Online DGA Monitoring Techniques

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IEEE Transformers Committee
Fall 2021 Virtual Meeting

aps

Agenda

- Brief Intro to APS' TOAN System
- Determining Gassing Rates of Change with Online DGA and Data Mining
- Load Dependent Gassing Analysis
- Insulation Aging Estimation
- Questions?

C57.143 Revision

- Much of the techniques discussed in this presentation are included in a proposed Annex to C57.143, IEEE Guide for Application of Monitoring to Liquid-Immersed Transformers and Components, which is currently scheduled for 12/31/2022.


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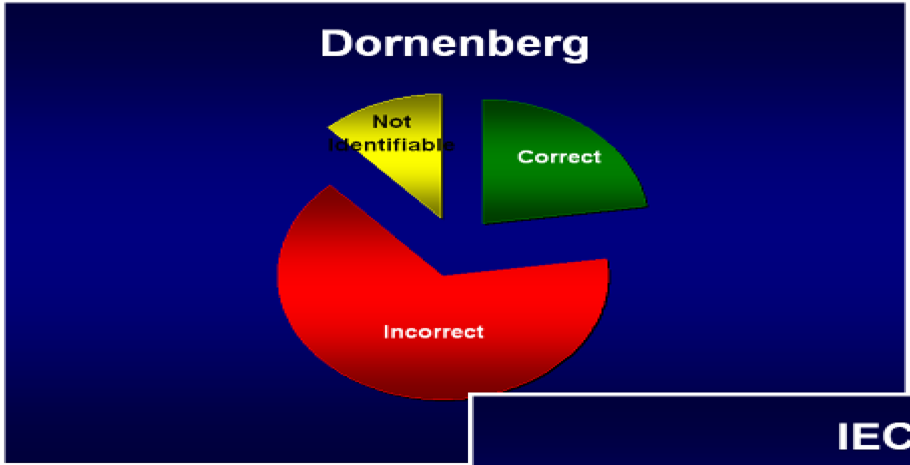
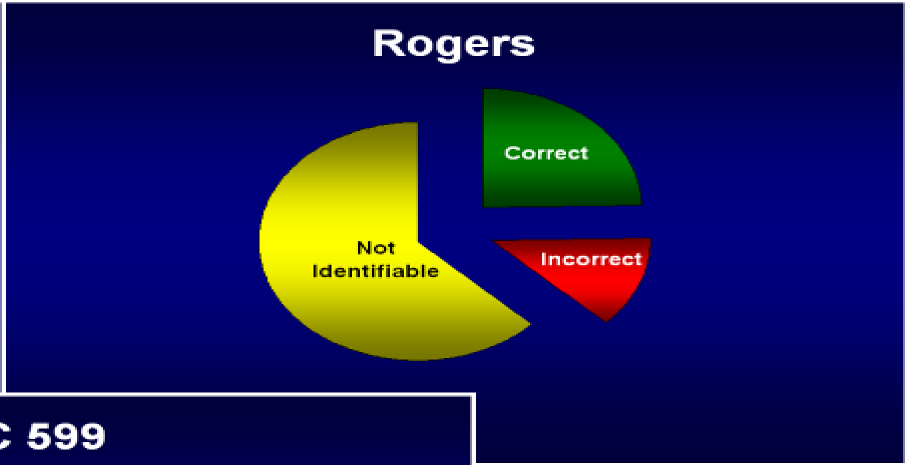
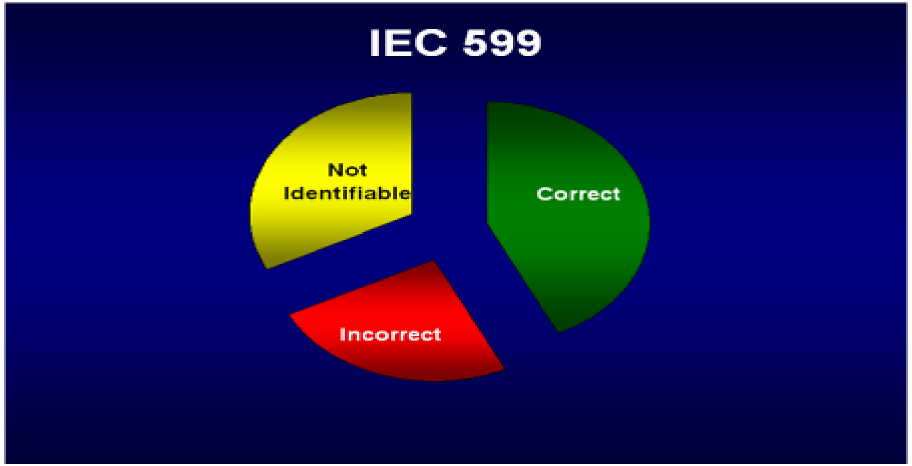
Accuracy of Traditional Methods







Correct
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APS On-Line DGA Monitoring

- Began utilizing in the summer of 2003
- Continuously sample eight gases (hydrogen, acetylene, methane, ethane, ethylene, CO, CO_2, O_2) and report every four hours through gas chromatography
- Currently installed on two hundred and seventy-eight APS transformers and shunt reactors.

The Need for Improved and Automated Diagnostics

- Cost, lead time, and operational impact of unplanned transformer loss
- Loss of expertise – aging workforce
- Workload/Volume of data
  - Need to turn voluminous data into actionable information
  - Data is highly repetitive

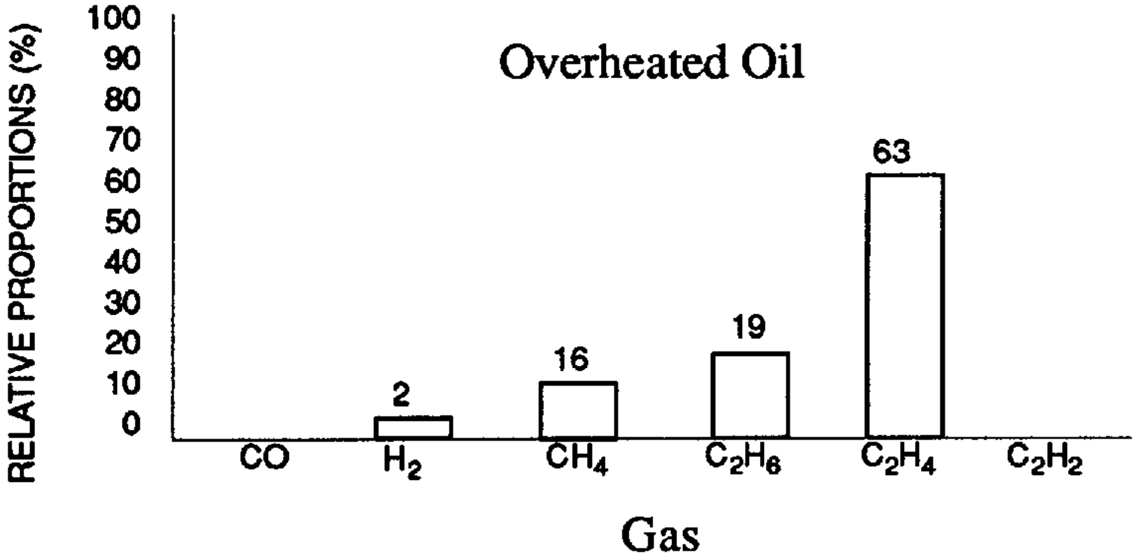
Transformer Oil Analysis and Notification (TOAN) - Objectives

- Designed to reduce the workload of DGA Analysts
  - Exception-Based data processing required
- Improve accuracy of the analysis
- Bring consistency to the analysis

Key Gas Method – Overheated Oil

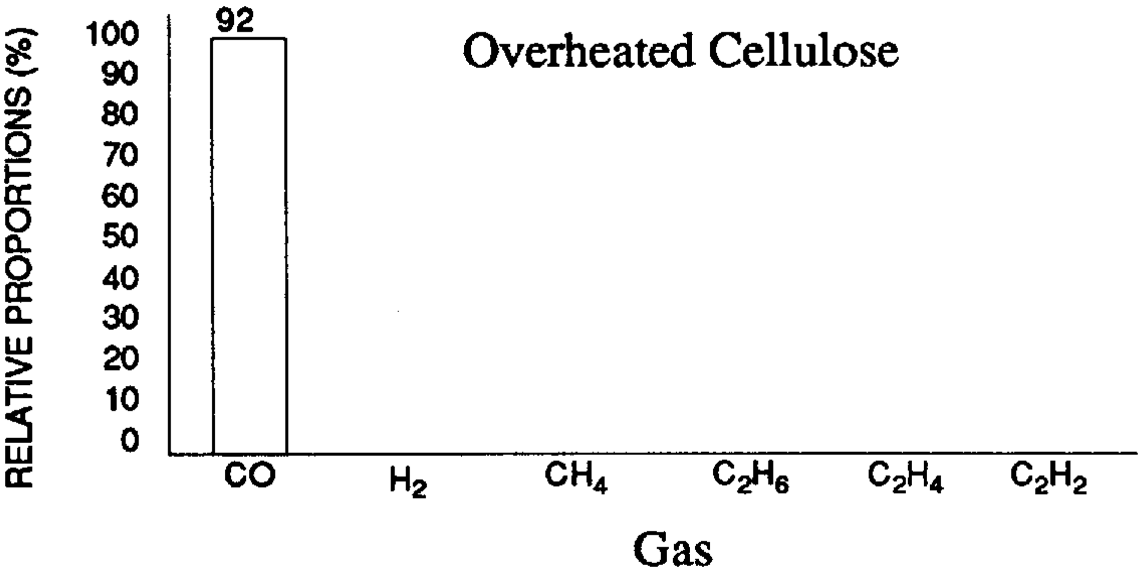
1. Thermal—Oil: Decomposition products include ethylene and methane, together with smaller quanities of hydrogen and ethane. Traces of acetylene may be formed if the fault is servere or involves electrical contracts.

Principal Gas — Ethylene



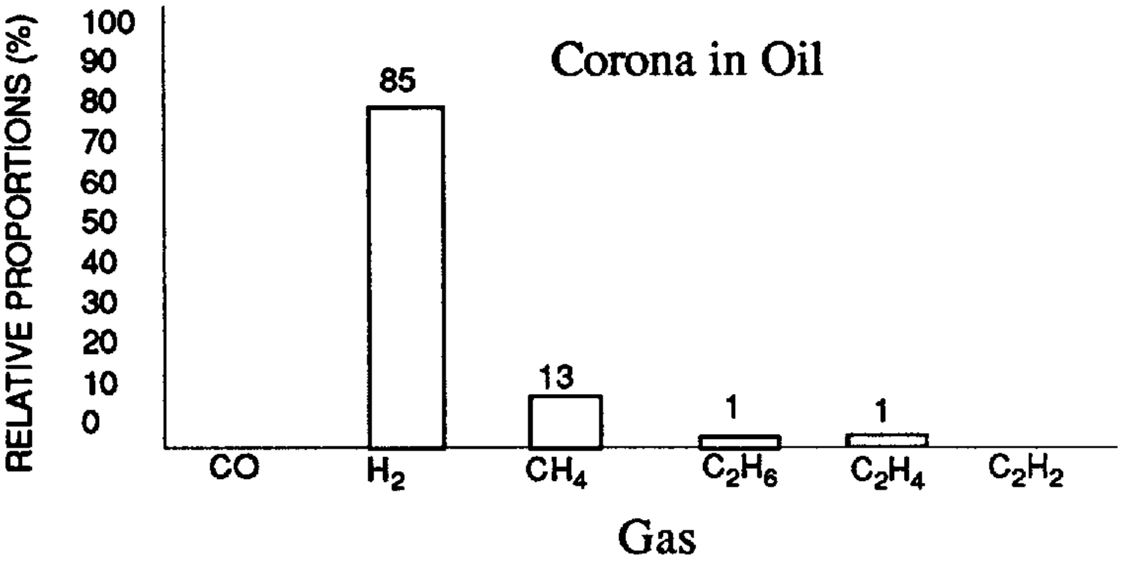
Key Gas Method – Overheated Cellulose

2. <u>Thermal—Cellulose</u>: Large quantities of carbon dioxide and carbon monoxide are evolved from overheated cellulose. Hydrocarbon gases, such as methane and ethylene, will be formed if the fault involves an oil-impregnated structure. Principal Gas — Carbon Monoxide



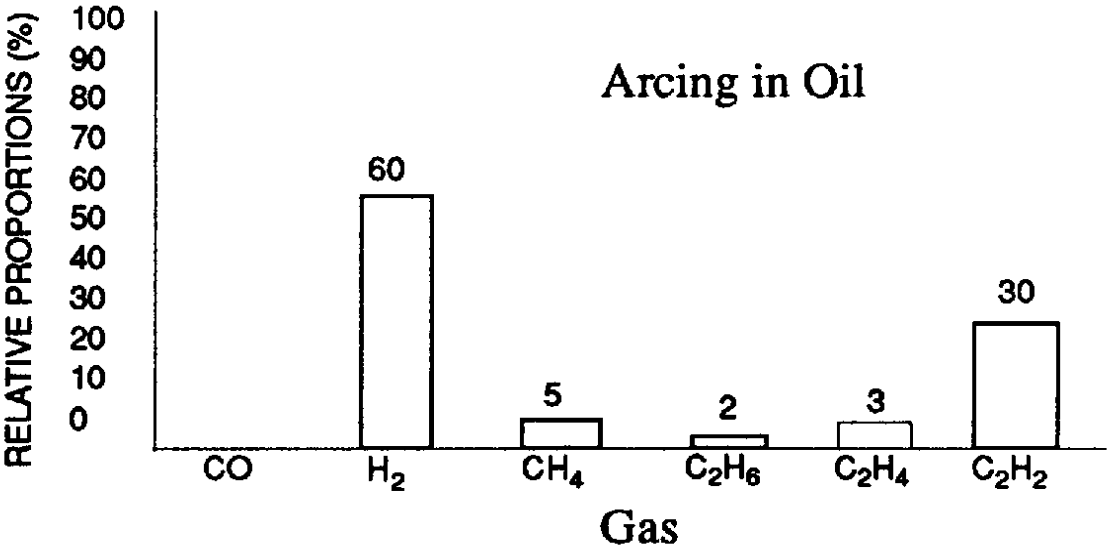
Key Gas Method – Corona

3. Electrical—Corona: Low-energy electrical discharges produce hydrogen and methane, with small quanities of ethane and ethylene. Comparable amounts of carbon monoxide and dioxide may result from discharges in cellulose.
Principal Gas — Hydrogen



Key Gas Method - Arcing

4. Electrical—Arcing: Large amounts of hydrogen and acetylene are produced, with minor quantities of methane and ethylene. Carbon dioxide and carbon monoxide may also be formed if the fault involves cellulose. Oil may be carbonized. Principal Gas — Acetylene



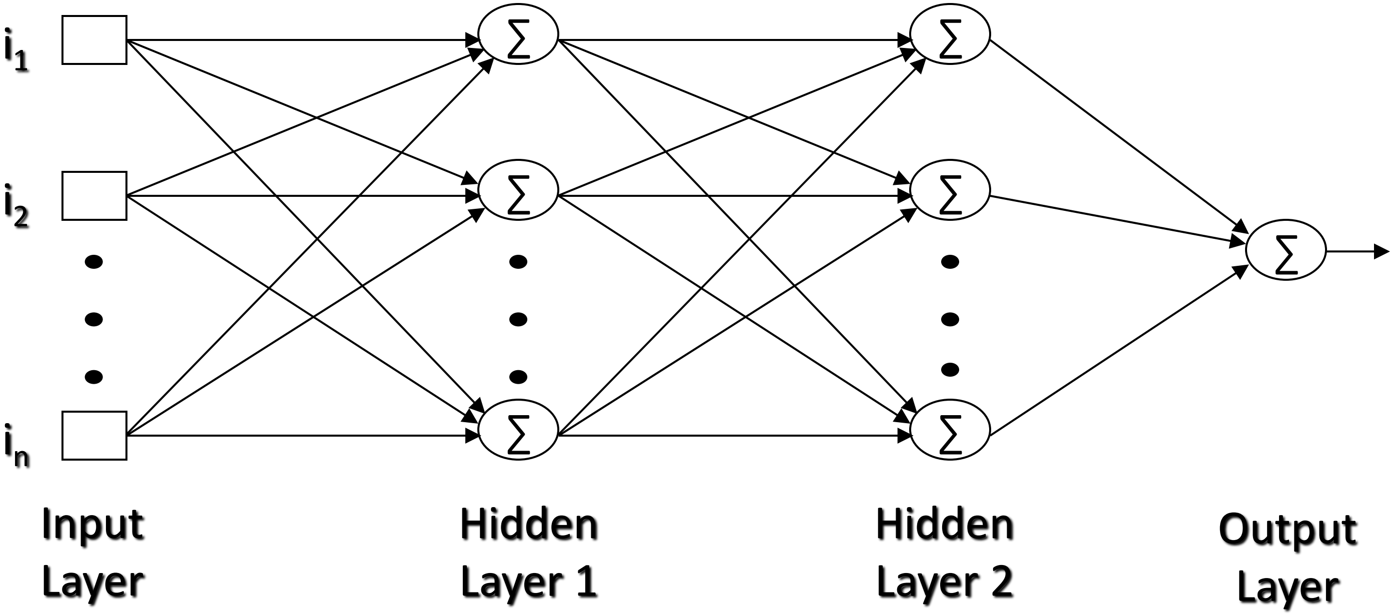
TOAN – How it Works

- On-line DGA Monitors
- Polling Engine
- Analysis Engine
  - Artificial Neural Networks and Expert System
  - Fuzzy Logic
- Exception Based Notification Module
  - Emails responsible individuals when:
    - Fault type changes and/or
    - Fault severity changes

Artificial Neural Networks

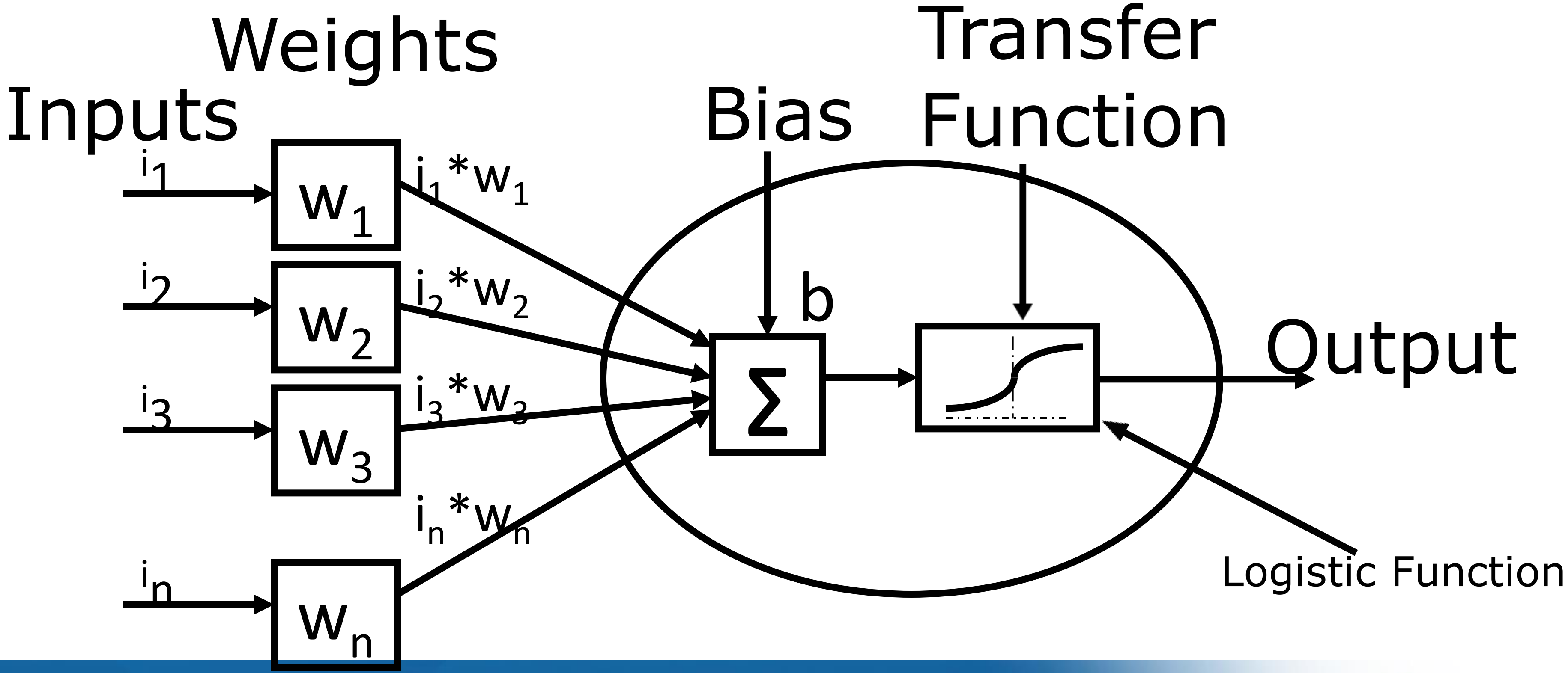
- A network of nodes and weighted connections, which are loosely analogous to the neurons and synapses in the brain.
- Each node sums the inputs from several incoming weighted connections and then applies a transfer function to the sum.
- The transfer function is a smooth, non-linear function
  - logistic function
  - hyperbolic tangent

Artificial Neural Networks

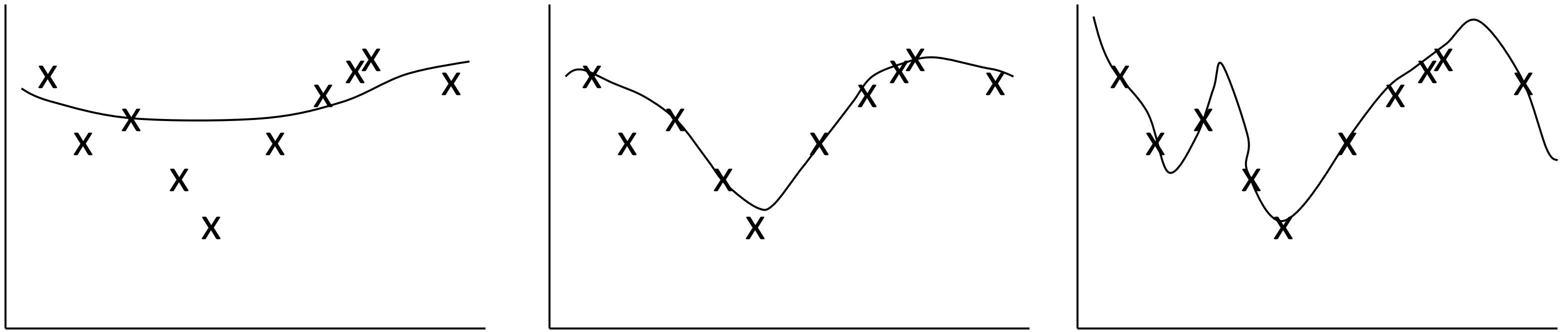


TOAN uses 5 – 15 – 1 and 7 – 21 - 1 MLPs

Artificial Neural Networks

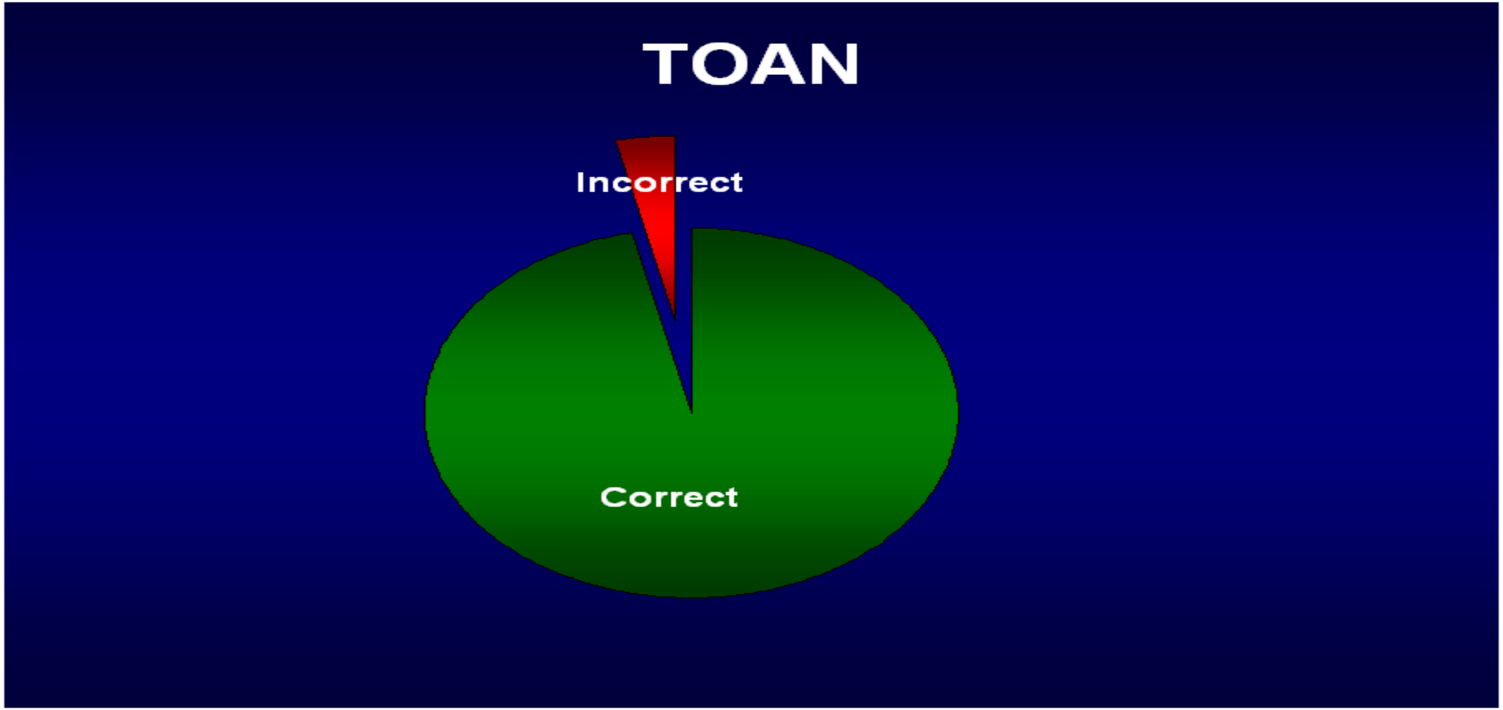


Underfitting and Overfitting



Underfitting | Correct Fit | Overfitting

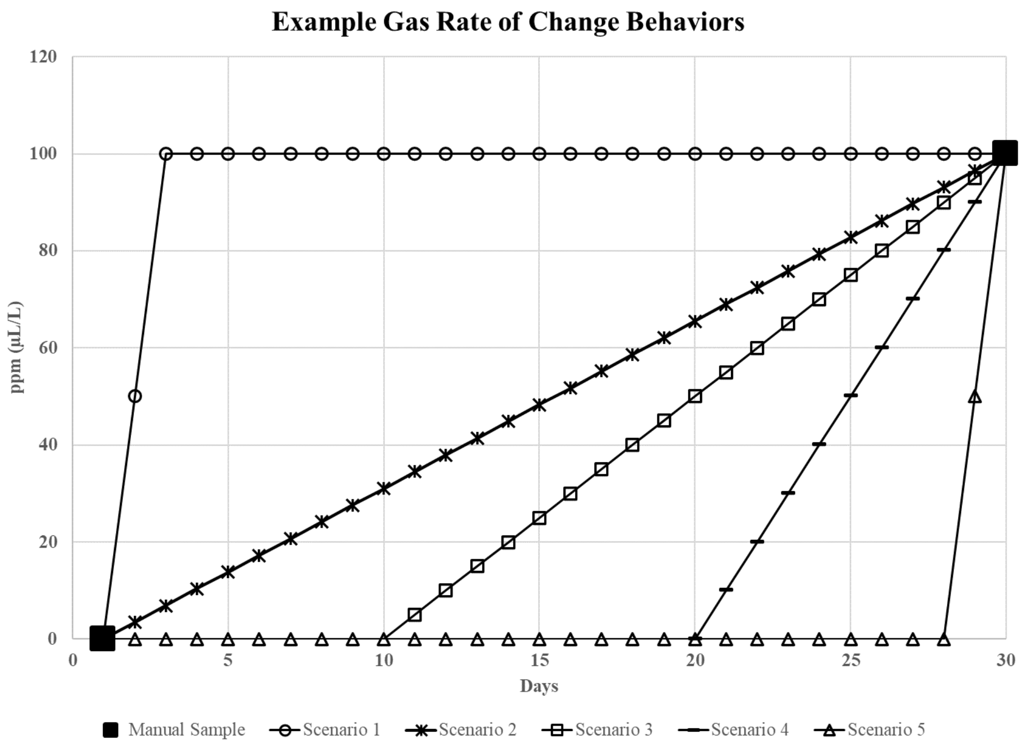
Combined Accuracy of Four TOAN ANNs



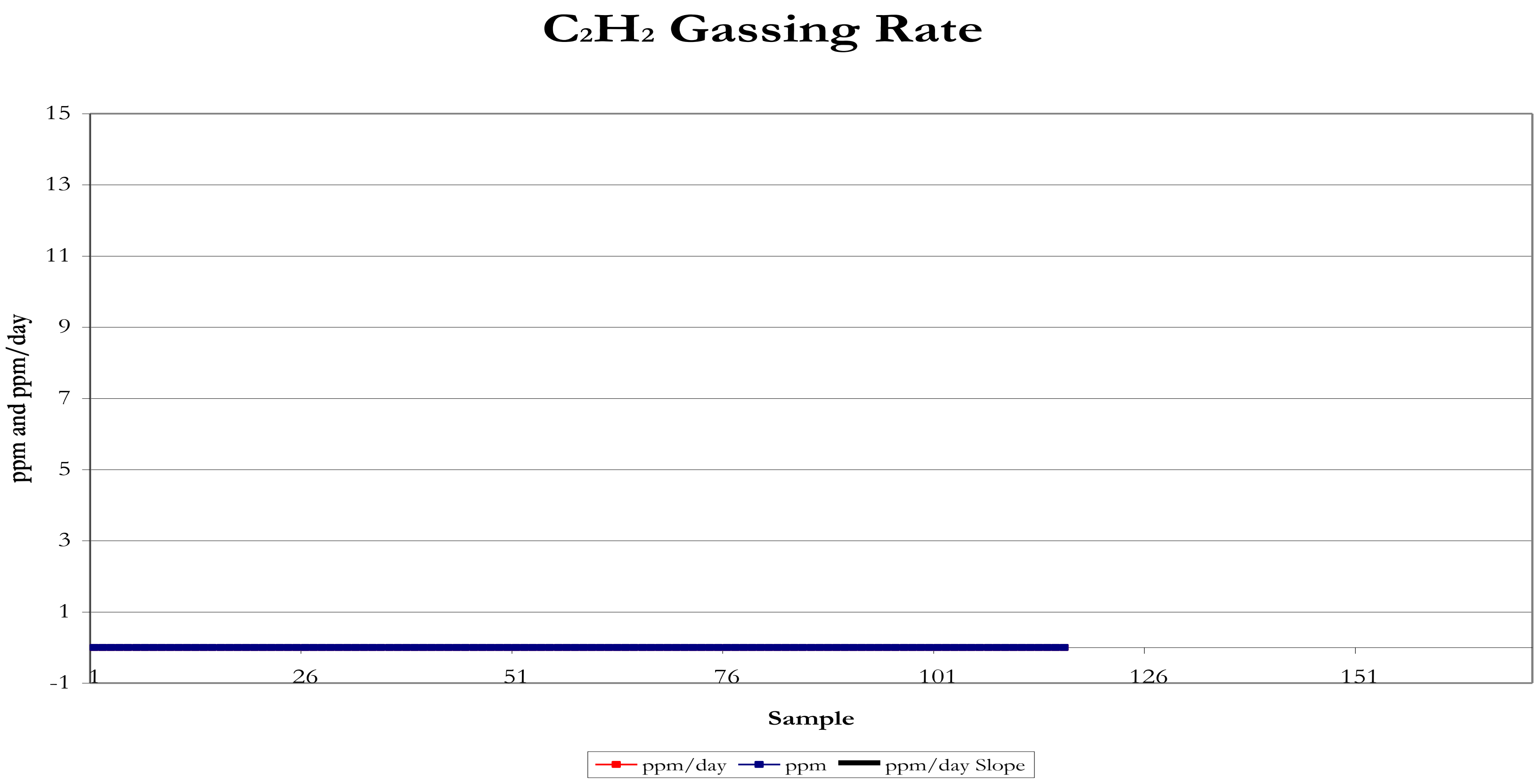
TOAN Results

- It turns mountains of data into ***actionable information***
- > 600,000 DGA samples/year
  - Exception based processing system is 99.9% effective. Only ***0.1%*** of samples are presented to Engineers.

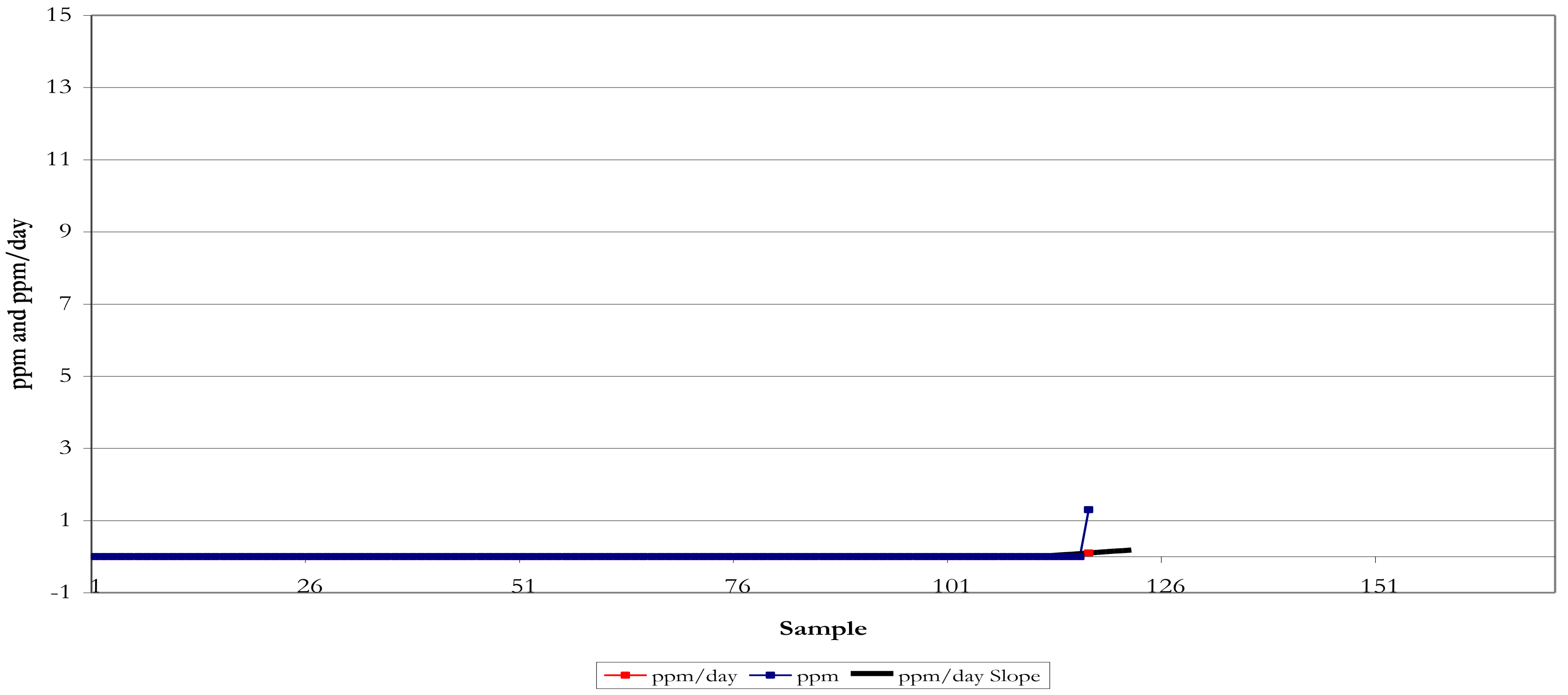
Calculating Rate of Change with Online Monitors



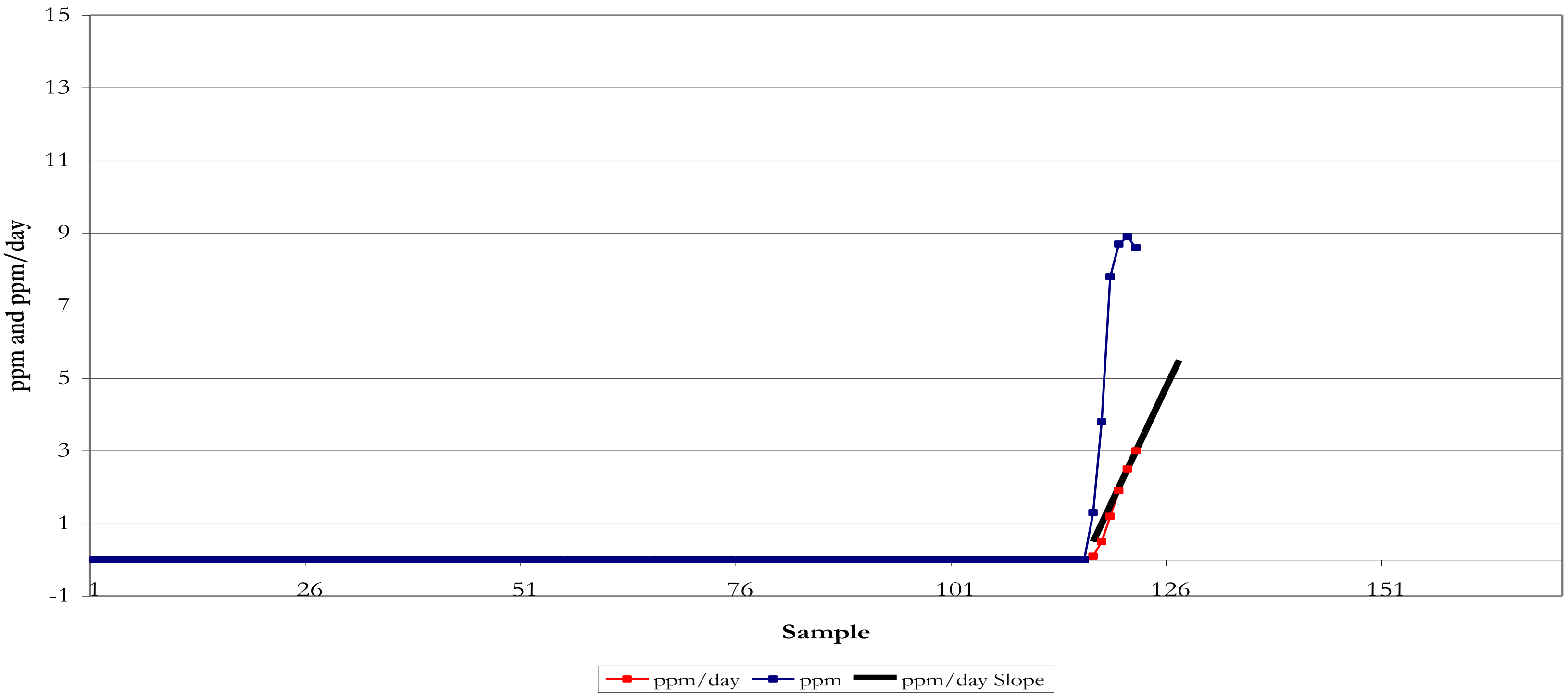
	Rate of Change
Manual Sample	3.33 ppm/day
Scenario 1	0 ppm/day
Scenario 2	3.33 ppm/day
Scenario 3	4.00 ppm/day
Scenario 4	10.00 ppm/day
Scenario 5	50.00 ppm/day

