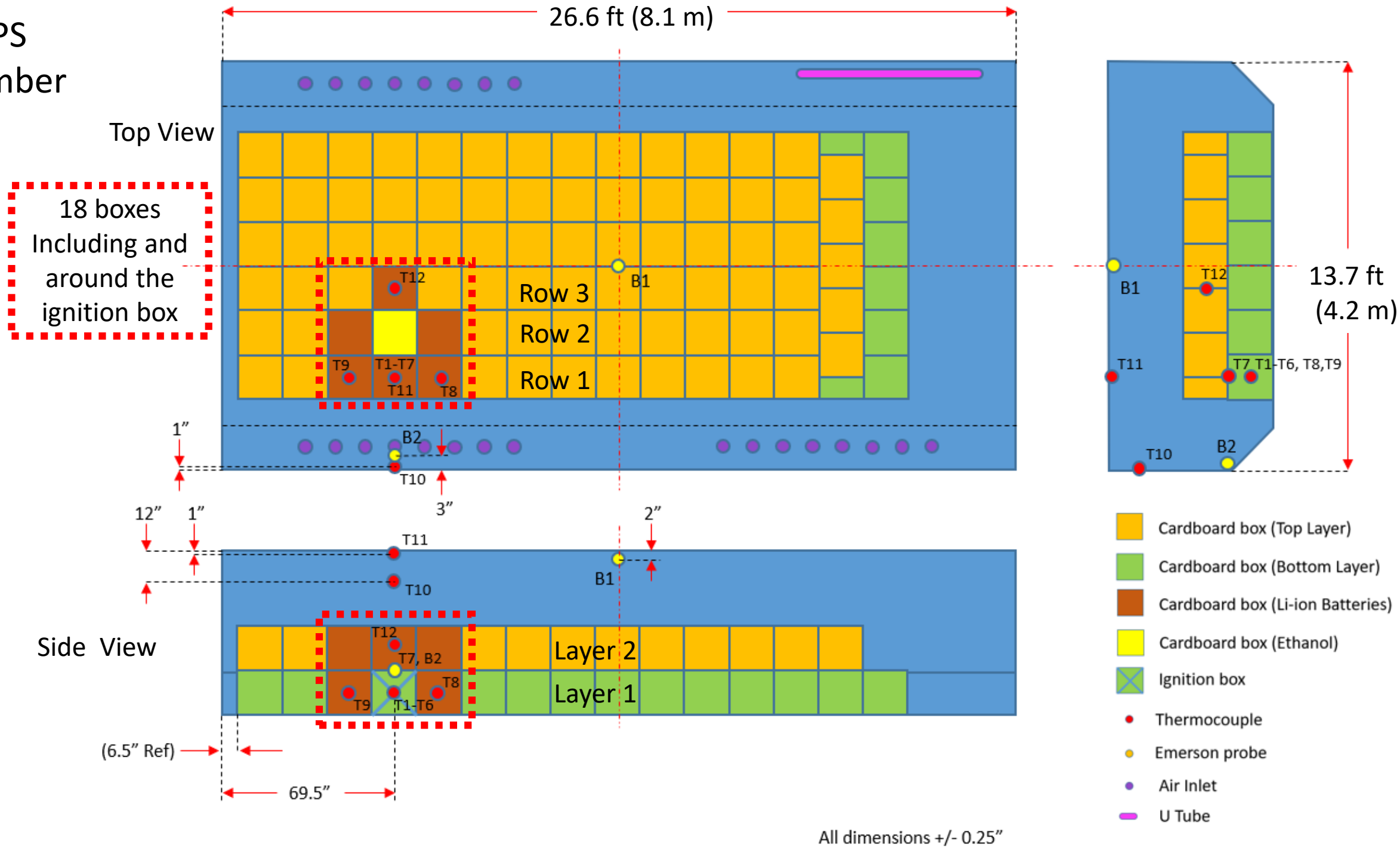
Team:

George McEachen, Pat Baker, David Shaw

Nick Mavriplis, Prash Bhat, Allison Horney, Oscar Lezcano

Nels Olson and Ryan Wilson

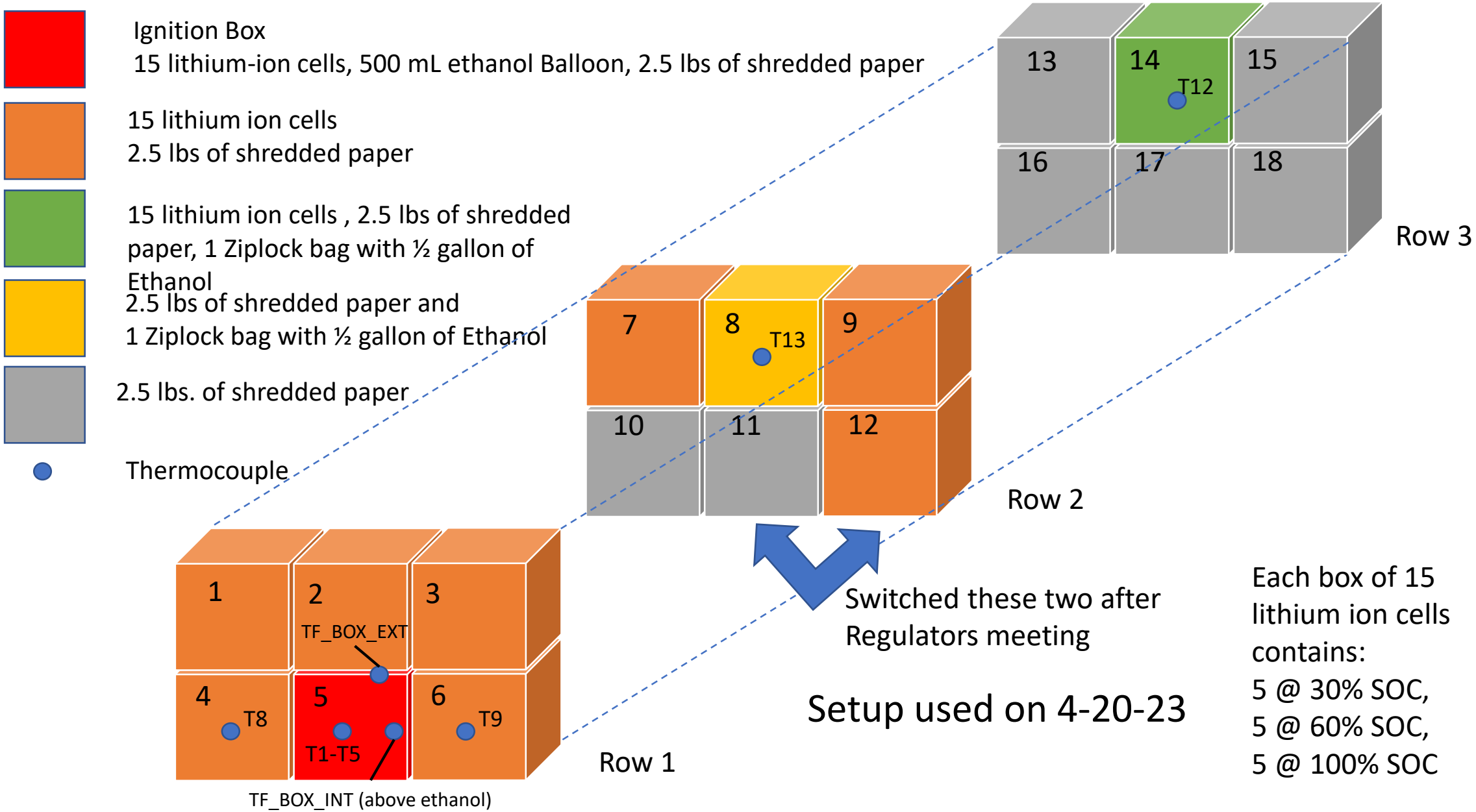
MPS Chamber



All dimensions +/- 0.25”

18 boxes

Including and around the ignition box



Ignition Box
15 lithium-ion cells, 500 mL ethanol Balloon, 2.5 lbs of shredded paper

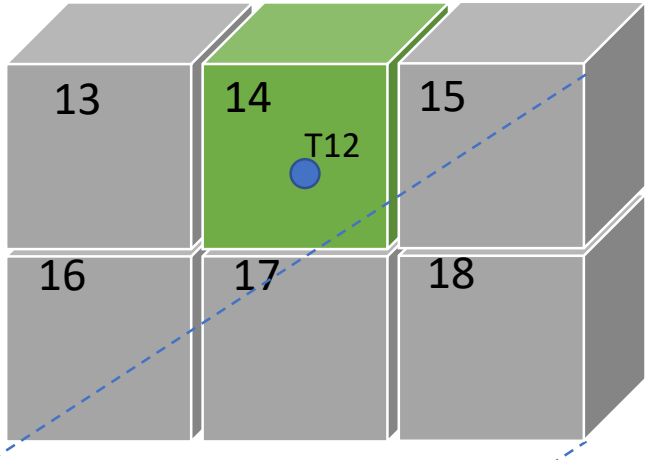
15 lithium ion cells
2.5 lbs of shredded paper

15 lithium ion cells , 2.5 lbs of shredded paper,
1 Ziplock bag with ½ gallon of Ethanol

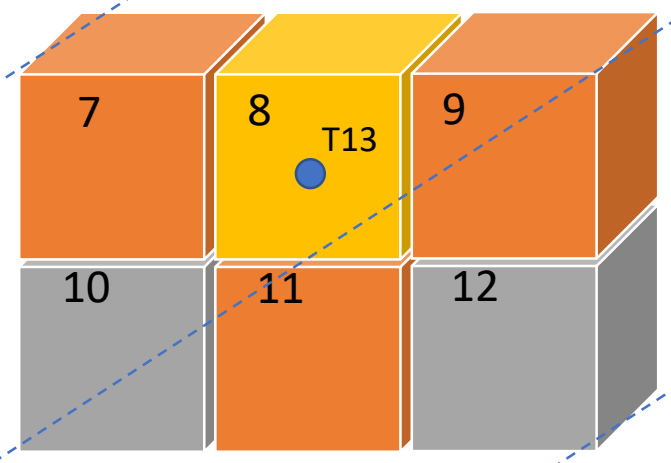
2.5 lbs of shredded paper and
1 Ziplock bag with ½ gallon of Ethanol

2.5 lbs. of shredded paper

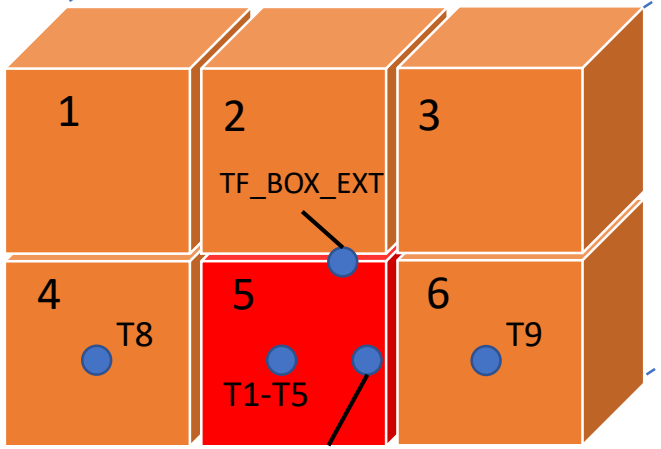
Thermocouple



Row 3



Row 2



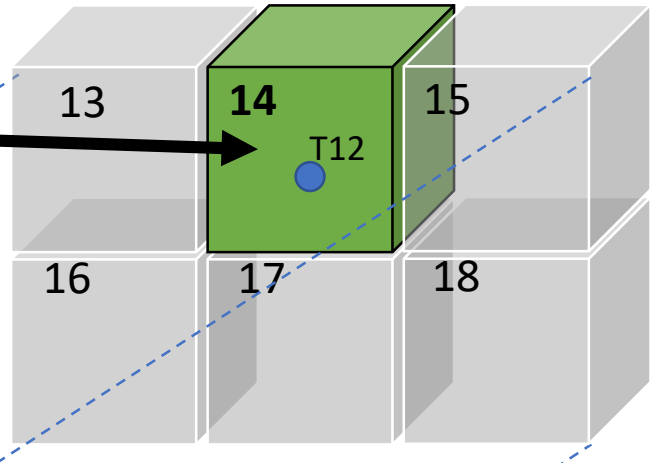
TF_BOX_INT (above ethanol)

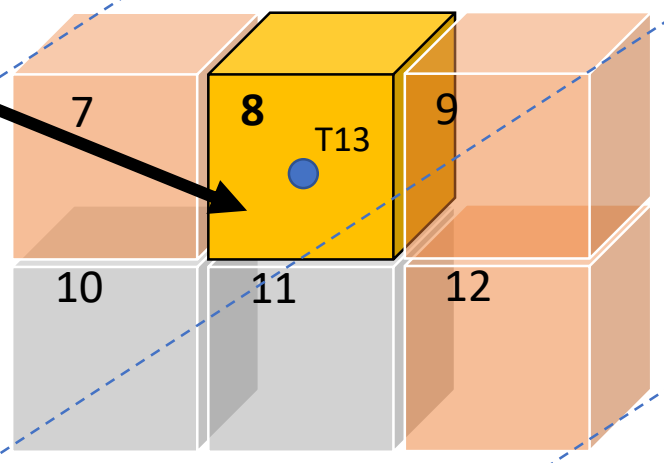
Row 1

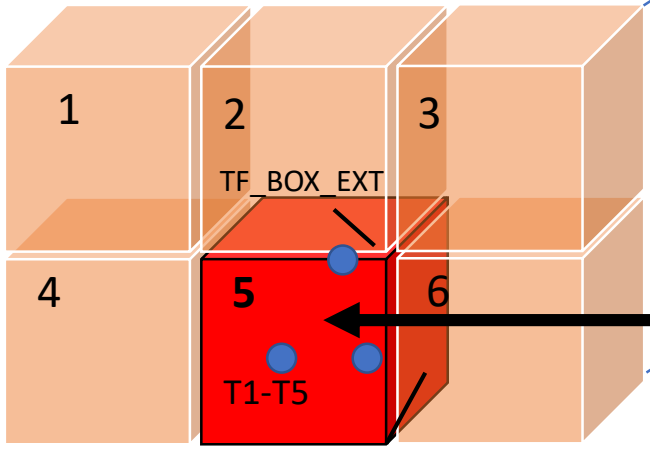
New Test
Approved by regulators
5-2-23

Each box of 15 lithium ion cells contains:
5 @ 30% SOC,
5 @ 60% SOC,
5 @ 100% SOC

½ gallon Ethanol in
12” x 12” bag







TF_BOX_INT (above ethanol)

½ liter Ethanol bag w/
7 ft Nichrome wire

High Level Results – Unsuppressed Multiple Fuel Fire 04-20-2023

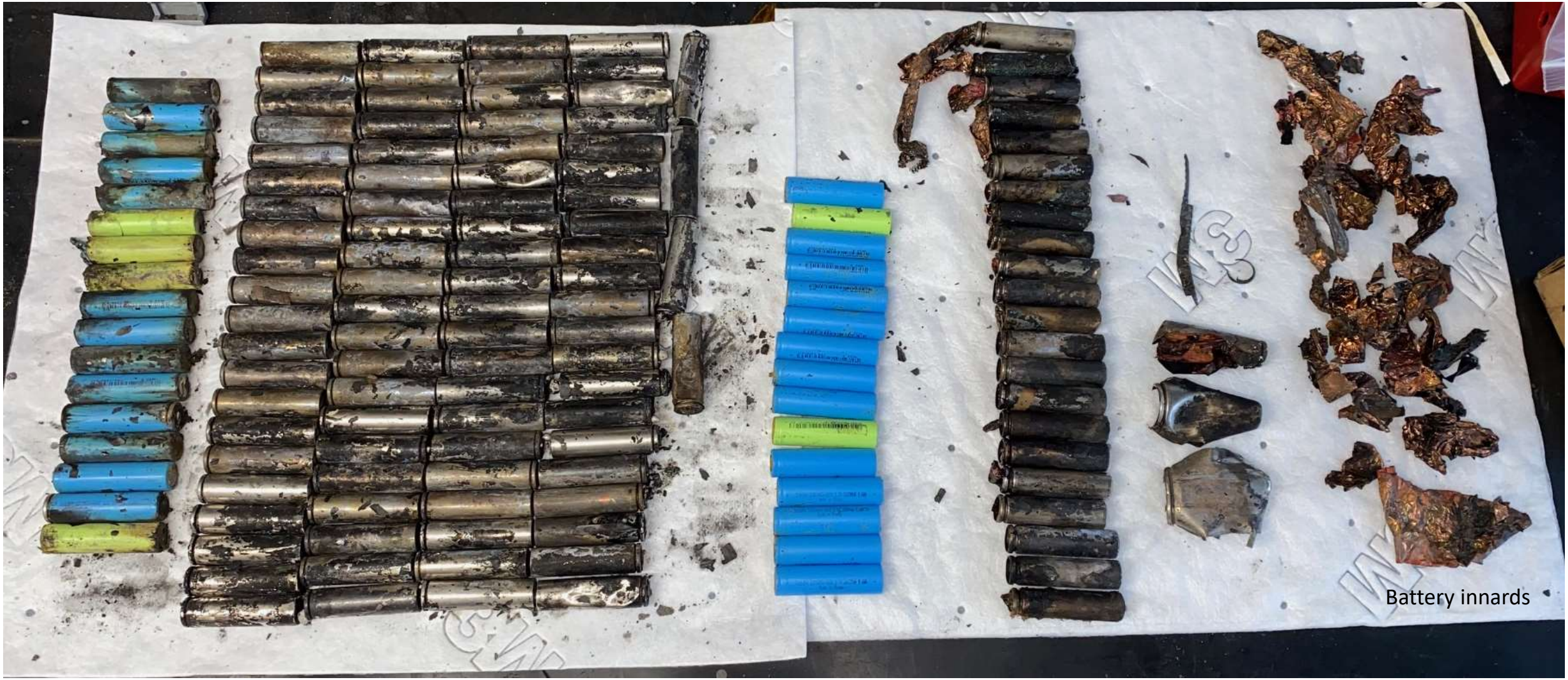
- ~22 equivalent full boxes were involved in the fire.
- Many only partly burnt – fire mostly spread by the bottom boxes
- Boxes 2, 5 were entirely consumed and reduced to ash
  - Battery cells in the area of the ignition box were all fully involved and had vented
- Box 8 (ethanol bag box) was entirely consumed, unable to find bag after test
- Box 14 was largely untouched, both the ethanol bag and box of batteries were intact
  - Bag of ethanol was leaking after test, paper inside appeared wetted