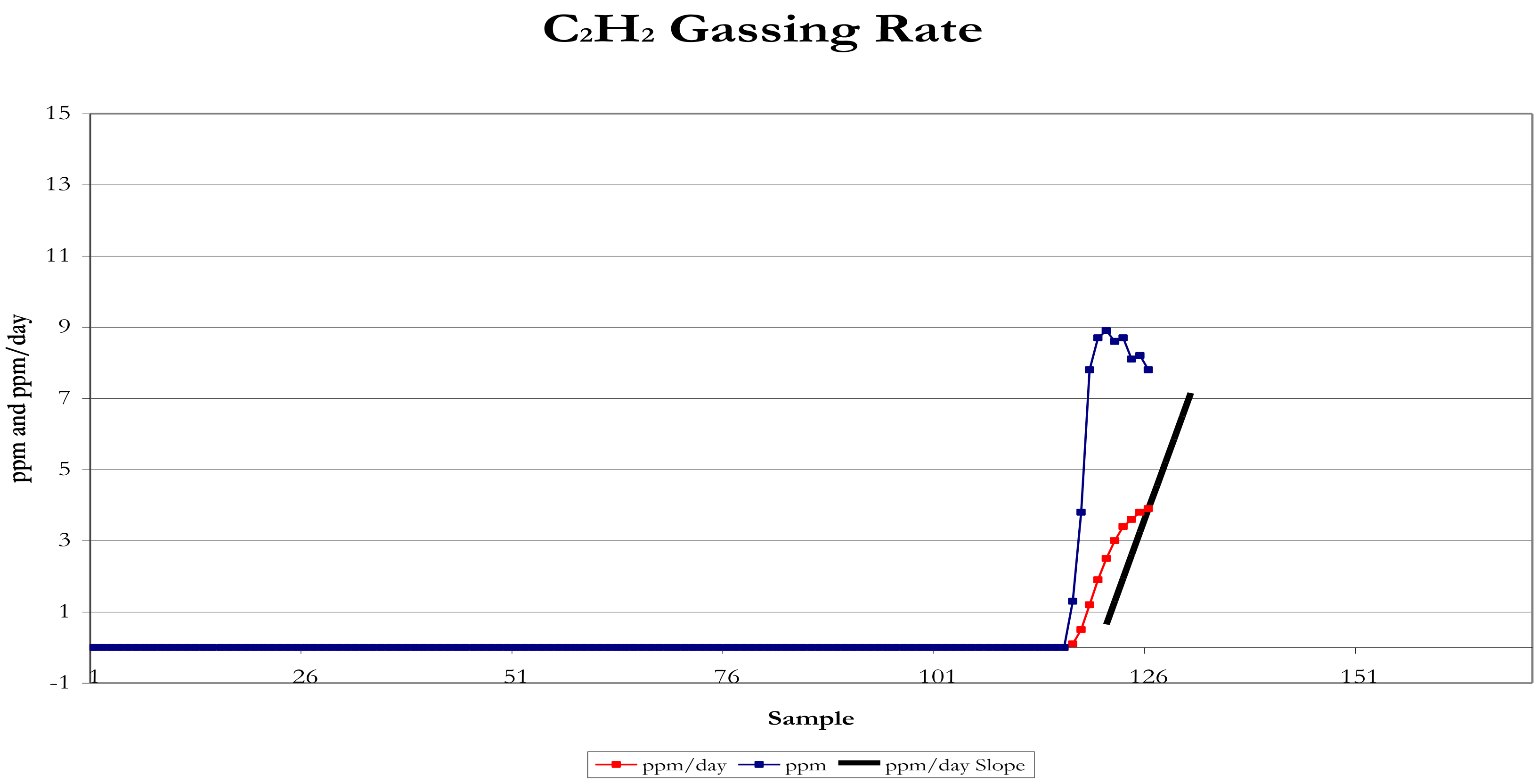

C2H2 Gassing Rate
ppm and ppm/day
15
13
11
9
7
5
3
1
-1
1
26
51
76
101
126
151
Sample
ppm/day
ppm
ppm/day Slope

C_2H_2 Gassing Rate



C_2H_2 Gassing Rate




C₂H₂ Gassing Rate
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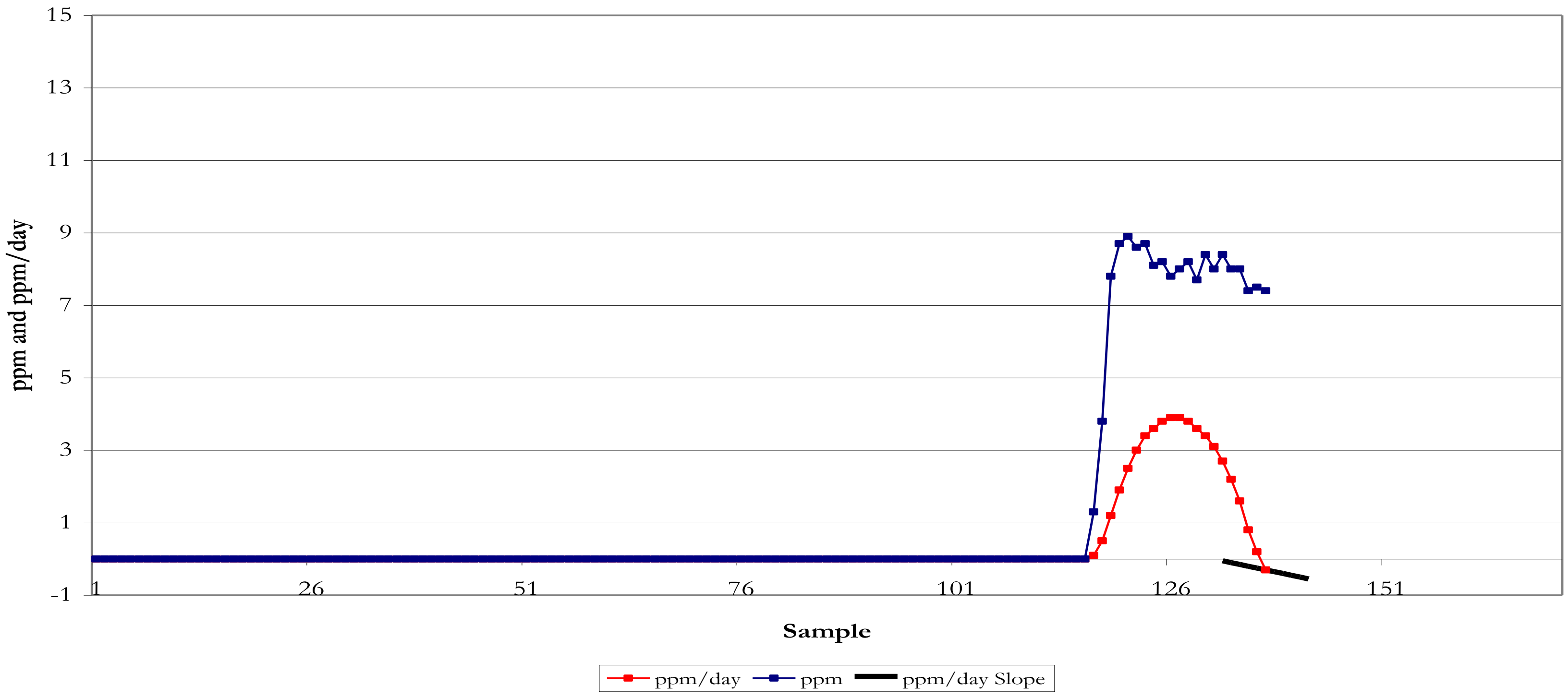
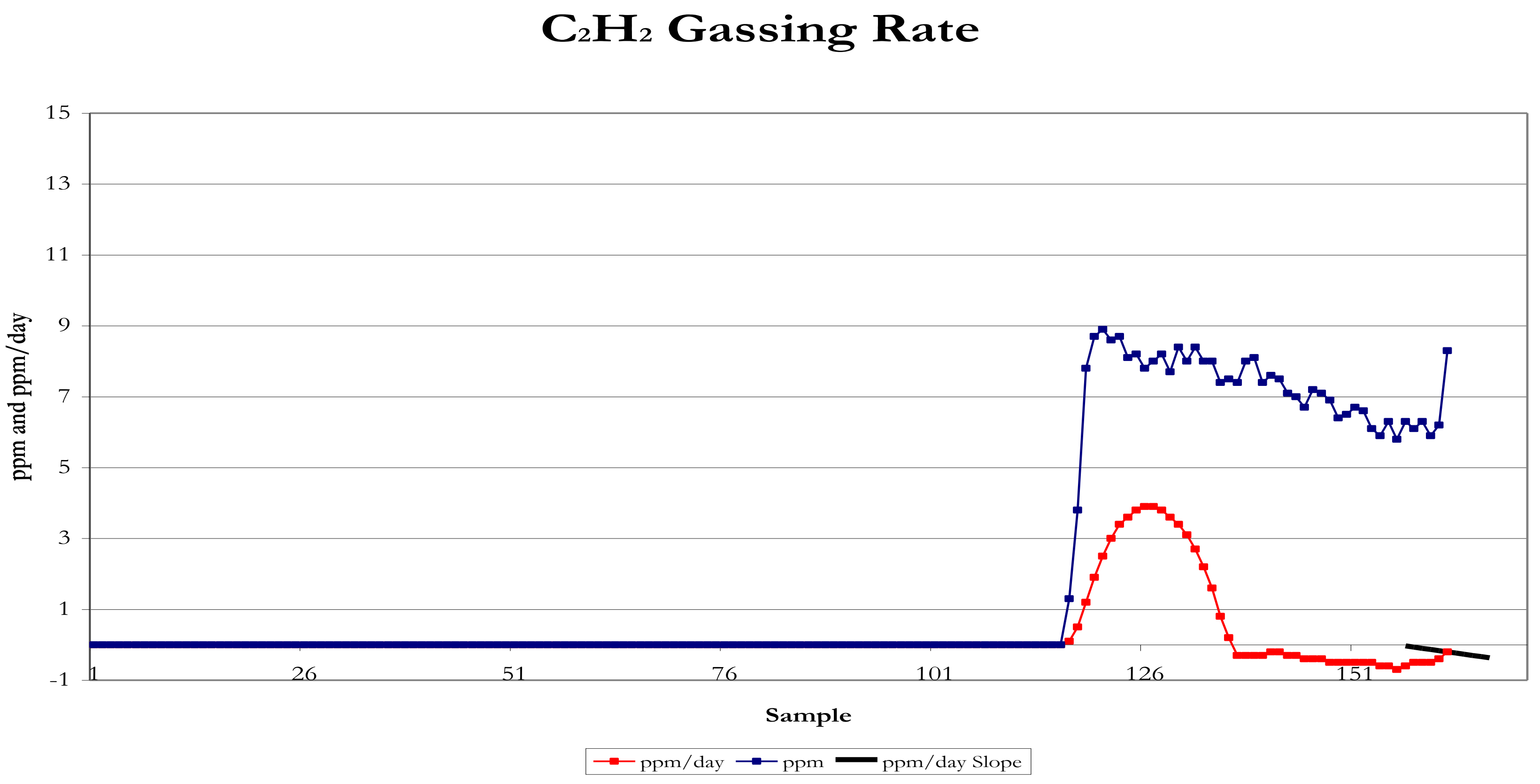
Sample
ppm/day
ppm
ppm/day Slope

C_2H_2 Gassing Rate

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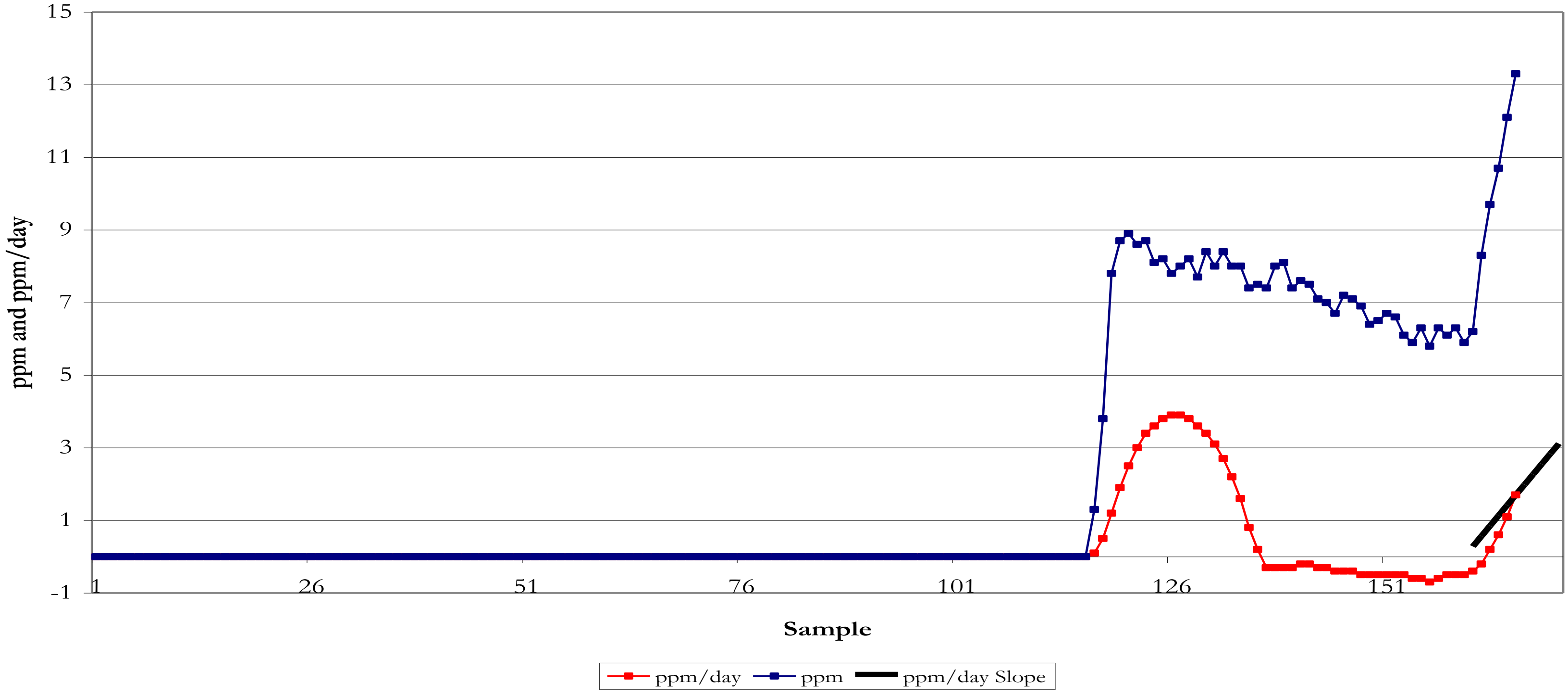

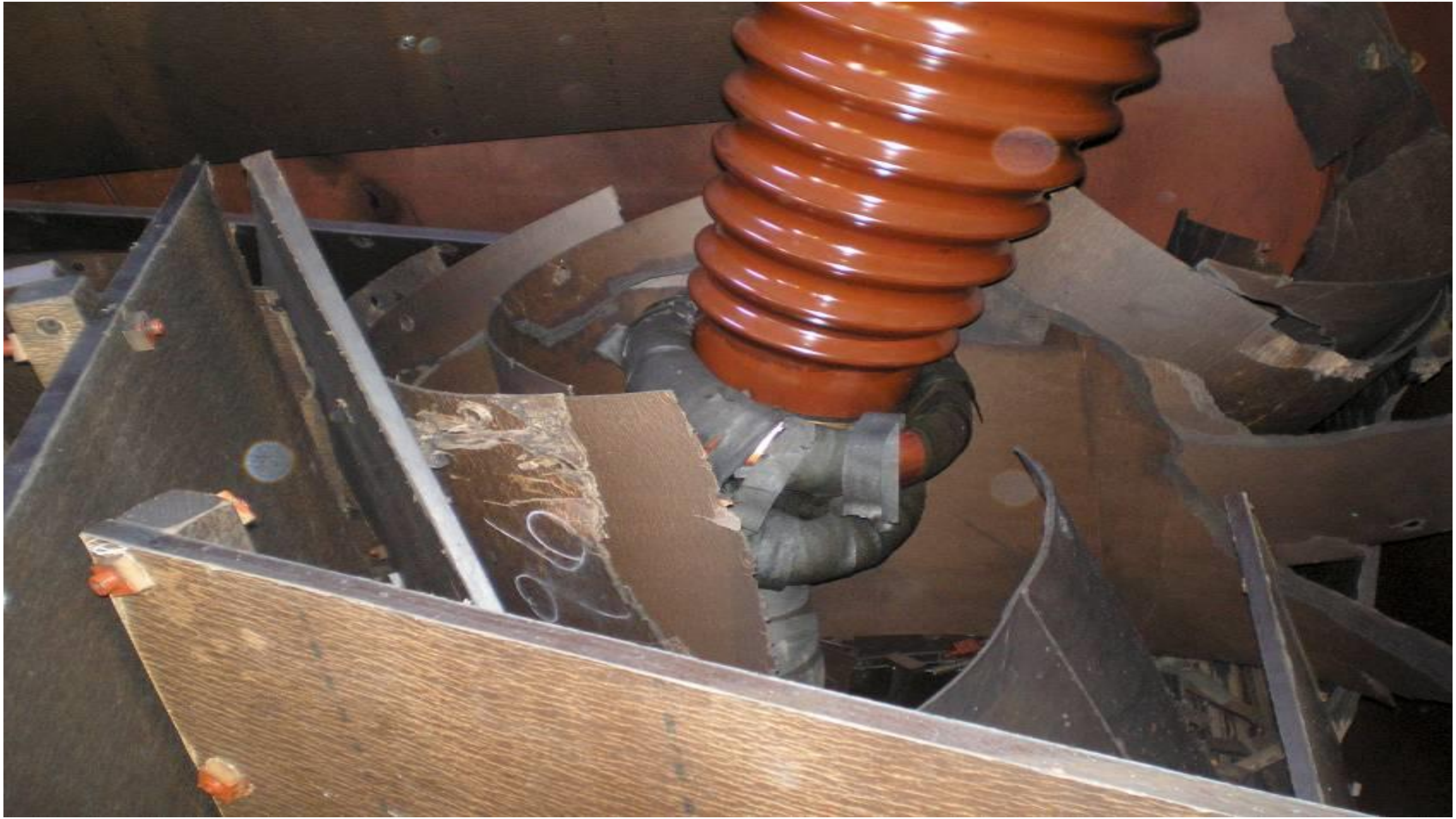

Weaknesses in Current Technology

- When the gassing pattern of a transformer begins to change, the on-line monitors':
  - Estimation of gassing rate lags the actual gassing rate
  - The reported gassing rate underestimates the actual gassing rate

Time Series Data Mining

- Spot trends in large volume of data
- Techniques exist for data mining on-line data
  - Can spot trends as they are happening
- Techniques don’t rely on fixed intervals

U.S. - Canadian Foreign Exchange Rate (Canadian Dollars to One U.S. Dollar)

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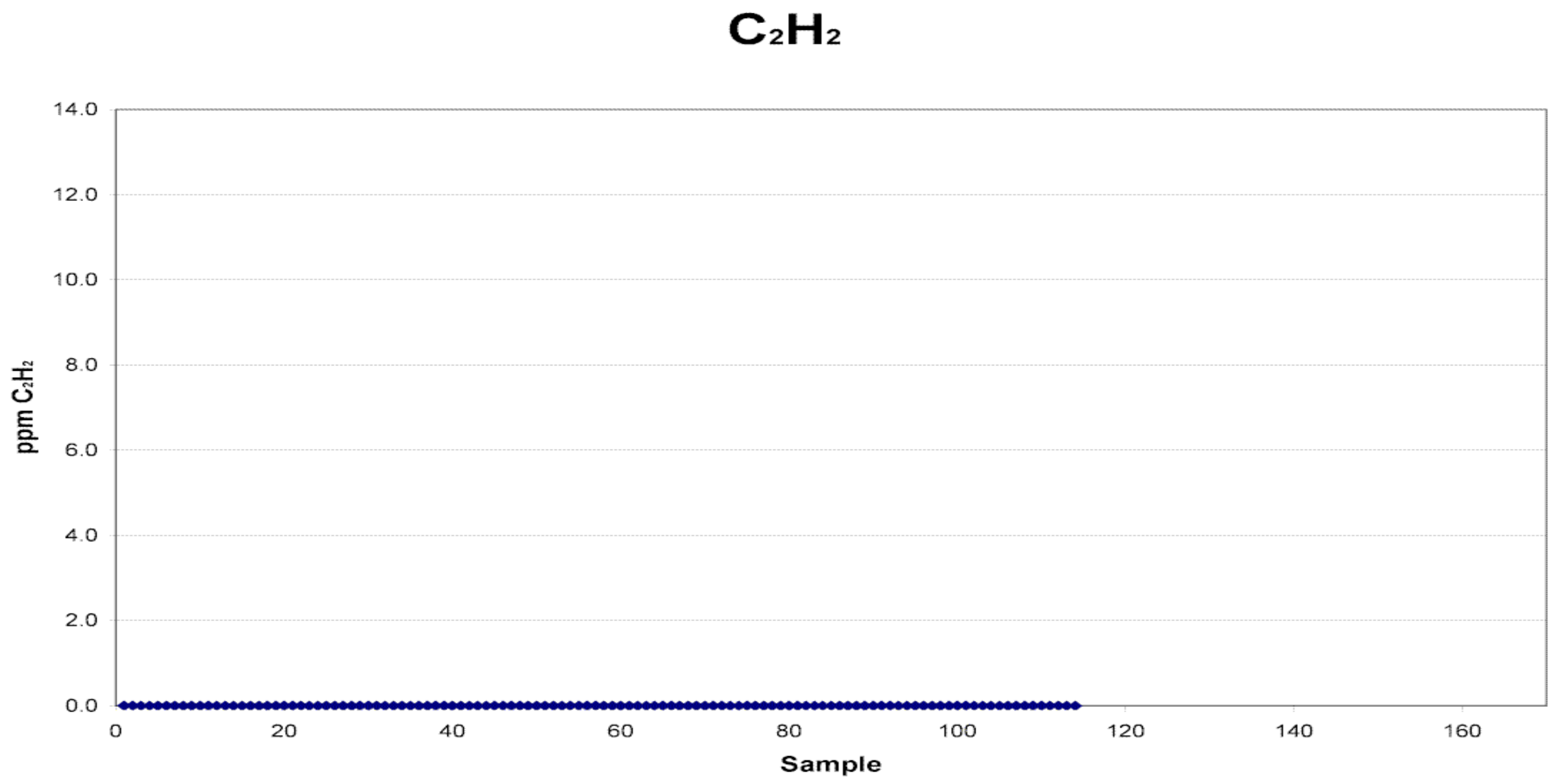
Piecewise Linear Approximation

- Used for representing time series data
  - Electrocardiograms
  - Stock market closing prices
  - Monetary exchange rate
- Can compress large amounts of data
- Provides an alternative to fixed intervals
- For DGA the gassing rate is the segment’s slope


C2H2
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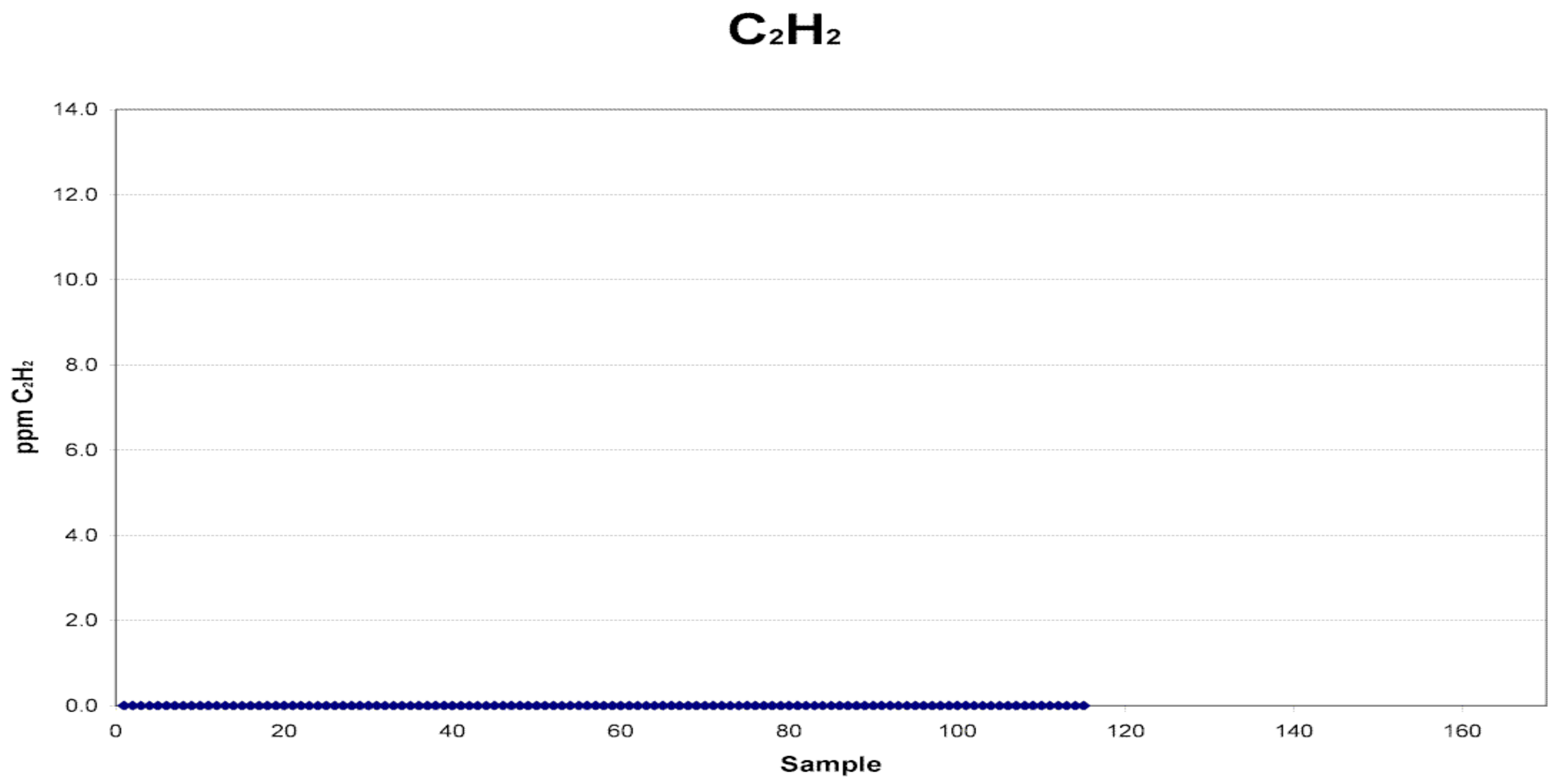

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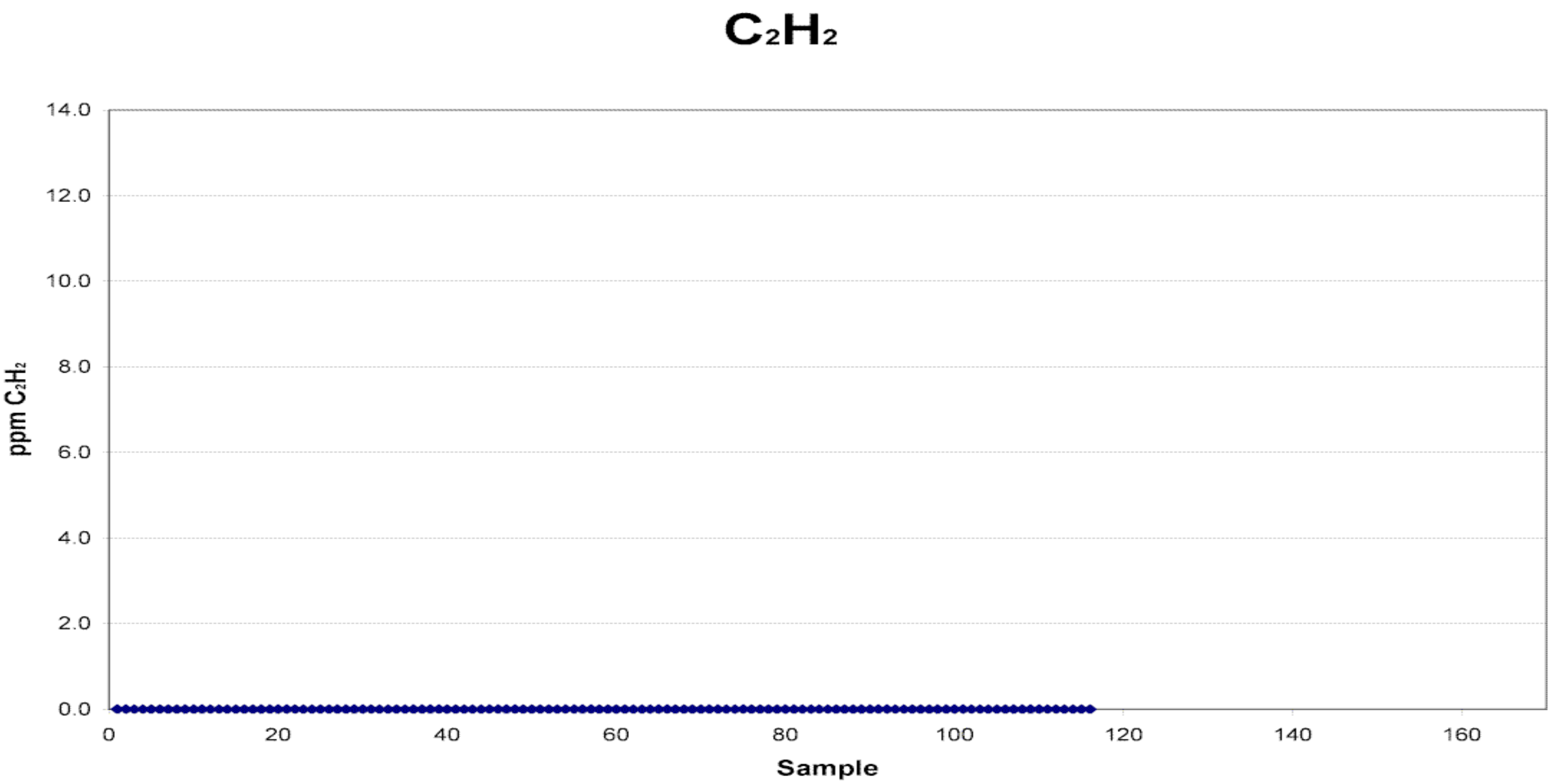
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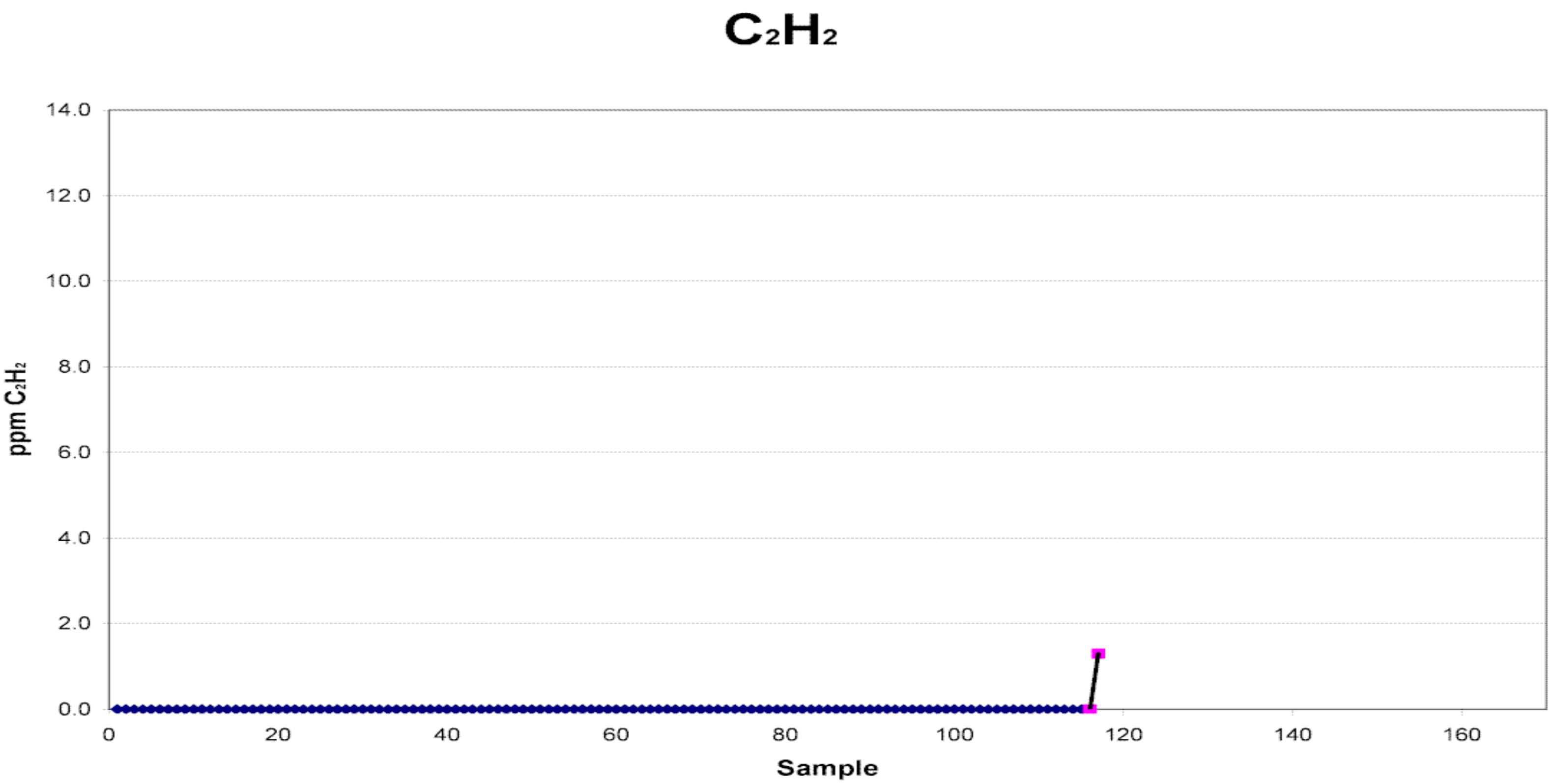

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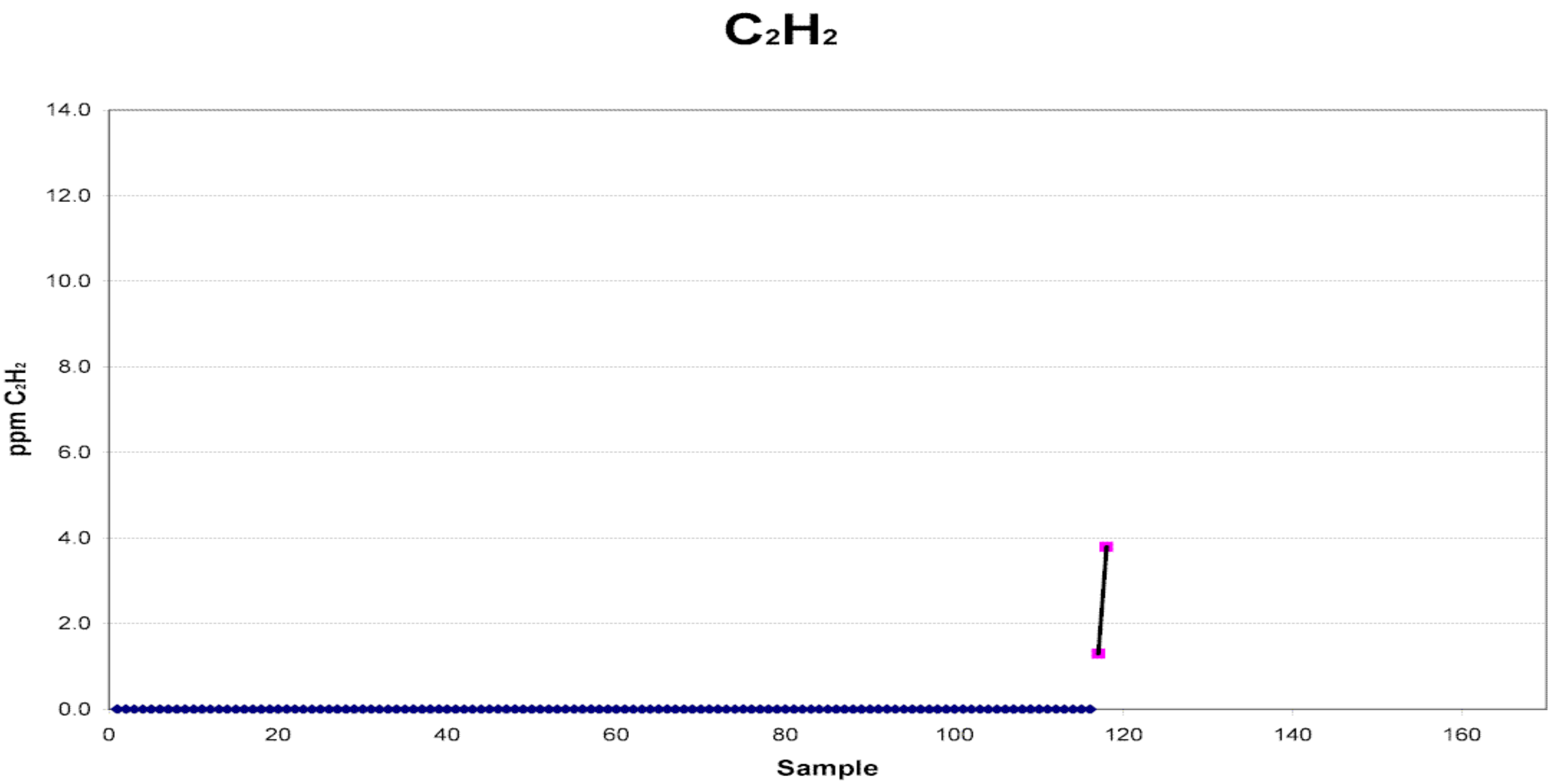

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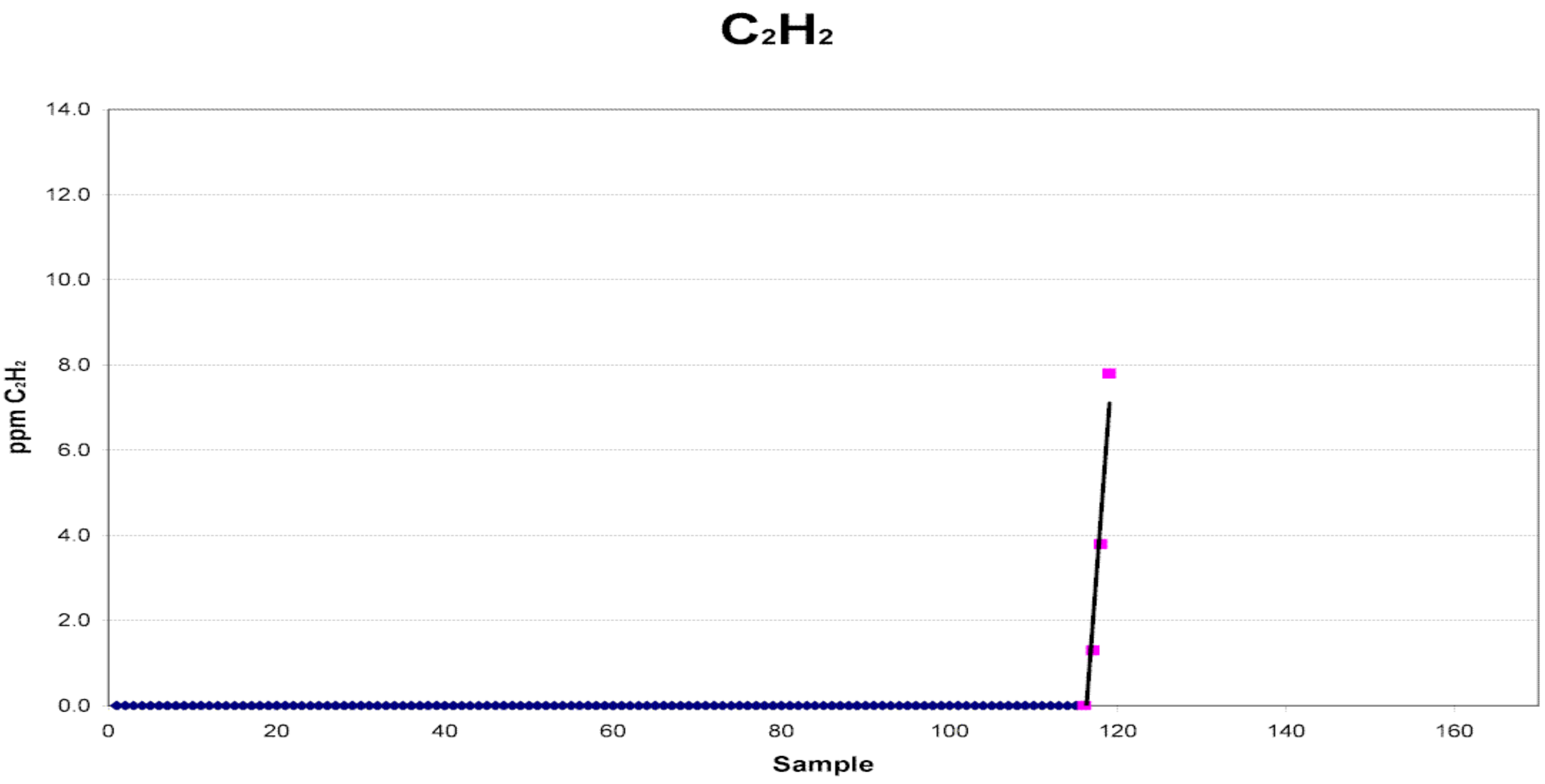

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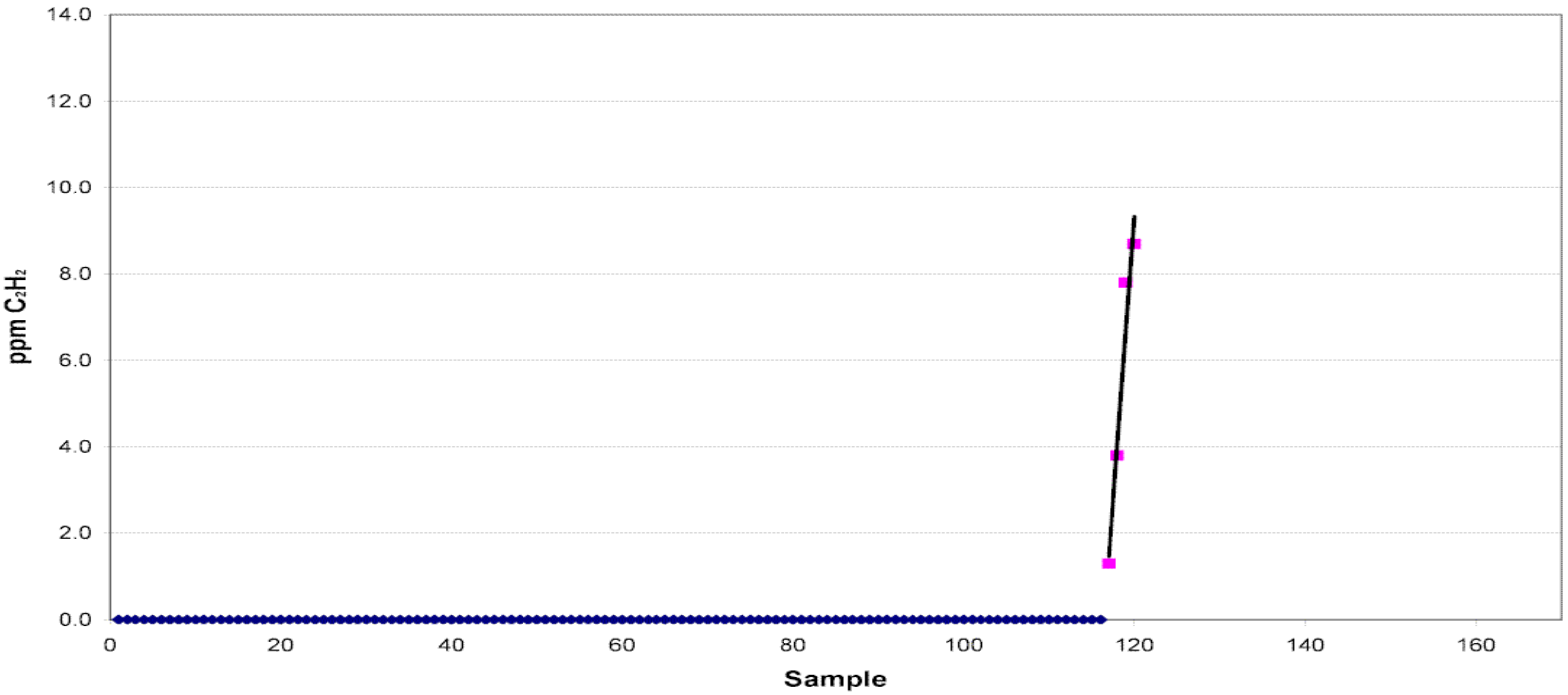
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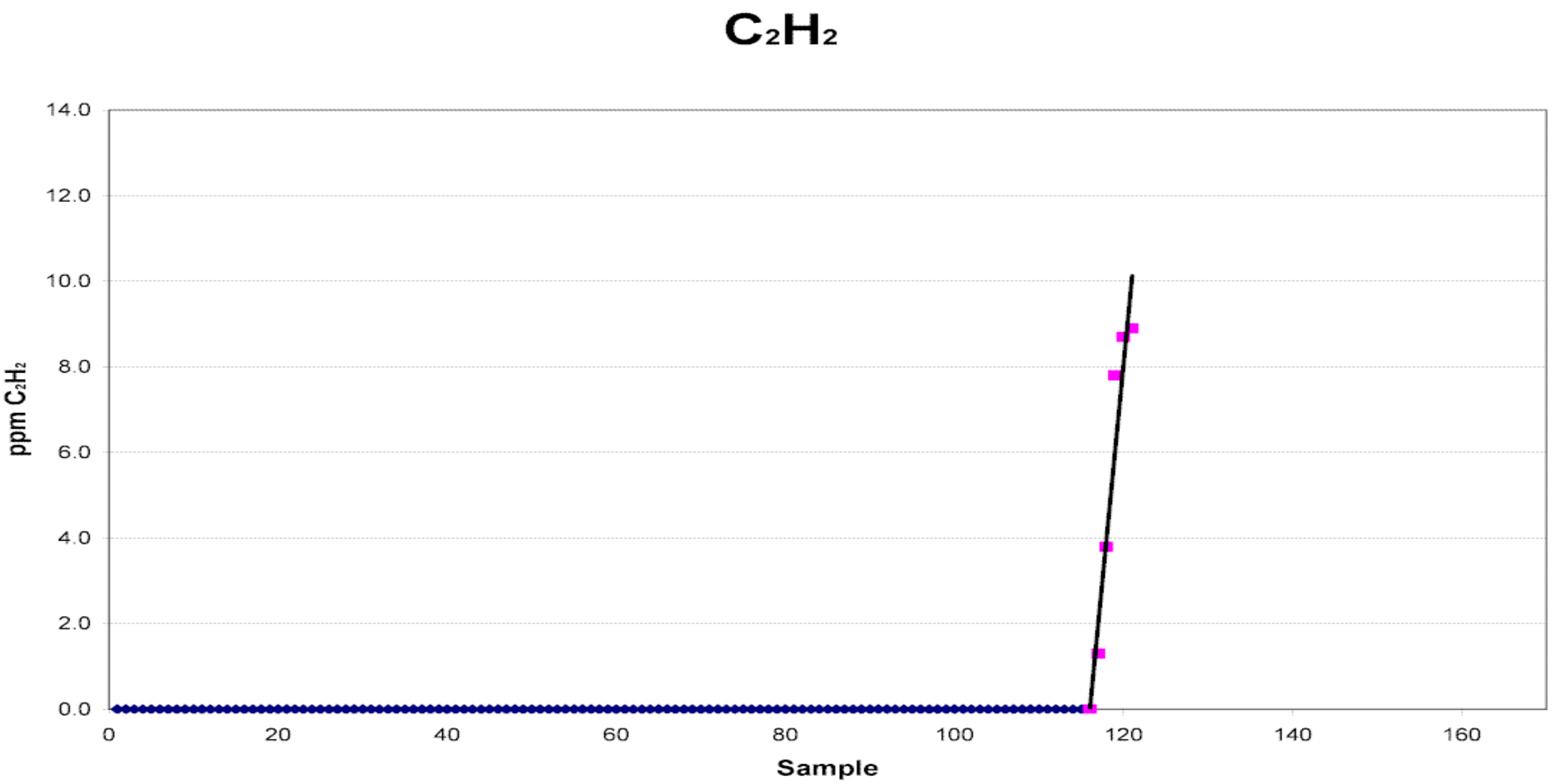

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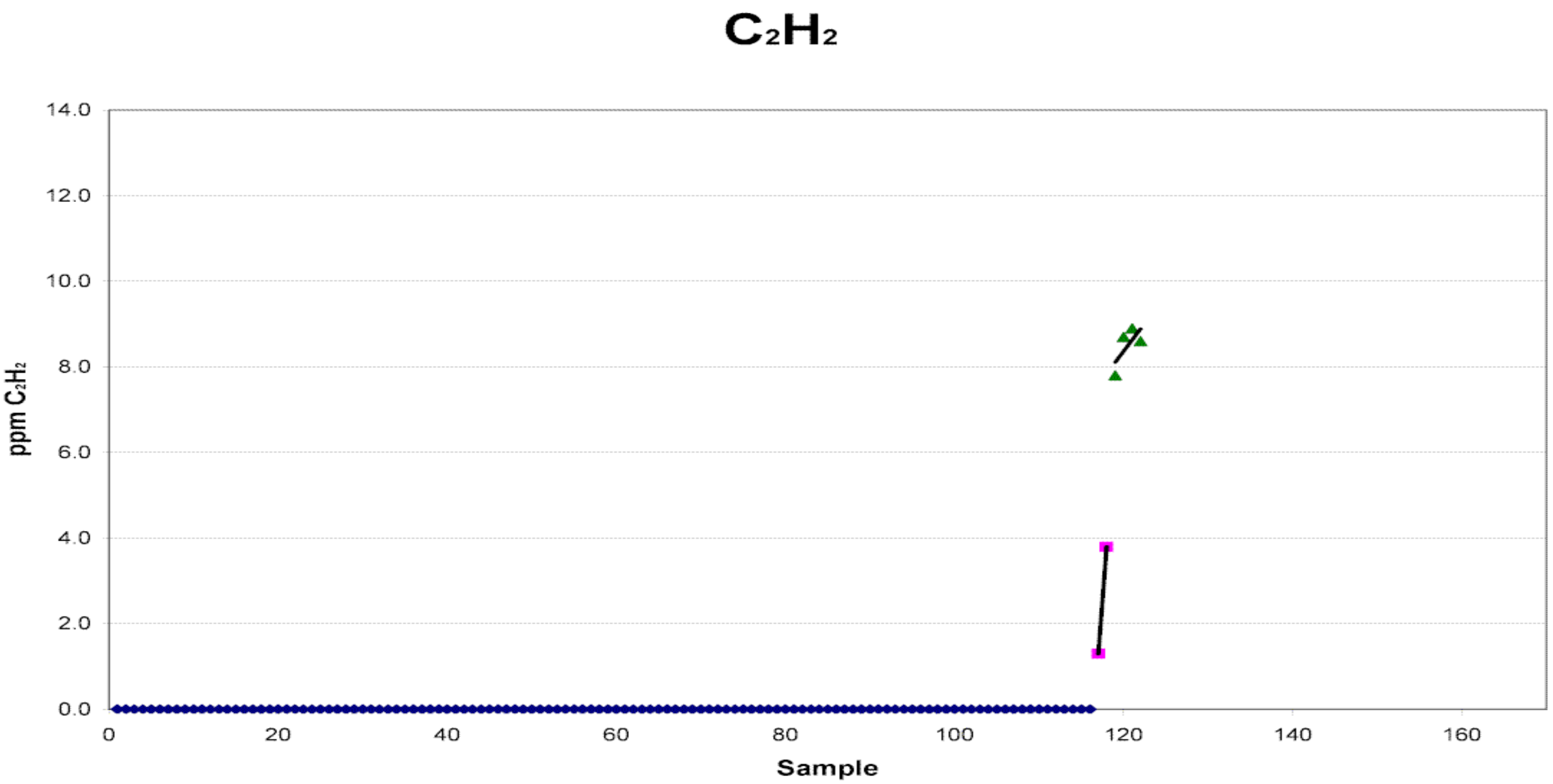
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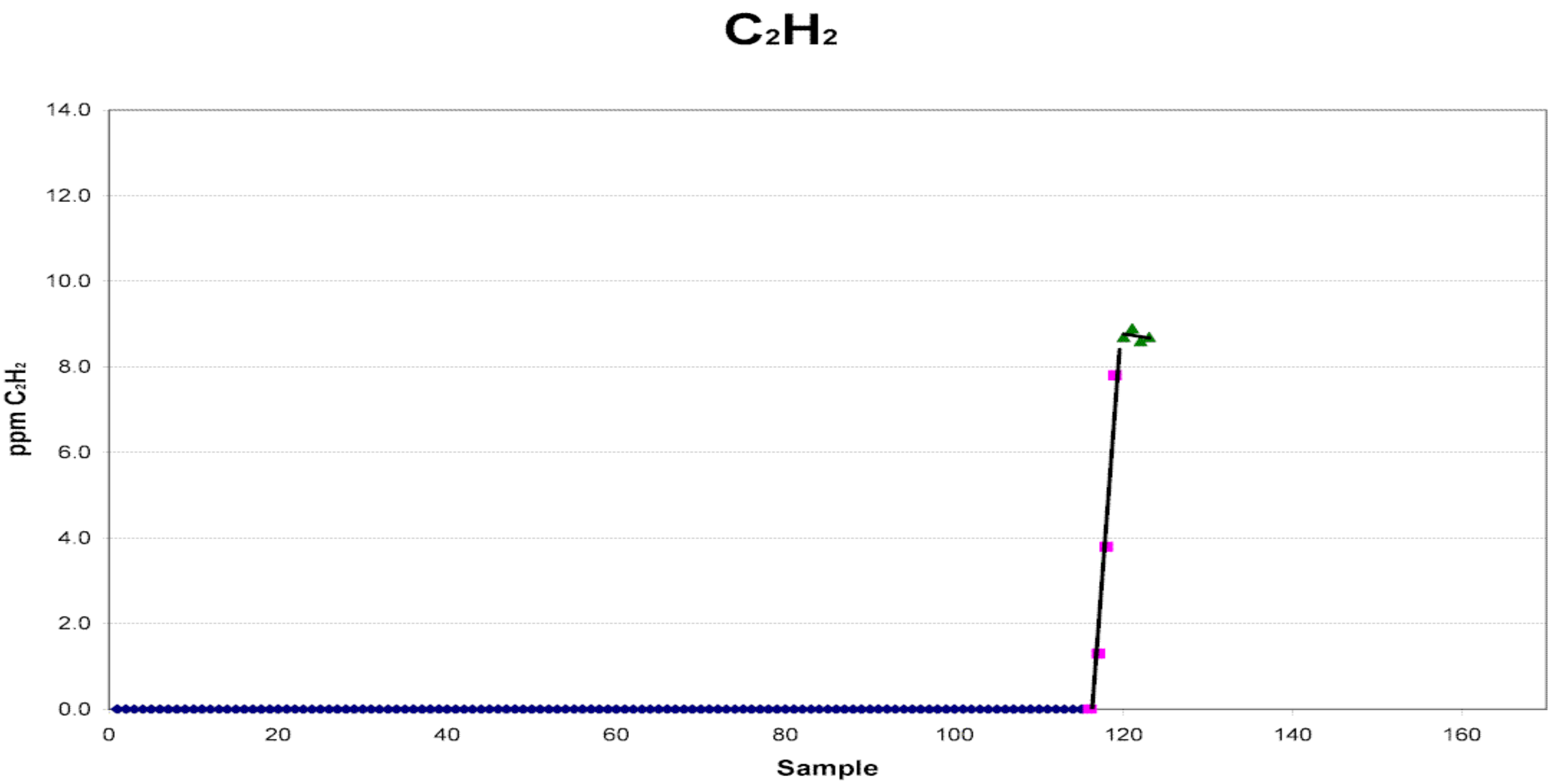

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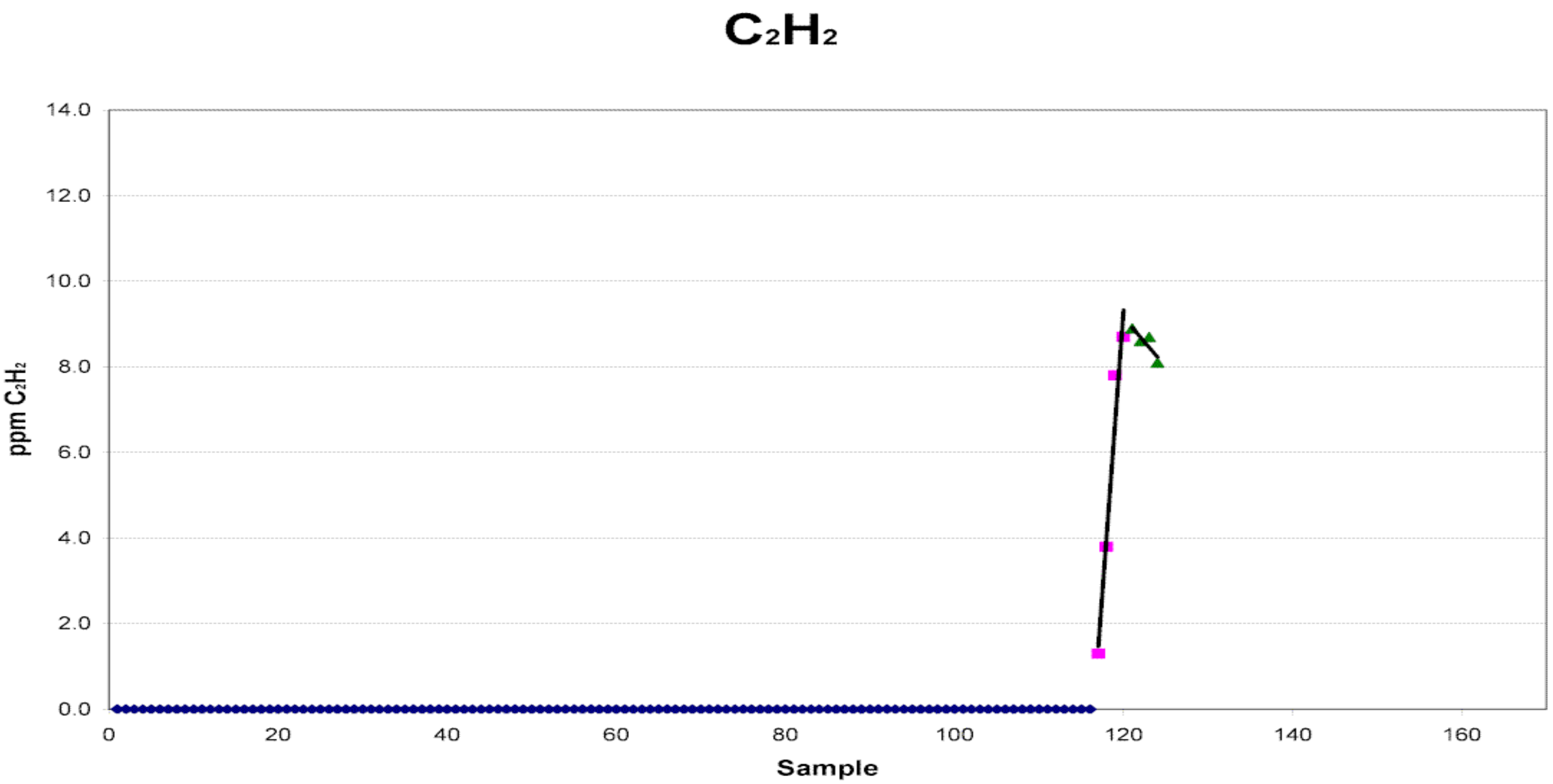

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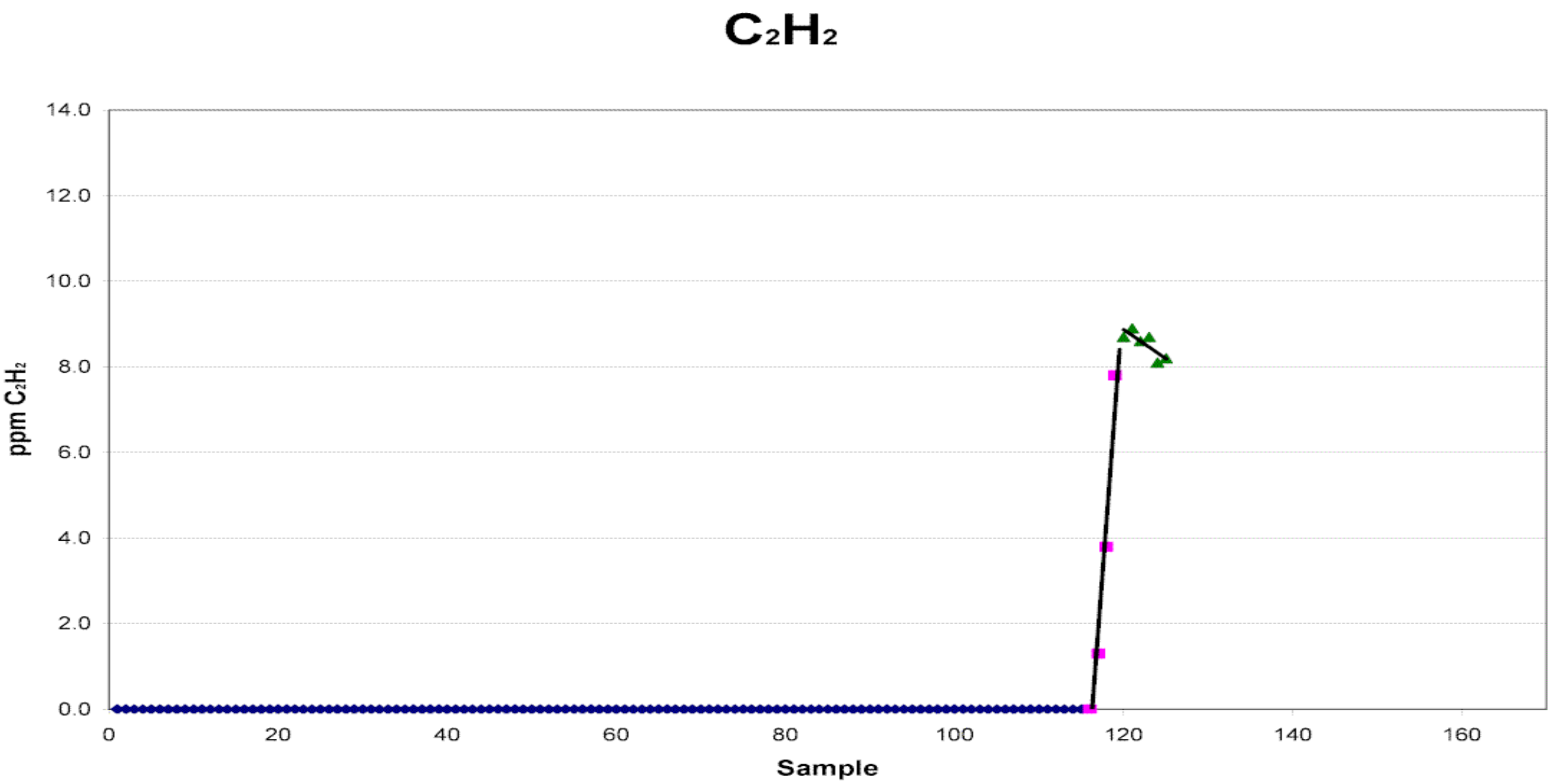
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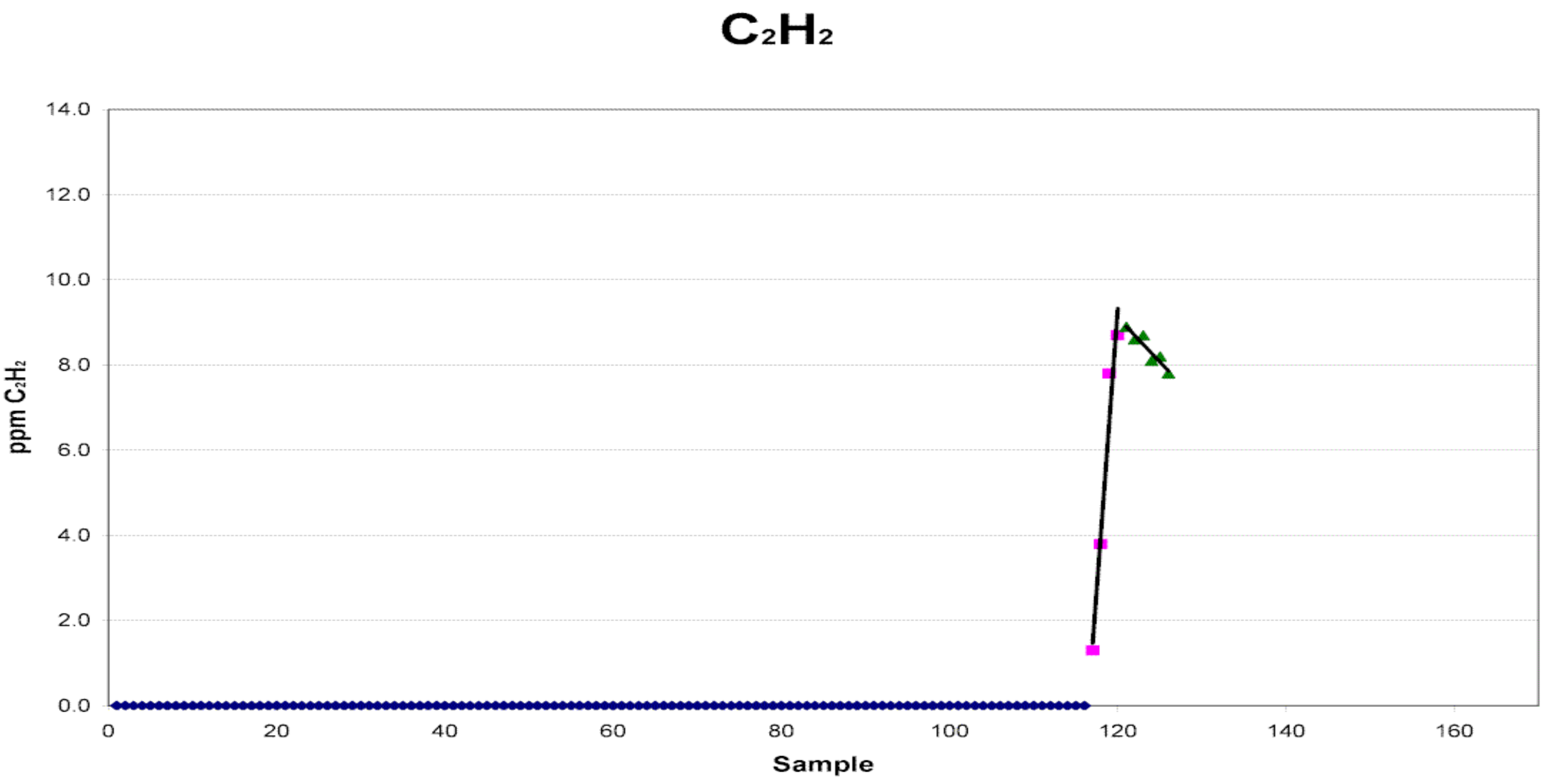

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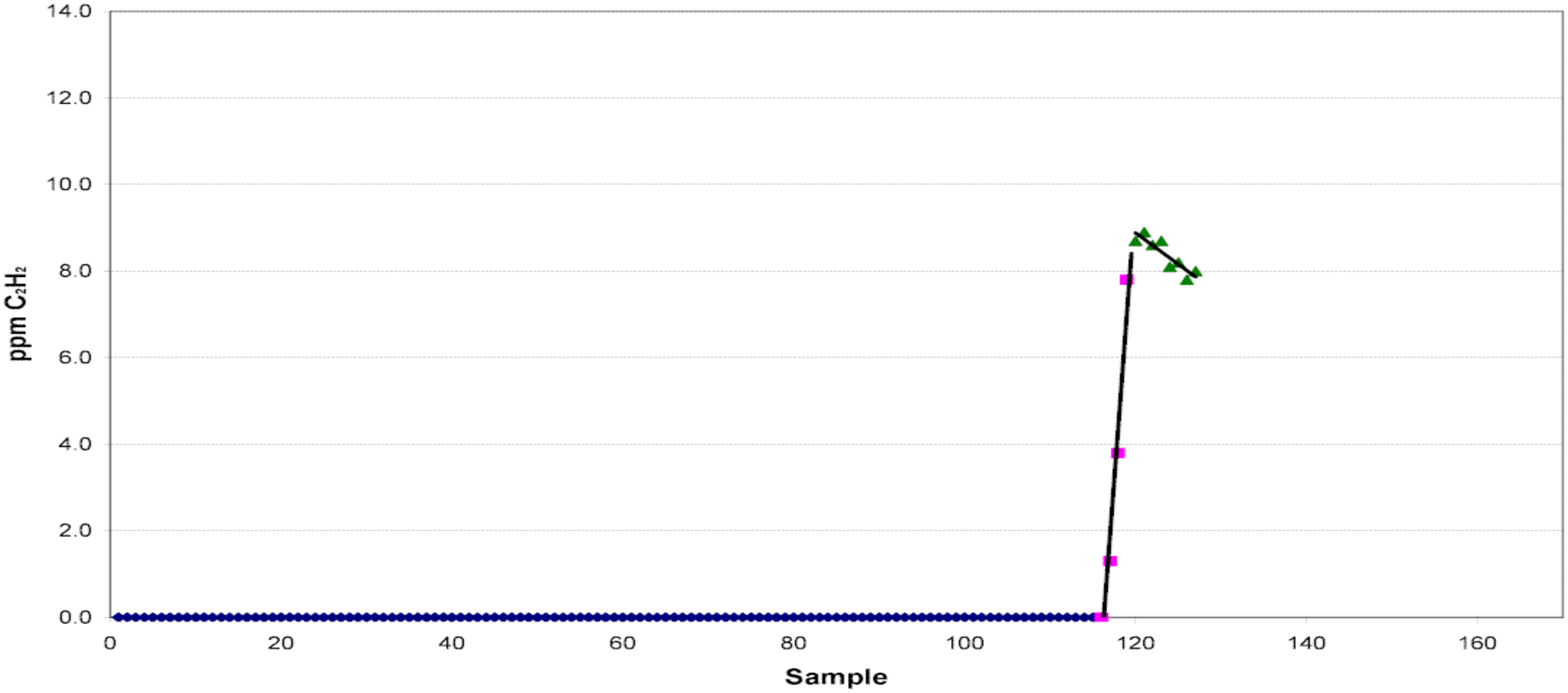

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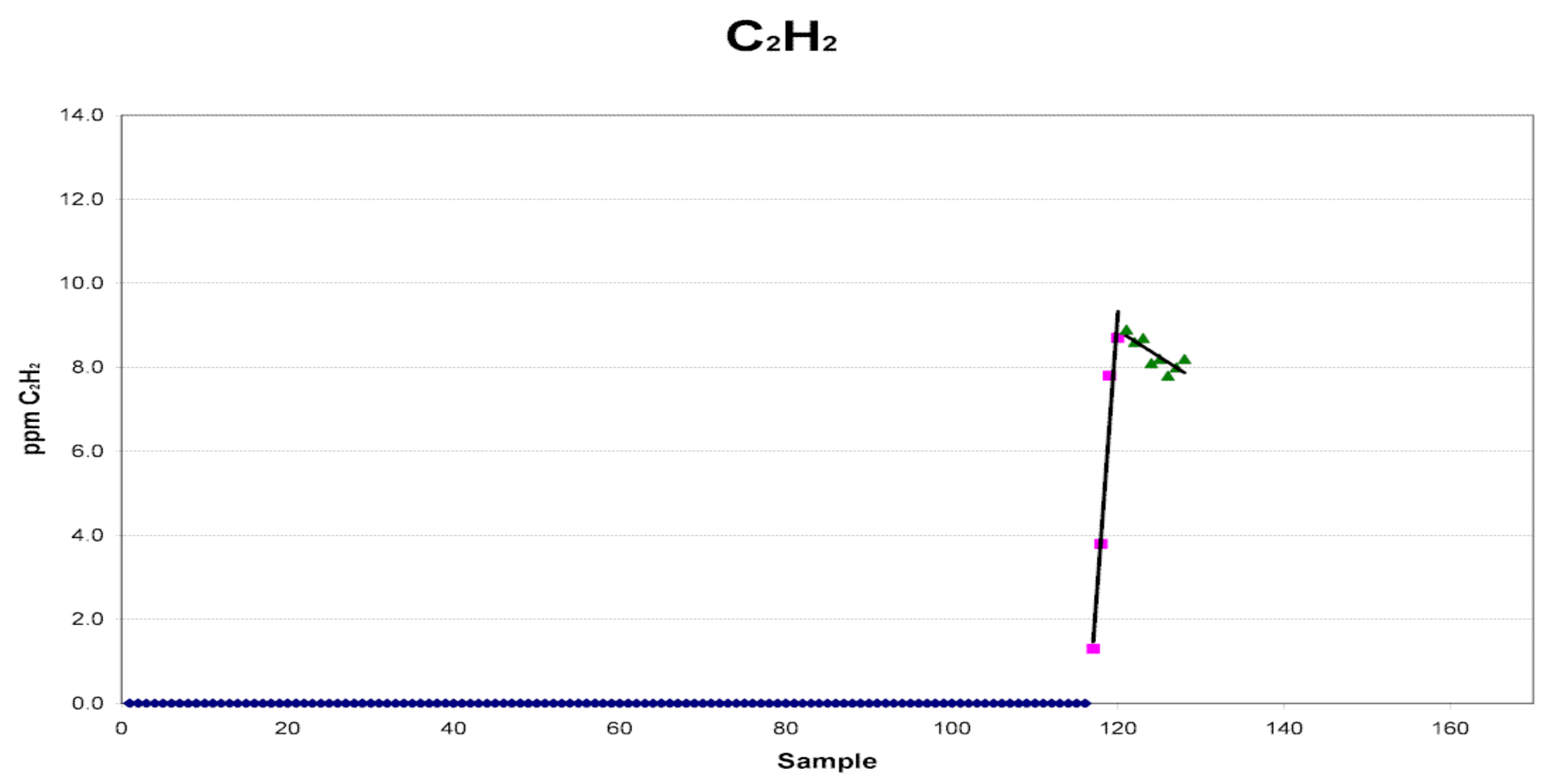