High Level Results – Unsuppressed Multiple Fuel compared to other Tests:

- ~22 equivalent full boxes were involved in the fire.
  - Verdagent suppressed MFF burned ~13 boxes
  - Unsuppressed Bulk Load burned ~18

Note:
Exposed to water after the test

Cleanup– Unsuppressed Multiple Fuel Fire 04-20-2023

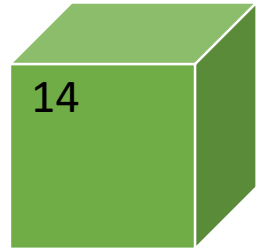


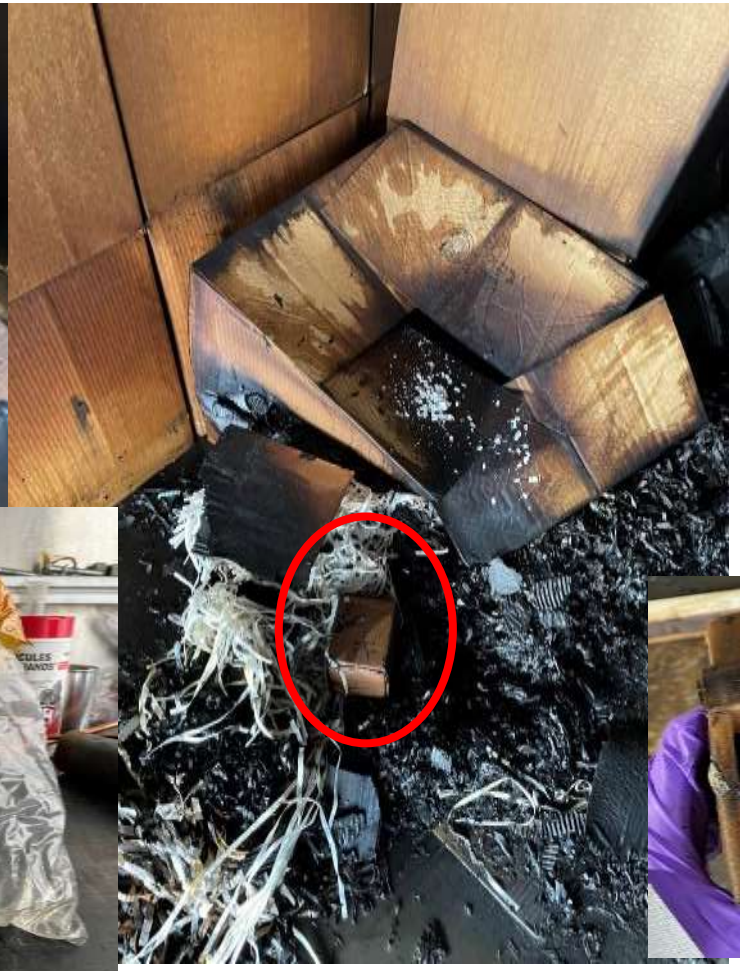
17	**88**	**15**	**22***	**3***	**145 Recovered / 150 total *5 missing**
Lightly burned, Full mass	Moderately burned, Mostly to partially full mass	Unburnt in Box 14	Burnt, Mostly to fully empty, no tops	Exploded battery casings	

*Note that 22+3+5 = 30 batteries (2 boxes)

Box 14

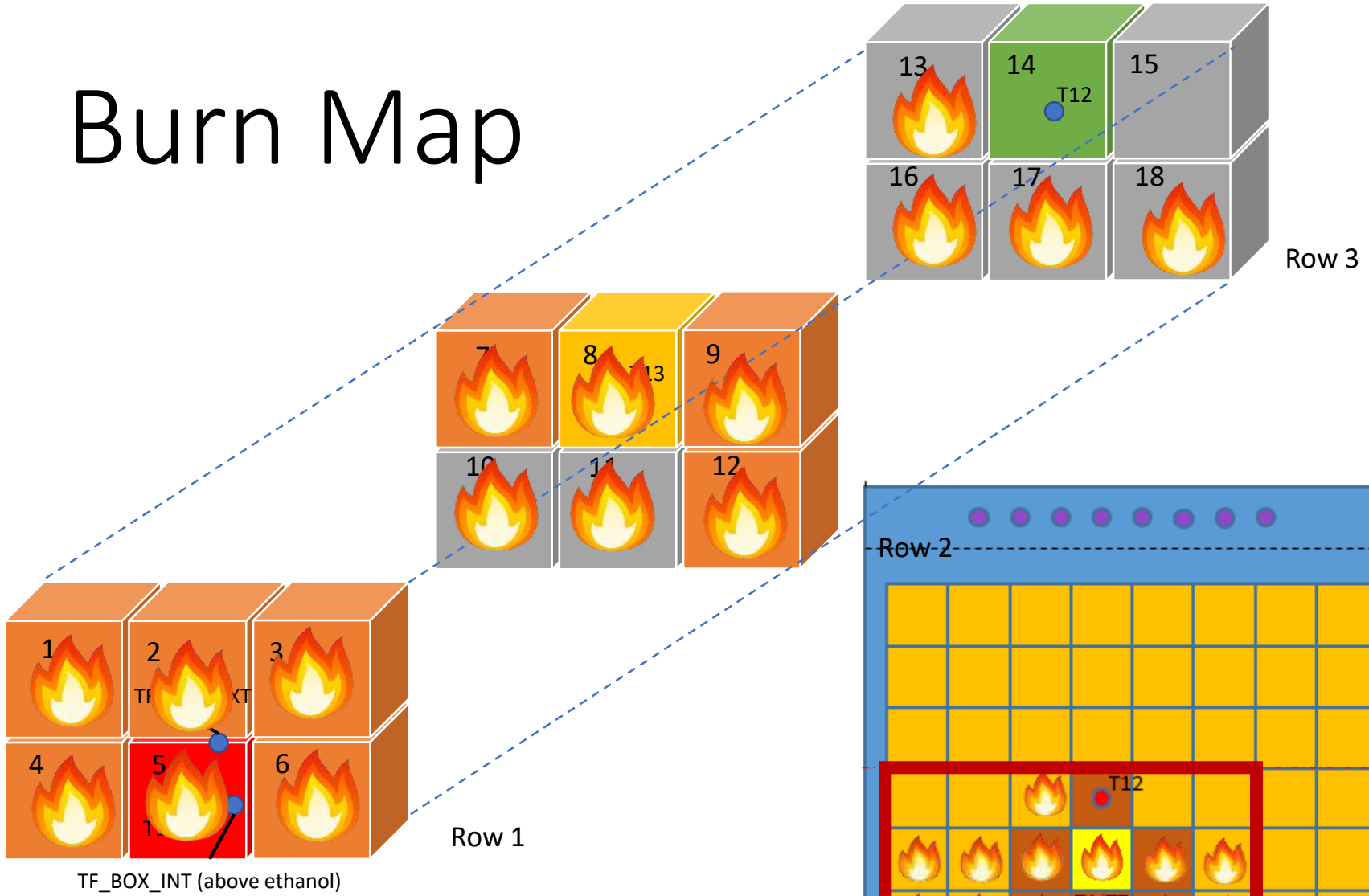
- Data reports extremely high temperatures (1400 F) but the box, batteries, and ethanol bag are un-burnt.
- T12 was placed inside the box of batteries, inside box 14

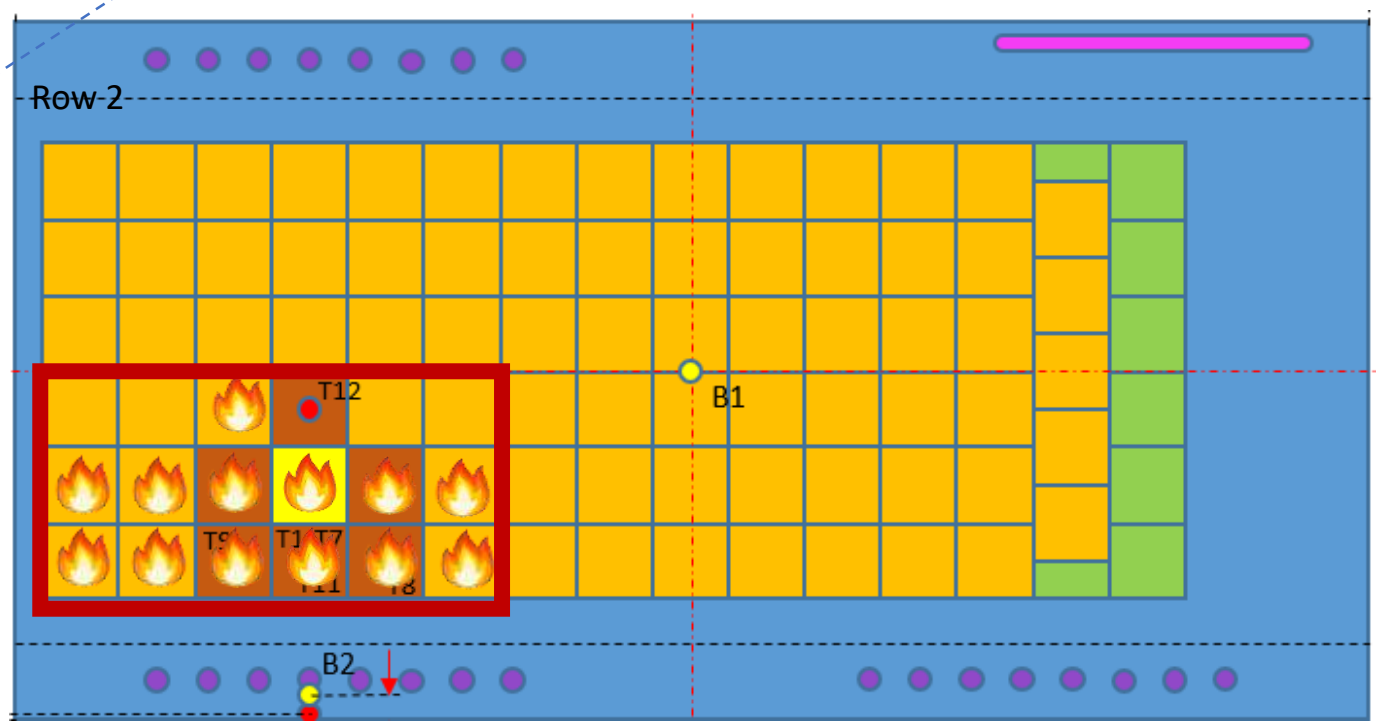




15 lithium ion cells , 2.5 lbs of shredded paper, 1 Ziplock bag with ½ gallon of Ethanol

Burn Map





= totally to mostly burned

36 boxes removed – all affected by the fire (fully burned to only a corner burned)

Boeing MPS Team:

George McEachen, Pat Baker, David Shaw, Noel Spurlock, Nick Mavriplis

Prash Bhat, Rachel Darr, Allison Horney, Oscar Lezcano

Nels Olson, Ryan Wilson and Wes Quigley

Section 2:
Boeing MPS Chamber: A Comparison of Suppressed and Unsuppressed Multiple Fuel Fire and Bulk Load Fire Data

Rachel Darr and Wes Quigley

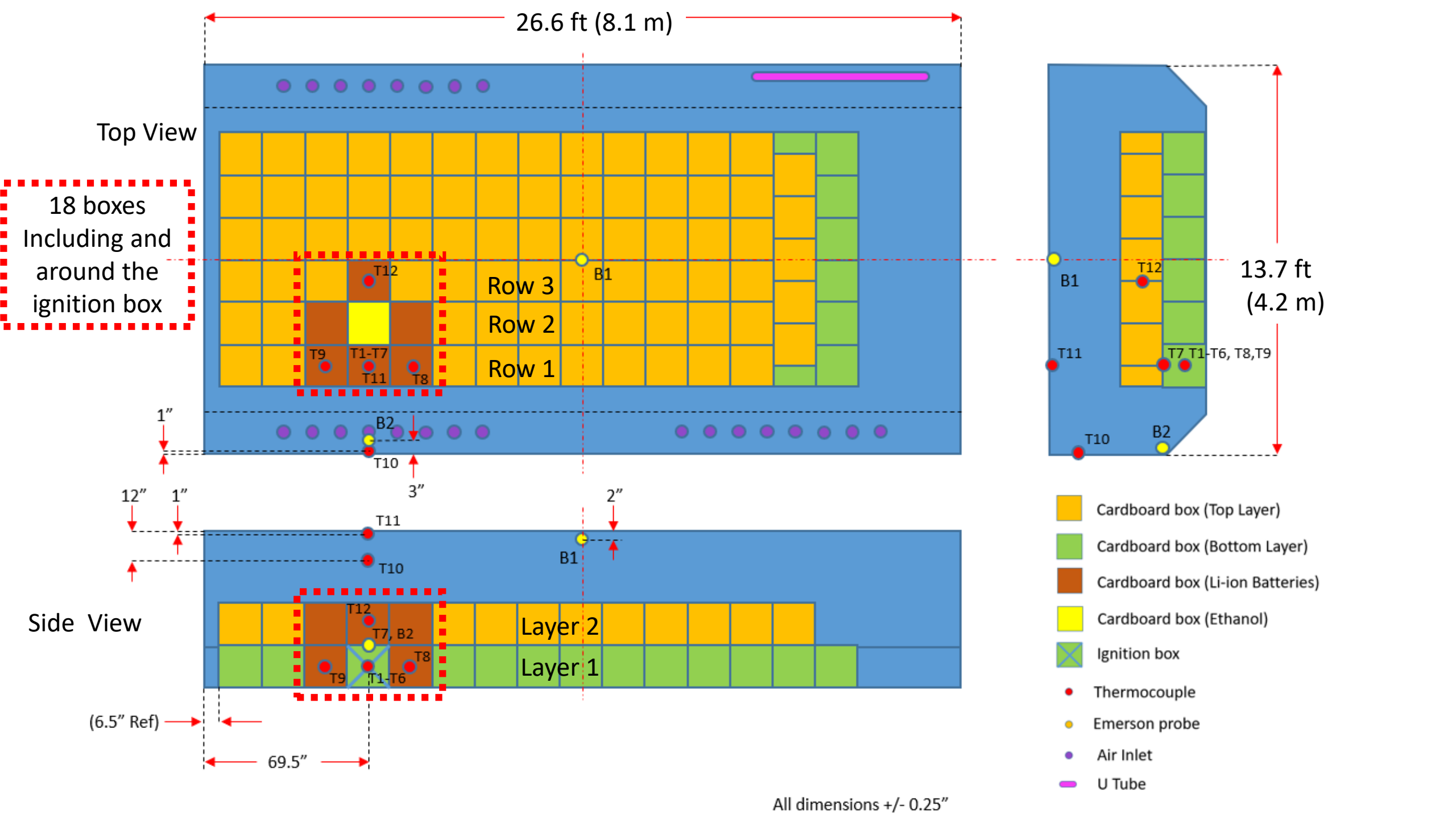
Team:

George McEachen, Pat Baker, David Shaw

Nick Mavriplis, Prash Bhat, Allison Horney, Oscar Lezcano

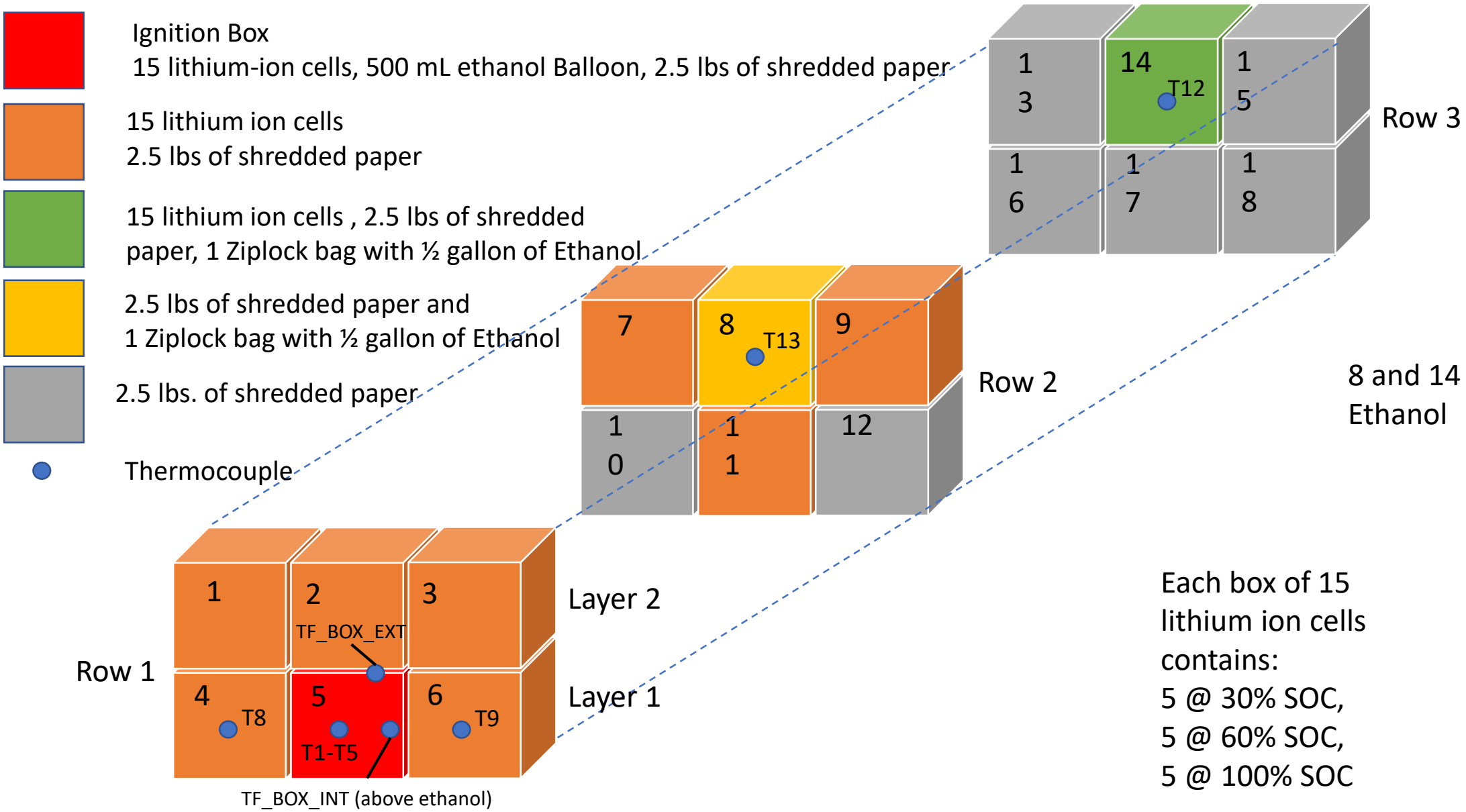
Nels Olson and Ryan Wilson

All tests performed in April 2023
Except the Unsuppressed bulk load fire which was done in June 2019

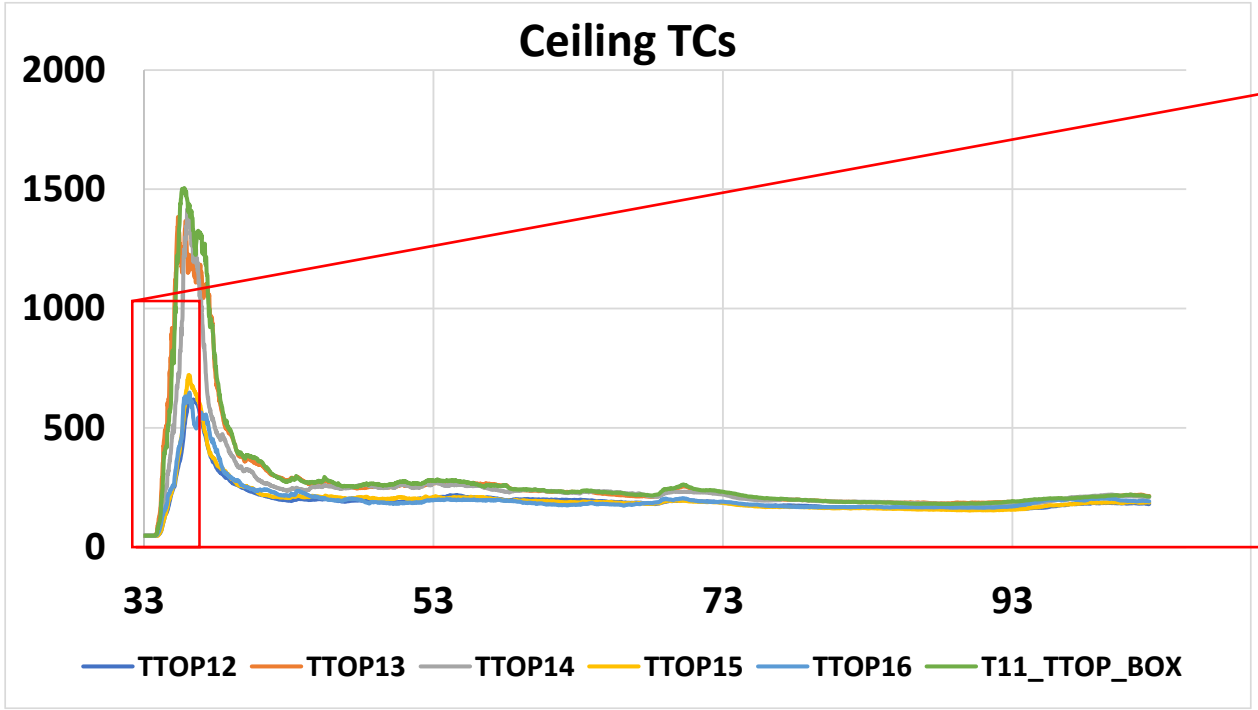

26.6 ft (8.1 m)
Top View
18 boxes
Including and
around the
ignition box
T12
T9
T1-T7
T11
T8
Row 3
Row 2
Row 1
B1
1”
B2
T10
3”
12”
1”
T11
T10
2”
B1
Side View
T12
T7, B2
T8
T9
T1-T6
Layer 2
Layer 1
(6.5” Ref)
69.5”
B1
T12
T11
T7 T1-T6, T8,T9
T10
B2
13.7 ft
(4.2 m)
Cardboard box (Top Layer)
Cardboard box (Bottom Layer)
Cardboard box (Li-ion Batteries)
Cardboard box (Ethanol)
Ignition box
Thermocouple
Emerson probe
Air Inlet
U Tube
All dimensions +/- 0.25”

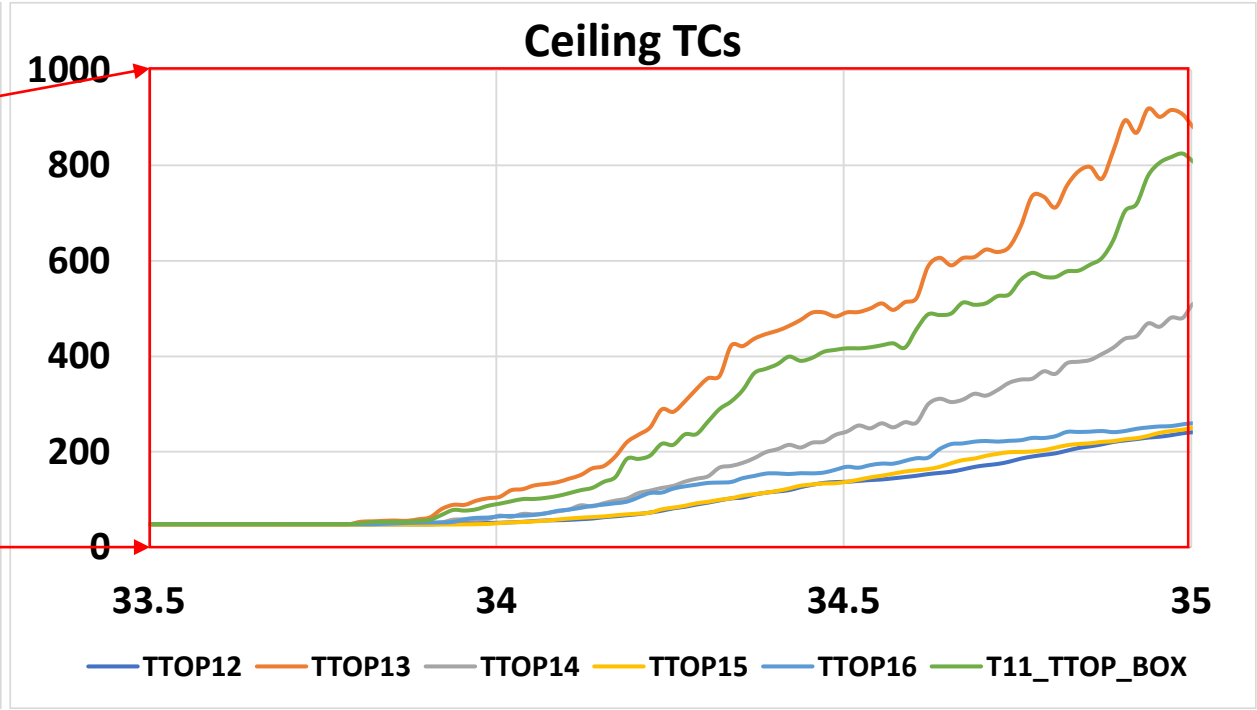
18 boxes

Including and around the ignition box



All of these tests use ceiling thermo couple (TC) data to time align the data for direct comparison



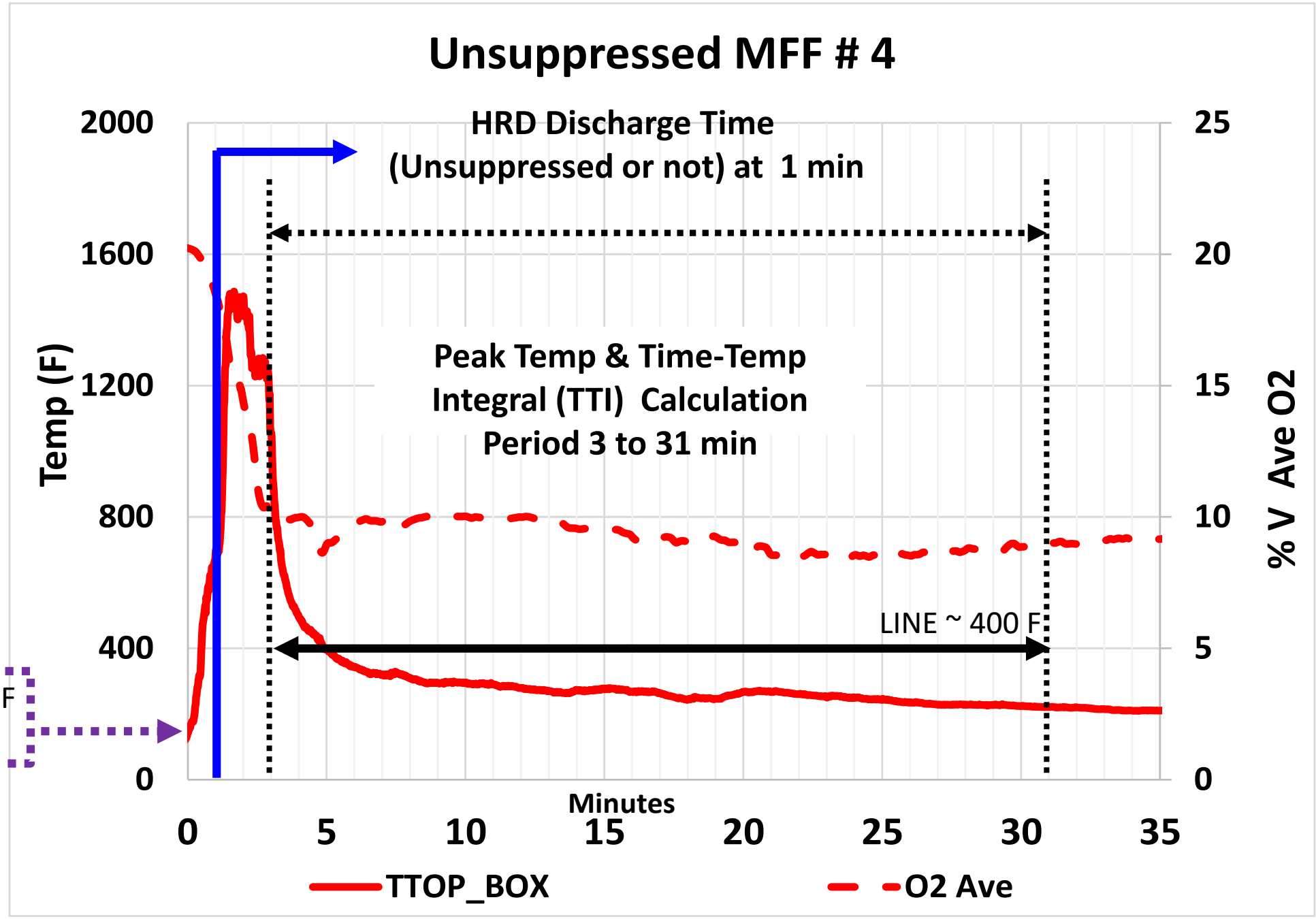


TTOP 13 reached 200 @ 34.2 min
TTOP Box reached 200 3 seconds later

Unsuppressed
MFF
5-9-23

Max Temp
1057

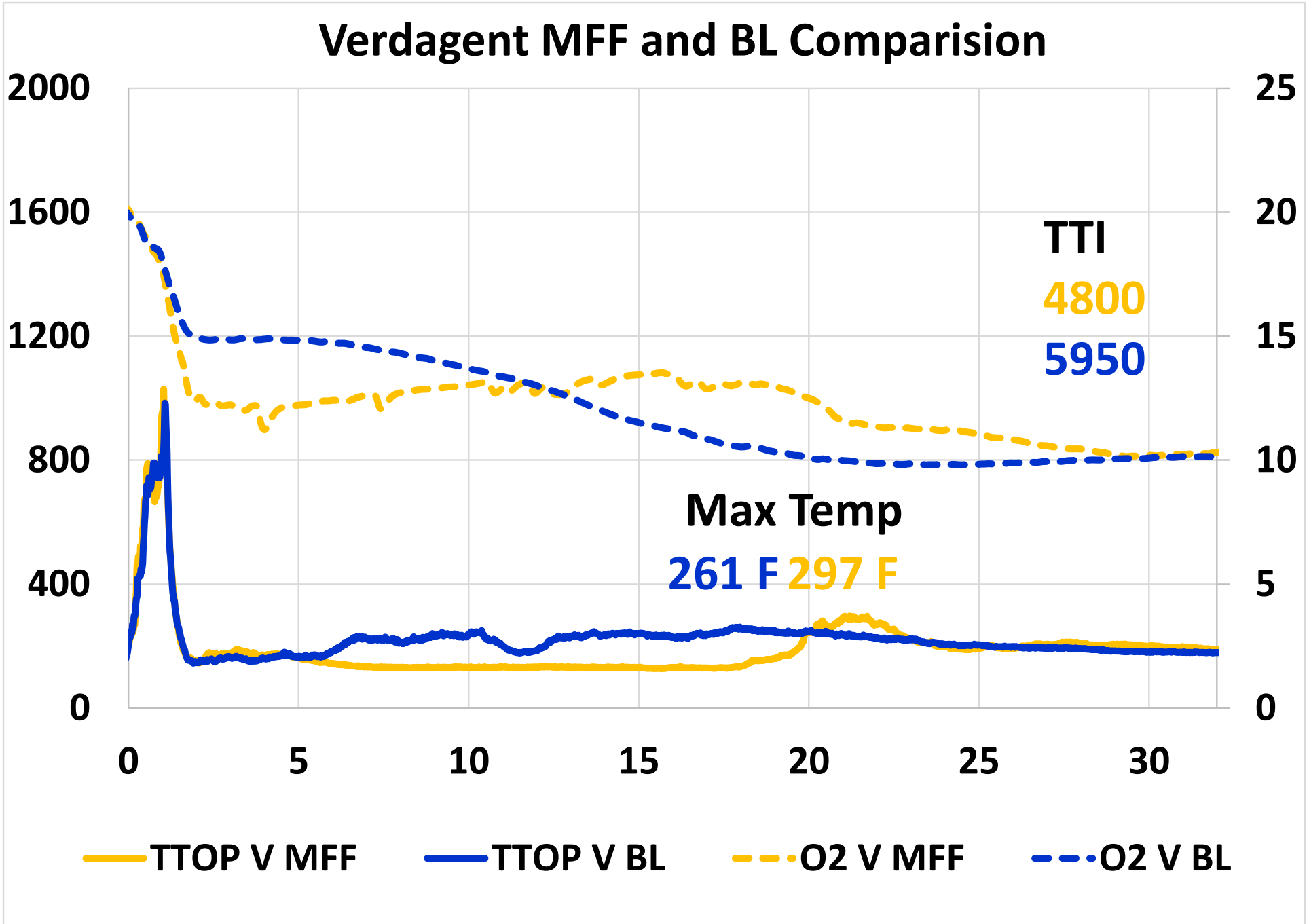
TTI
8064



First MFF Fire
(Suppressed)

Suppressed
(Verdagent)
Multiple Fuel Fire (MFF)
Bulk Load (BL)