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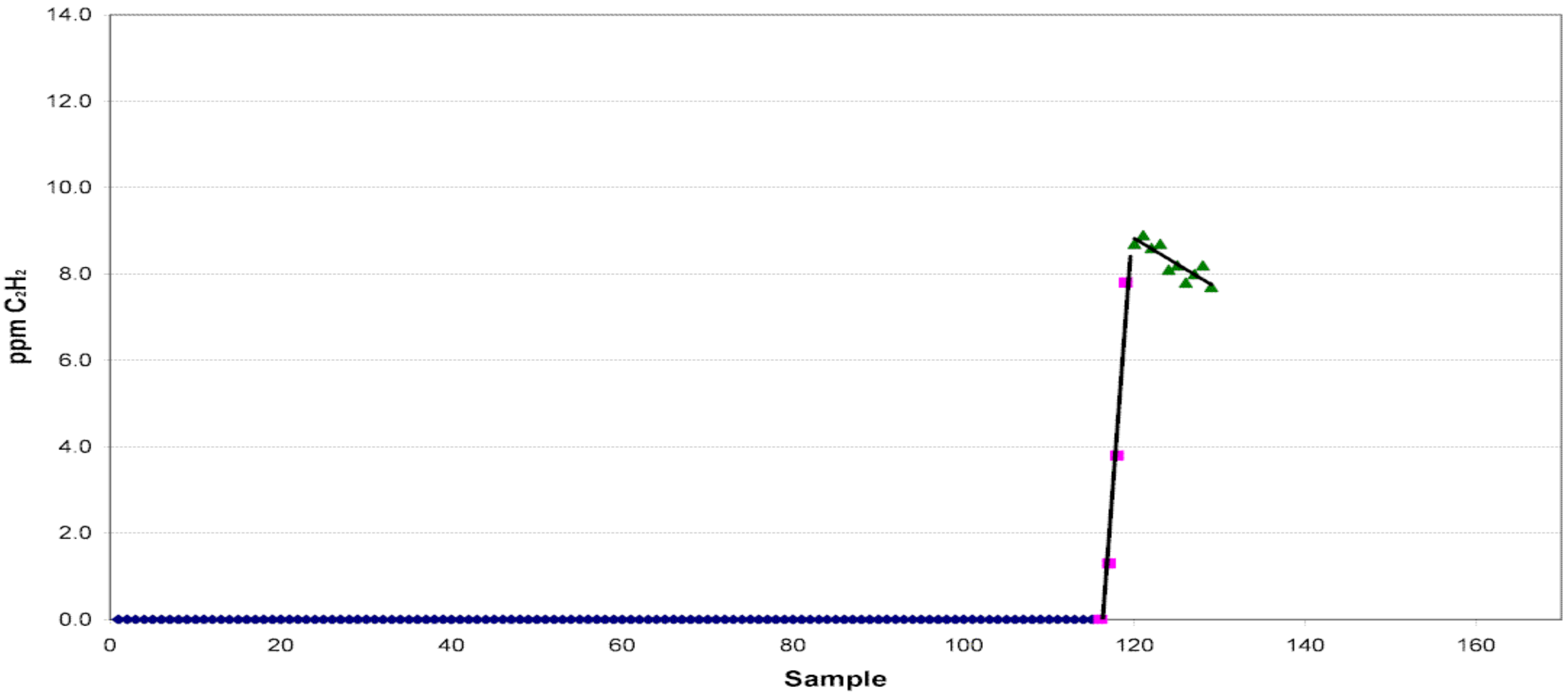

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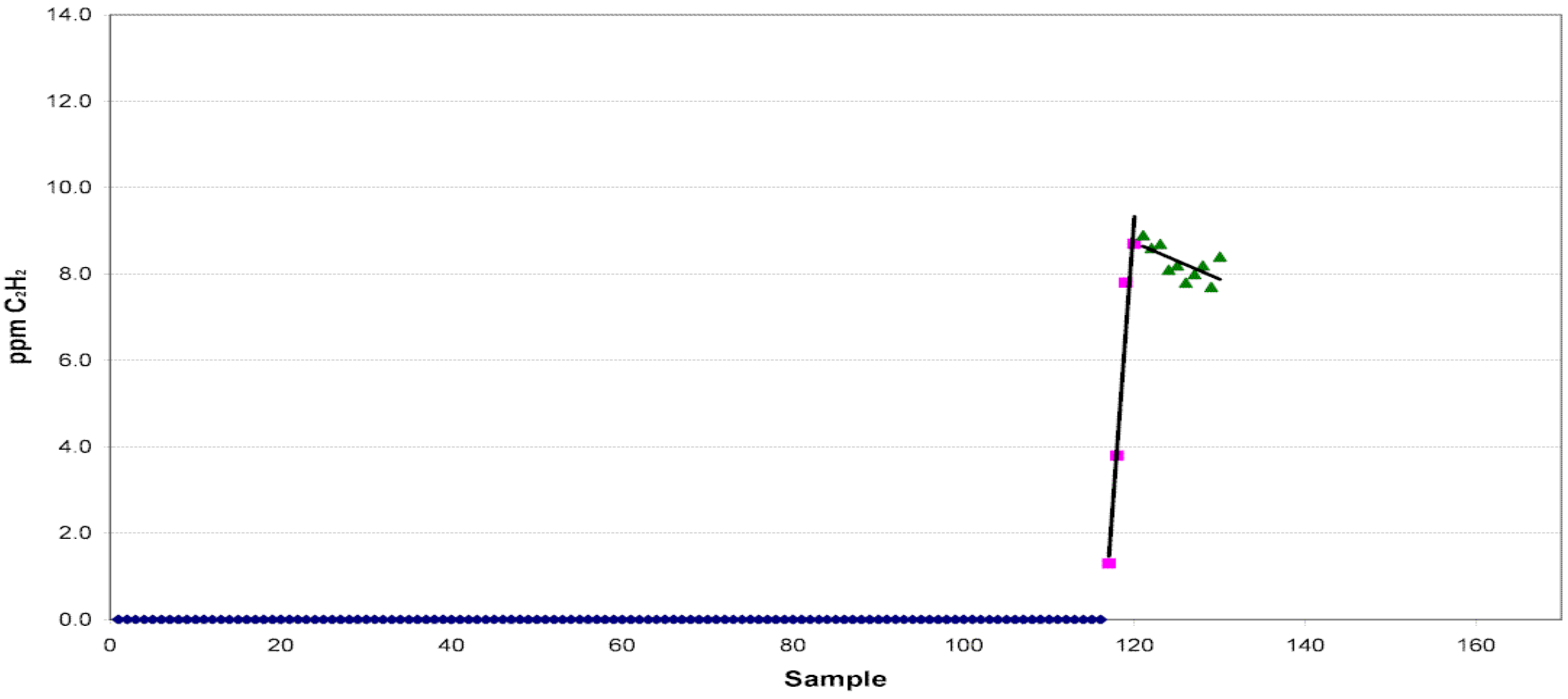

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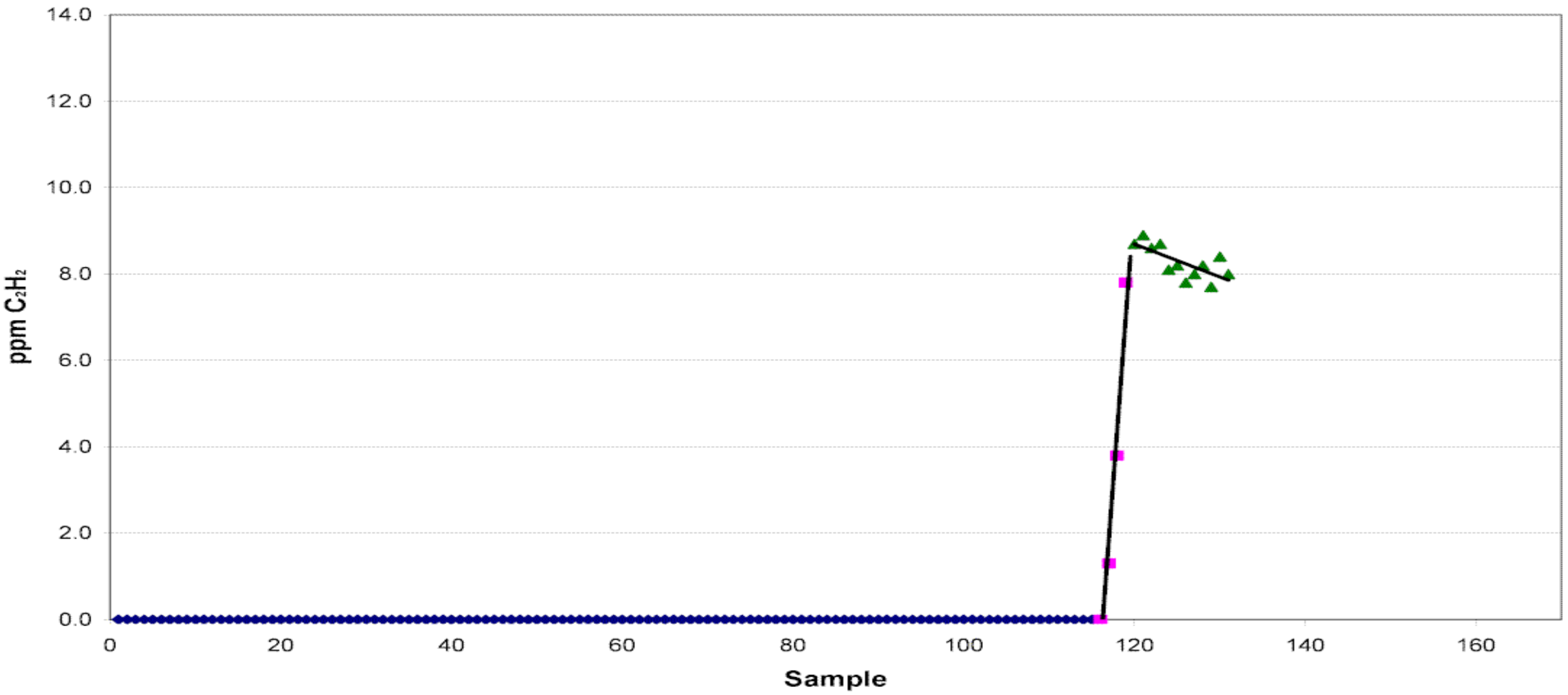

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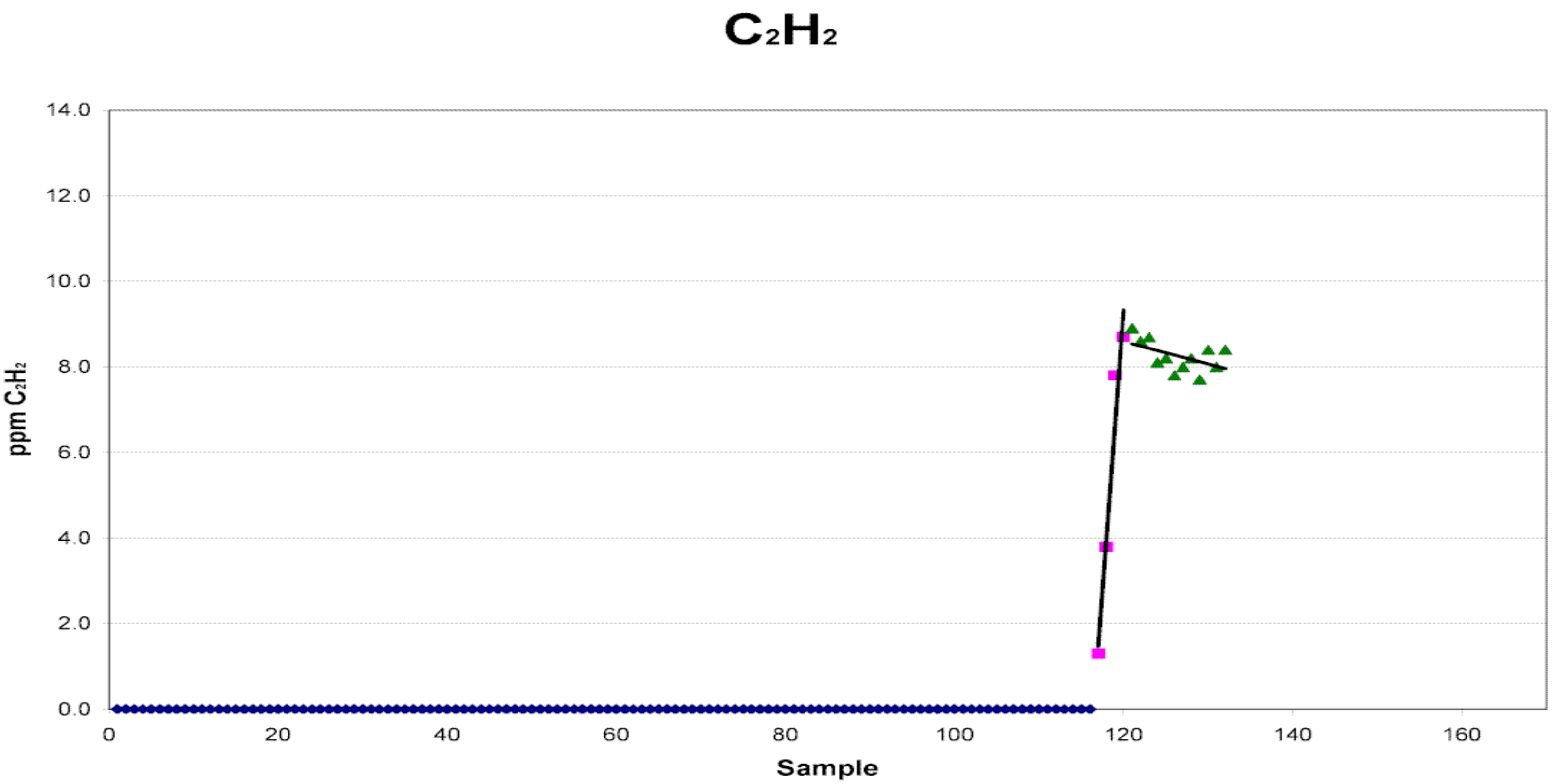

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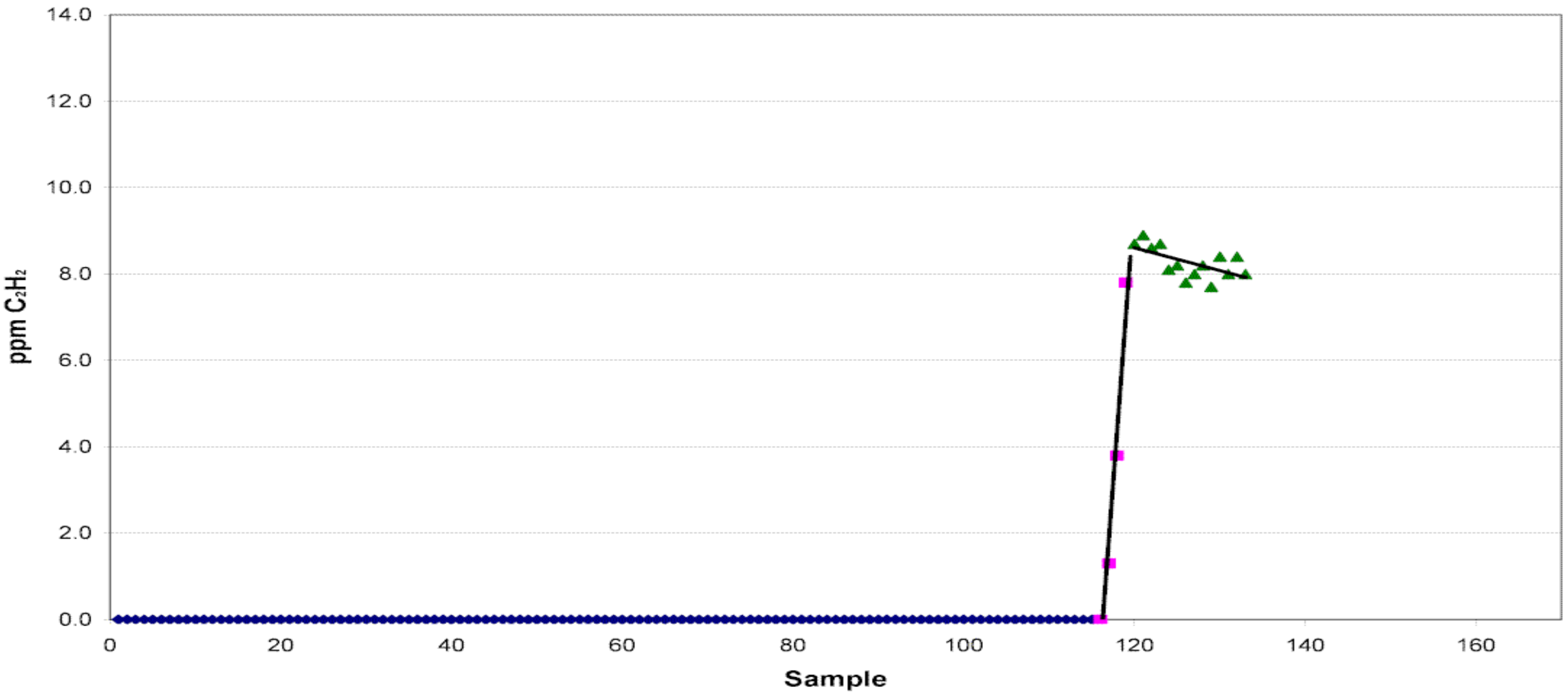
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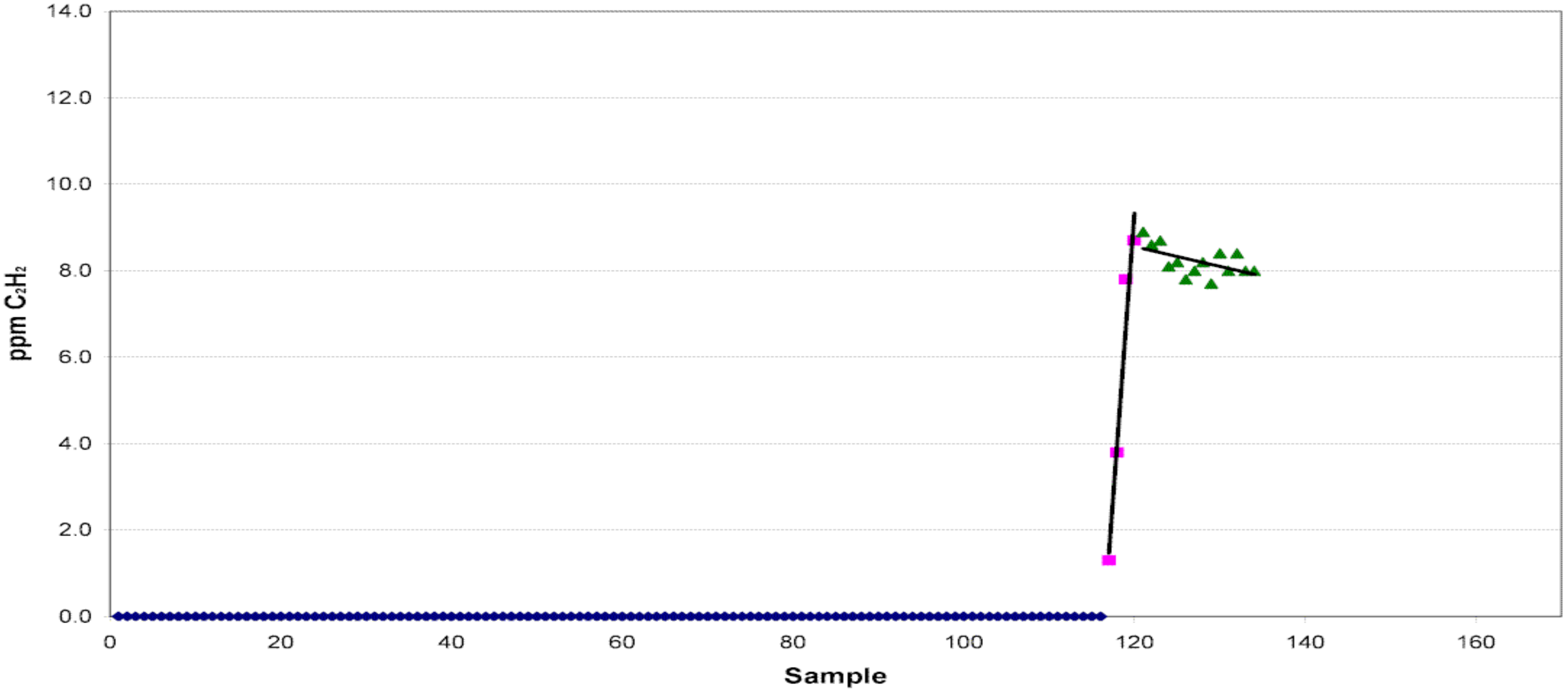
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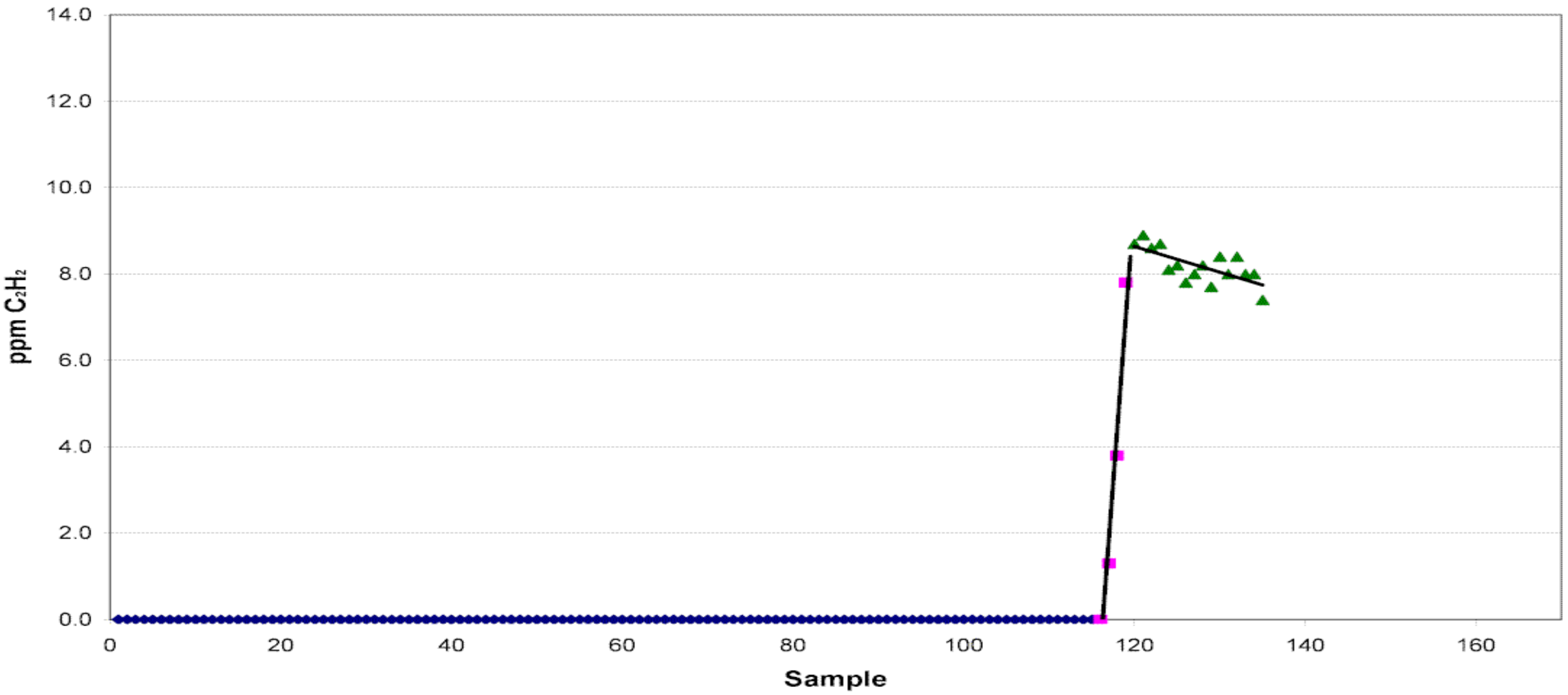

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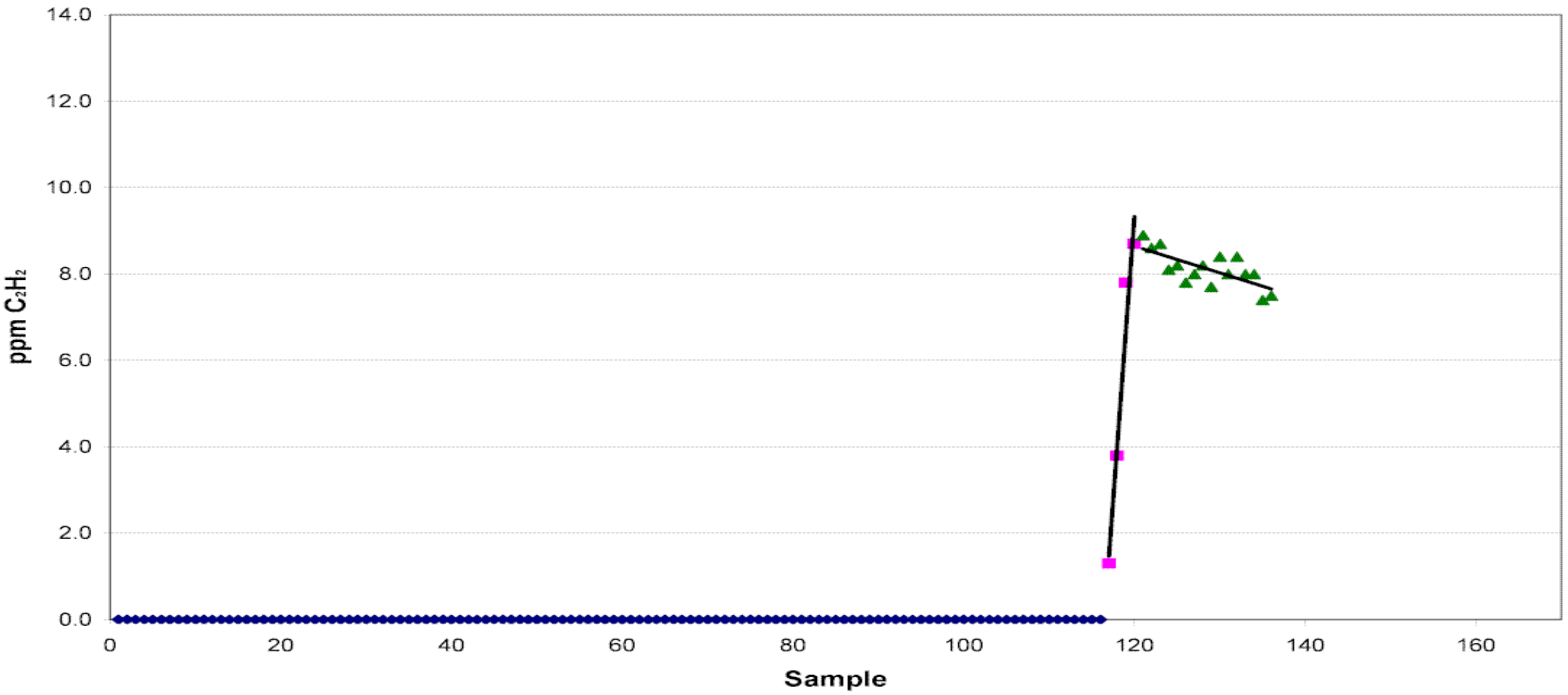

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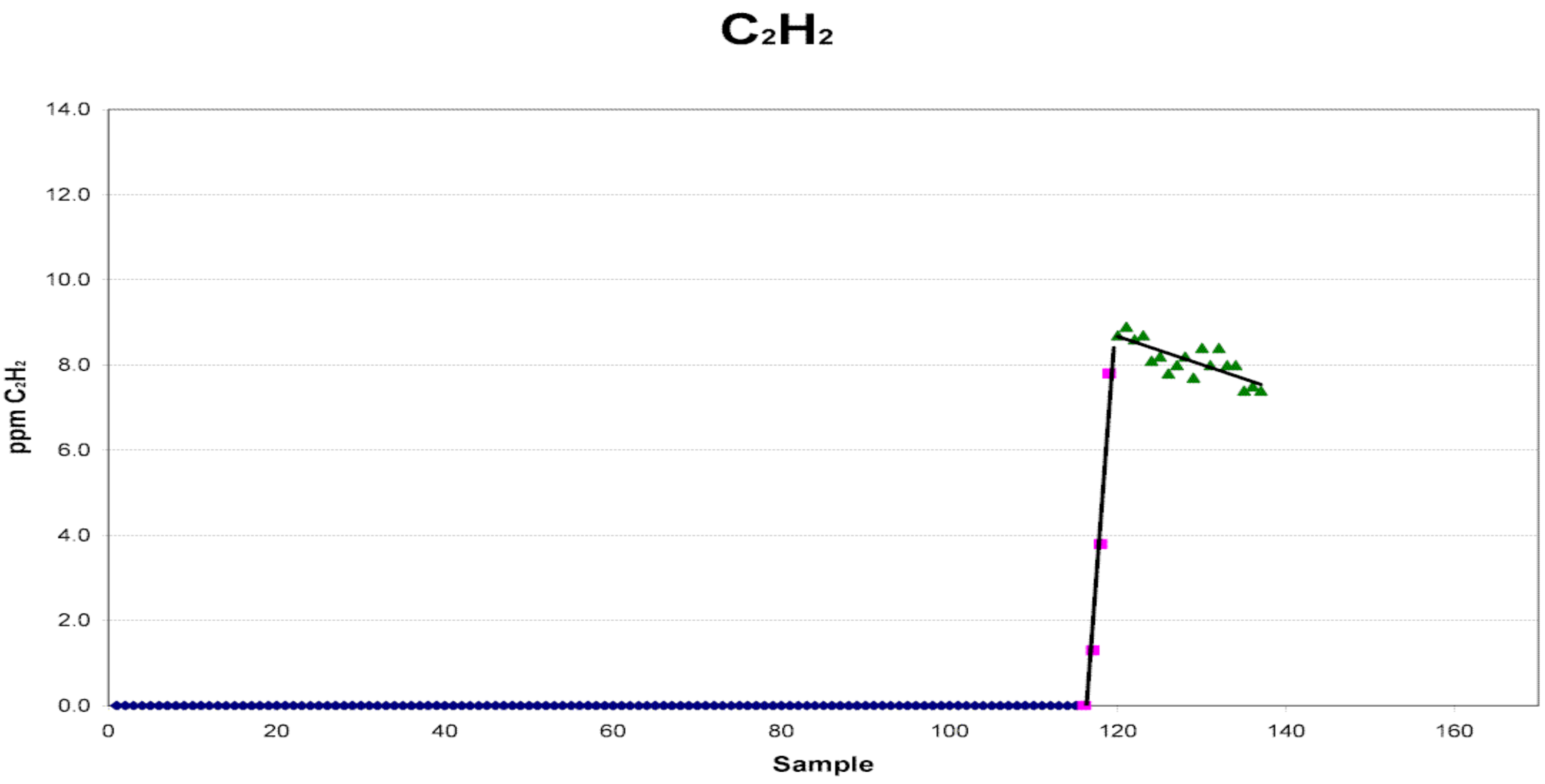

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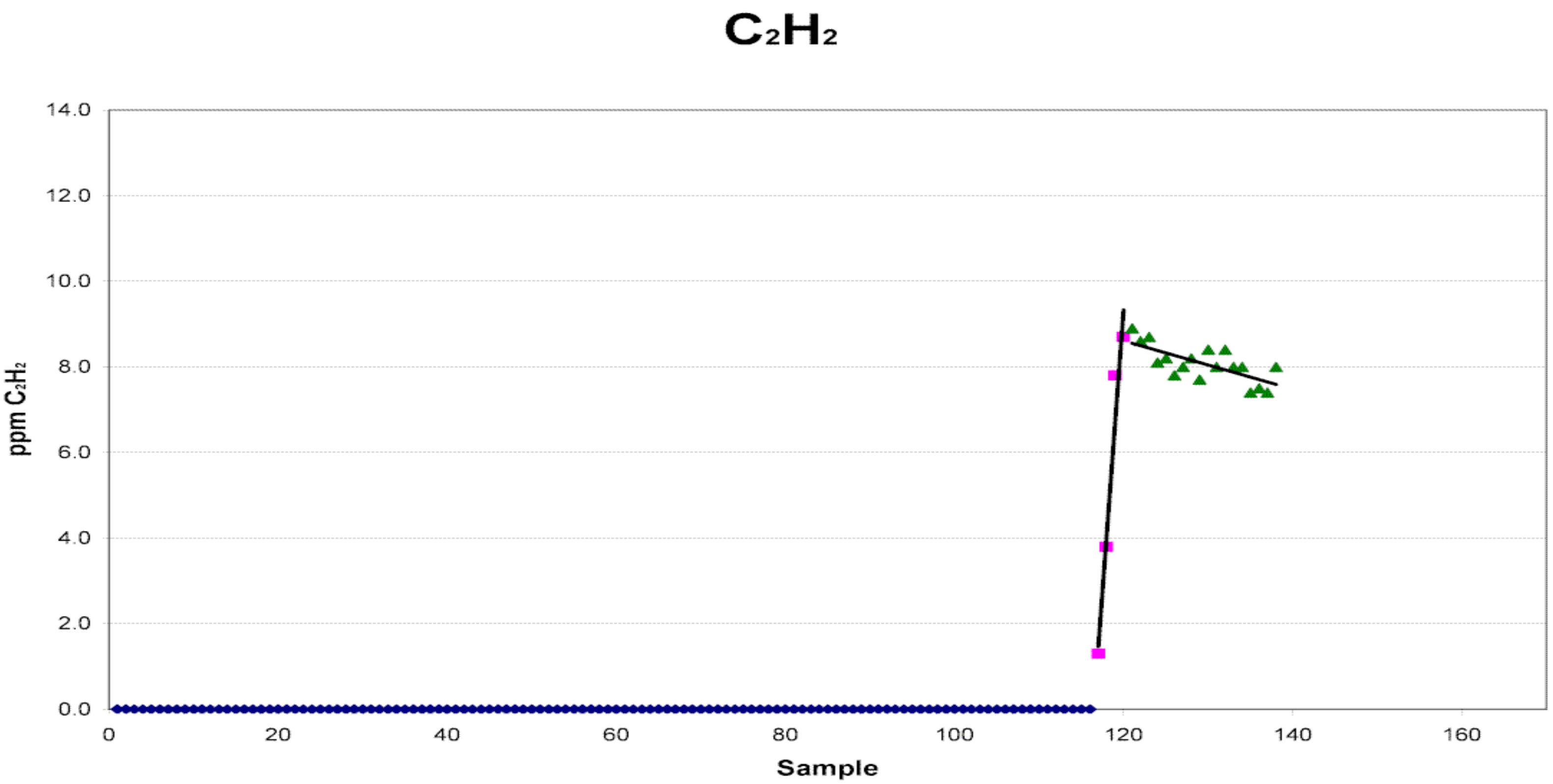
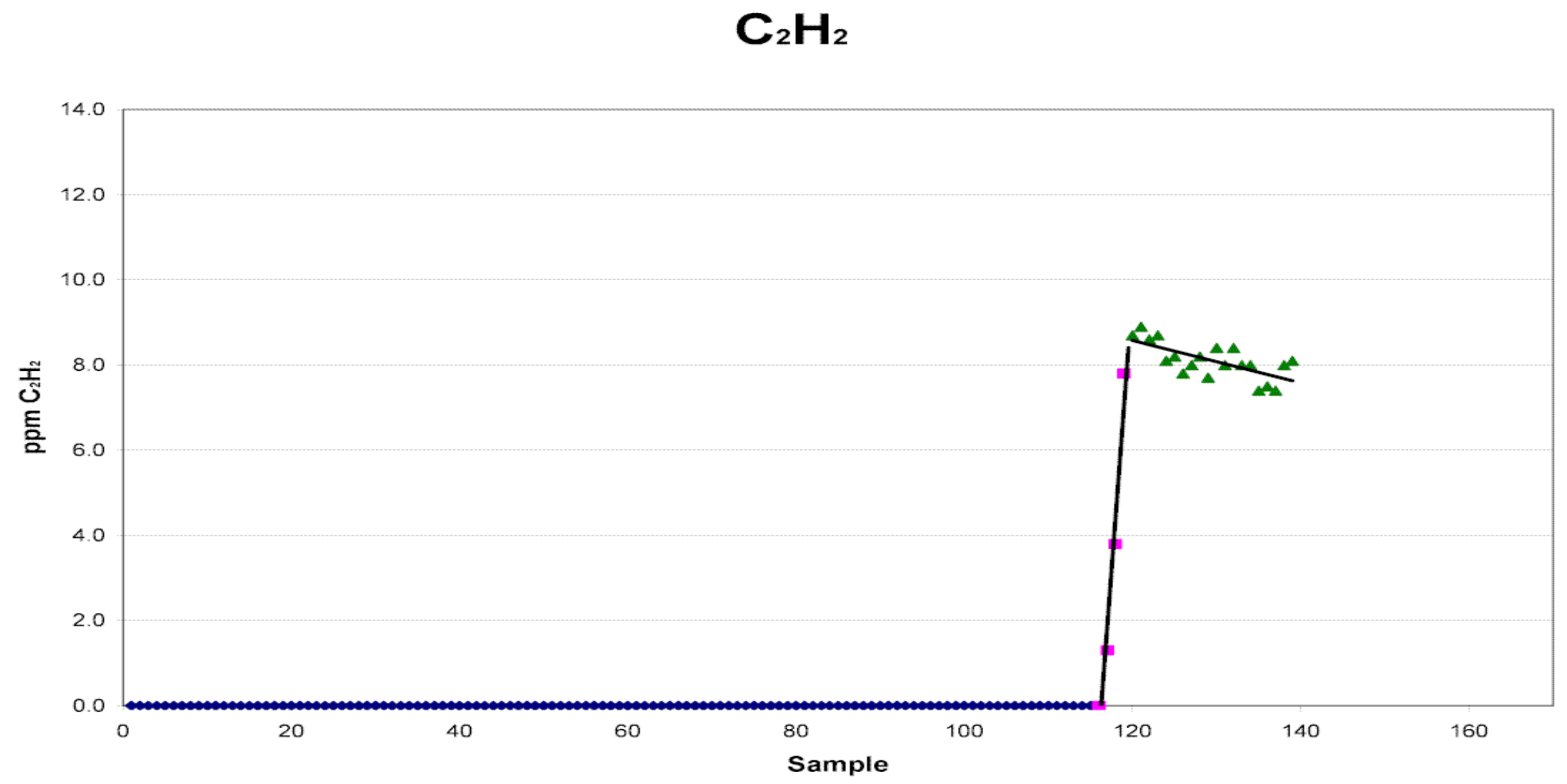
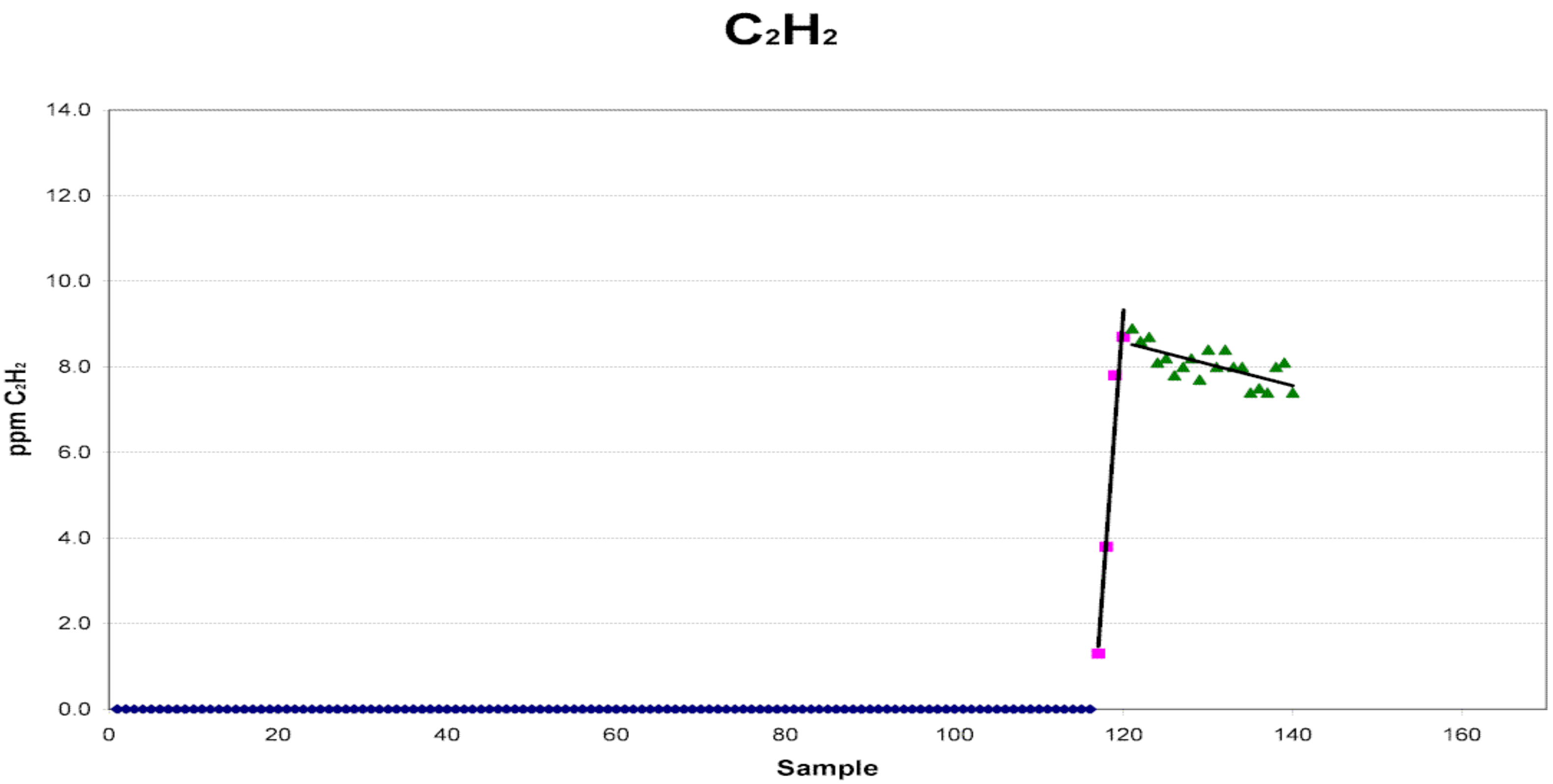
160
Sample

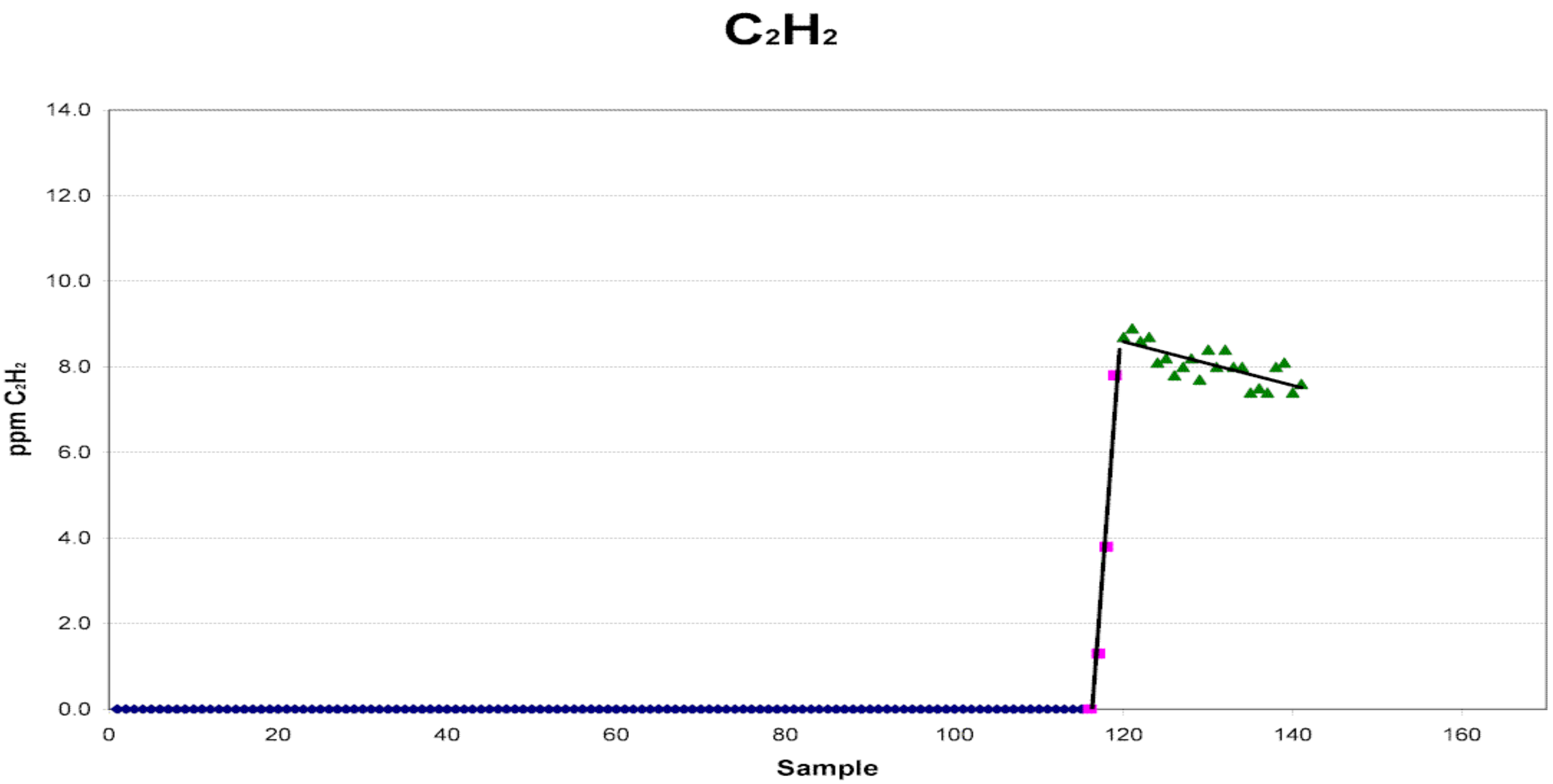

C2H2
ppm C2H2
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
20
40
60
80
100
120
140
160
Sample



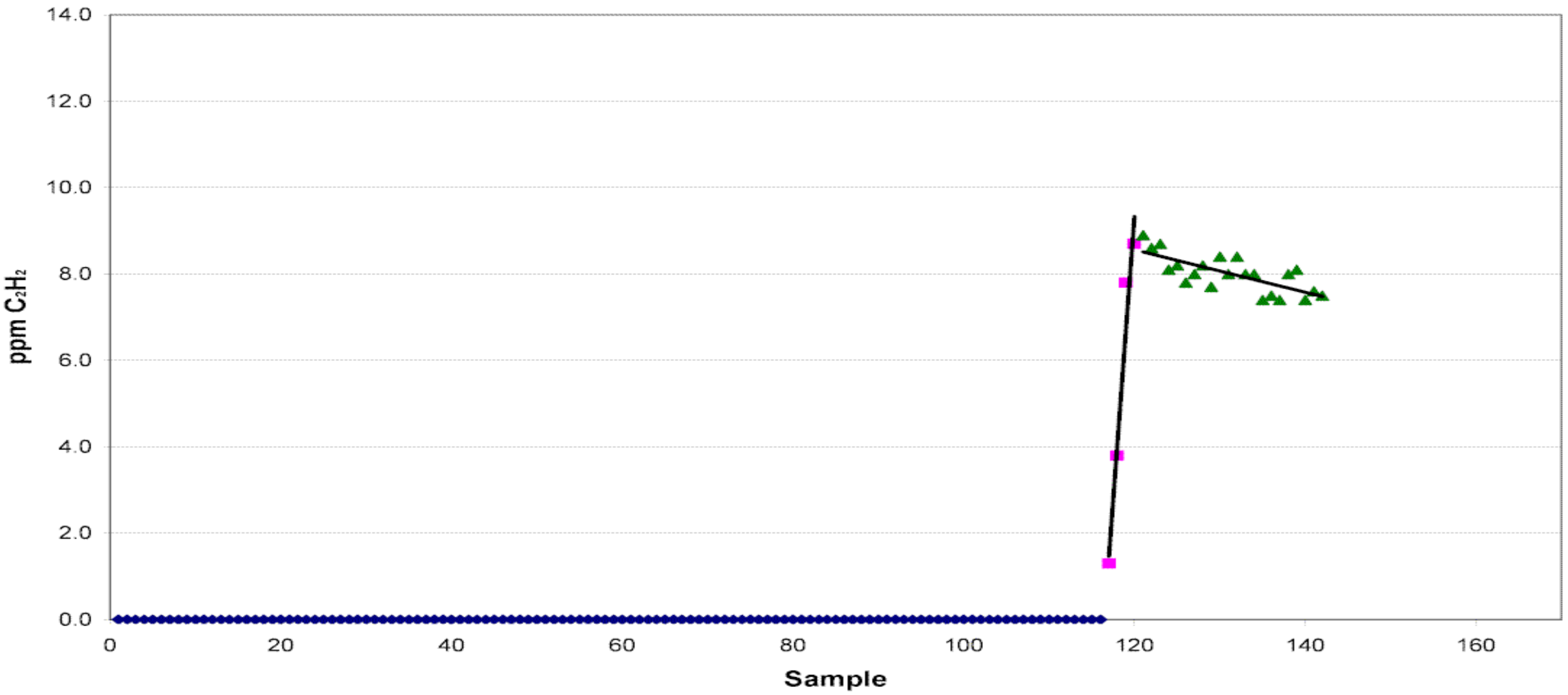
C2H2
ppm C2H2
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
20
40
60
80
100
120
140
160
Sample

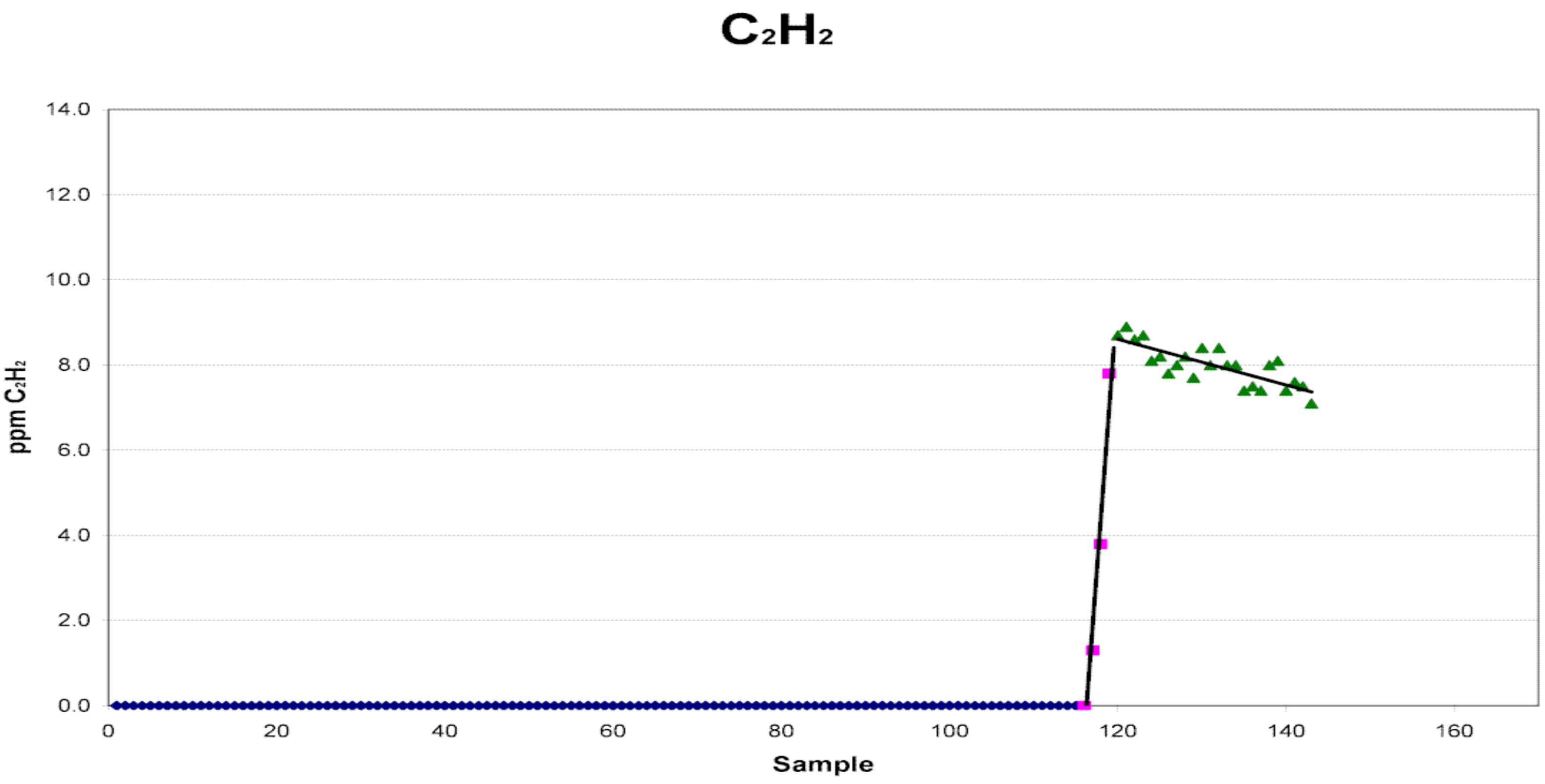


C2H2
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
ppm C2H2
0
20
40
60
80
100
120
140
160
Sample


C2H2
ppm C2H2
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
20
40
60
80
100
120
140
160
Sample

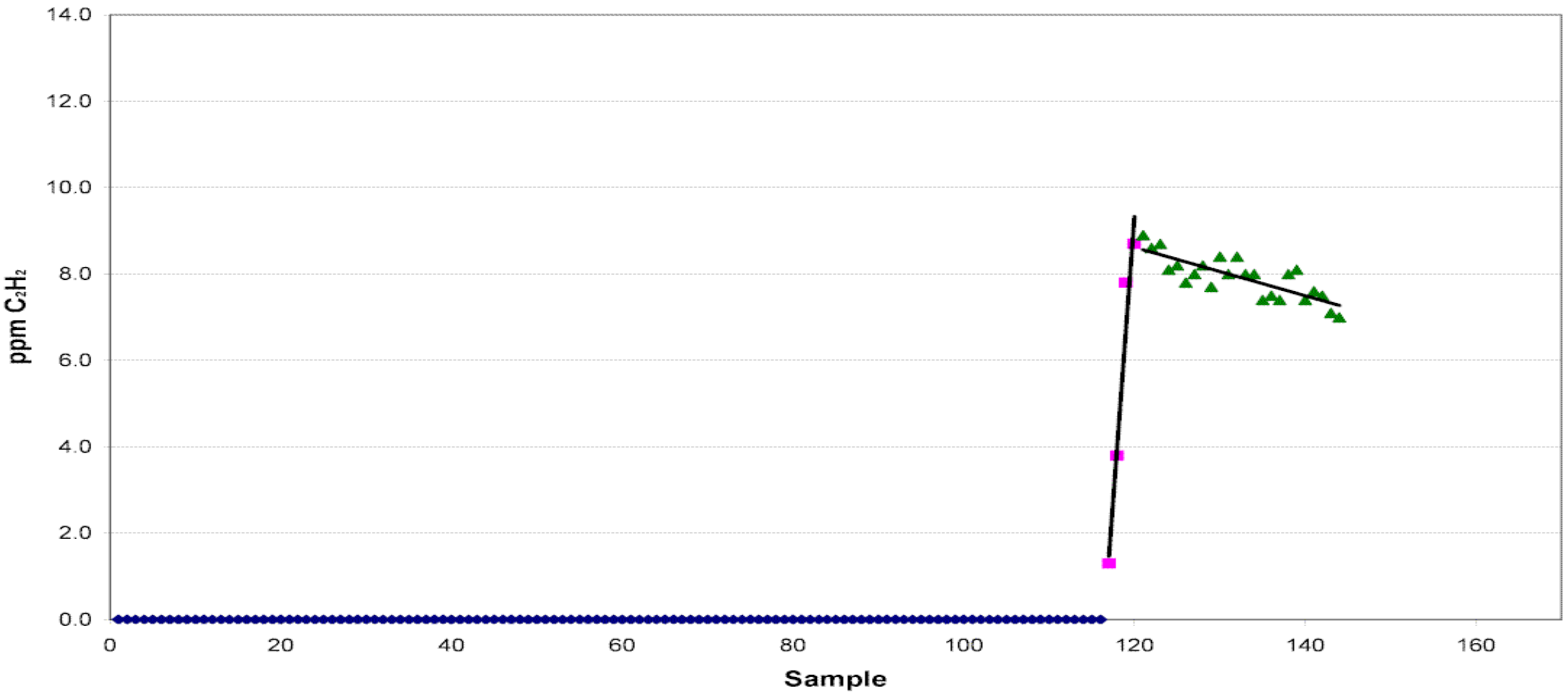
C_2H_2


14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
ppm C_2H_2
0
20
40
60
80
100
120
140
160
Sample

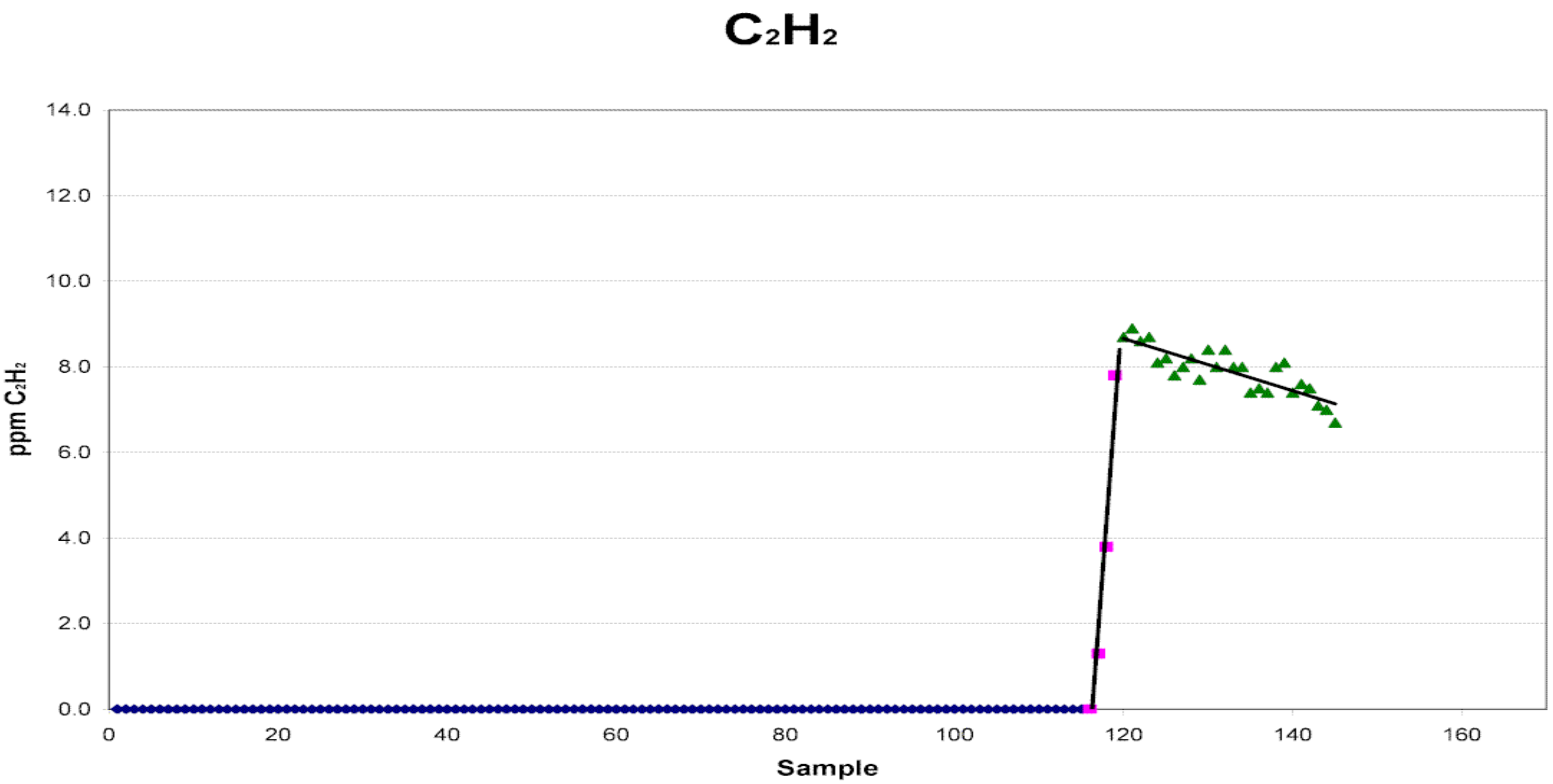


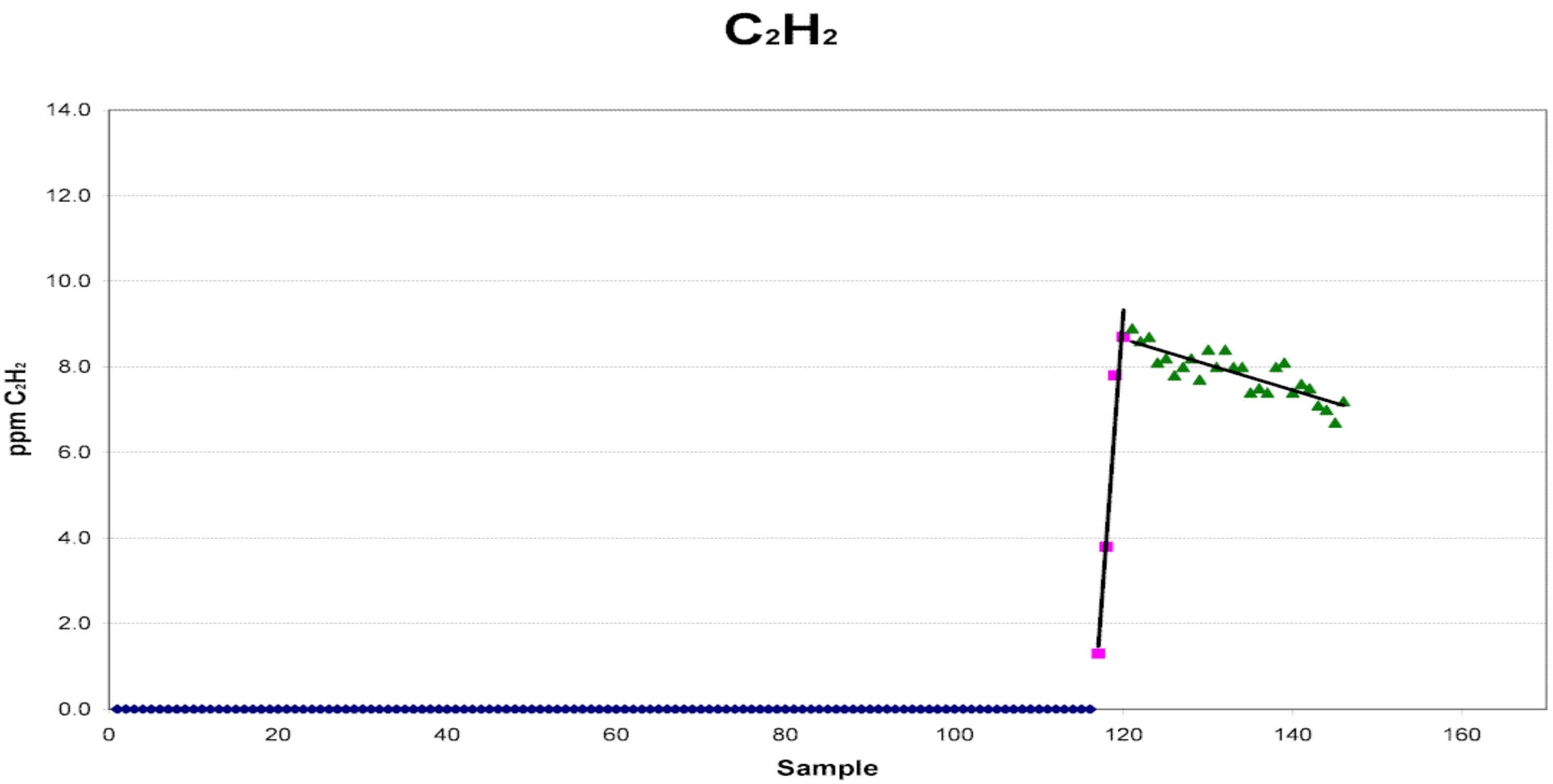
C2H2
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
ppm C2H2
0
20
40
60
80
100
120
140
160
Sample

C_2H_2

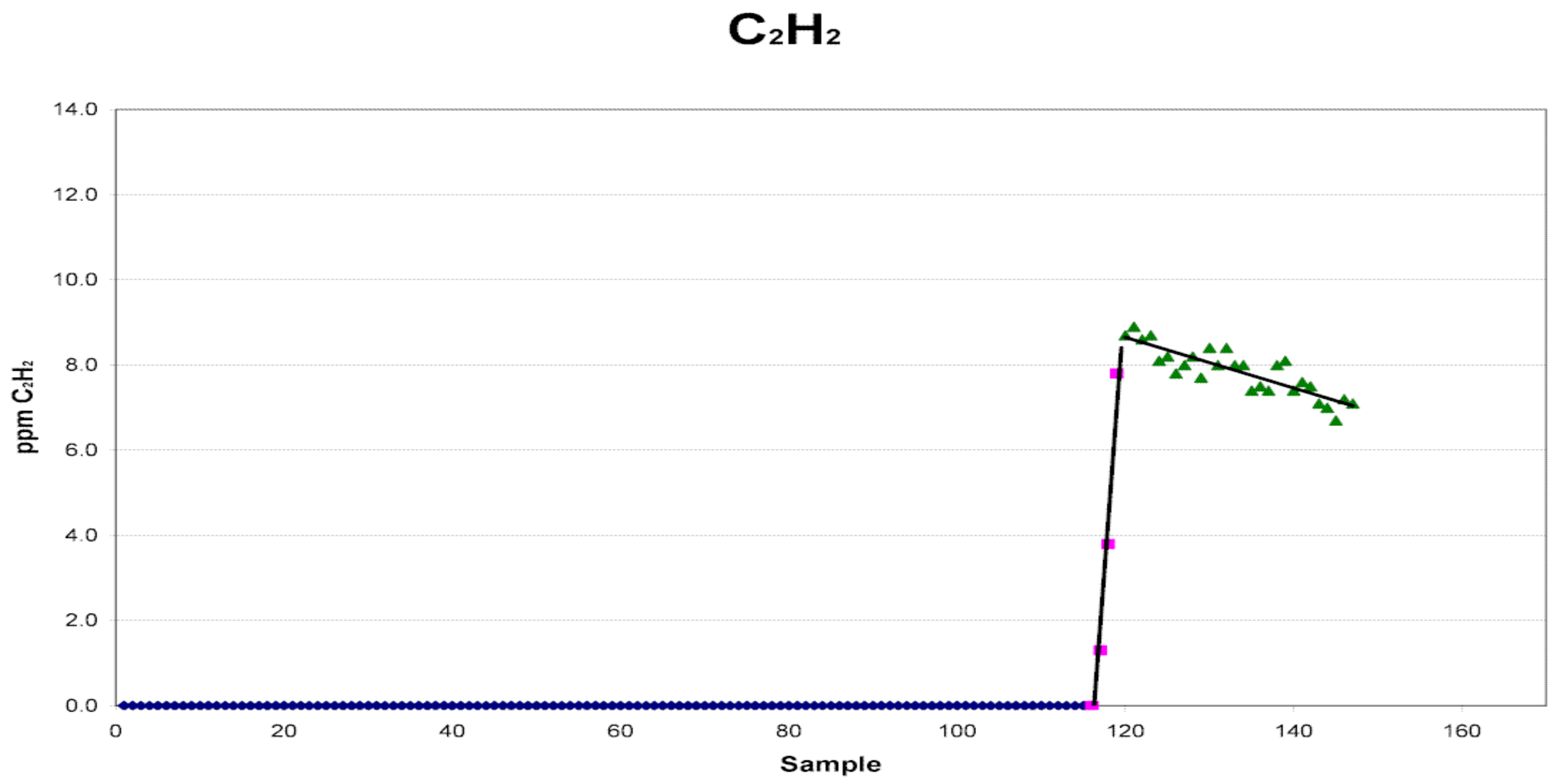


14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
ppm C2H2
0
20
40
60
80
100
120
140
160
Sample

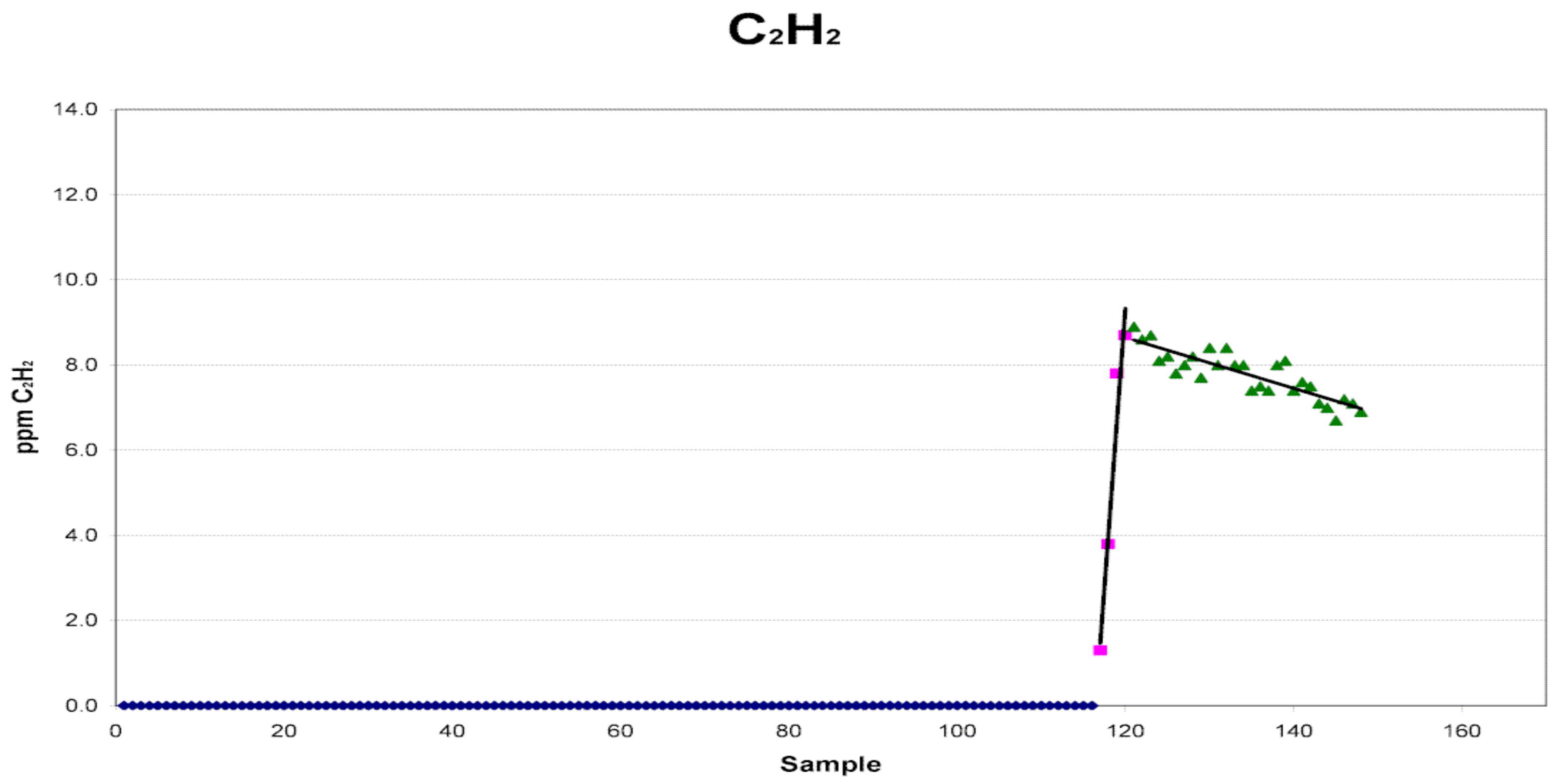

C2H2
ppm C2H2
Sample
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
20
40
60
80
100
120
140
160



C₂H₂
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
ppm C₂H₂
0
20
40
60
80
100
120
140
160
Sample

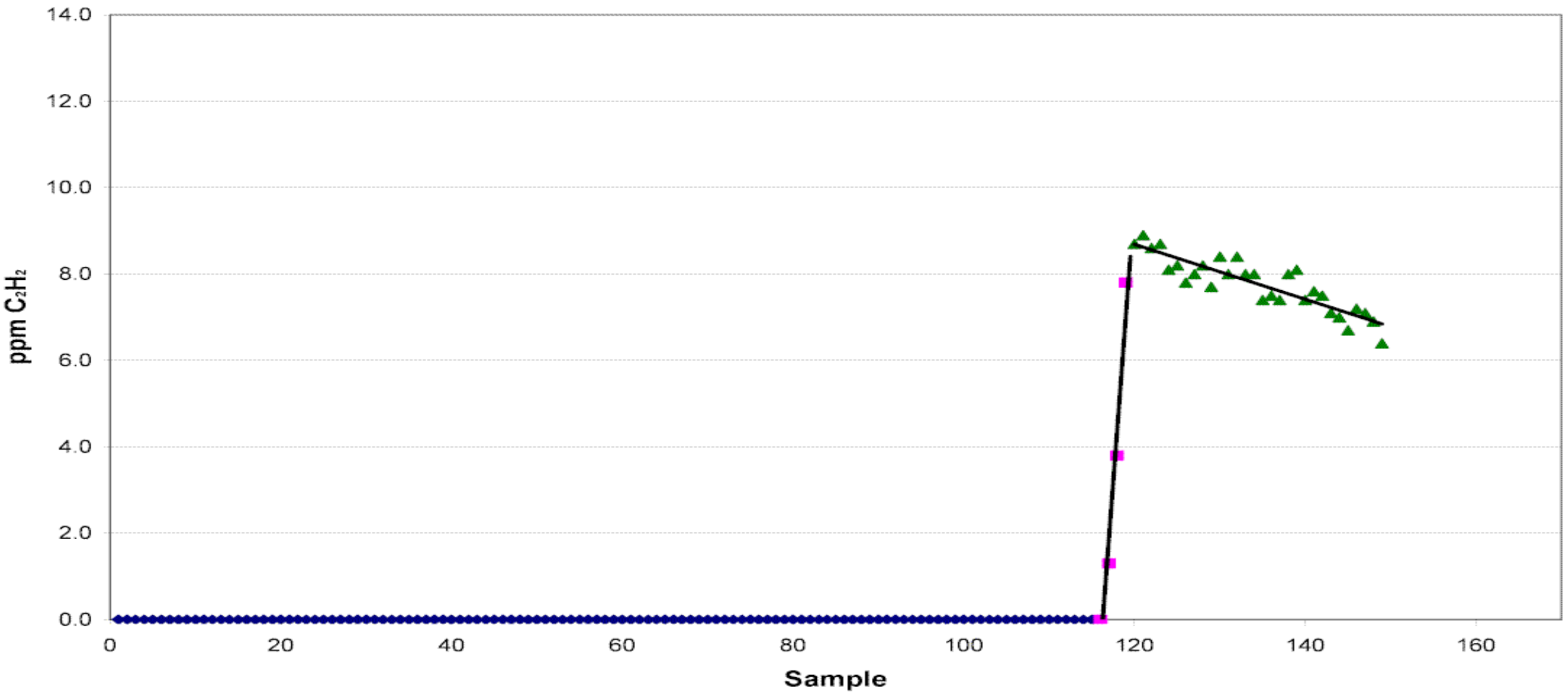


C2H2
ppm C2H2
Sample
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
20
40
60
80
100
120
140
160



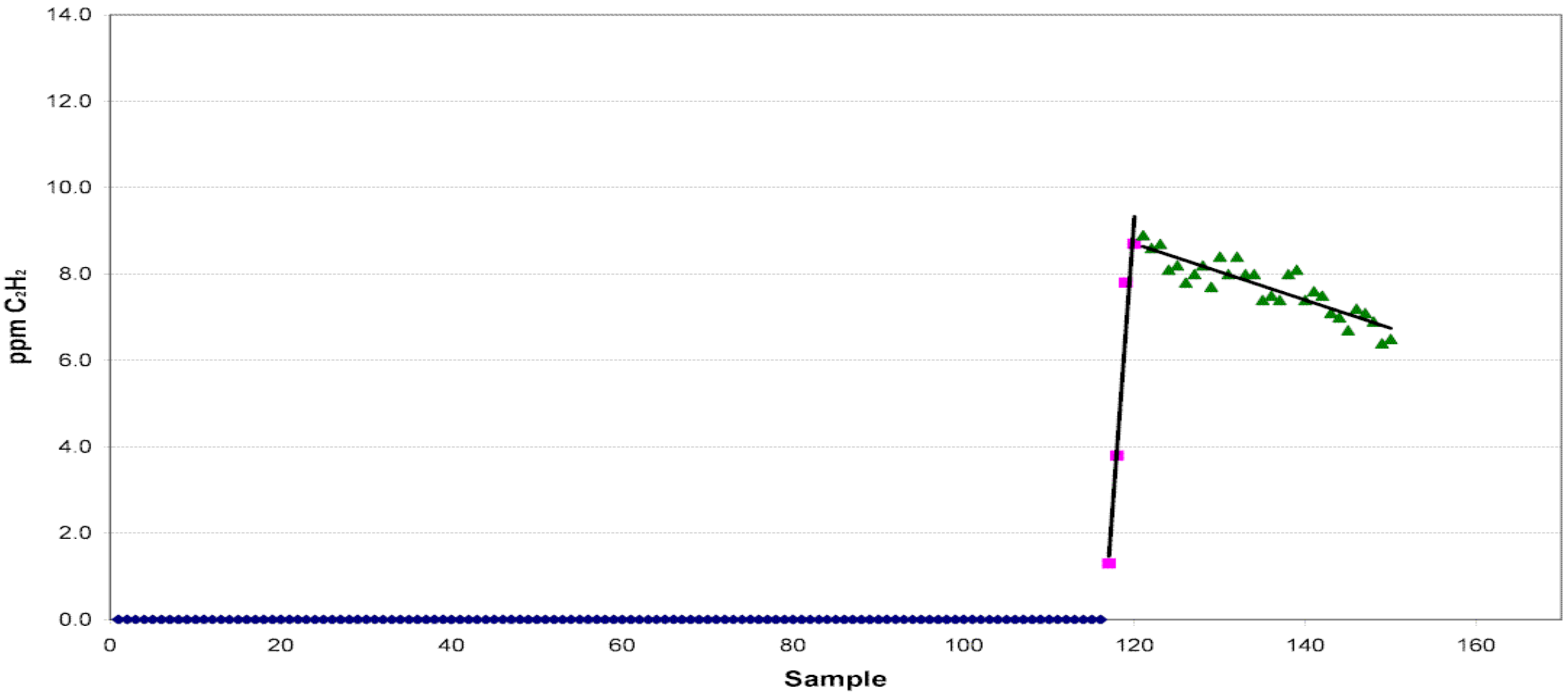
C2H2
ppm C2H2
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
20
40
60
80
100
120
140
160
Sample