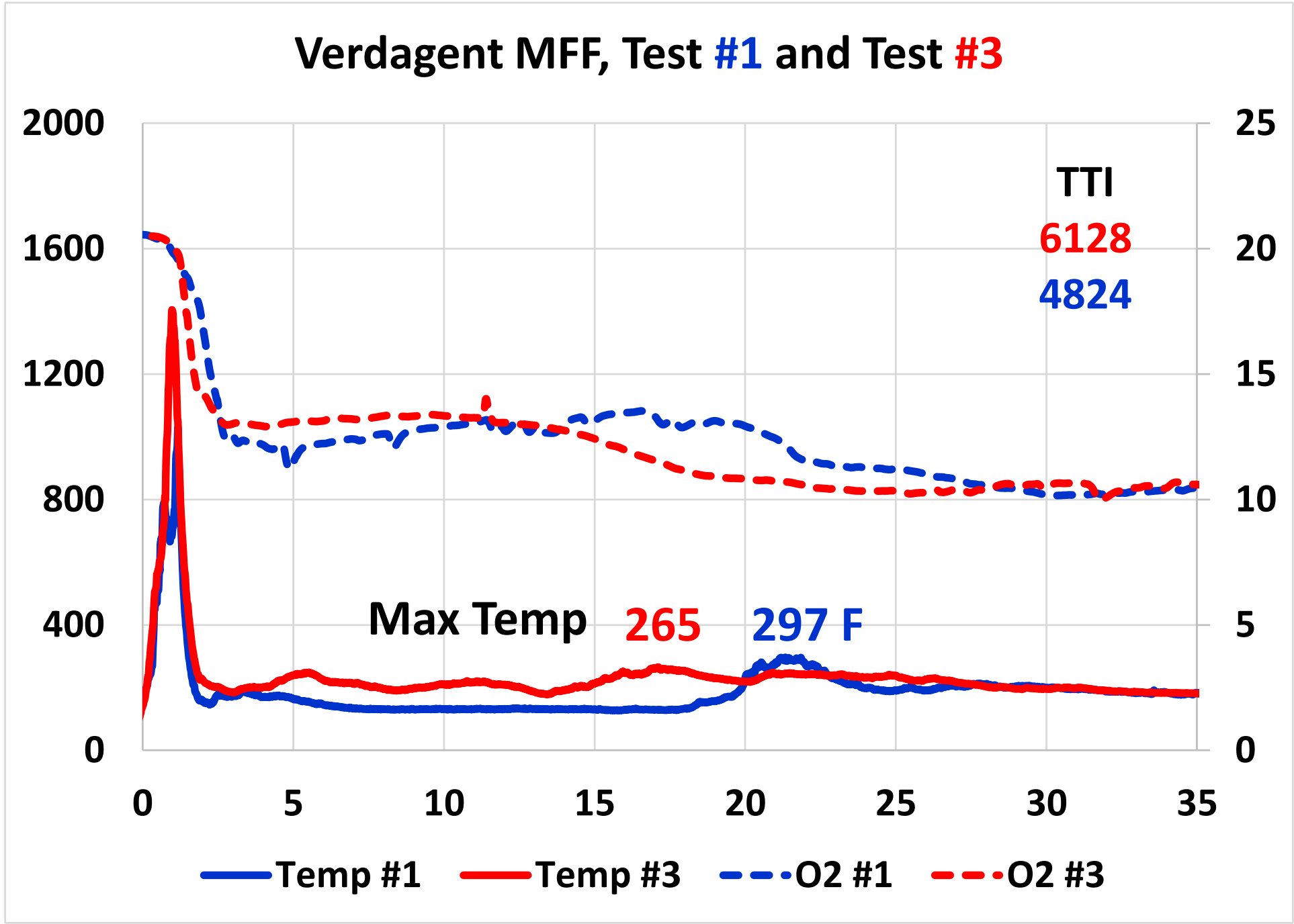
MFF # 1
IATA Boxes
8 and 14
Ethanol
Were not involved



Second MFF
Compared to First
(Suppressed)

Bags of ethanol
instead of IATA Boxes

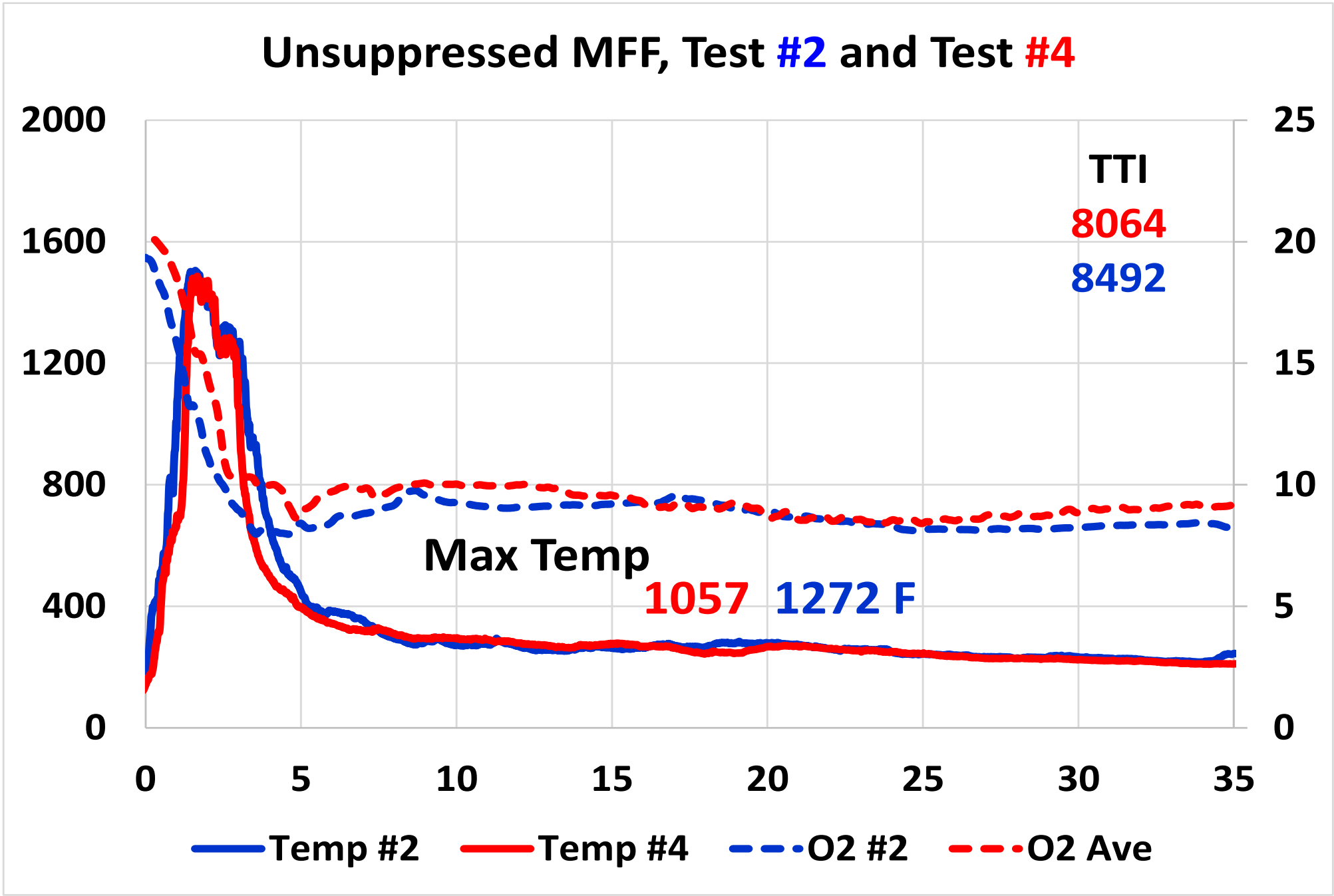
Box 8 was involved
Box 14 was not



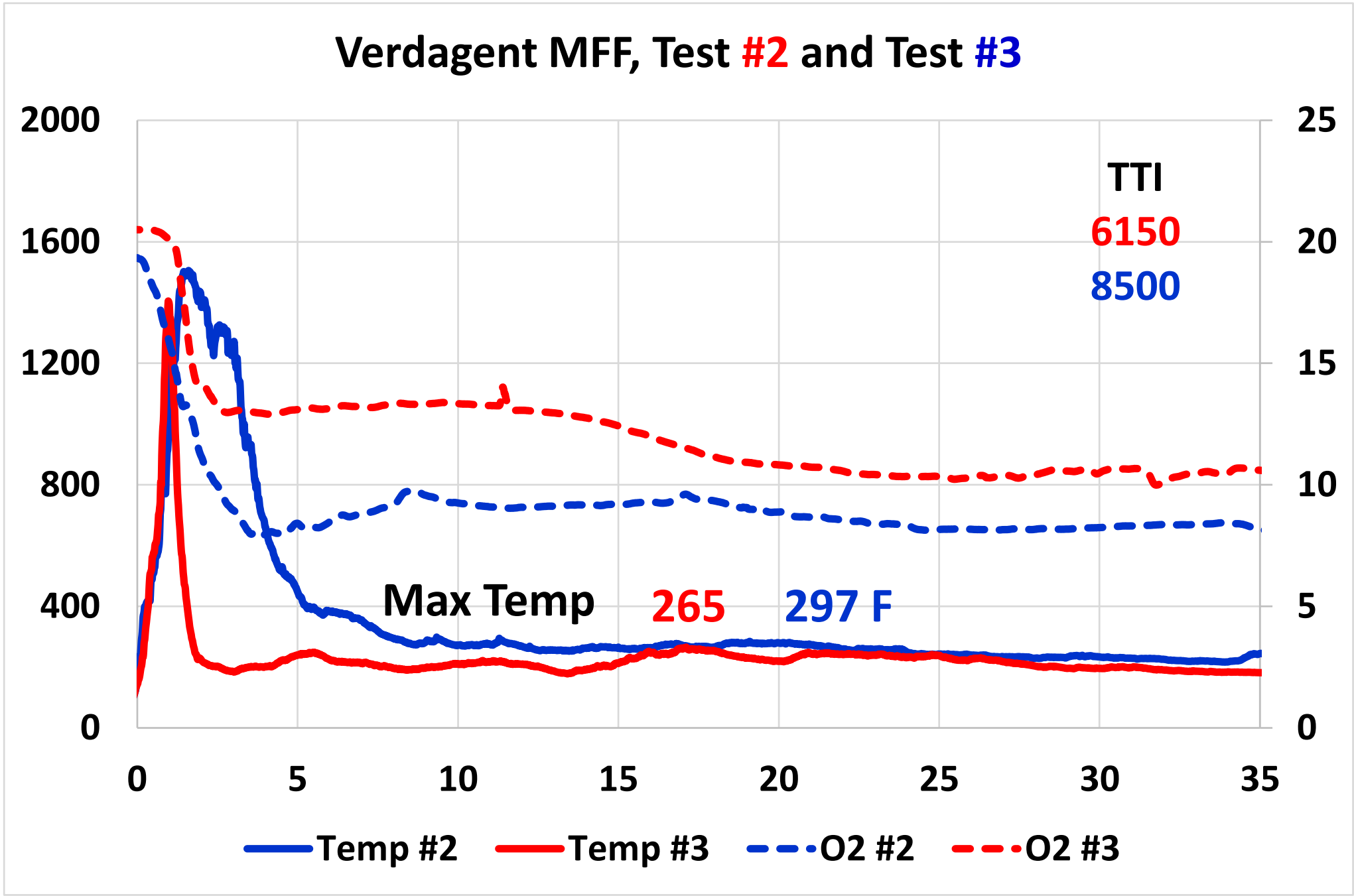
2 Unsuppressed
Multiple Fuel Fires

Bags of ethanol

Box 8 was involved
Box 14 was not



Suppressed
And
Unsuppressed
Multiple Fuel Fire

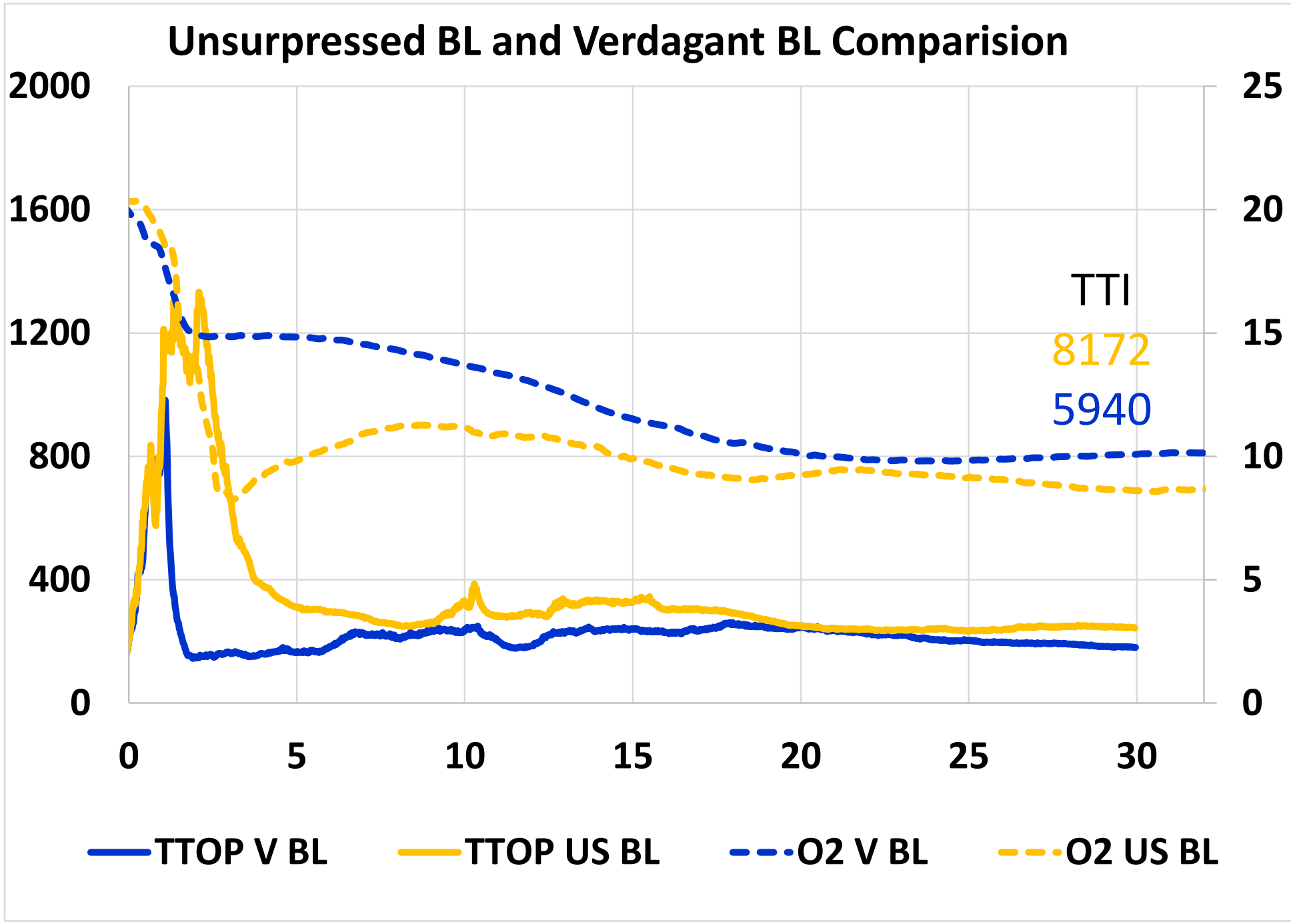


Suppressed

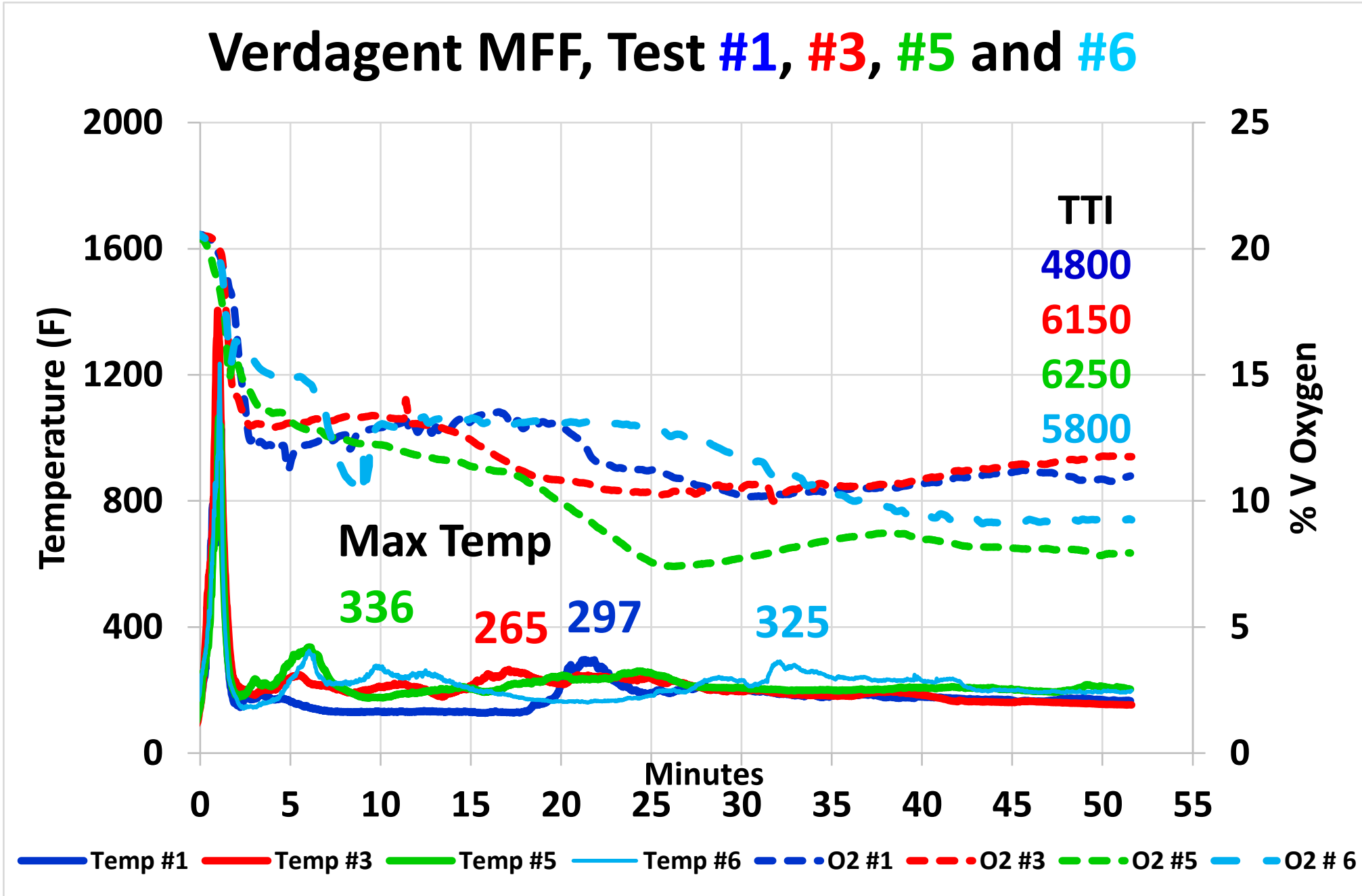
And

Unsuppressed

Bulk Load (BL)