C_2H_2

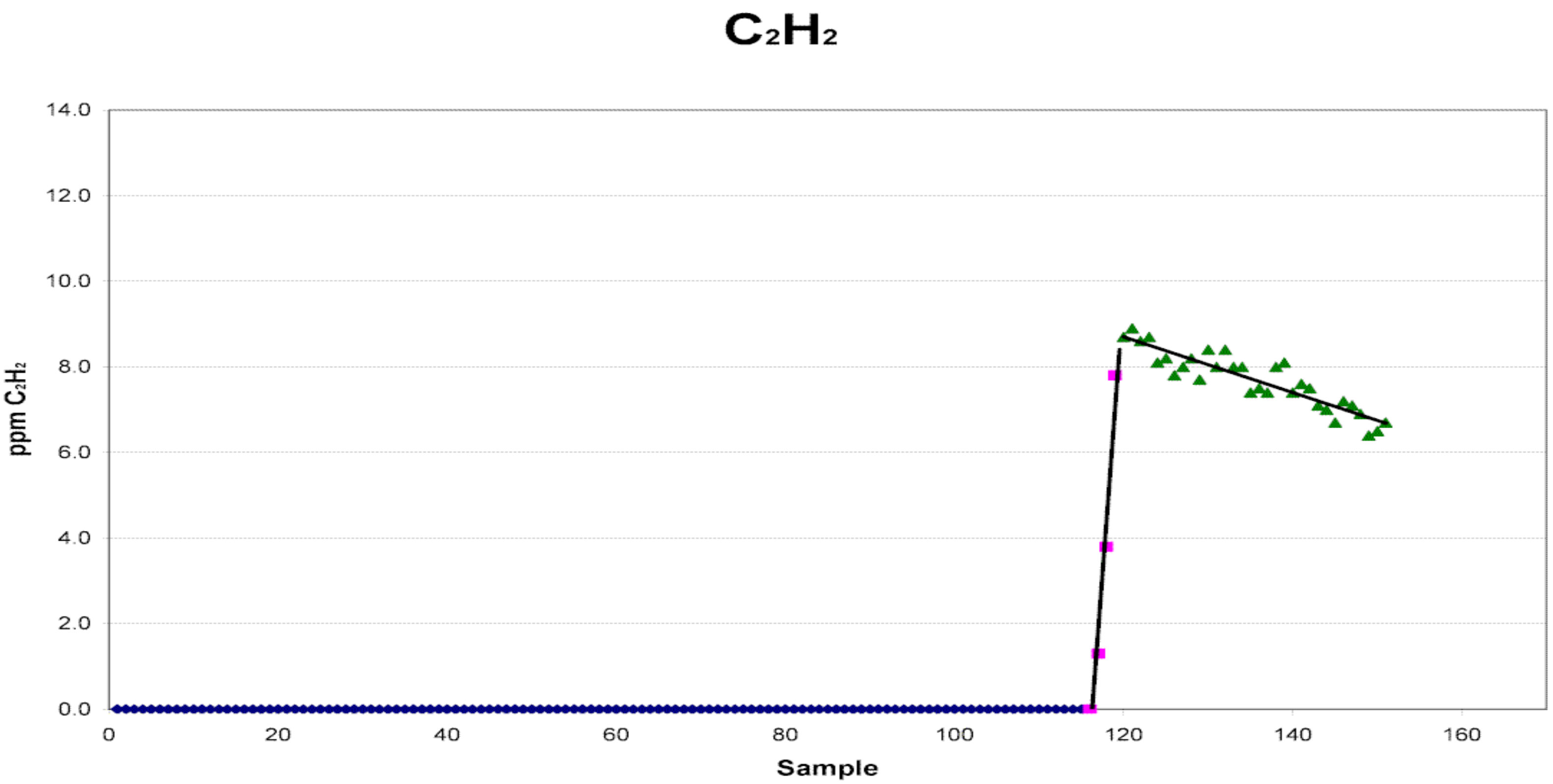


14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
ppm C_2H_2
0
20
40
60
80
100
120
140
160
Sample

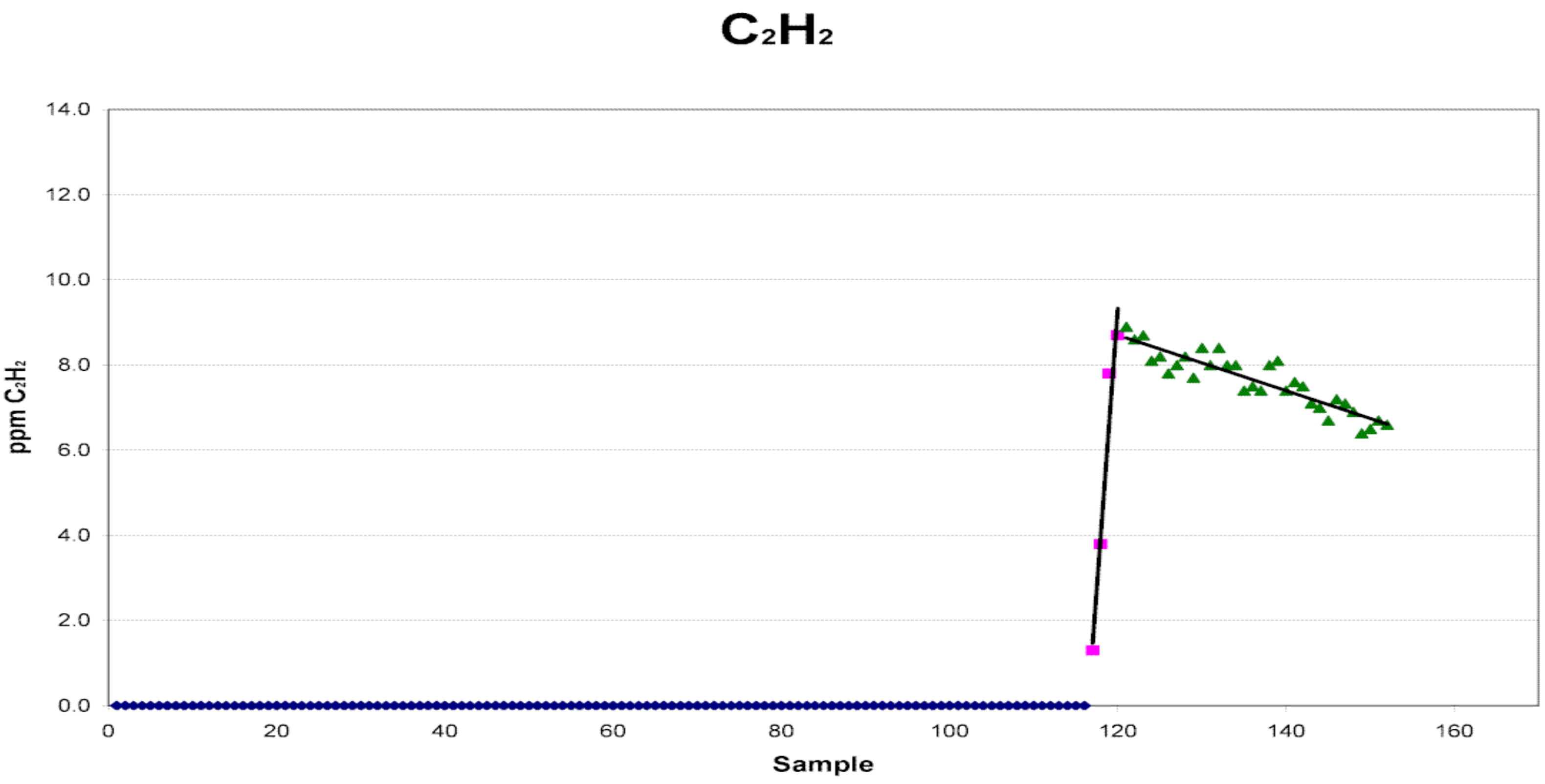
C_2H_2



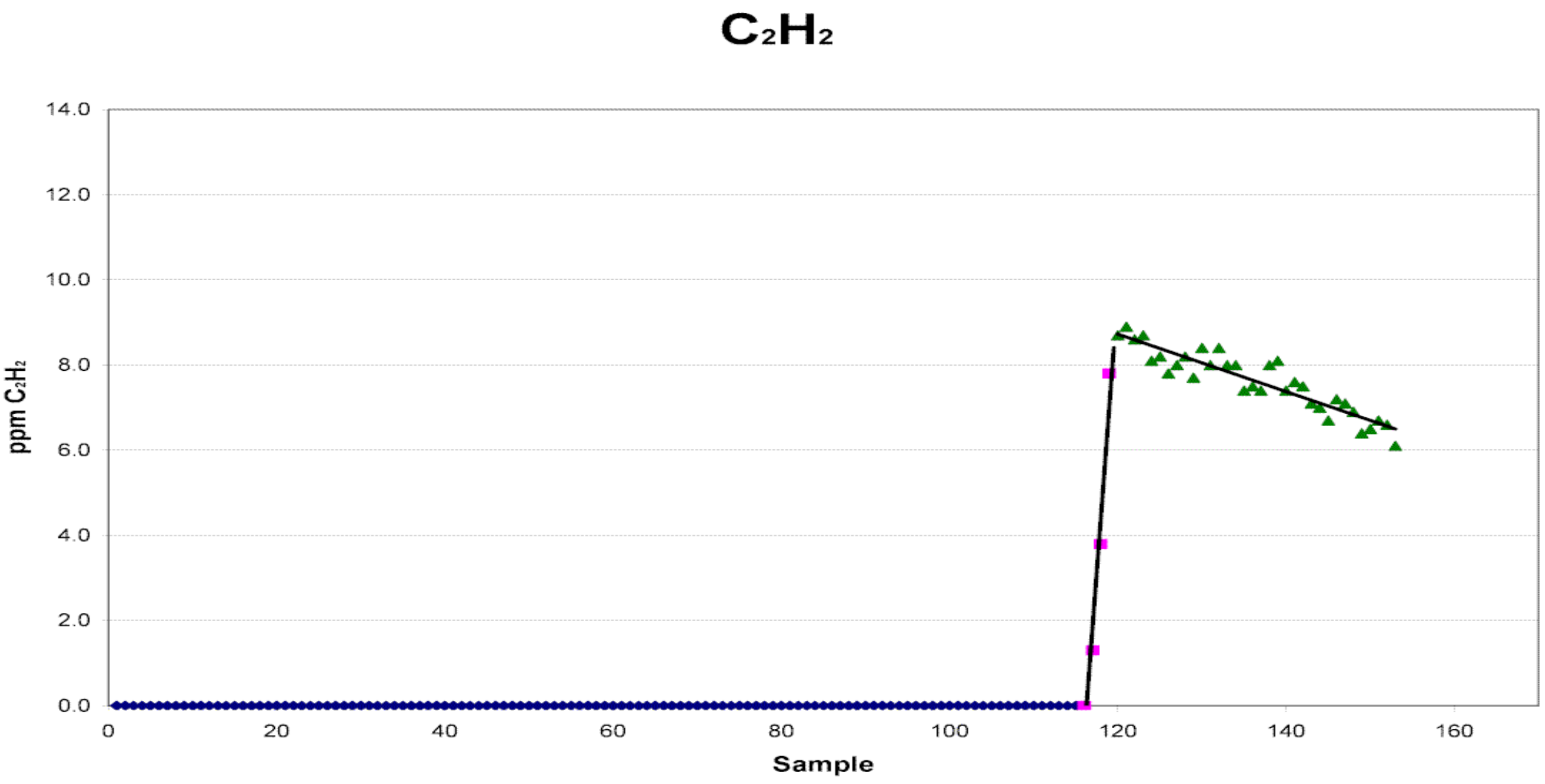
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
ppm C_2H_2
0
20
40
60
80
100
120
140
160
Sample



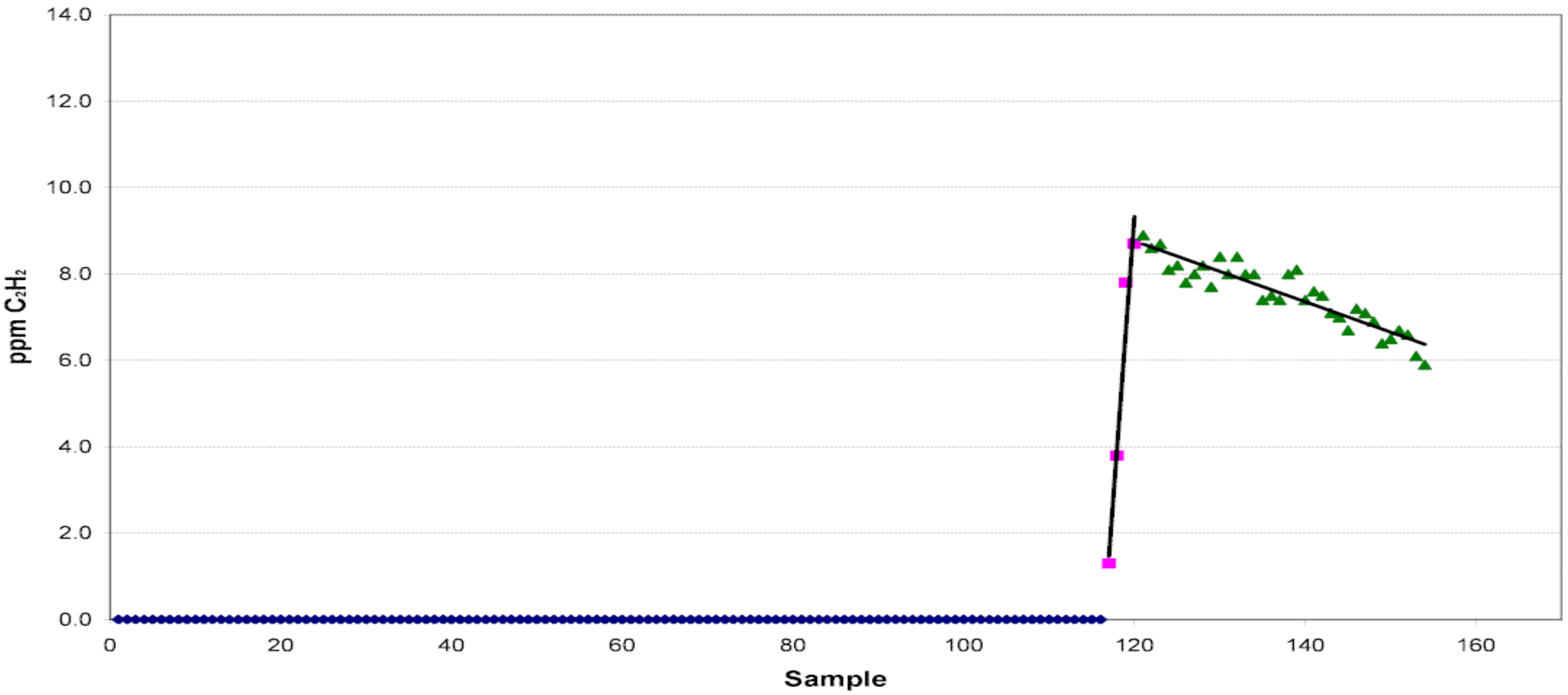
C2H2
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
ppm C2H2
0
20
40
60
80
100
120
140
160
Sample



C2H2
ppm C2H2
Sample
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
20
40
60
80
100
120
140
160

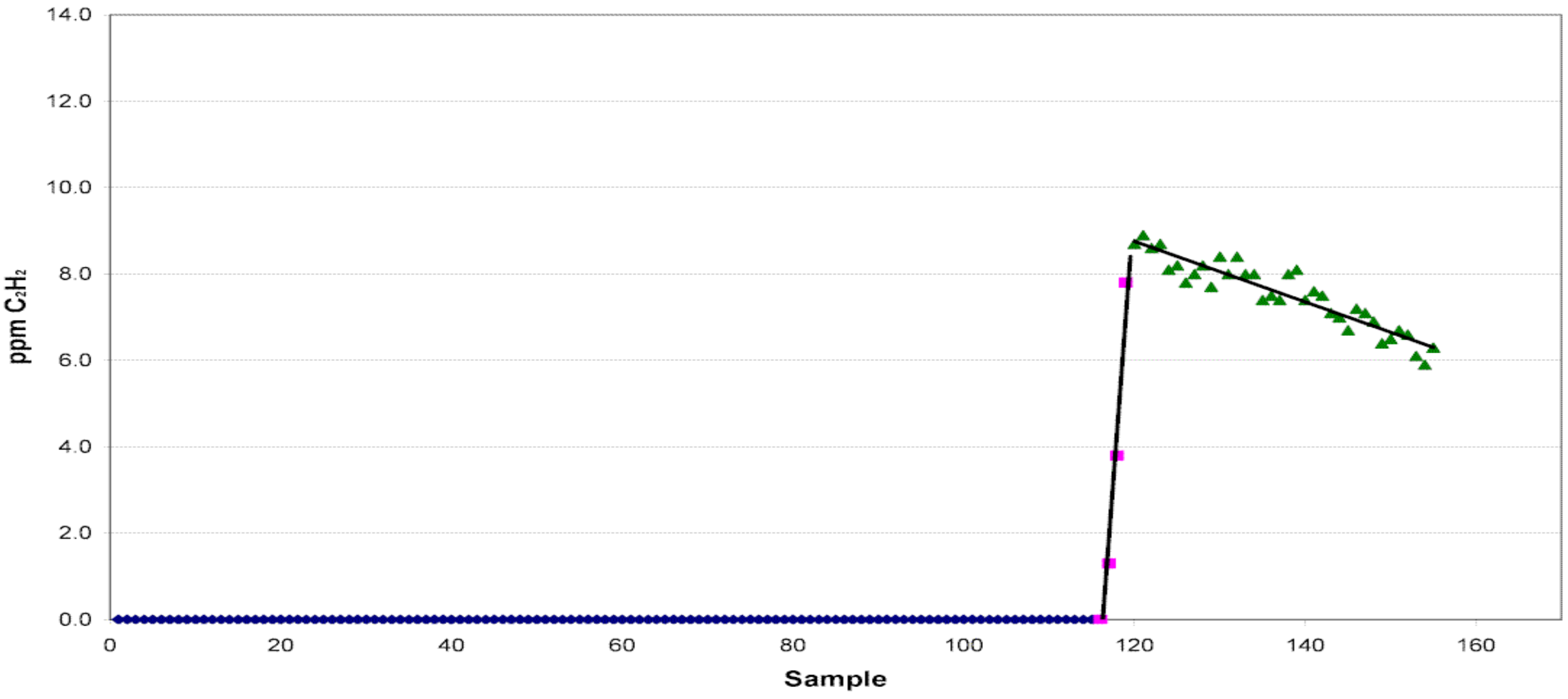

C2H2
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
ppm C2H2
0
20
40
60
80
100
120
140
160
Sample

C_2H_2

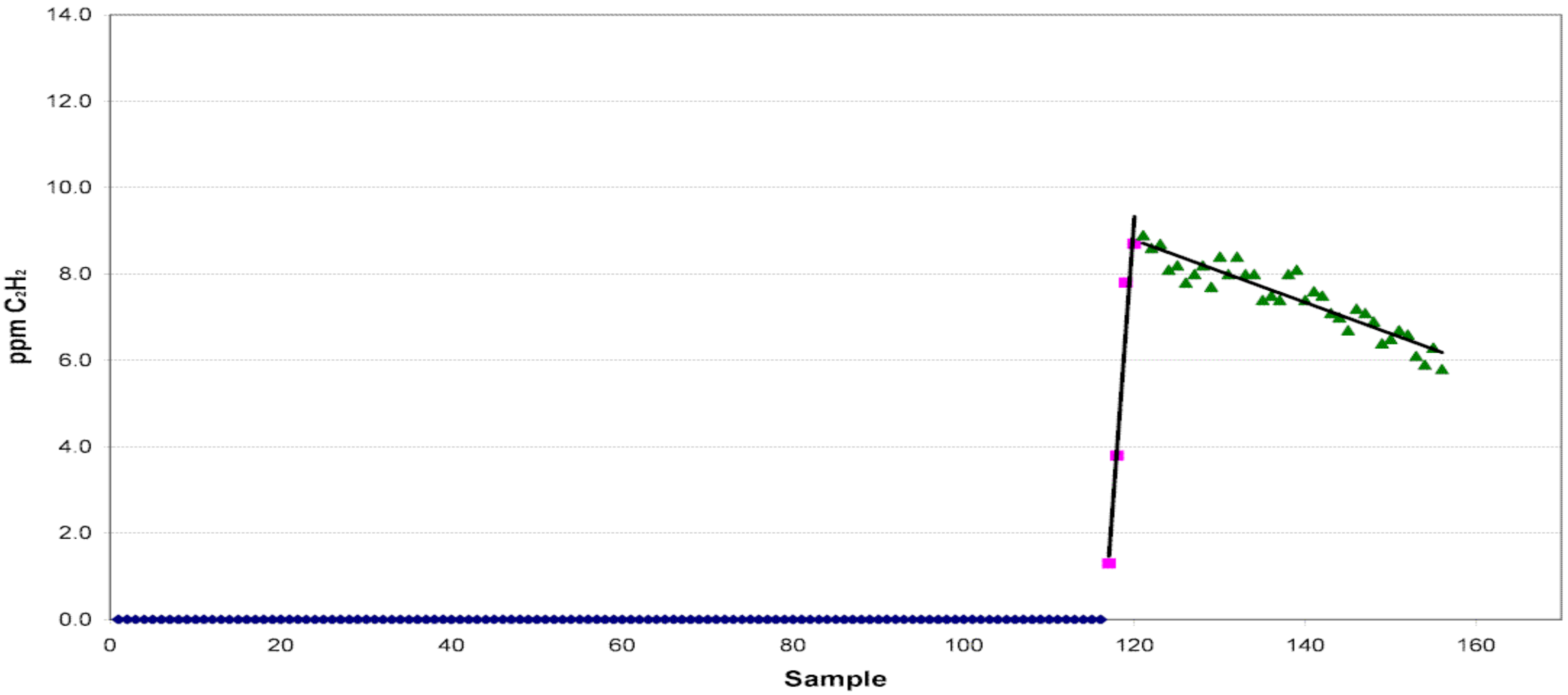


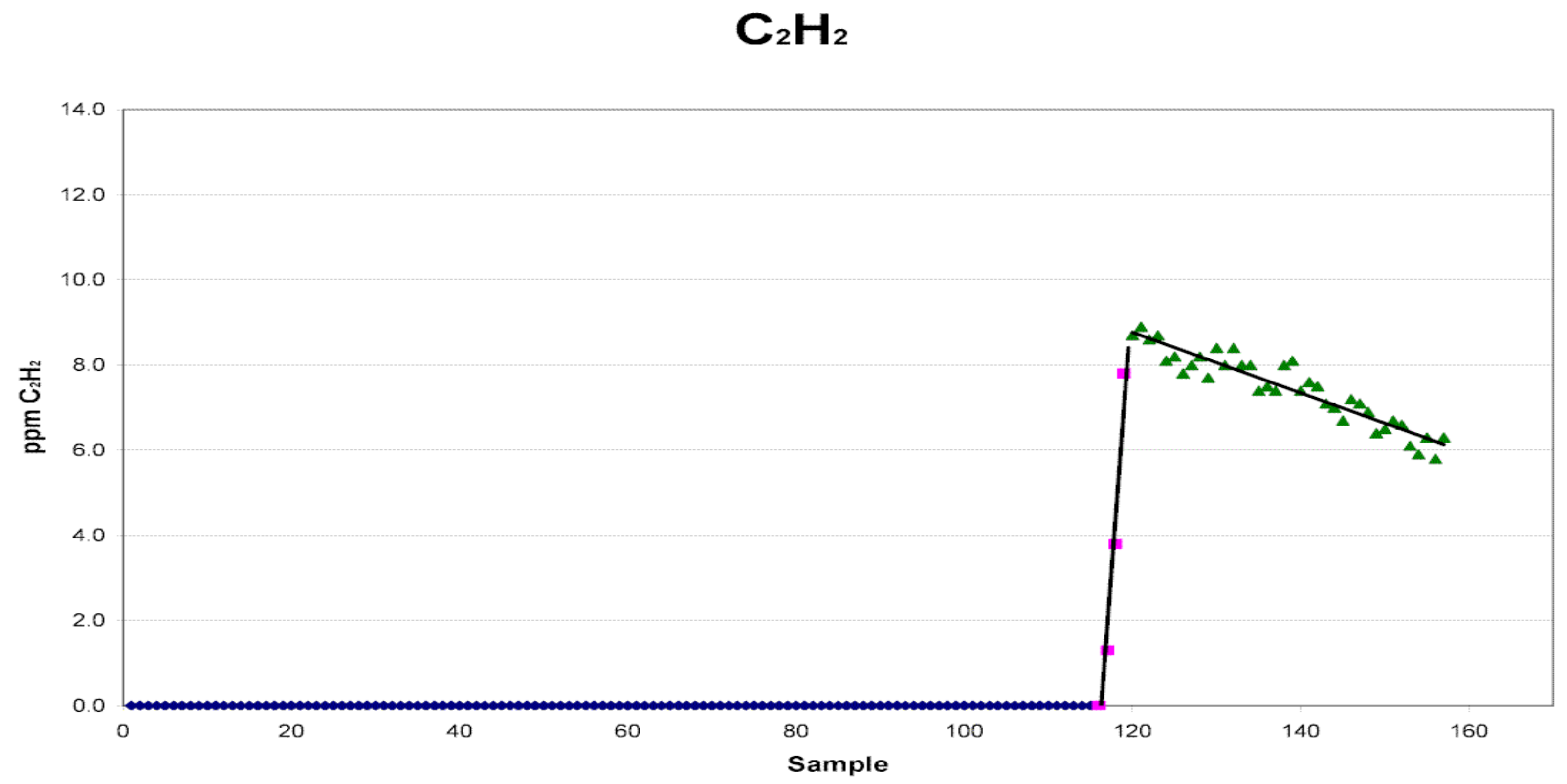
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
ppm C2H2
0
20
40
60
80
100
120
140
160
Sample

C_2H_2

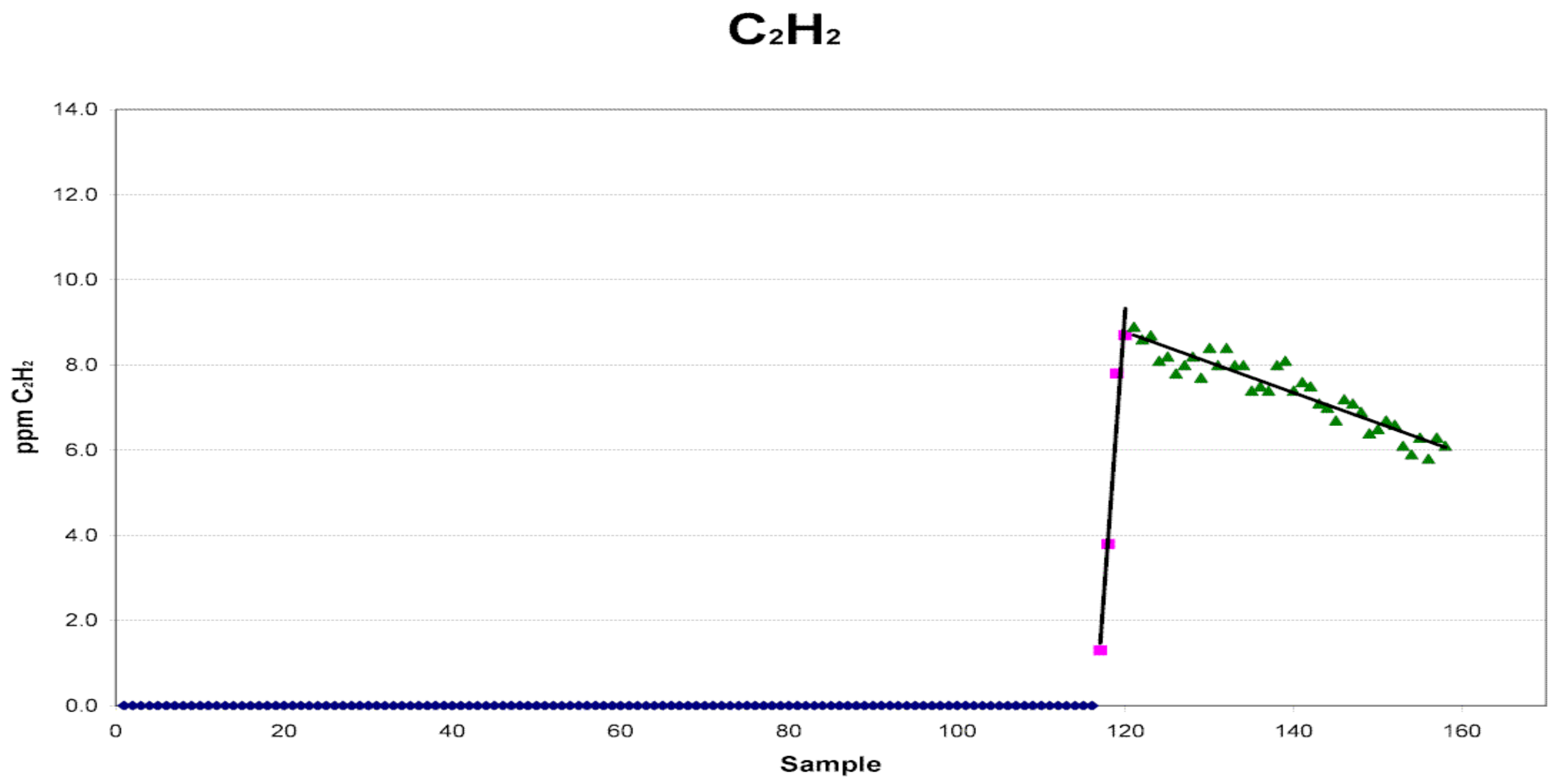

14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
ppm C_2H_2
0
20
40
60
80
100
120
140
160
Sample

C_2H_2

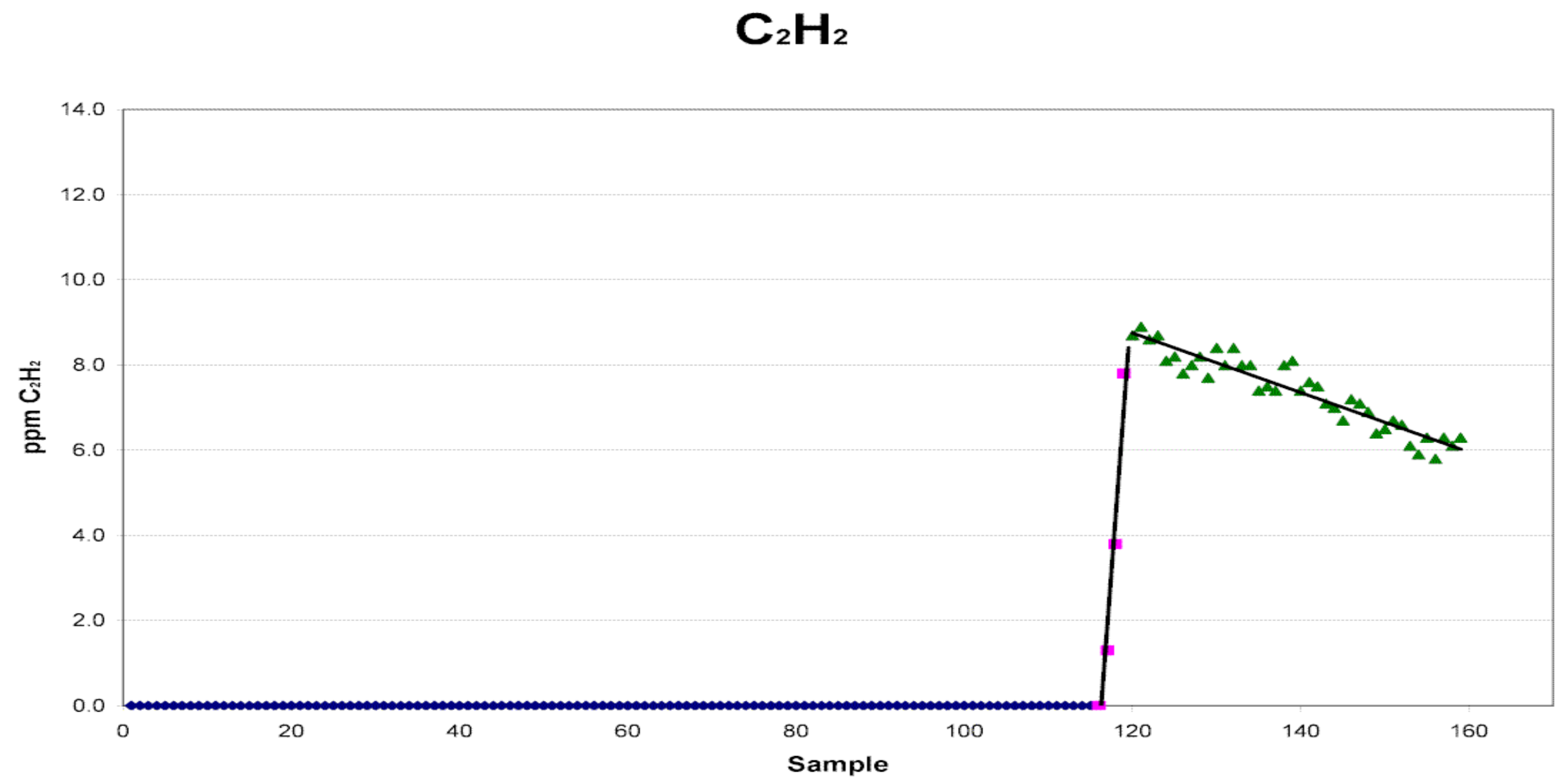

14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
ppm C2H2
0
20
40
60
80
100
120
140
160
Sample



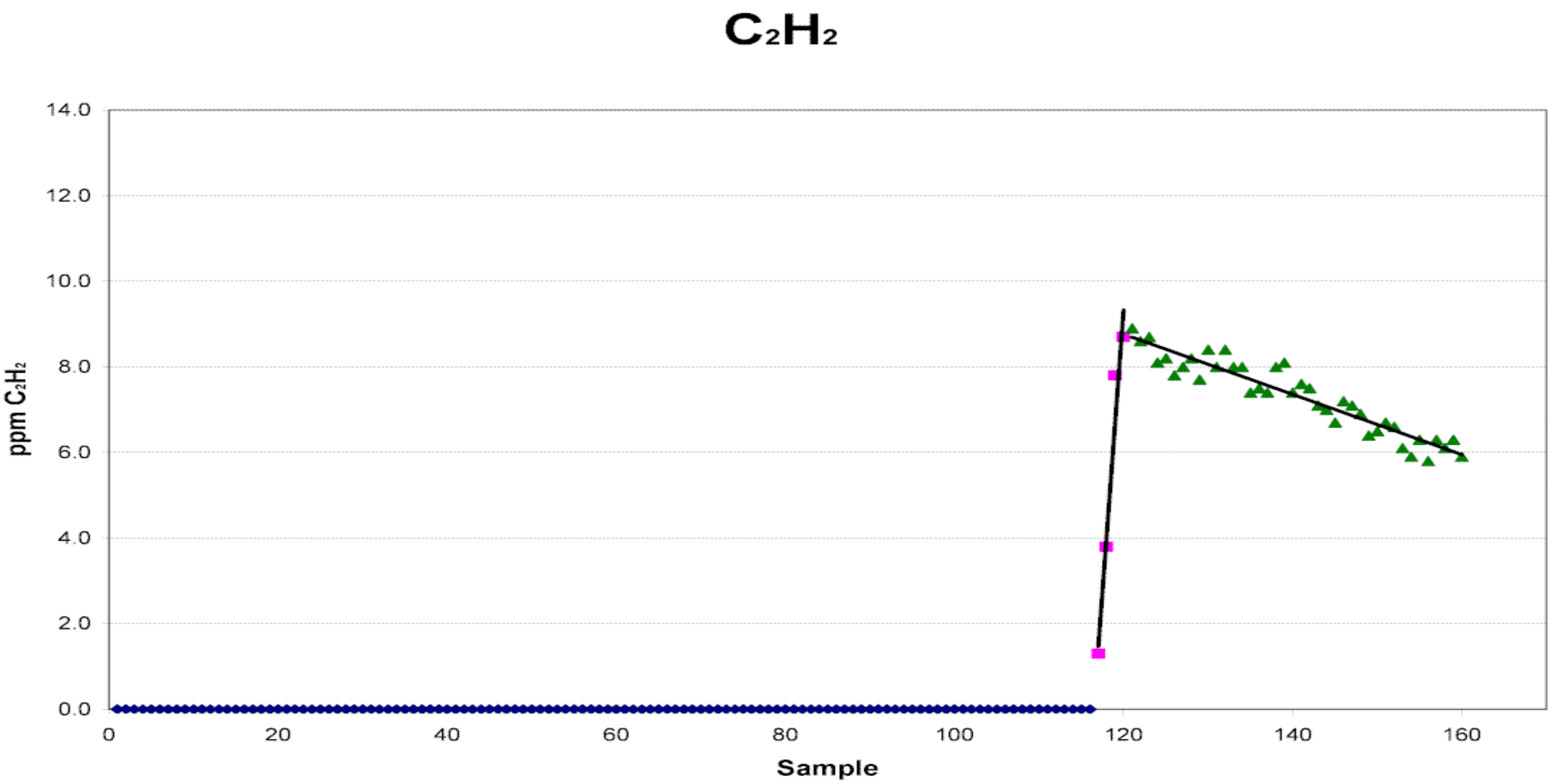
C2H2
ppm C2H2
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
20
40
60
80
100
120
140
160
Sample