Comparison of all 4 MFF Tests Fires to Date (Suppressed)



Additions to the Boeing MPS Chamber for the MMF Testing

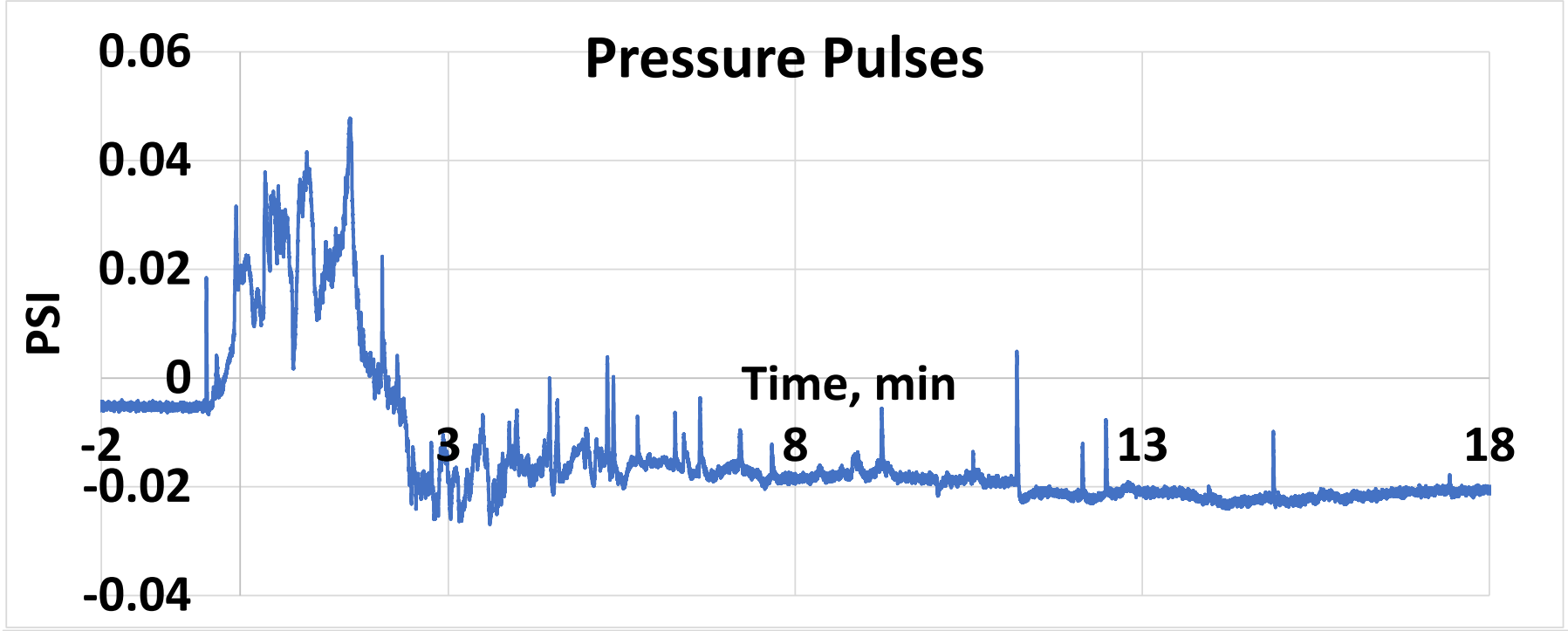
- Total Hydrocarbon data
- Added an SRI GC with FID detector (temporary)
- Currently installing Pressure Compensated Thermo Fischer FID

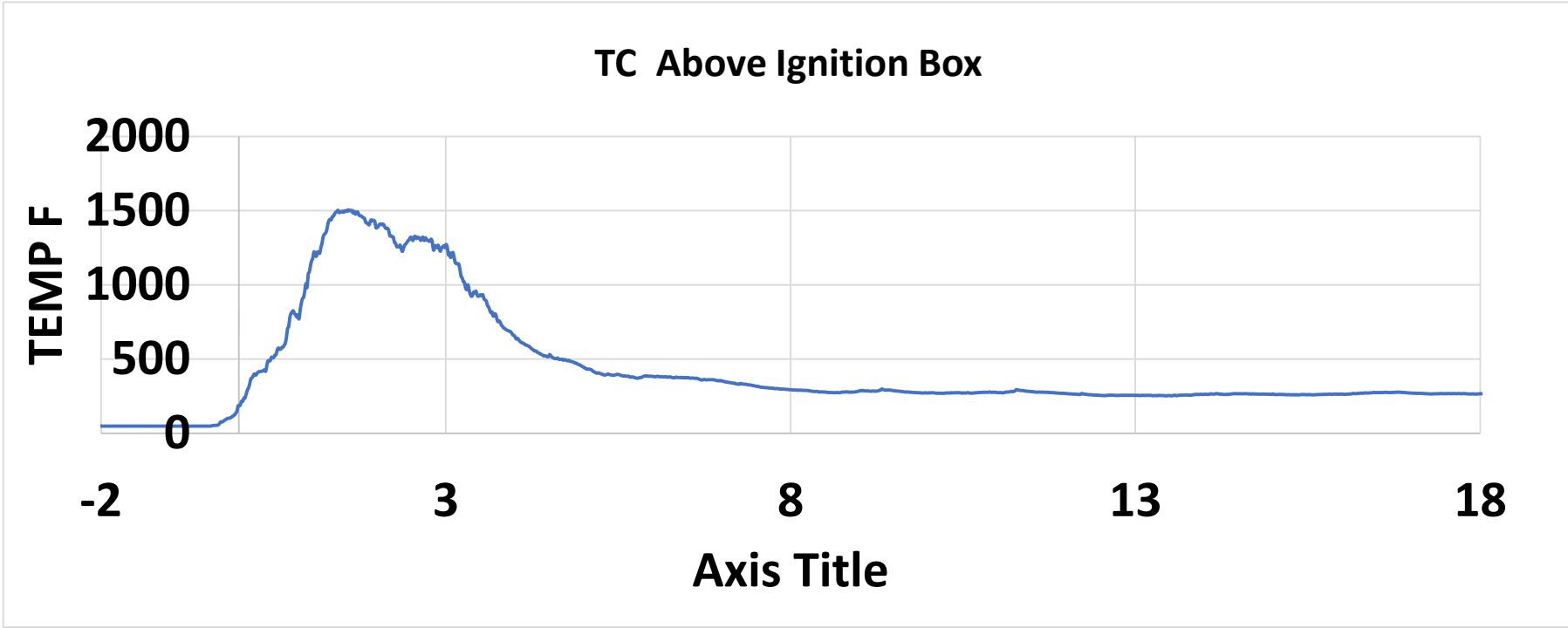
- Hydrogen measurement
  - Hiden Mass Spectrometer

- Also collecting High Speed Pressure data for battery gas release events

High Speed
Pressure Data
Compared to Ceiling
Thermocouple just above
ignition Box

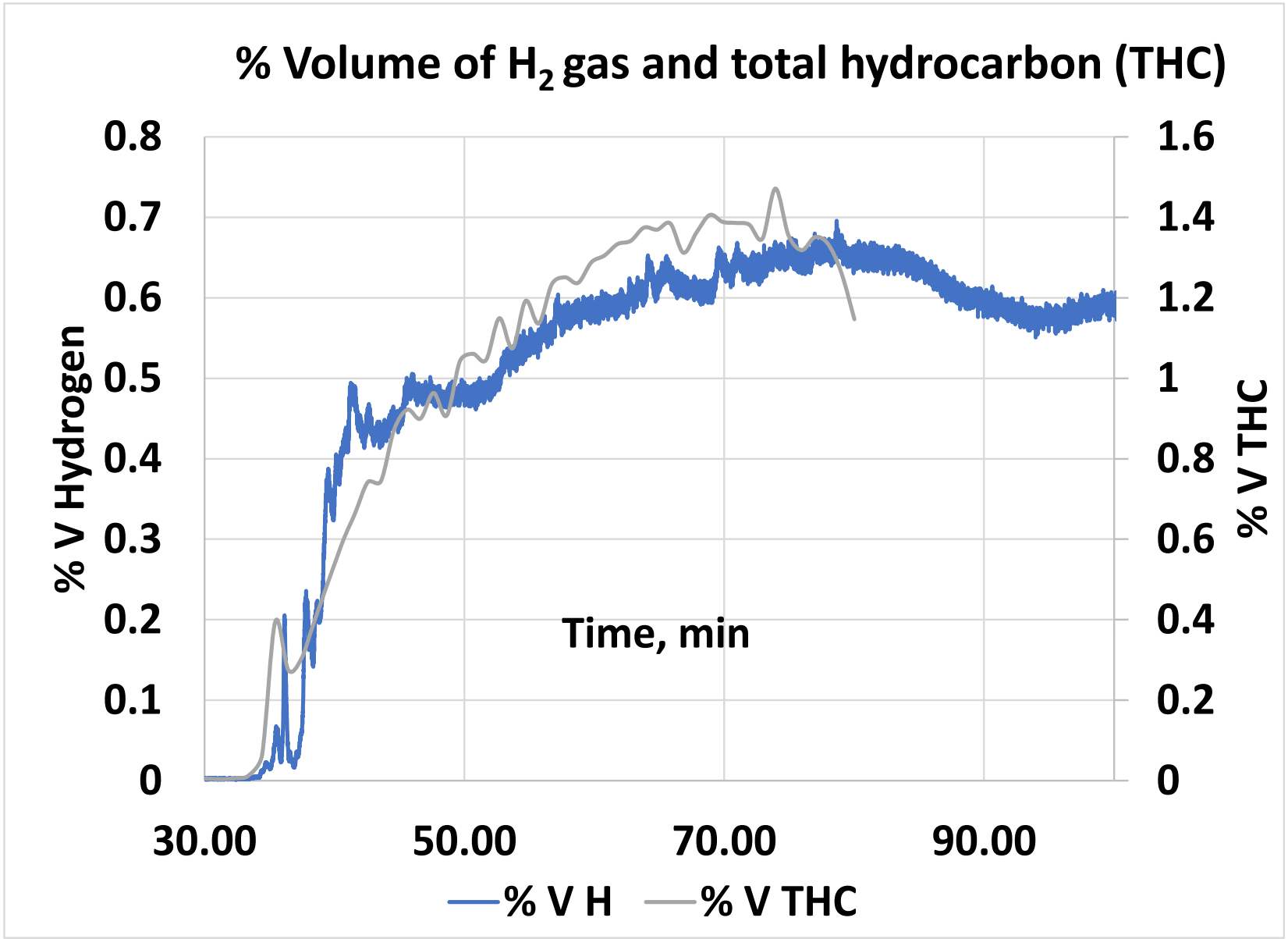
The larger areas (timed events) in pressure are believed to be from class A and Class B combustion
The sharp peaks are have been observed to be battery release events





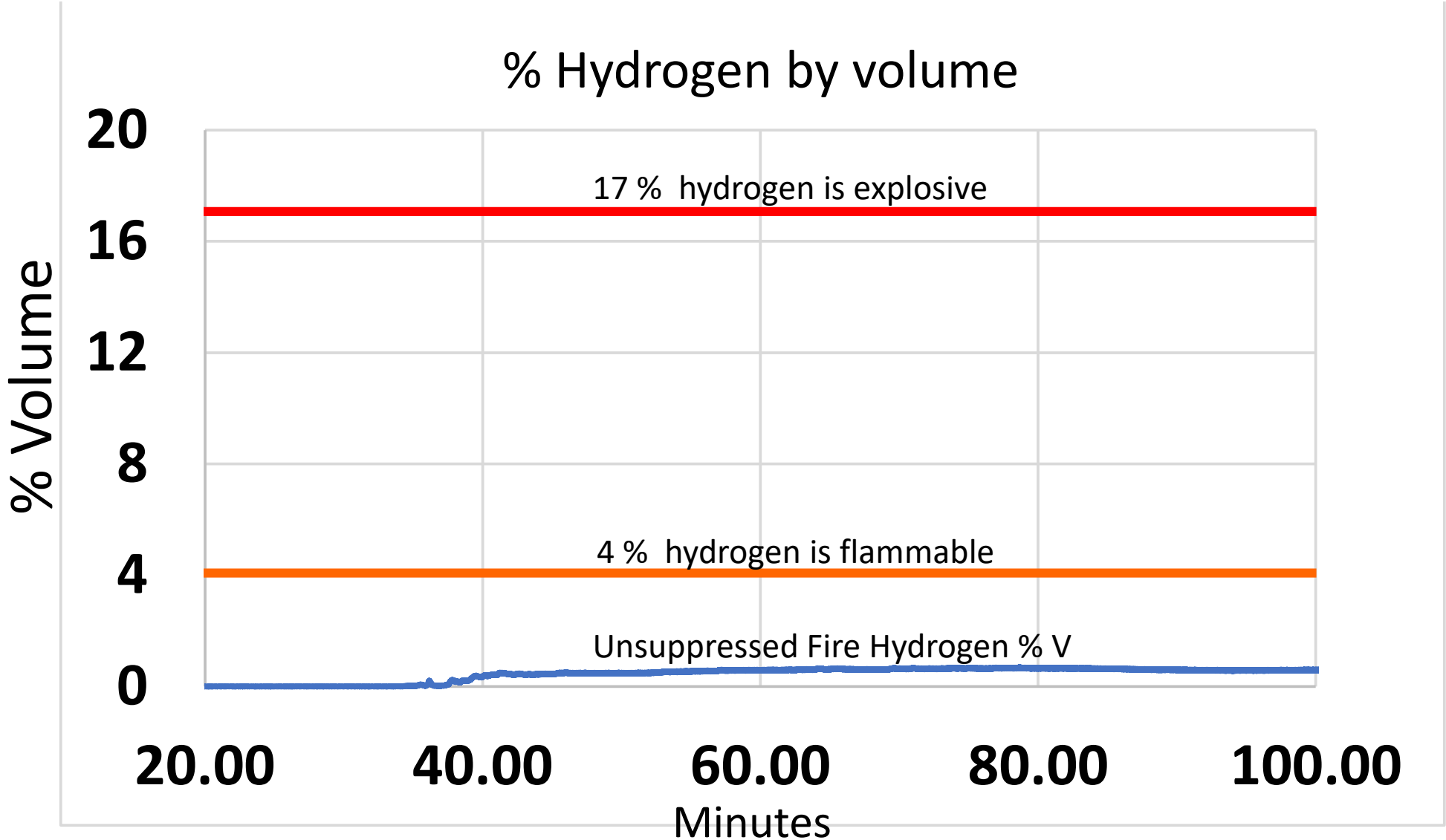
Unsuppressed MFF #1

THC and H_2 gas is shown from an Unsuppressed Multiple Fuel Fire (MFF test#2)



Unsuppressed MFF

H_2 from an Unsuppressed Multiple Fuel Fire (MFF test#2) compared to the flammability and explosive points of hydrogen gas



Boeing MPS Team:

George McEachen, Pat Baker, David Shaw,

Noel Spurlock, Nick Mavriplis, Prash Bhat,

Rachel Darr, Allison Horney, Oscar Lezcano

Nels Olson, Ryan Wilson and Wes Quigley

END of Section 2

Cargo Compartment Halon Replacement

Advantages of Selective Gas Analyzers for the Measurement of Fire Suppression Agents