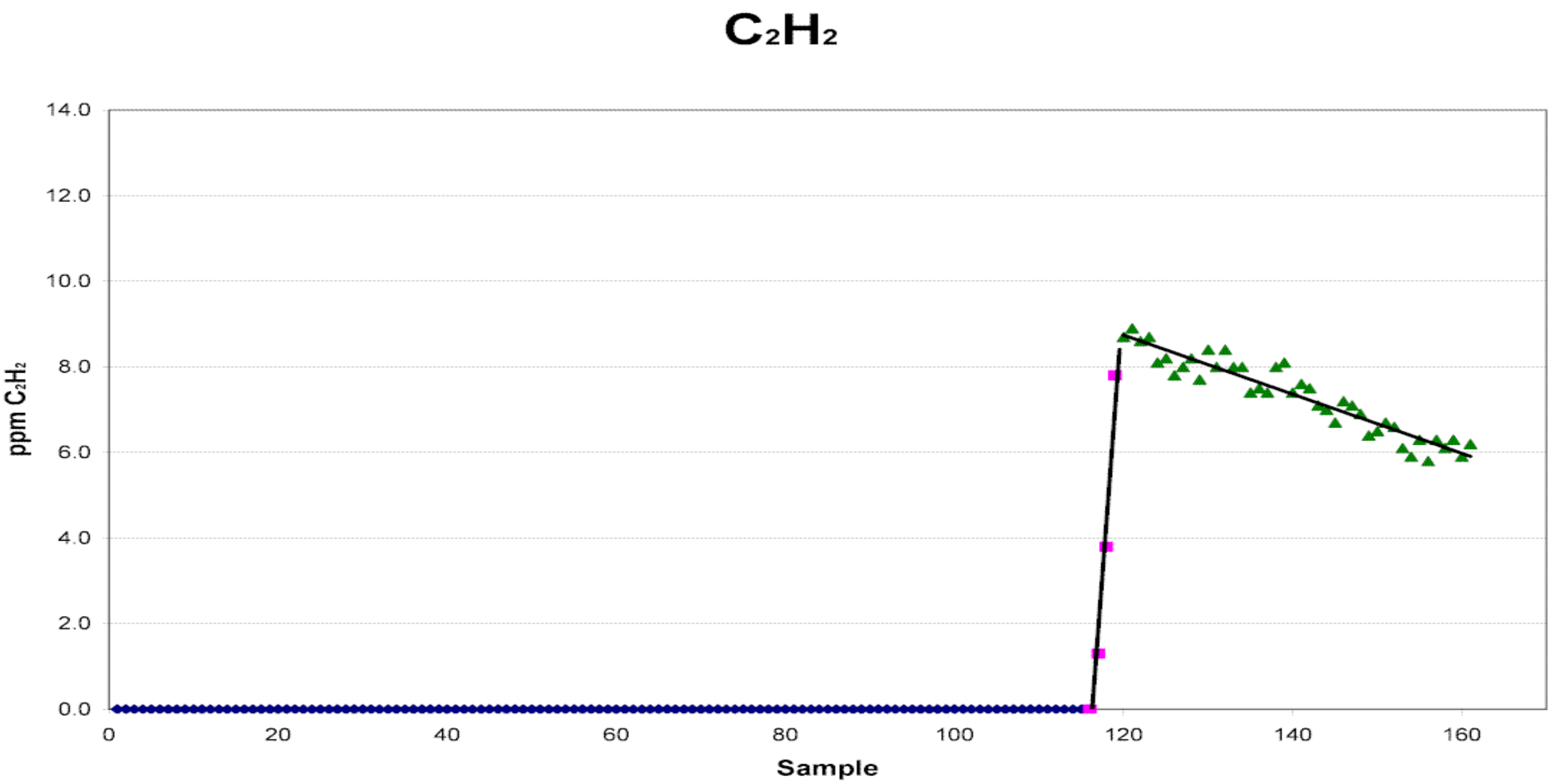
C_2H_2
ppm C_2H_2
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
20
40
60
80
100
120
140
160
Sample



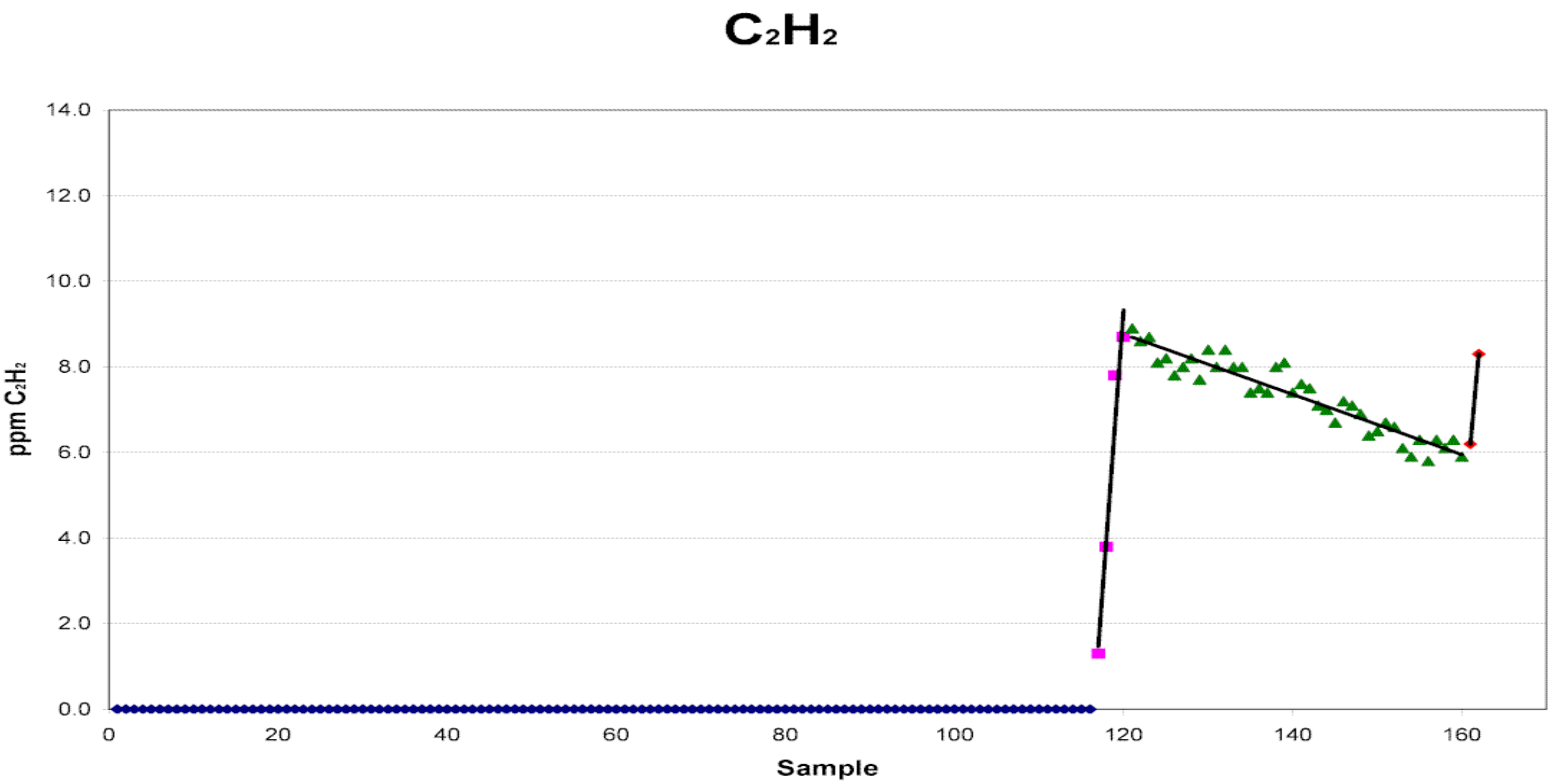
C₂H₂
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
ppm C₂H₂
0
20
40
60
80
100
120
140
160
Sample



C2H2
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
ppm C2H2
0
20
40
60
80
100
120
140
160
Sample

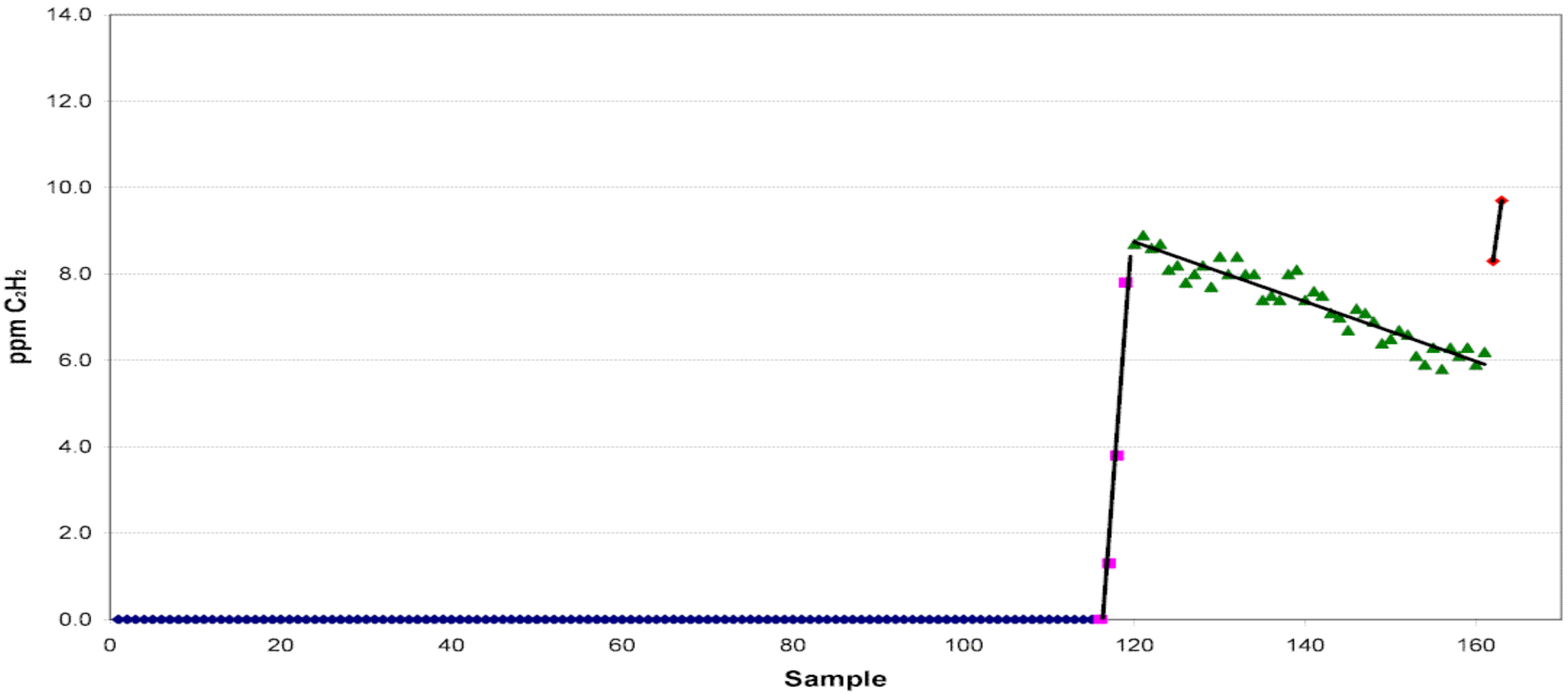


C2H2
ppm C2H2
Sample
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
20
40
60
80
100
120
140
160

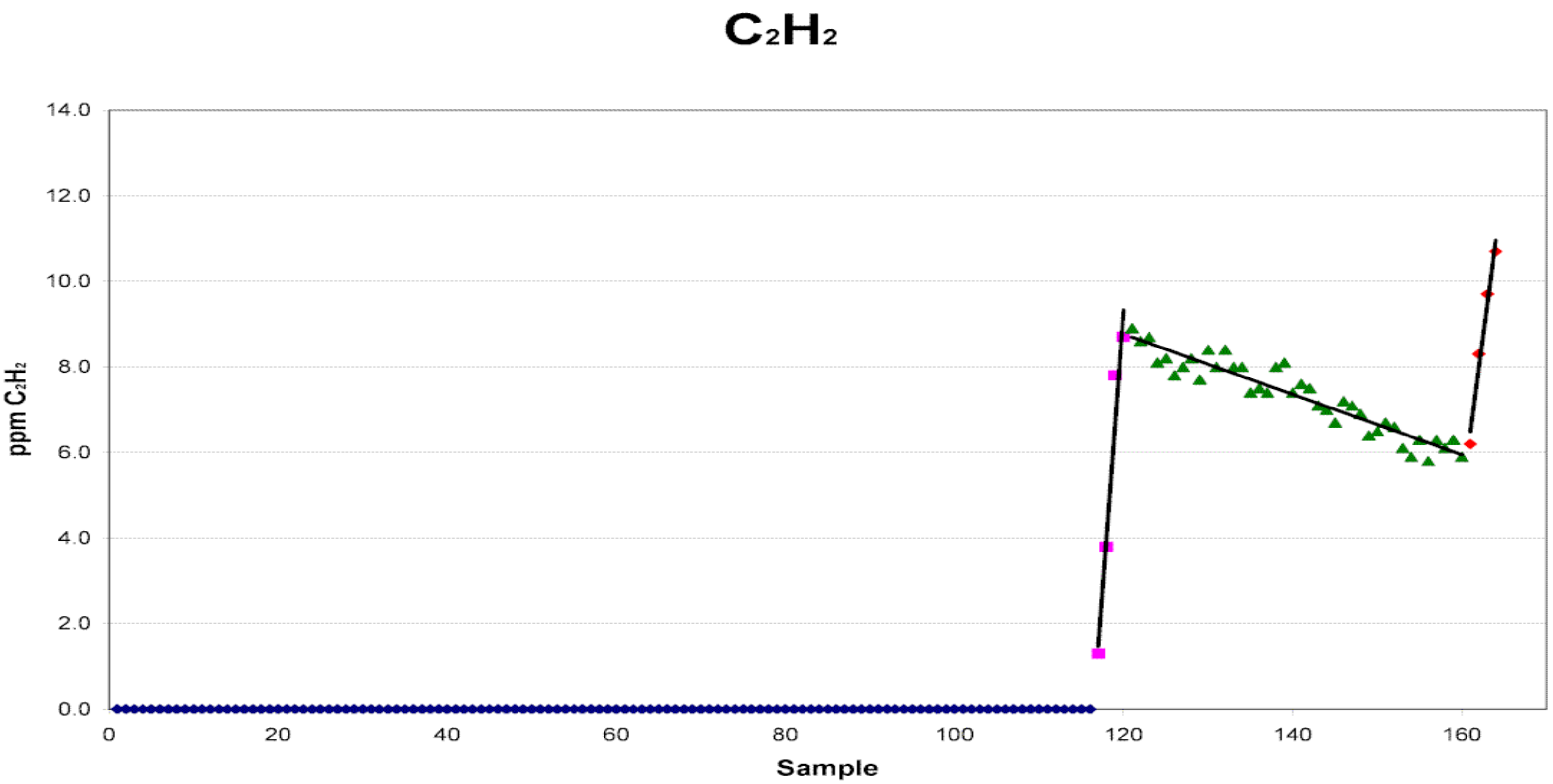


C2H2
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
ppm C2H2
0
20
40
60
80
100
120
140
160
Sample

C_2H_2

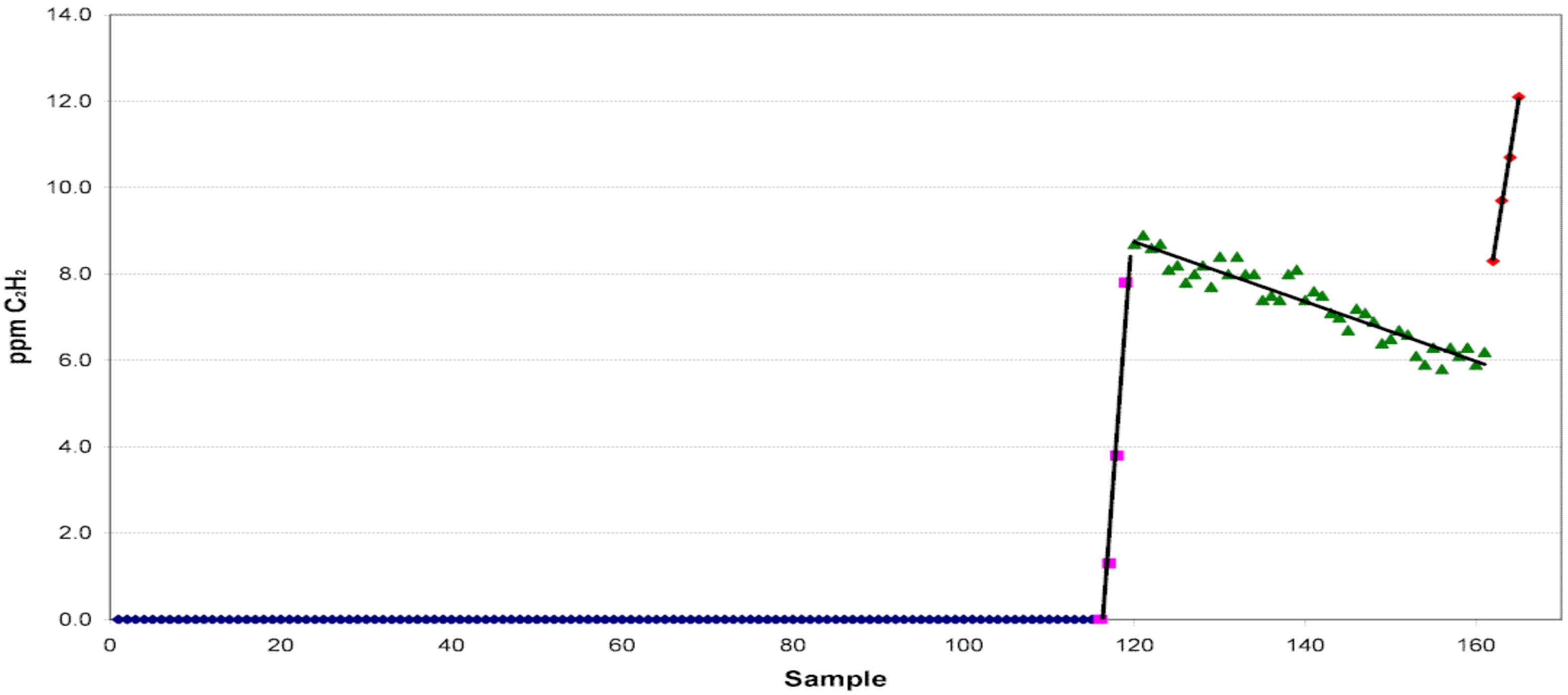


14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
ppm C2H2
0
20
40
60
80
100
120
140
160
Sample



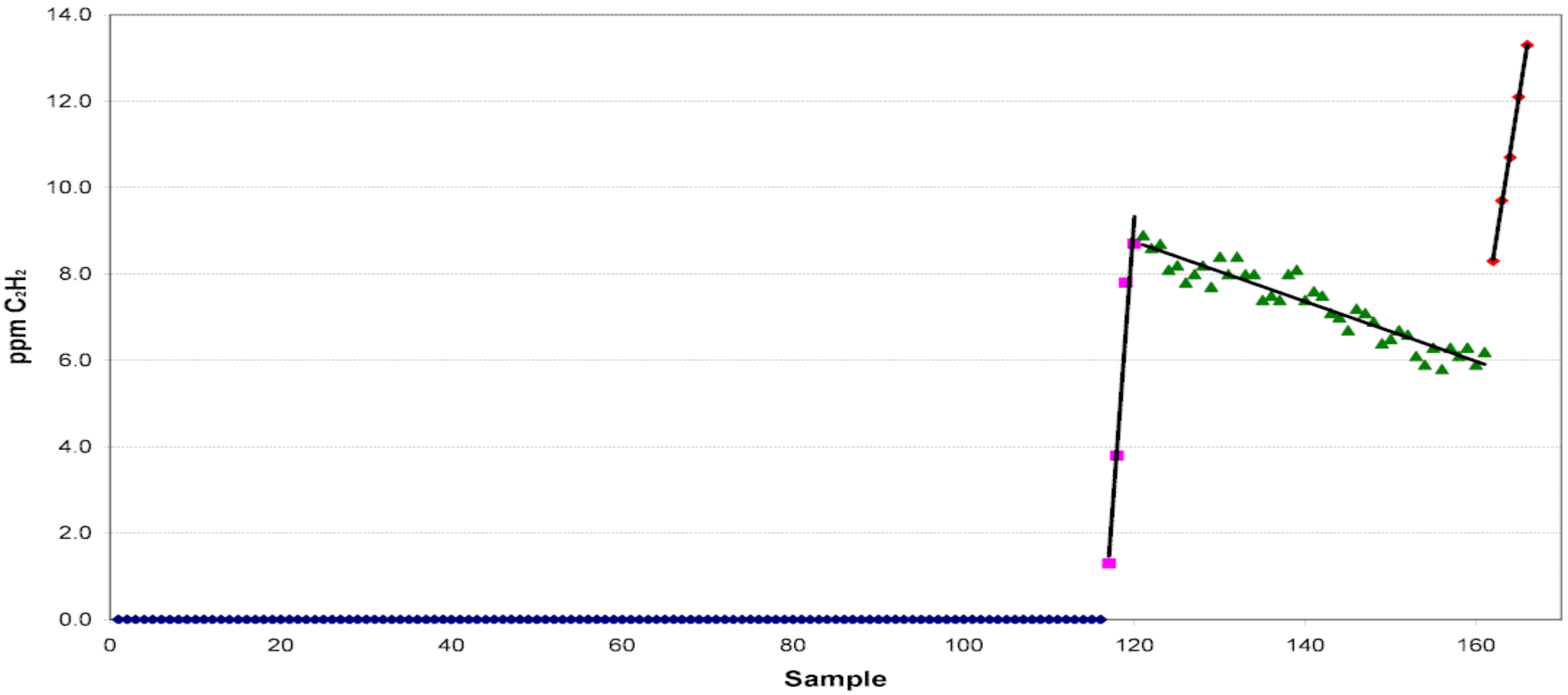
C2H2
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
ppm C2H2
0
20
40
60
80
100
120
140
160
Sample

C_2H_2



14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
ppm C_2H_2
0
20
40
60
80
100
120
140
160
Sample

C_2H_2



Compare with C57.104-2019, Figure B.2 “Multi-points rate example 2”

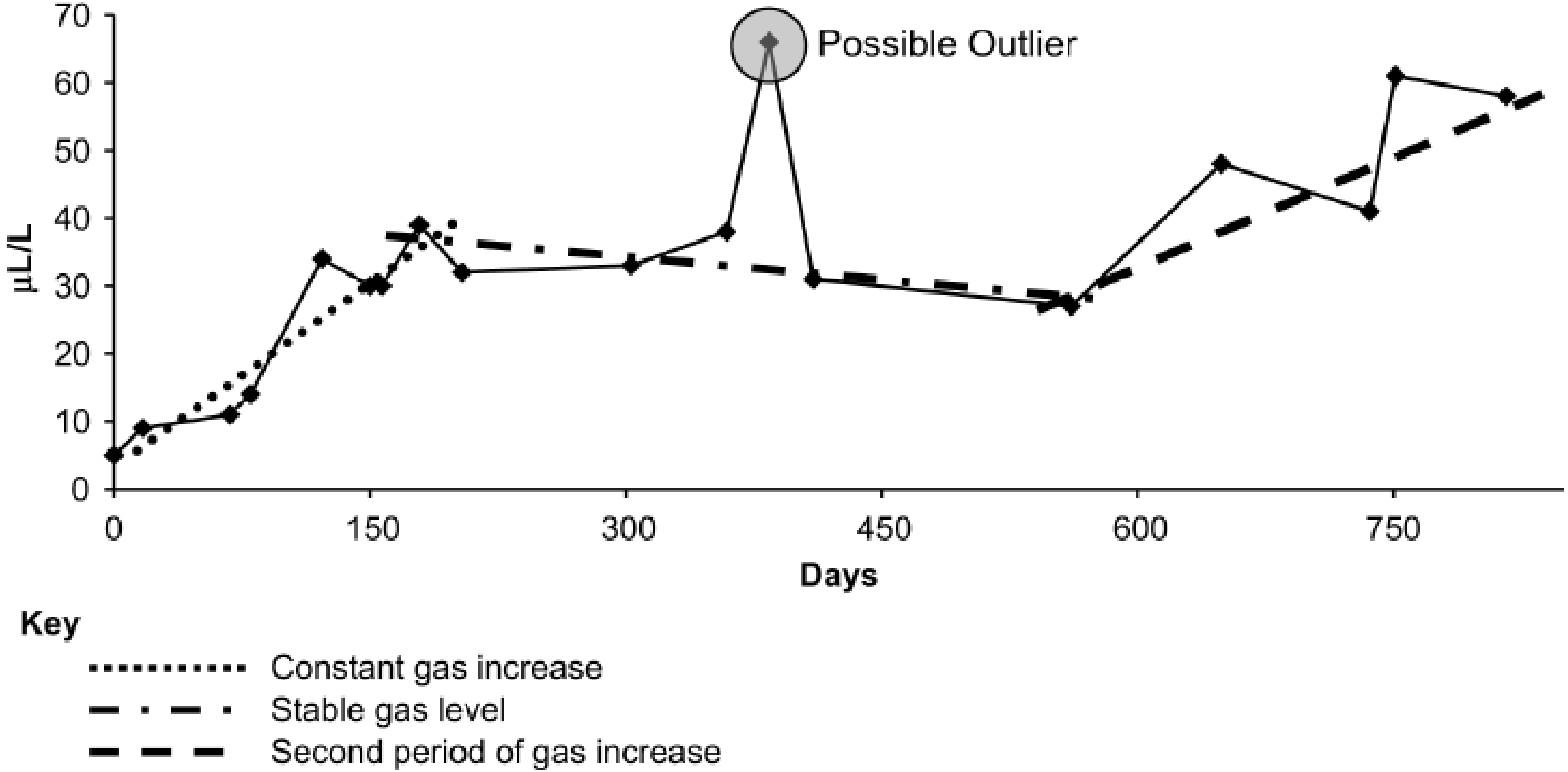
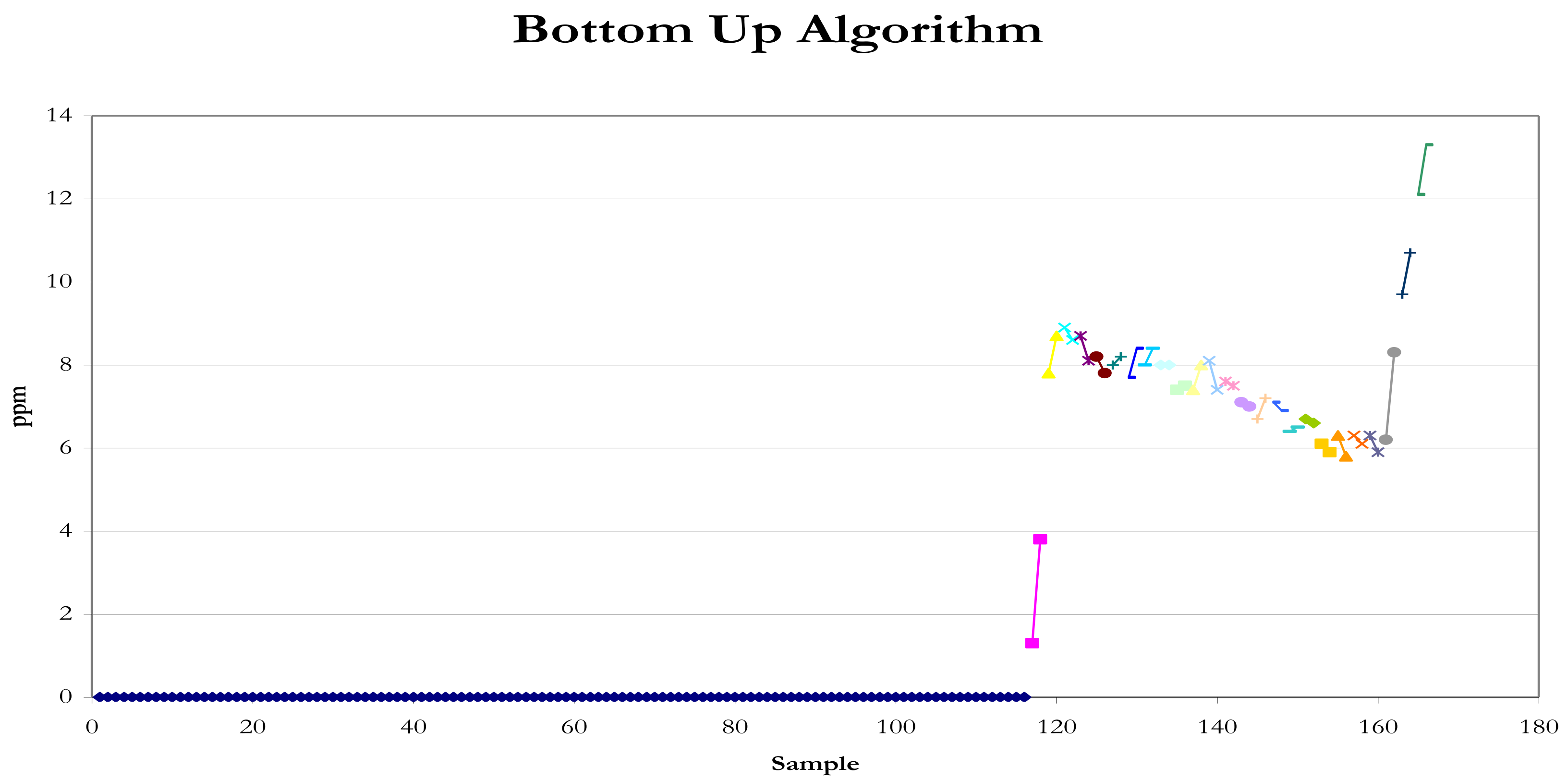
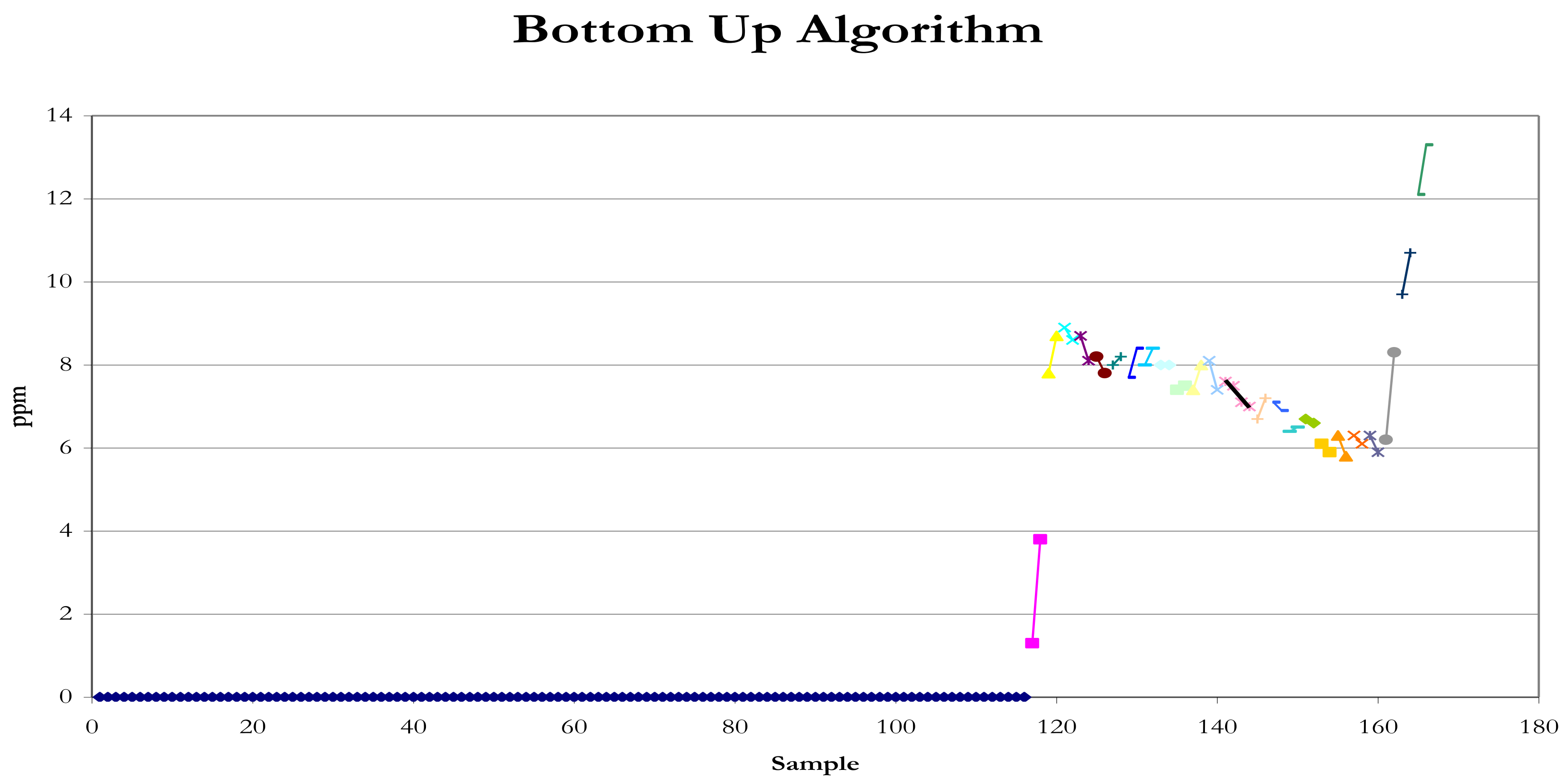


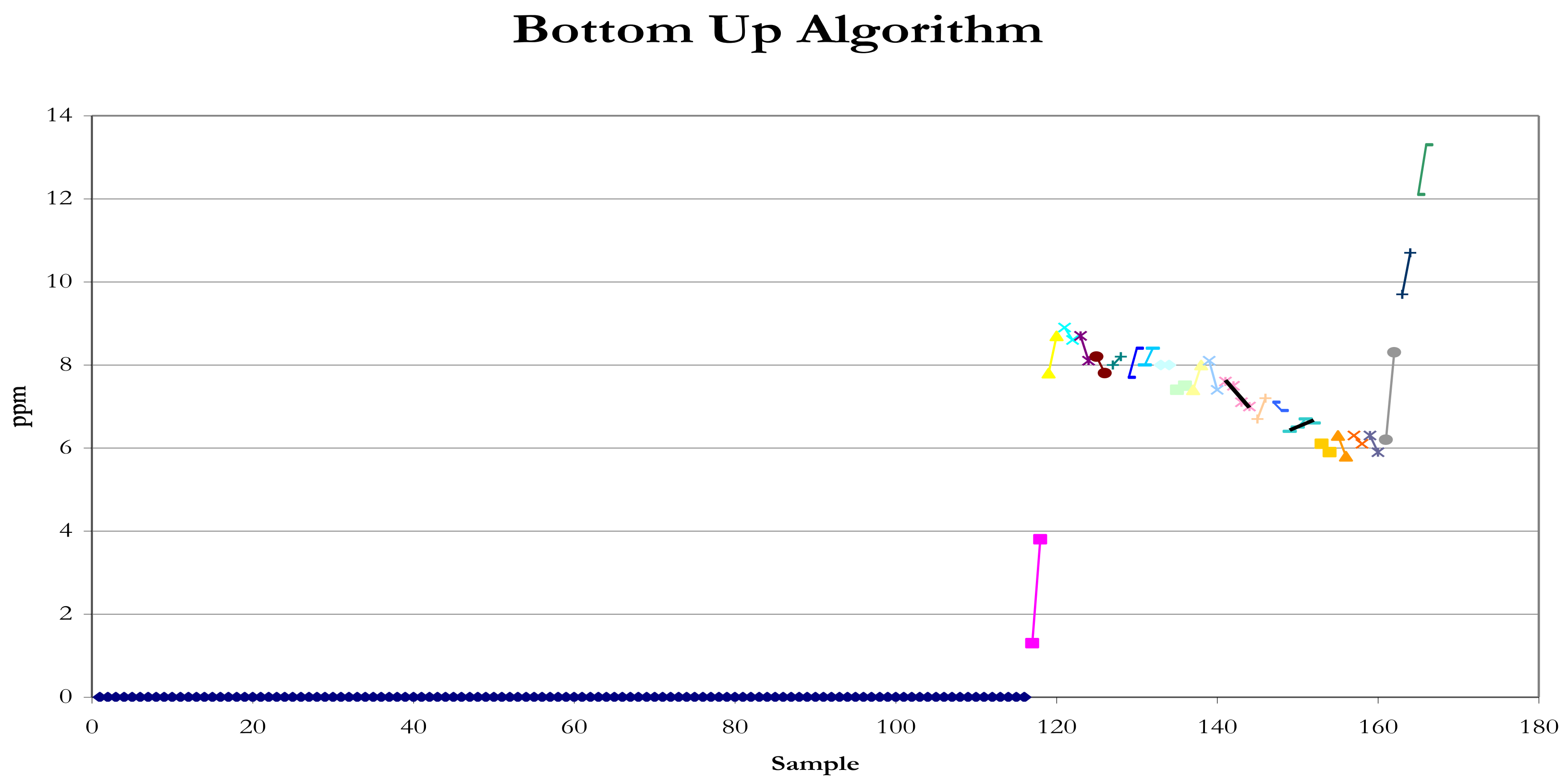
Figure B.2—Multi-points rate example 2

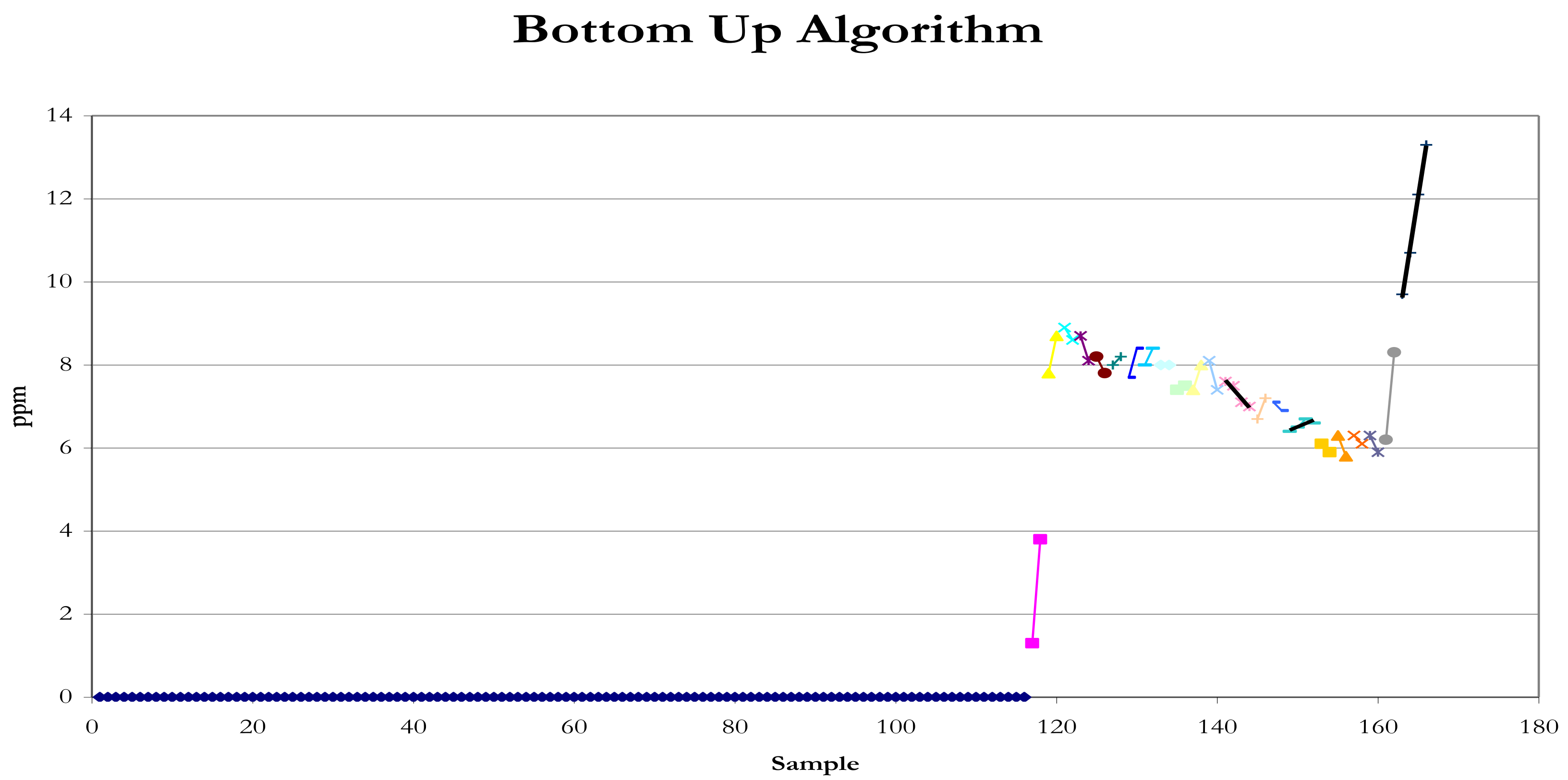
Bottom-Up Algorithm

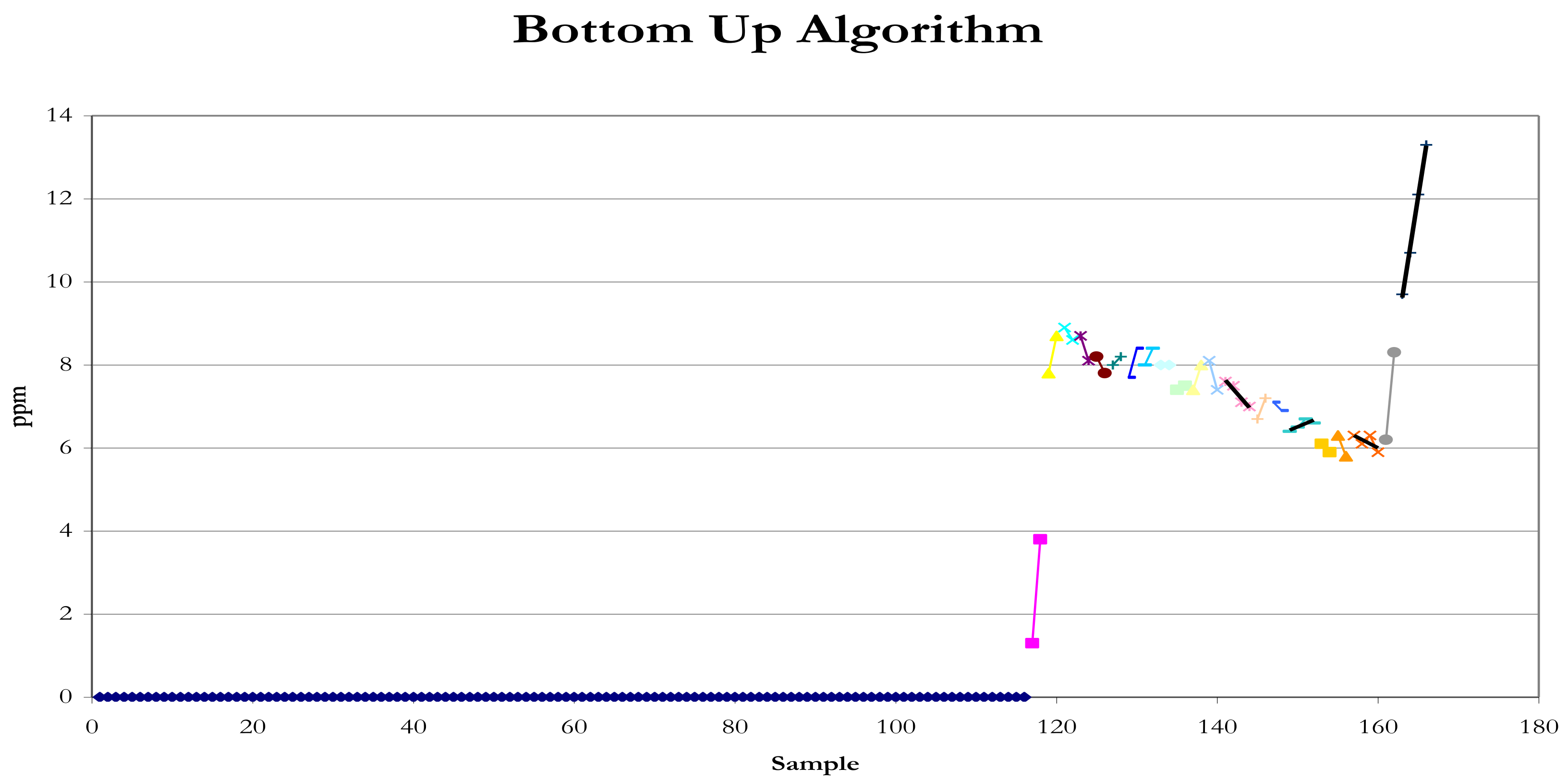
- Starts with the finest segmentation of the data as possible – data pairs
- Finds neighbor segments, that when merged, create the smallest error
- Continues merging until the stopping criteria is met
- For TOAN the stopping criteria is a function of the measurement accuracy and the amount of data