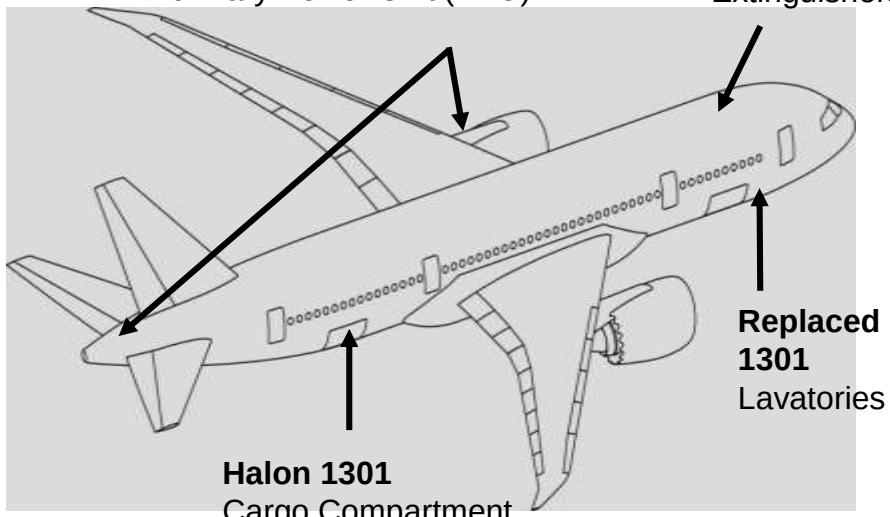
Wes Quigley

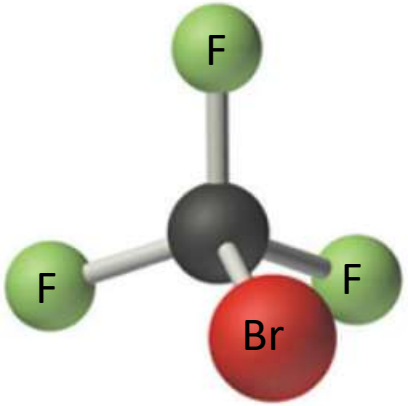
Nels Olson, Ryan Wilson

George McEachen, Pat Baker, David Shaw, Noel Spurlock, Prash Bhat, Rachel Darr, Allison Horney, Oscar Lezcano, Nick Mavriplis

Halon is an Ozone-Depleting Substance

- Halons have been used in aircraft cargo fire protection since the 1970s and system design has been based on FAA Fire Safety Branch full scale fire testing at the FAA Technical Center
- 1994 UN Montreal Protocol banned halon production
- Recycled stock currently used → global supply depleted ~2040



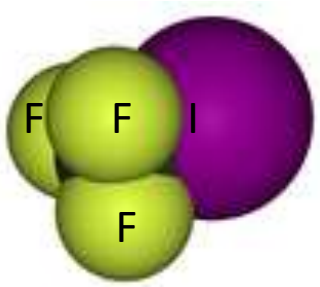


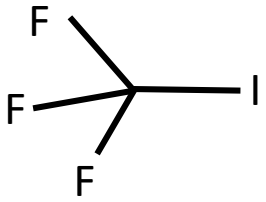
C	1	1
F	3	2
Cl	0	1
Br	1	1
I		

Impetus for banning of Halon 1301

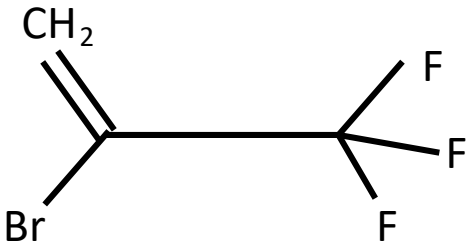
Ozone Depletion Potential	Global Warming Potential	½ life in Atmosphere
ODP = 10	GWP = 6900	~ 63 years

Cargo Fire Suppression Replacement Options





CF3I
ozone depleting potential less than one-thousandth that of Halon 1301
Being tested for Nacelles



2-BTP (2-bromo-3,3,3 trifluoro—prop-1-ene)

ozone depleting potential less than one-thousandth that of Halon 1301
Approved in lavatories
Being tested for Cargo Compartment

VERDAGENT® is a multi-component agent of 2-BTP (or simply BTP) and carbon dioxide, as opposed to Halon 1301 a single component agent; issues of homogenous distribution of the agent, blend-separation and delivery system could hinder its effectiveness as a Halon replacement agent

Testing a 50/50 by weight of BTP and CO2 (1:4 by molar ratio)

How do Replacements compare?

	Ozone Depletion Potential	Global Warming Potential	½ life in Atmosphere
1301	ODP = 10	GWP = 6900	~ 63 years
CF3I	ODP = ~0 (<0.008)	GWP = ~0 (< 5)	< 2 days
BTP	ODP = ~0	GWP = ~0	< 2 days

Fire Suppression and Testing History

- Halons have been used in aircraft cargo fire protection since the 1970s and system design has been based on FAA Fire Safety Branch full scale fire testing at the FAA Technical Center

- For most of that time, full scale fire testing was paced by the FAA Technical Center's ability to test one agent at a time in their facility in Atlantic City, NJ. Test programs often run a year or more, so this is a bottleneck
- The FAA and Boeing, along with other international regulators and industry participants have task groups for halon replacement testing and meet in conferences twice each year to update on progress

- In 2018, BCA and BR&T leadership committed to:
  - building a state-of-the-art facility to have a full scale fire test capability

- We have tested Halon 1301, CF_3I, a CF_3I blend, and a 2-BTP/CO_2 blend in our facility since 2019
- These tests have been critical to speeding the development of halon 1301 alternatives for cargo fire protection

- Our facility hosted the FAA, EASA, Transport Canada, and several industry representatives April 2023 for the second on-site team meeting at our facility

- The FAA, EASA and Transport Canada have been very appreciative of Boeing's investment in this testing and our commitment to speeding the advancement of halon alternatives

Fire Suppression and Testing History (cont)

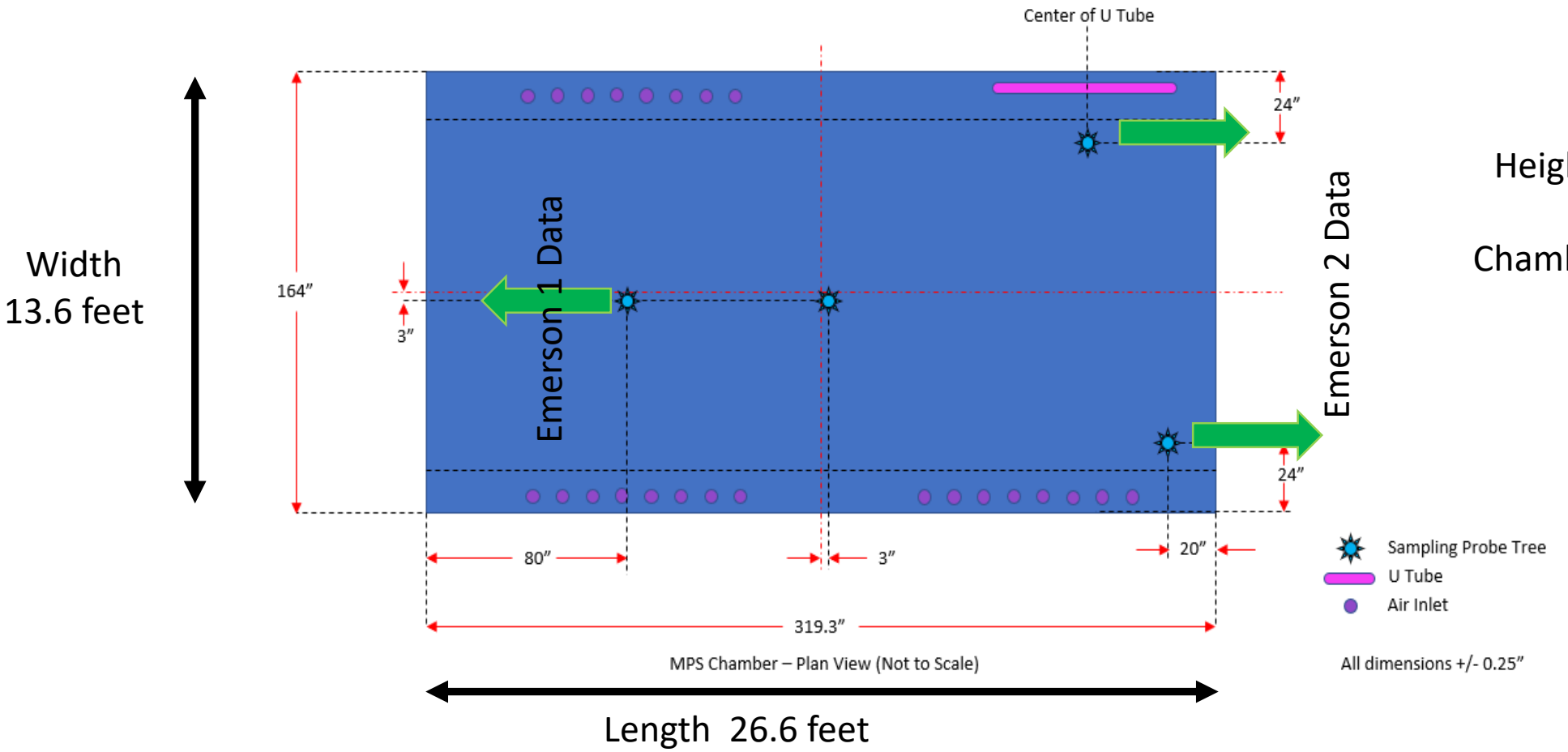
- Halons have been used in aircraft cargo fire protection since the 1970s and system design has been based on FAA Fire Safety Branch full scale fire testing at the FAA Technical Center

- The Halonyzer is based upon the original Statham Analyzer method from USAF ~ 1947
  - Measures the viscosity changes of gas mixtures and outputs % Volume of Halon and other suppression agents based upon viscosity changes
    - Noisy and non selective measurement

- The Halonyzer predates the FAA and has been the backbone of nearly all fire suppression data that the FAA has released the last 50 years for certification of fire suppression systems

- Recent advances in gas analyzers (Most based on IR spectroscopy) have shown better results
  - Less noise, can measure, CO2, CO, O2 and Agent concentrations directly
  - ROI for Emerson gas analyzers to replace Halonyzer occurs in weeks of testing
  - Halonyzer cost (~20 k /day) to lease

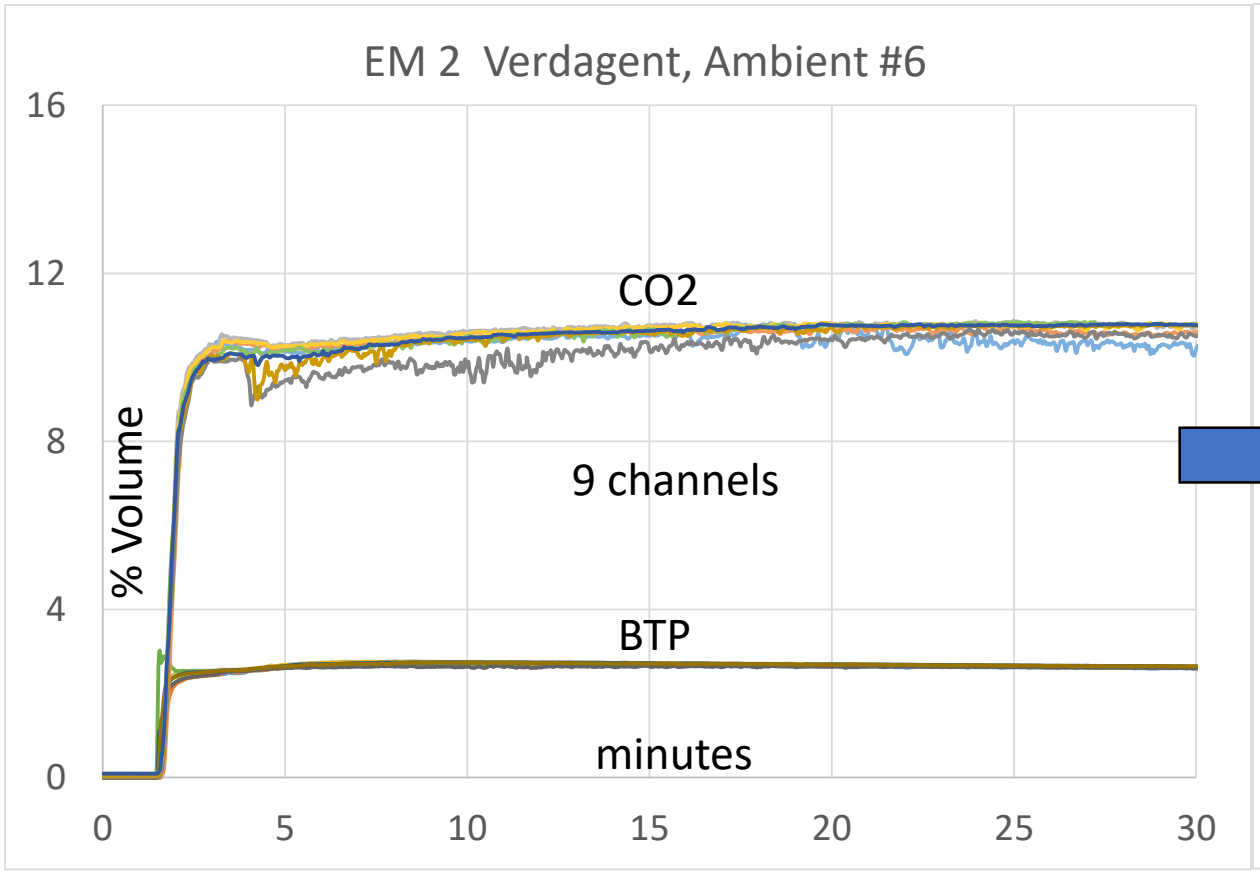
Boeing MPS Chamber Gas Sampling Locations

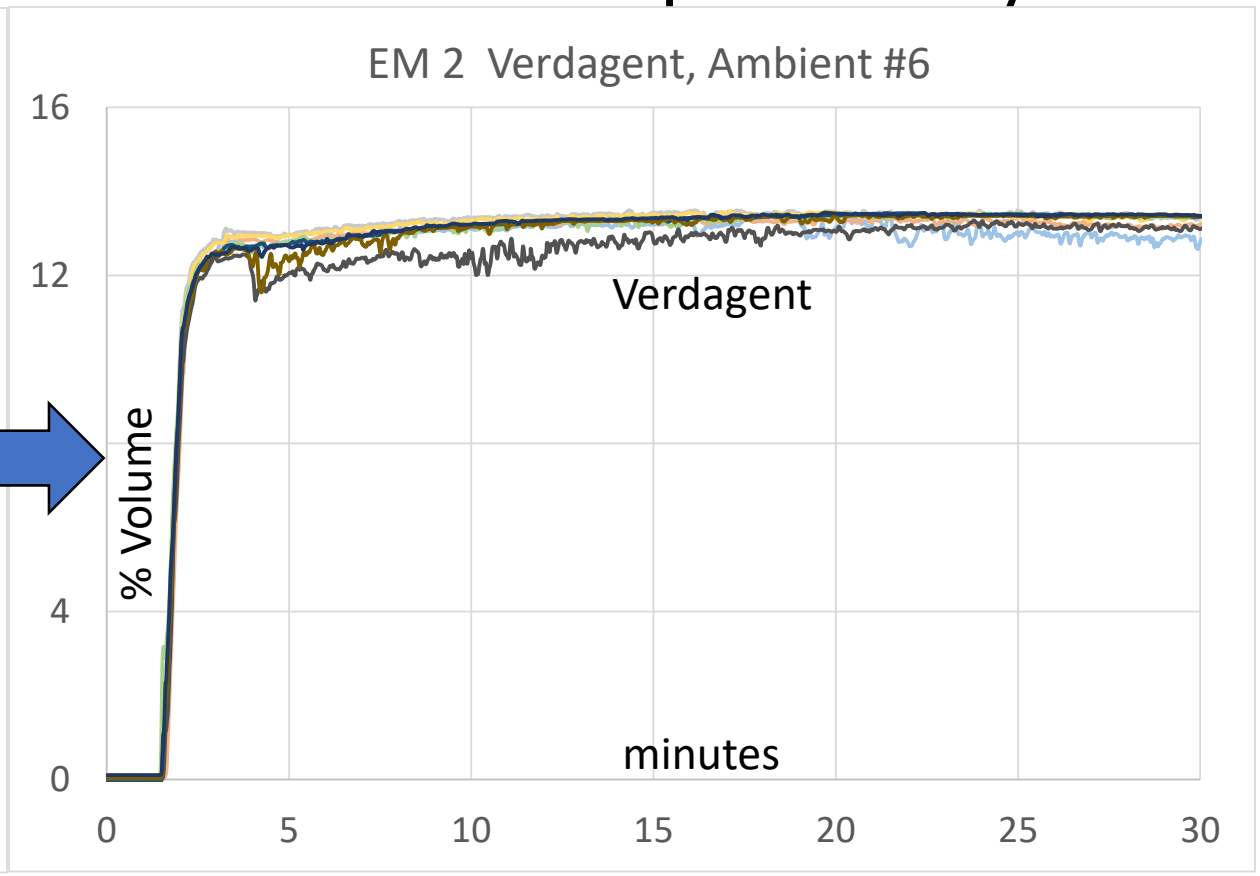


Height < less than 6 feet

Chamber ~ 2000 cubic feet

Emerson measures BTP and CO2 separately





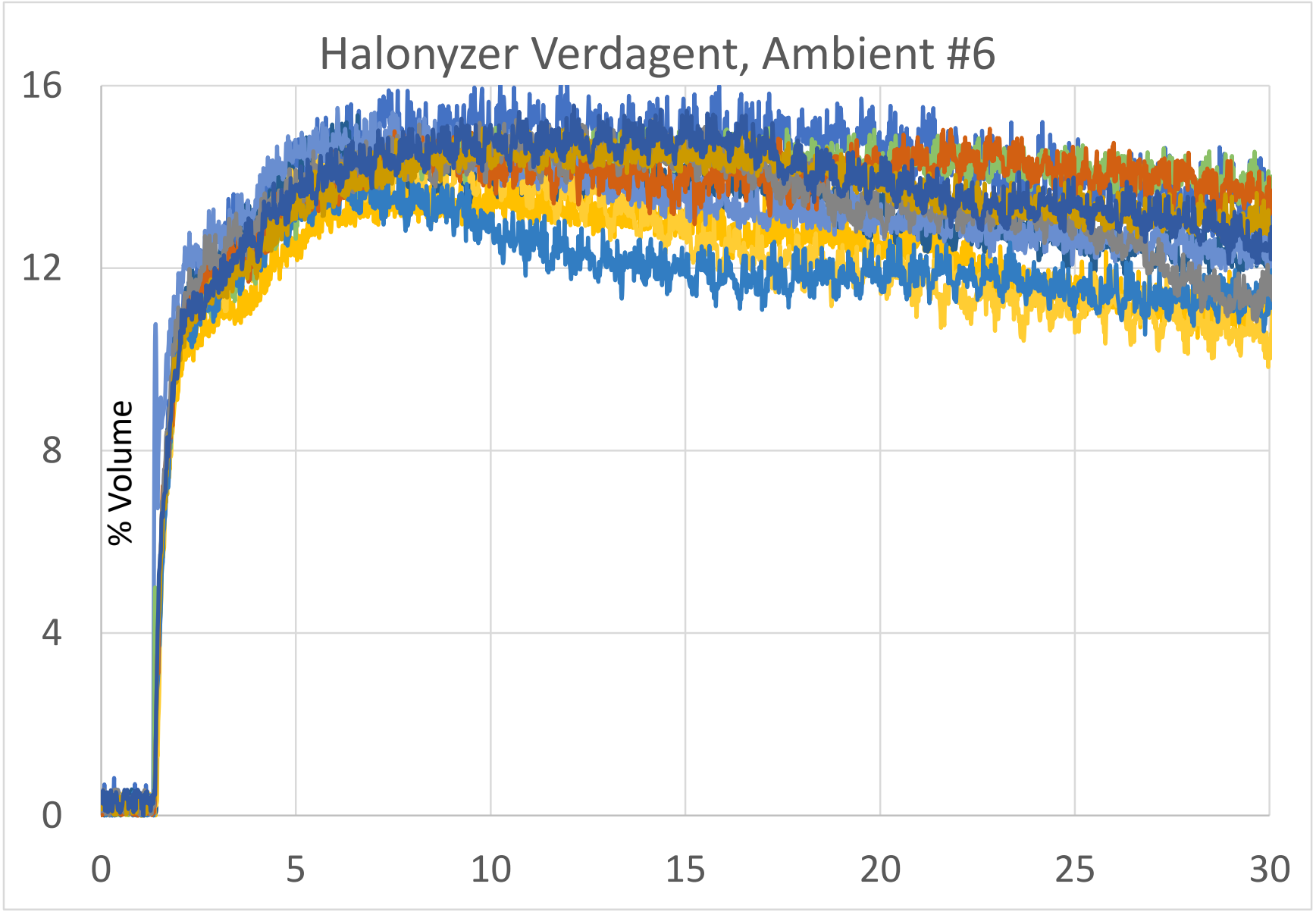
The addition of the BTP and CO2 = Verdagent

Halonyzer Data

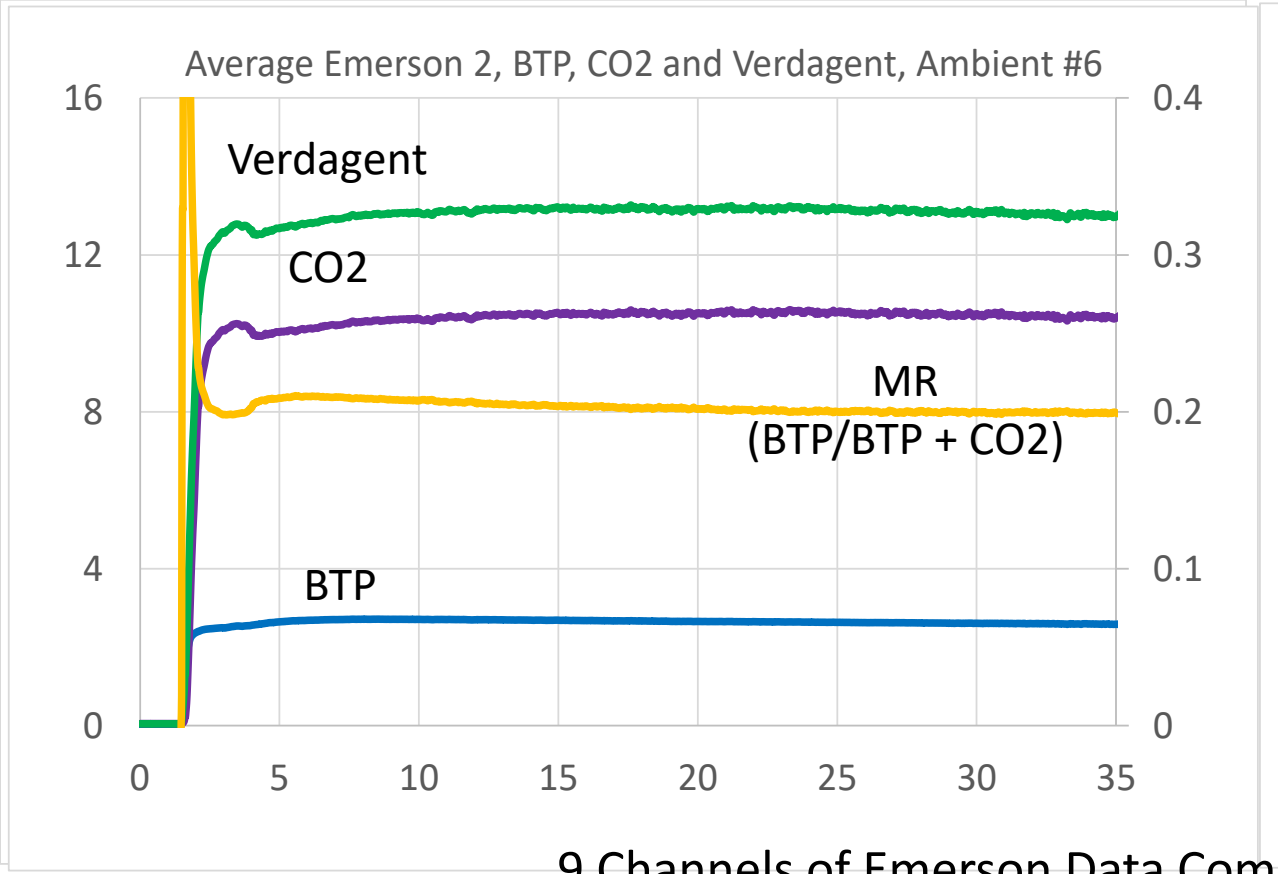
Stratification discussions often were used to discuss the variability between channels

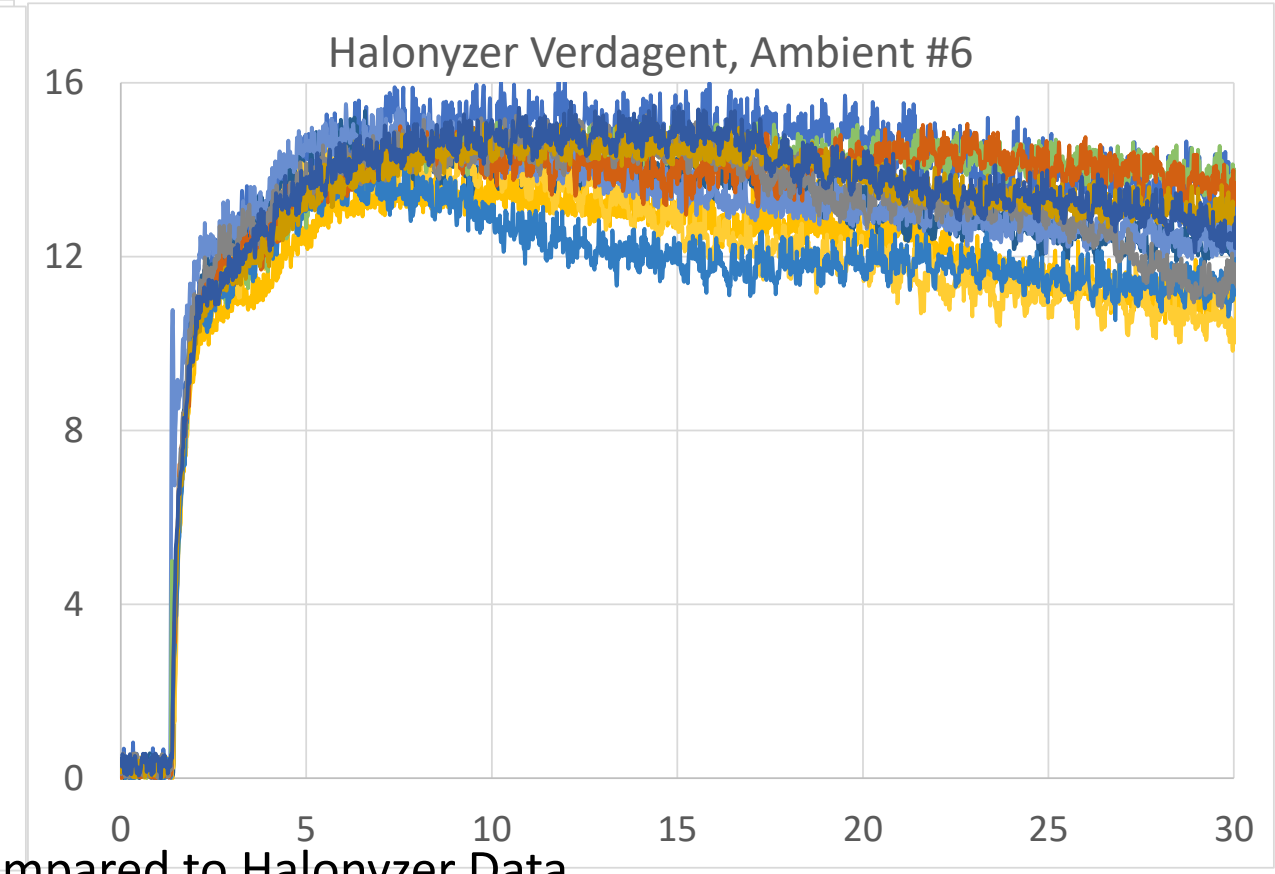
The results were often confusing

50 years of head scratching



Emerson Gas Analyzer Data vs Halonyzer Data





9 Channels of Emerson Data Compared to Halonyzer Data

Noise and Error for an Emersons instruments:

< 2% for all measurements

Virtually no difference between the units

Temperature and Pressure Compensated

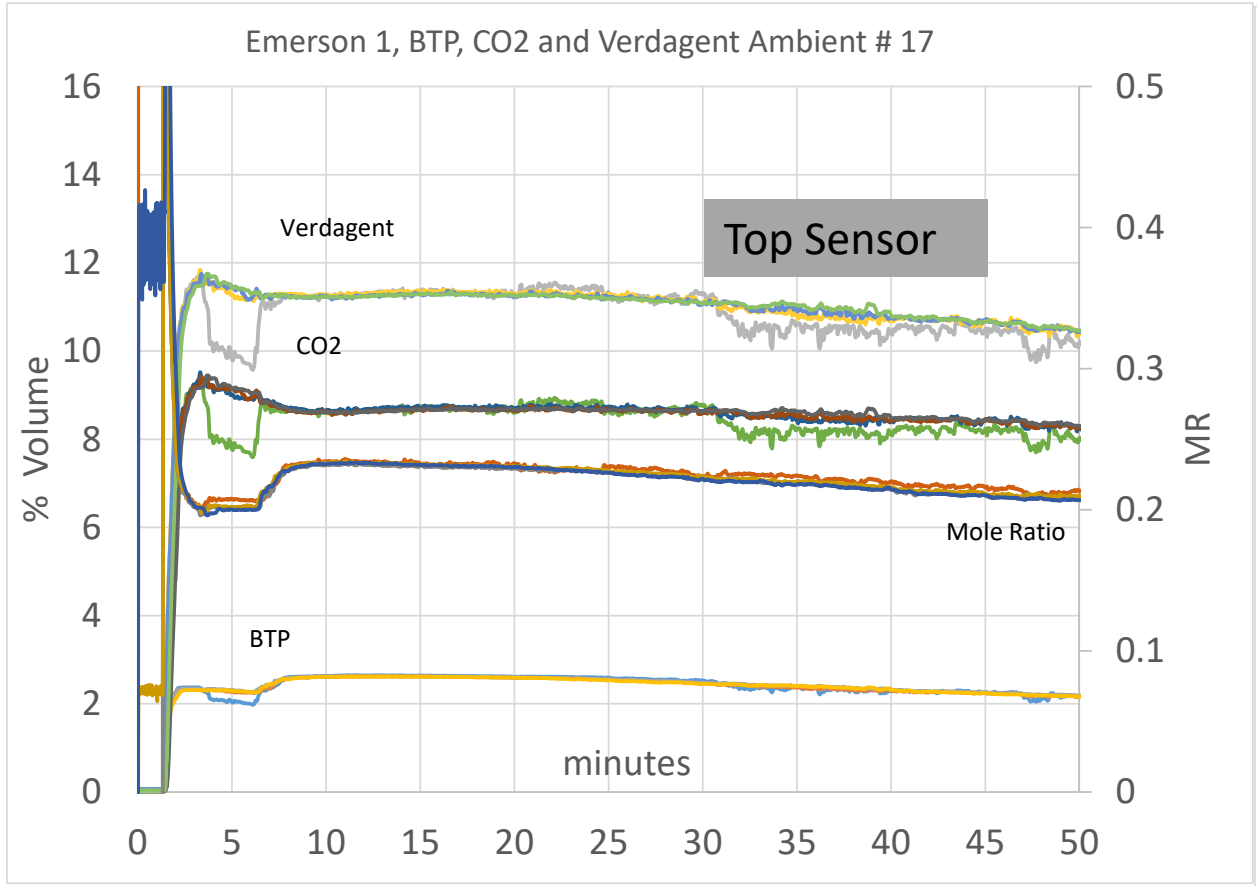
Sensor is measuring concentration

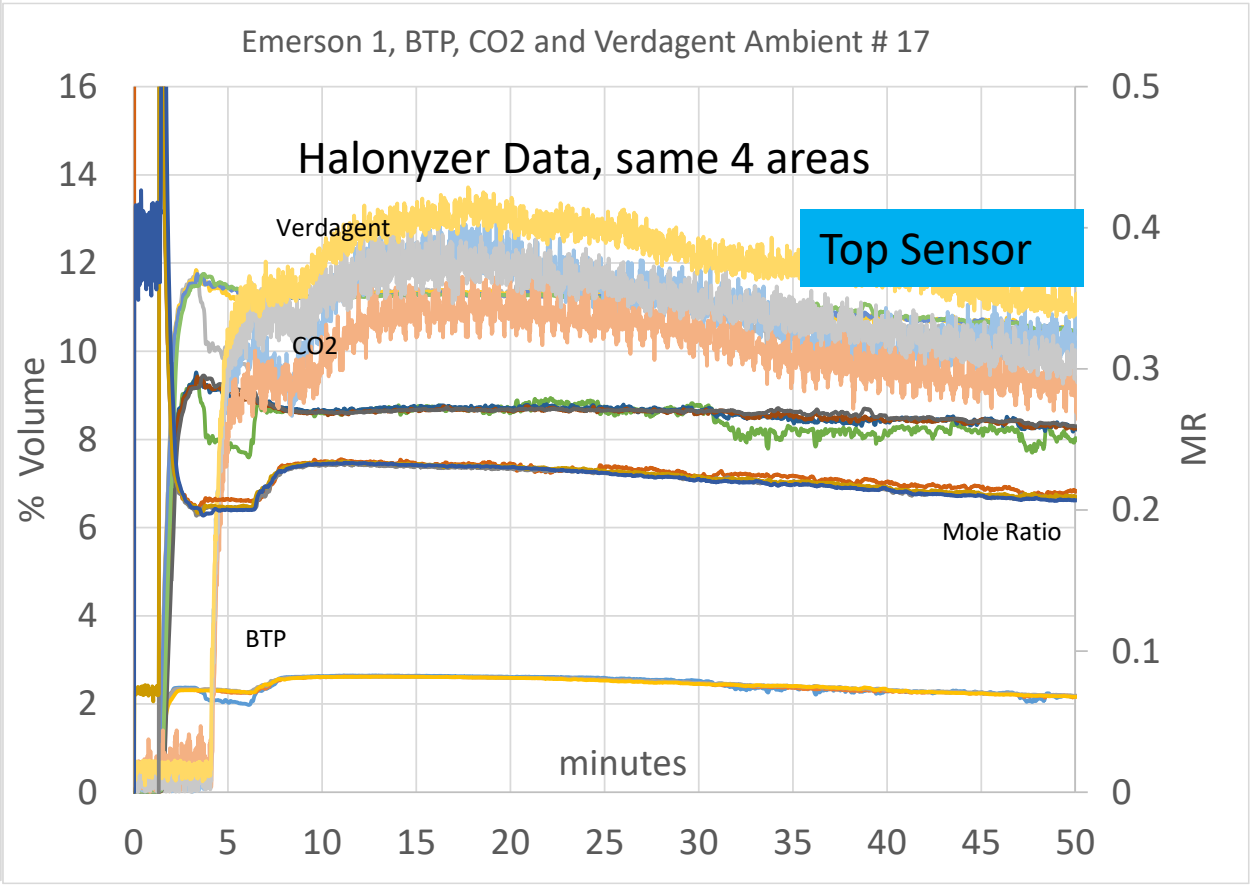
Noise and Error for Halonyzer is on the order ± 11% of the reading

Pressure and Temperature sensitive

Sensor is measuring a non-constant physical property

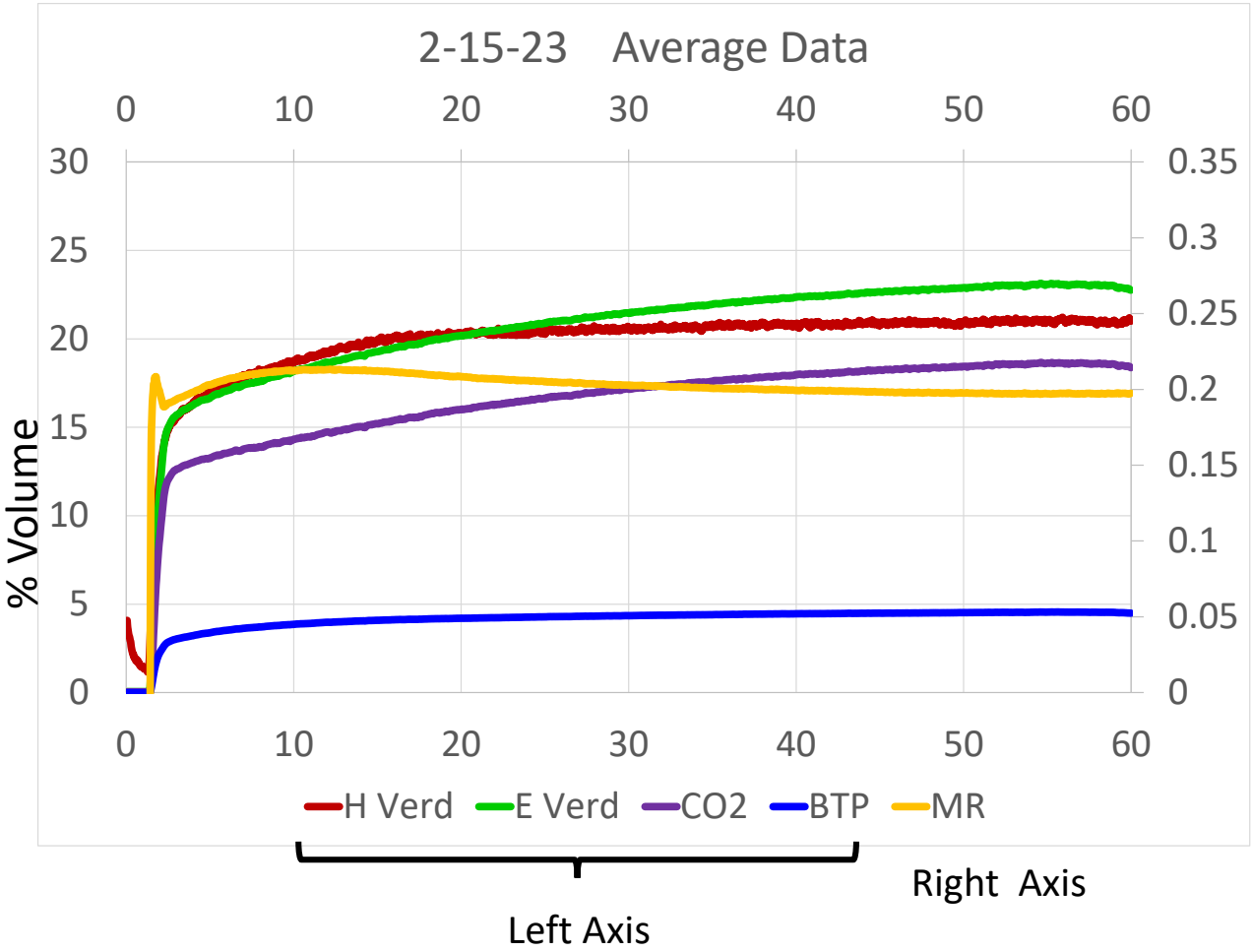
Verdagent (50% by mass is CO2 and 2-BTP) 4:1 by Mole Ratio (same as % V gas)



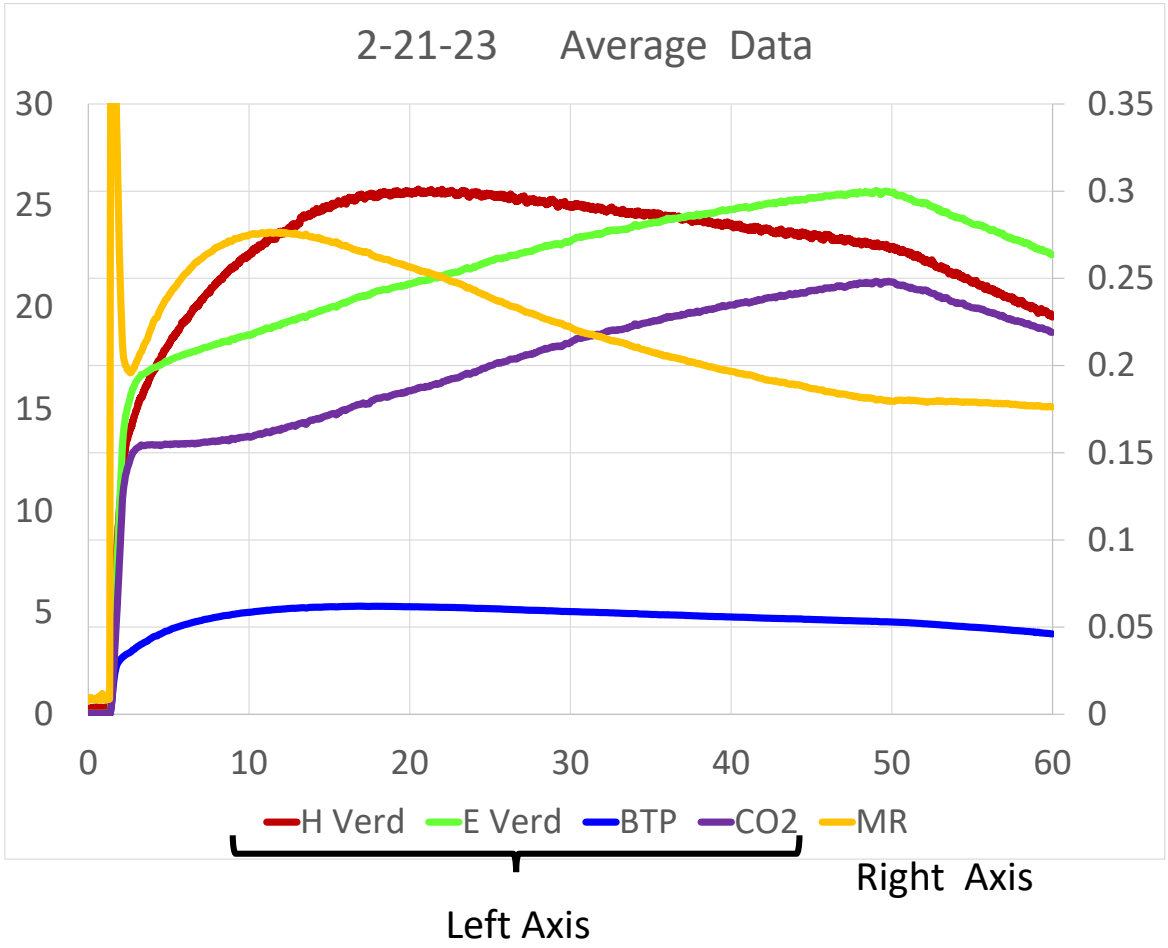


Lowest signal is from 2 inch from the top of the chamber

Average Tree Data for BTP, Verdagent, CO2 and mole ratio (MR), BTP/BTP+CO2)



When the BTP/BTP+CO2 ratio is near constant the Emerson and Halonyzer Data agree pretty well



When the BTP/BTP+CO2 ratio is not constant the Emerson and Halonyzer Data do not agree

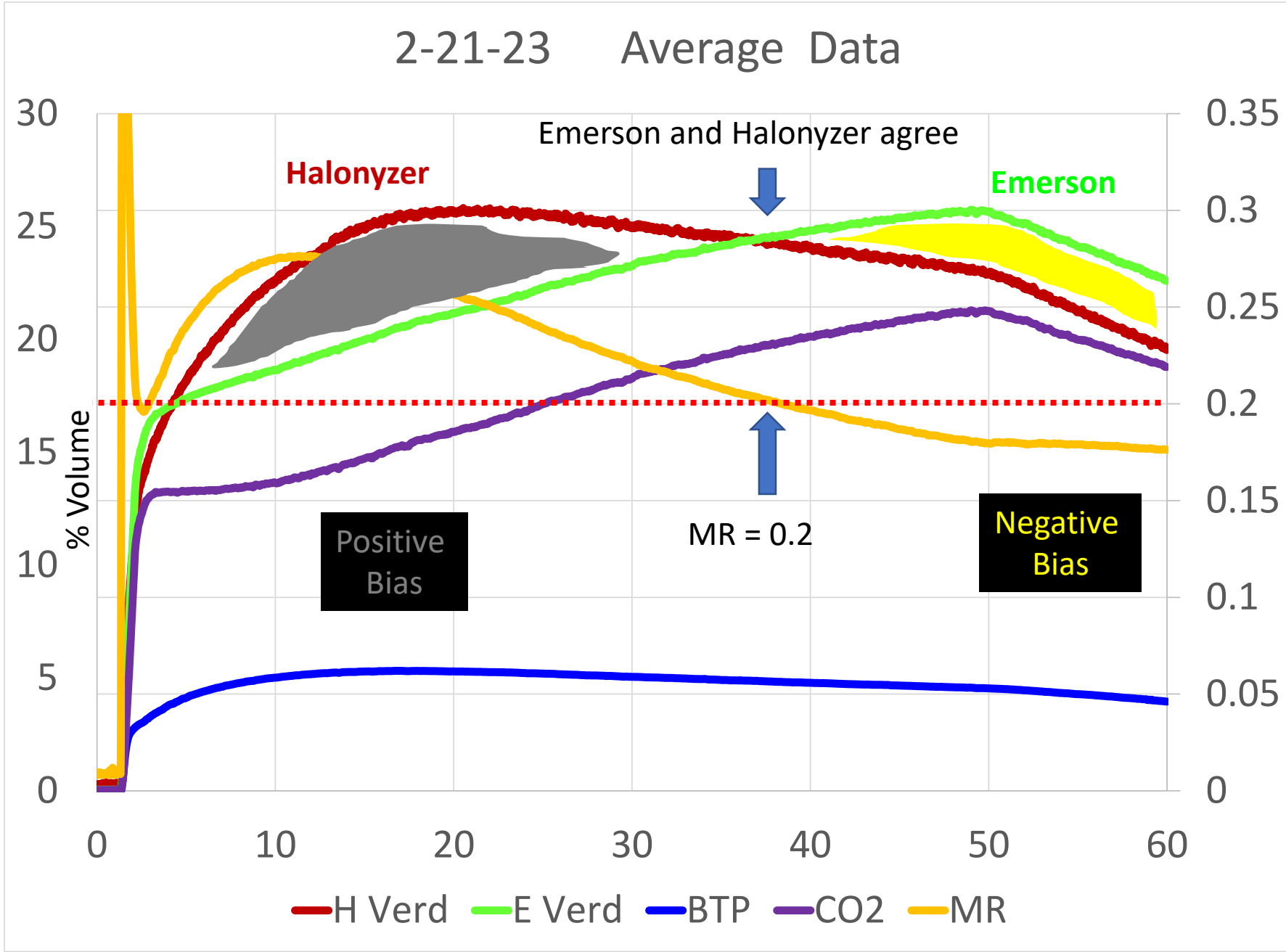
This data revealed a weakness in the delivery system that would have went unnoticed via Halonyzer data only

The halonyzer is calibrated on a 0.2 mole ratio (MR) of (BTP/BTP+CO2)

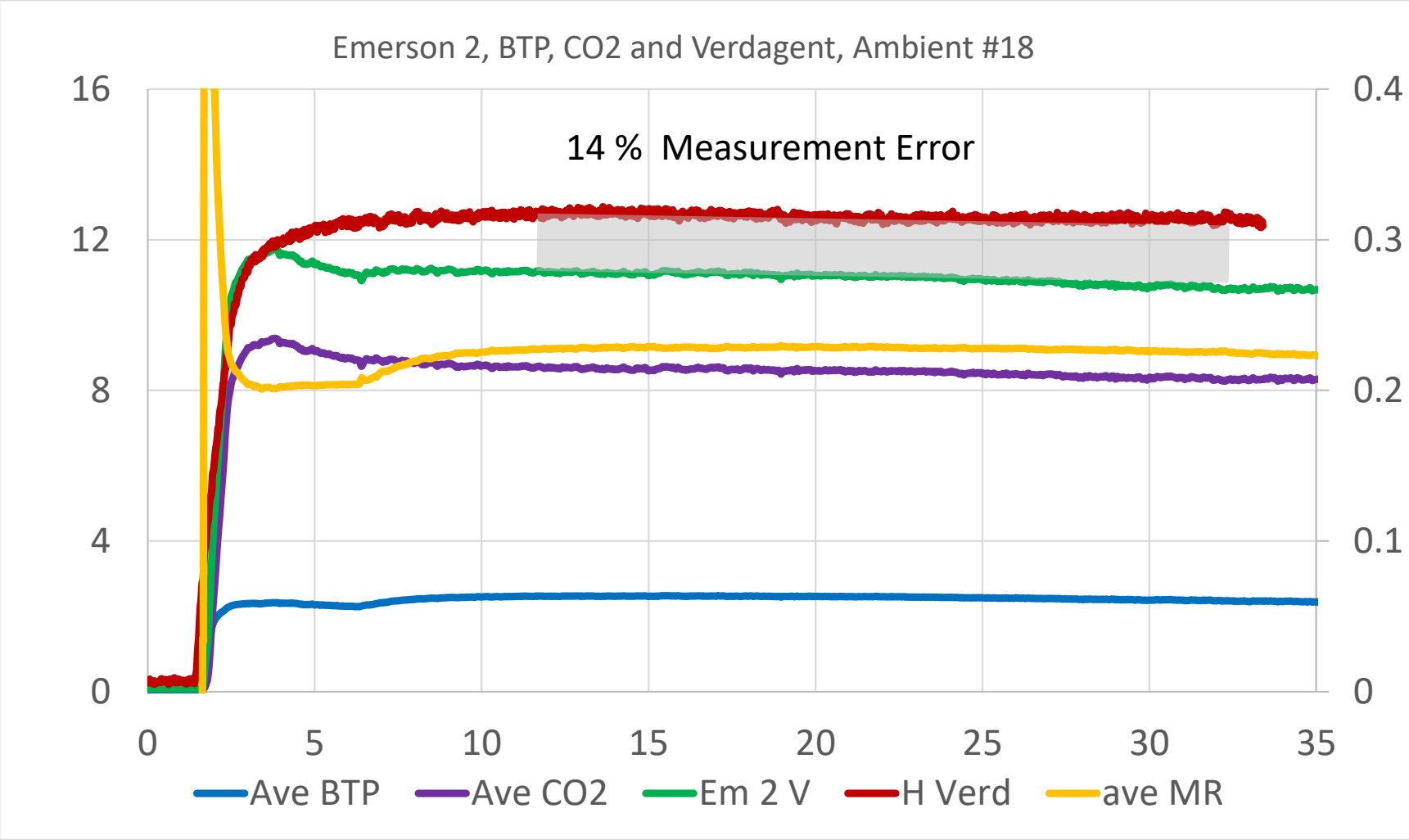
Viscosity (e-05 kg/(m-s))
Air 1.8
CO2 1.4
Verdagent 2.7 (0.2 MR)

When the MR is above 0.2 the Halonyzer should show a positive bias (Grey area)
Over 30% error

when the ratio is below 0.2 than the Halonyzer shows a negative bias (Yellow Area)



Real World Data Showing Halonyzer Positive Bias



- Measuring Halon with a Halonyzer system has a long history
  - The variability in the data has always been an issue Halonyzer
  - Results have frustrated the Fire community for years
  - This approved system is not good for binary mixtures
    - If the mole ratio is off, large errors are shown for the Halonyzer

- Emmerson gas analyzers are clearly superior
  - All figures of Merit, error, repeatability, standard deviation etc. are much better
  - Return Of Investment (ROI) is on the order of Weeks of testing
  - Much better fundamental understanding of suppression agents
  - Measure each component and be able to measure mole ratio
  - Can measure small differences due to stratification
  - Identified a weakness in the delivery system (working to improve it)
  - FAA will very likely require a system (like the one designed by Boeing) for the qualification and certification of fire suppression systems for the next decade or more

Boeing MPS Team:

George McEachen, Pat Baker, David Shaw,

Noel Spurlock, Nick Mavriplis, Prash Bhat,

Rachel Darr, Allison Horney, Oscar Lezcano

Nels Olson, Ryan Wilson and Wes Quigley

END of Section 3