Bottom Up Algorithm
ppm
14
12
10
8
6
4
2
0
0
20
40
60
80
100
120
140
160
180
Sample

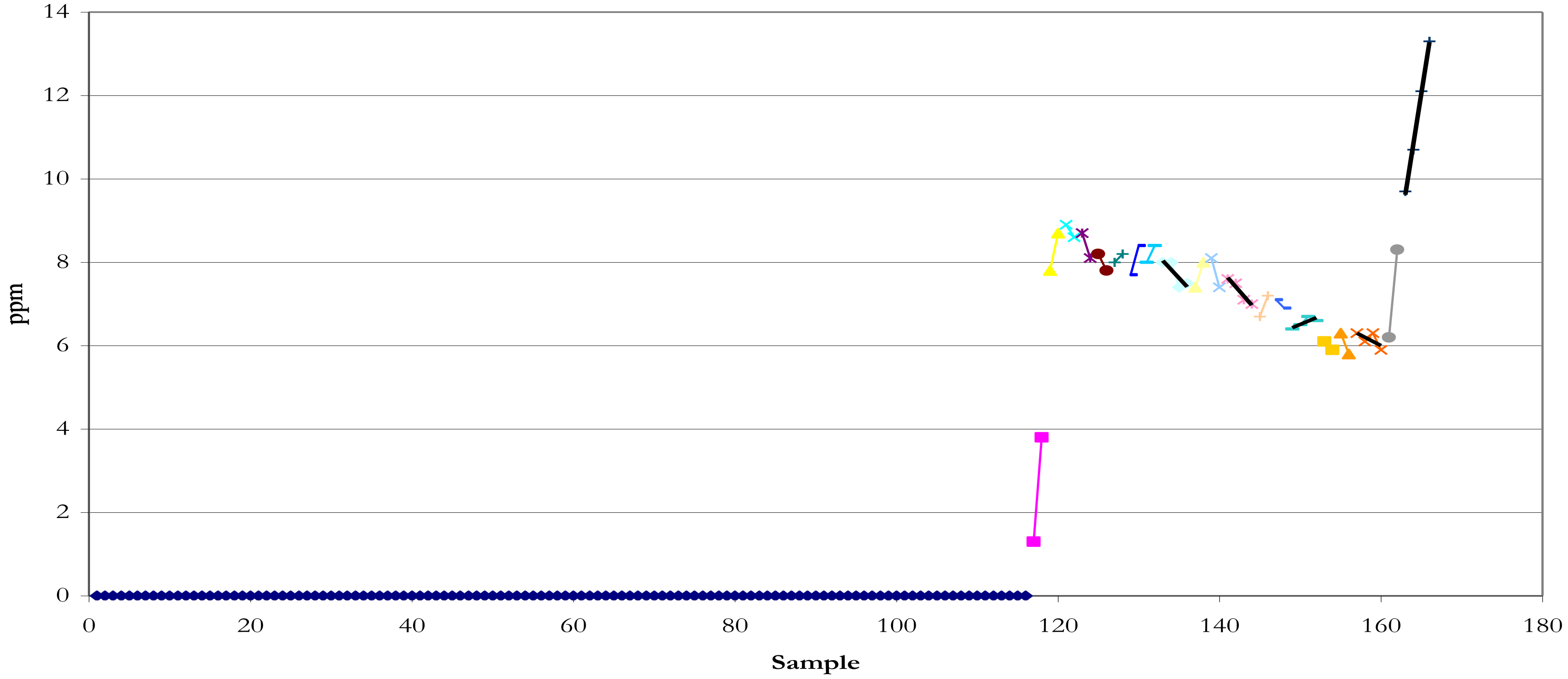

Bottom Up Algorithm
ppm
Sample
0
2
4
6
8
10
12
14
0
20
40
60
80
100
120
140
160
180

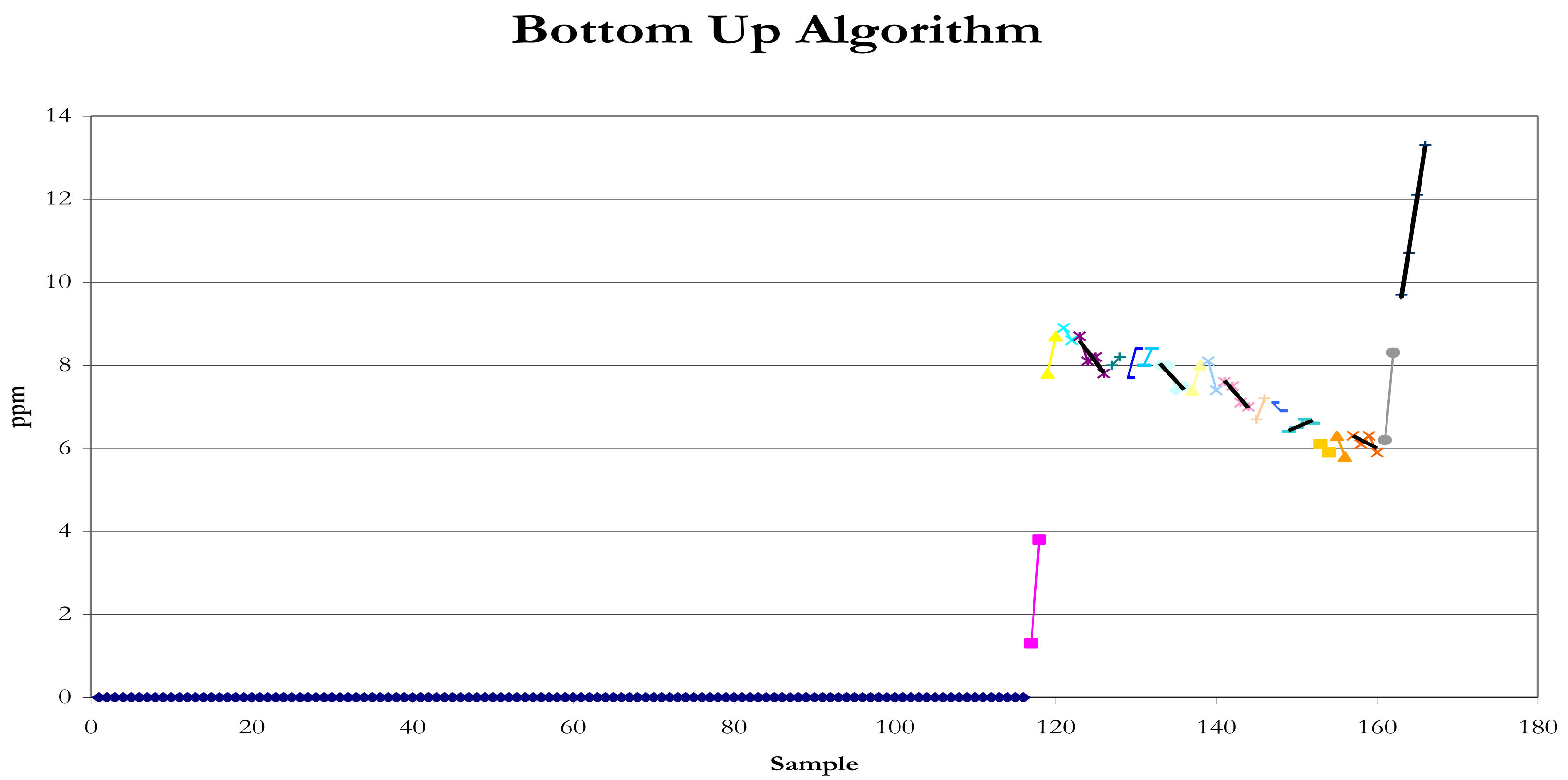

Bottom Up Algorithm
ppm
14
12
10
8
6
4
2
0
0
20
40
60
80
100
120
140
160
180
Sample


Bottom Up Algorithm
14
12
10
8
6
4
2
0
ppm
0
20
40
60
80
100
120
140
160
180
Sample

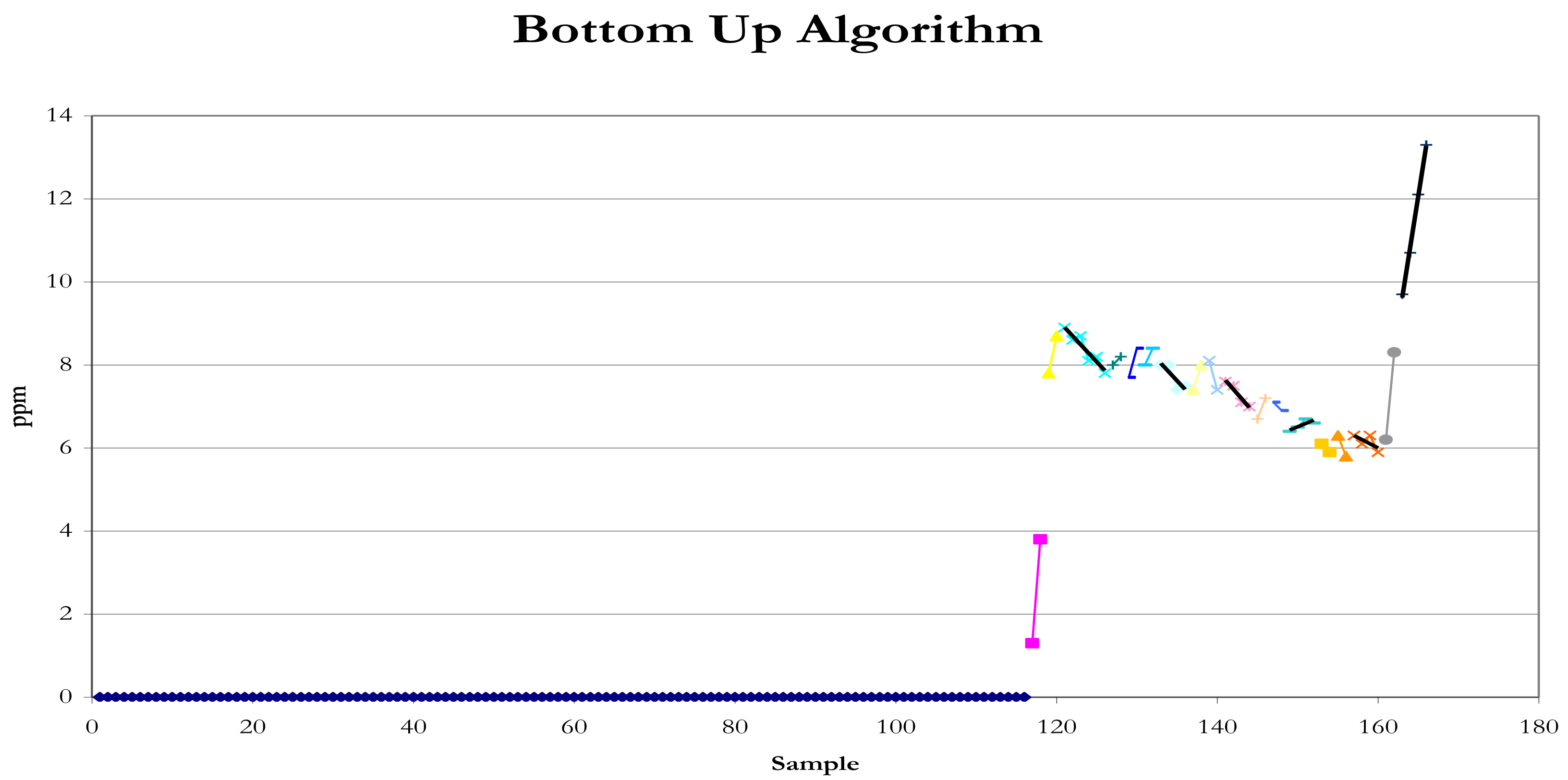

Bottom Up Algorithm
14
12
10
8
6
4
2
0
ppm
0
20
40
60
80
100
120
140
160
180
Sample

Bottom Up Algorithm

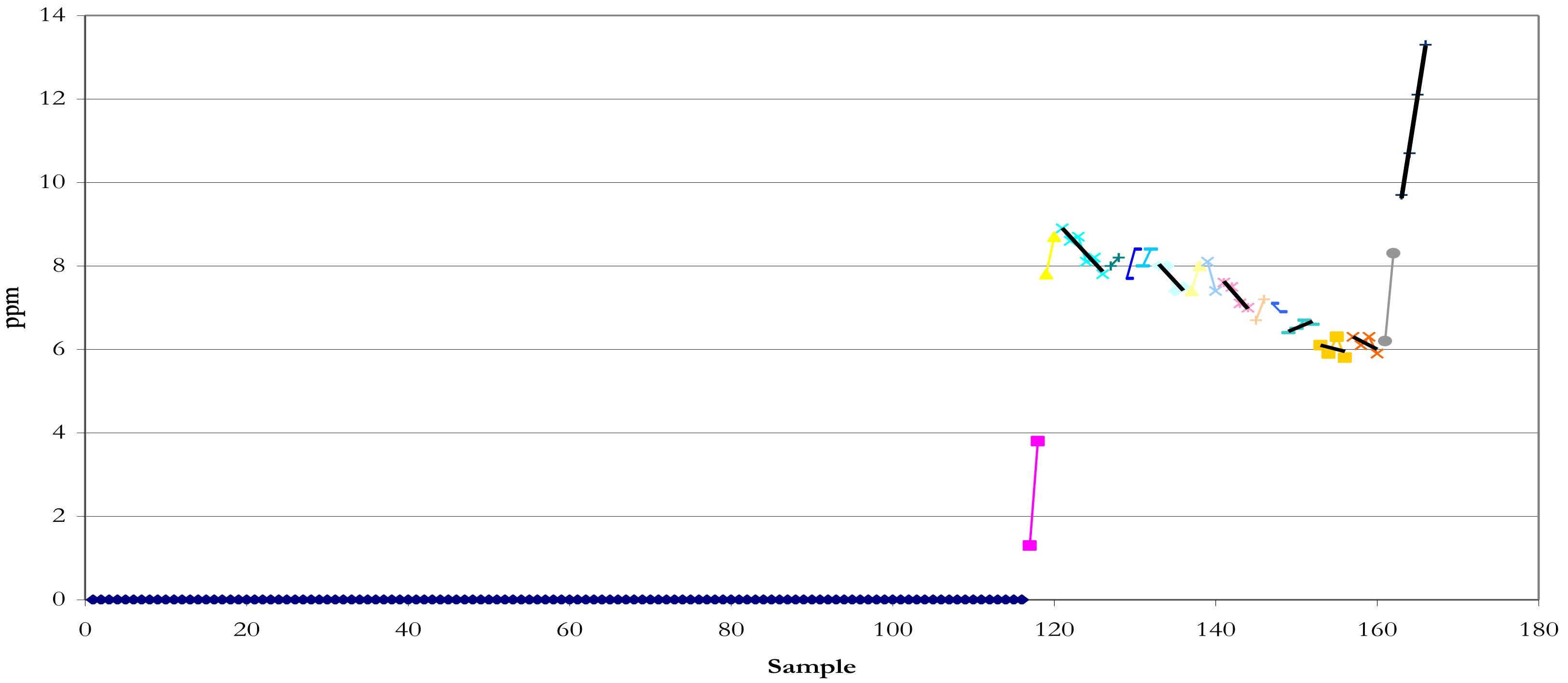




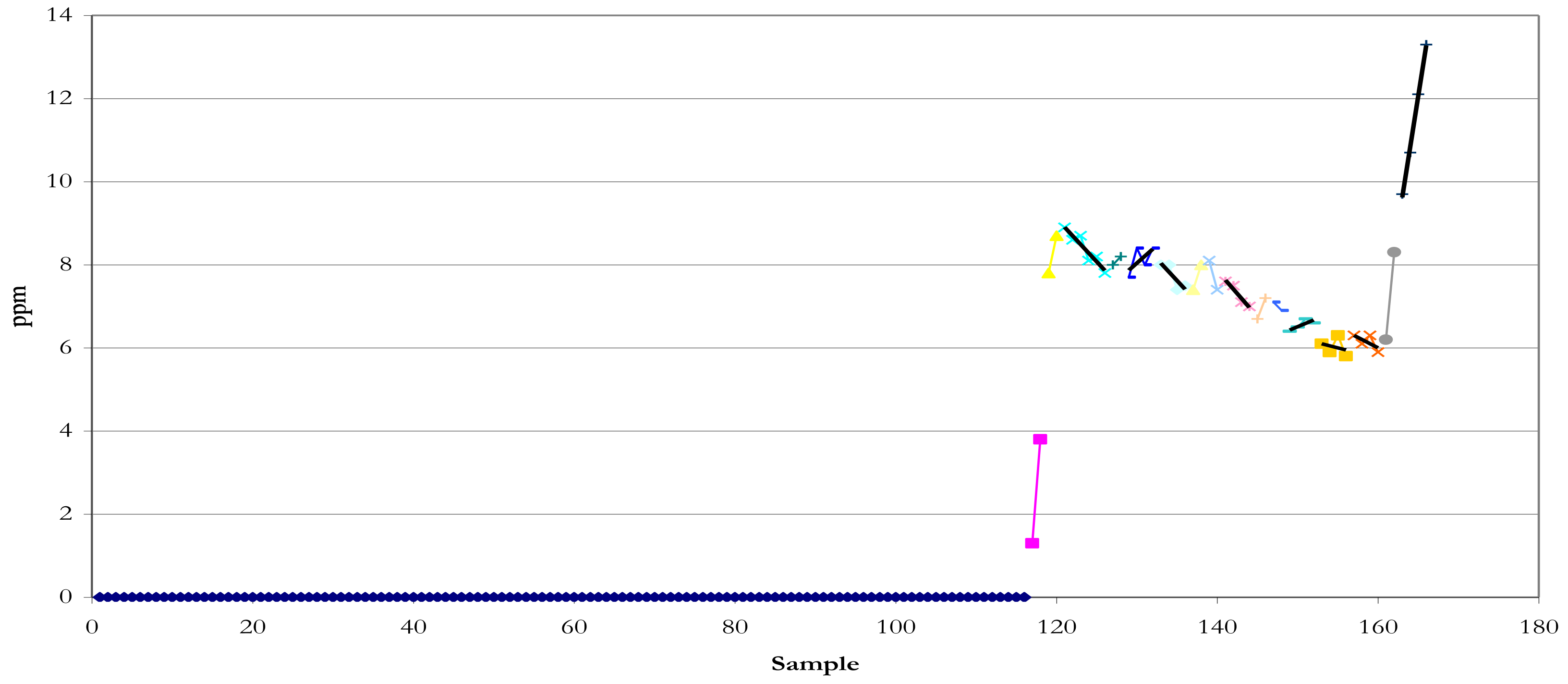
Bottom Up Algorithm
ppm
Sample
0
2
4
6
8
10
12
14
0
20
40
60
80
100
120
140
160
180


Bottom Up Algorithm
ppm
Sample
0
2
4
6
8
10
12
14
0
20
40
60
80
100
120
140
160
180

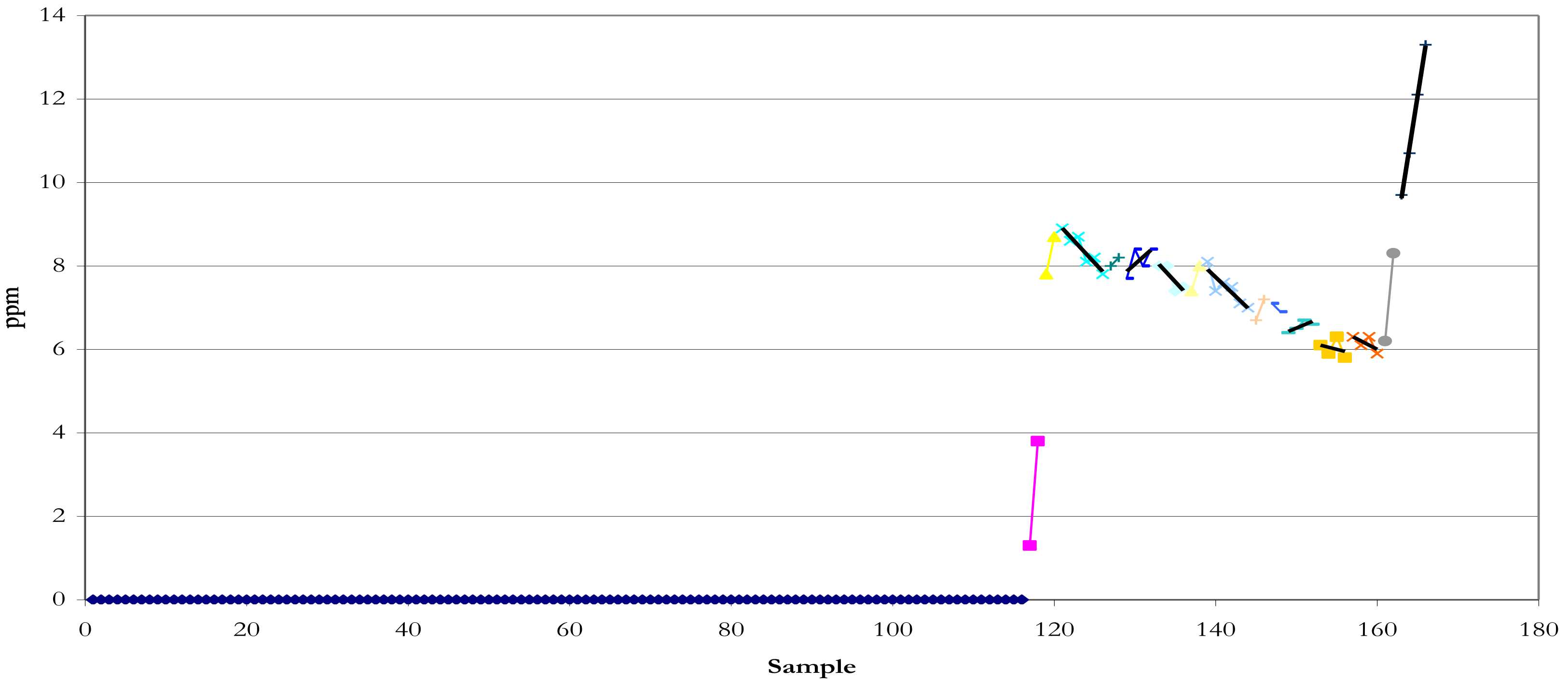
Bottom Up Algorithm

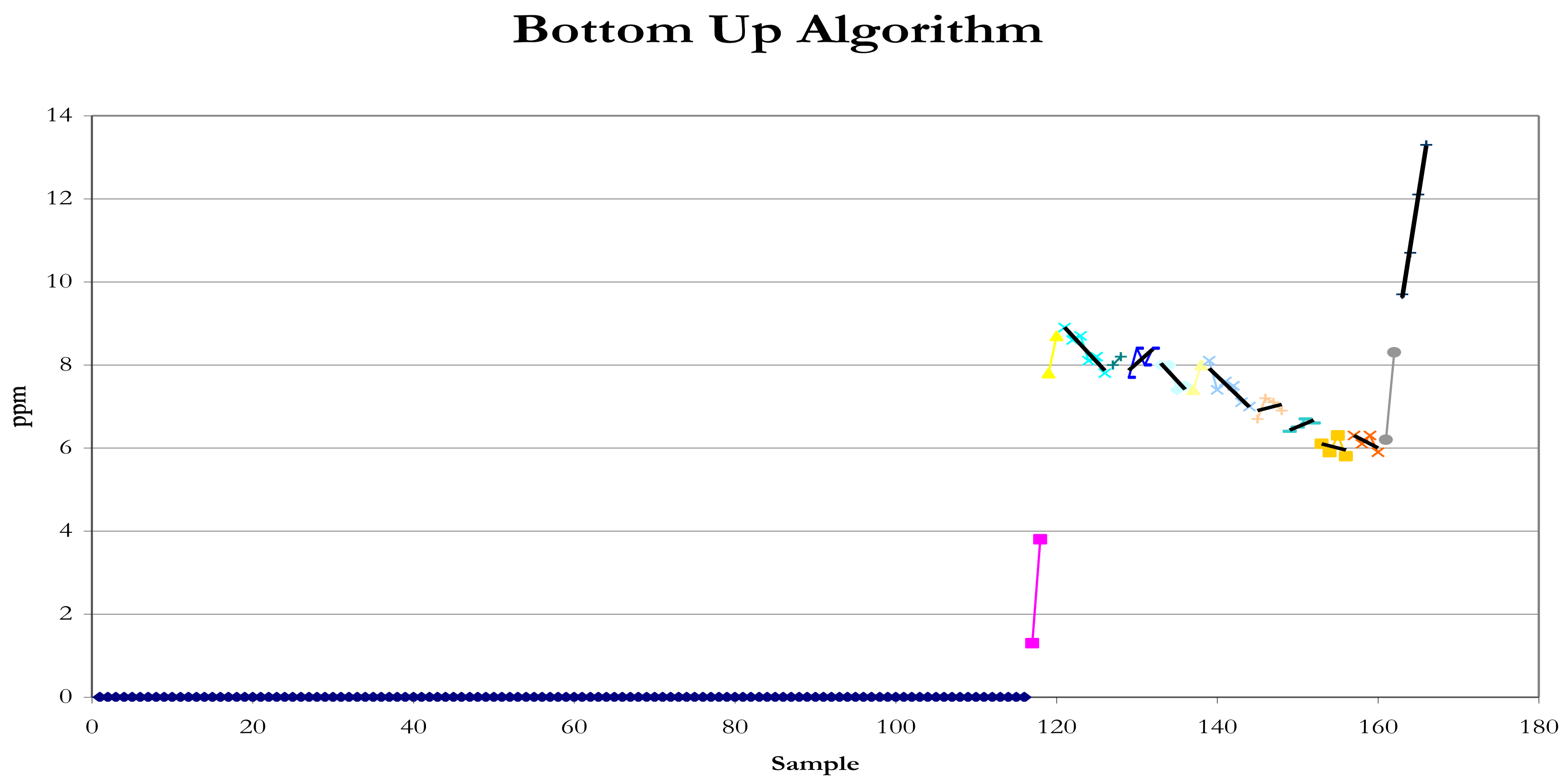


Bottom Up Algorithm



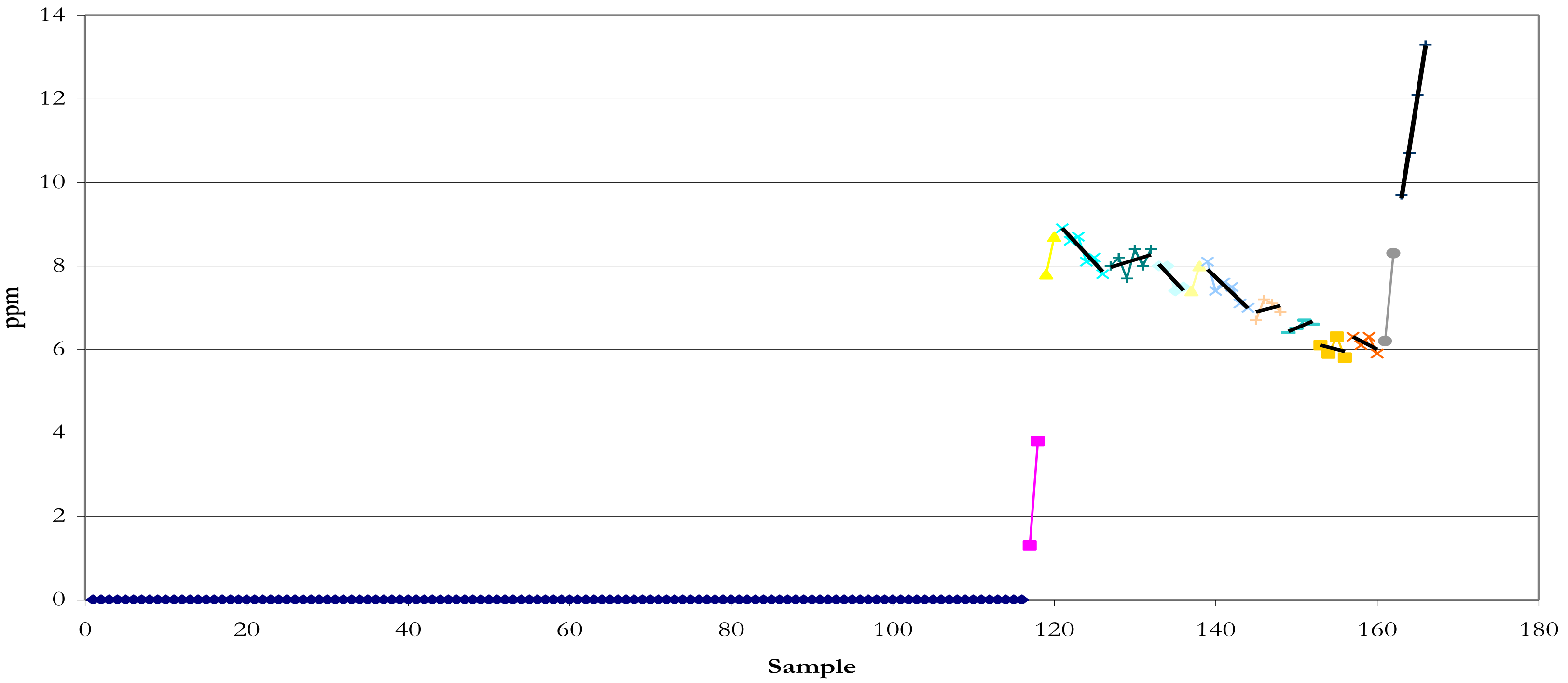
Bottom Up Algorithm

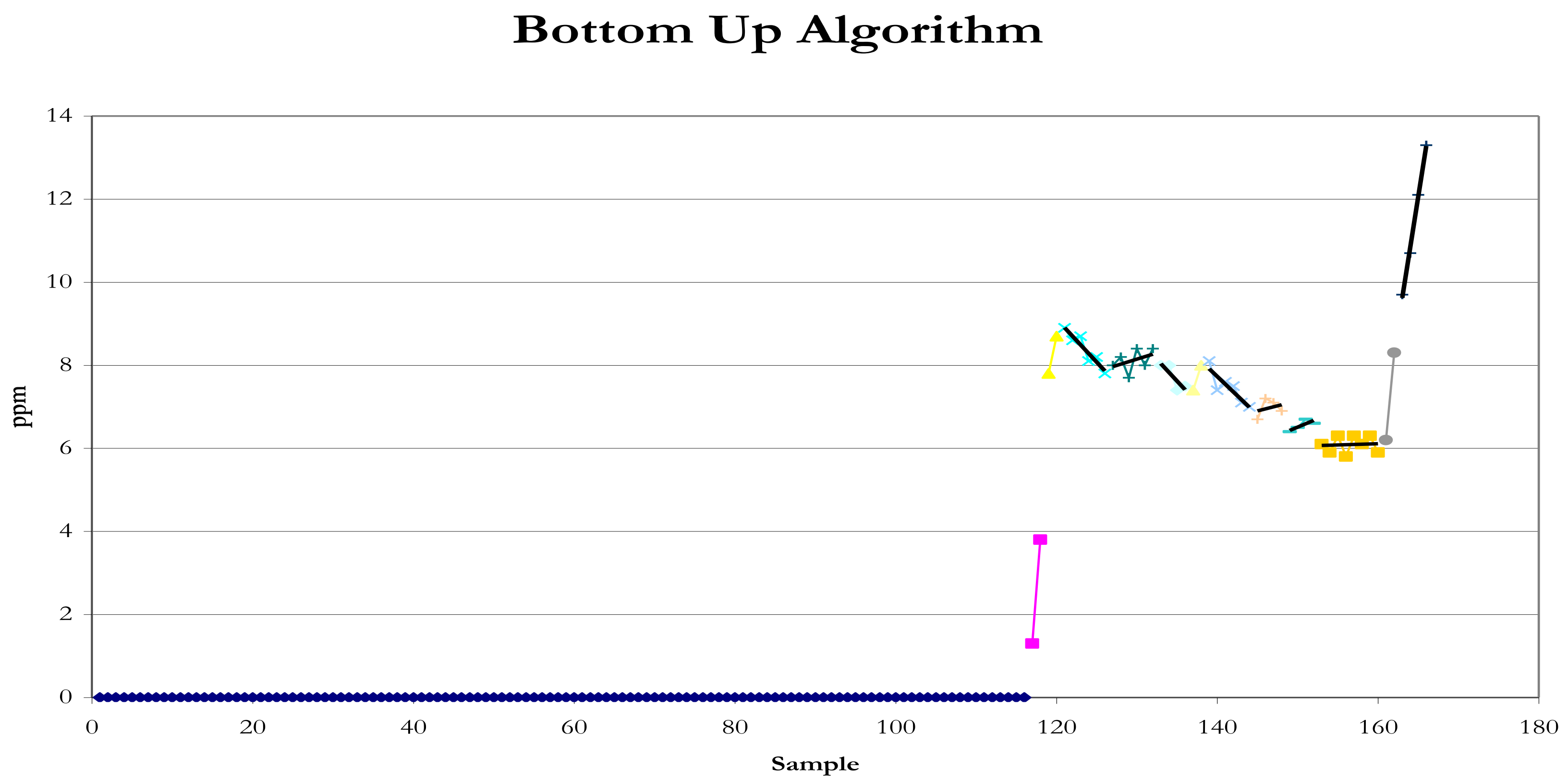




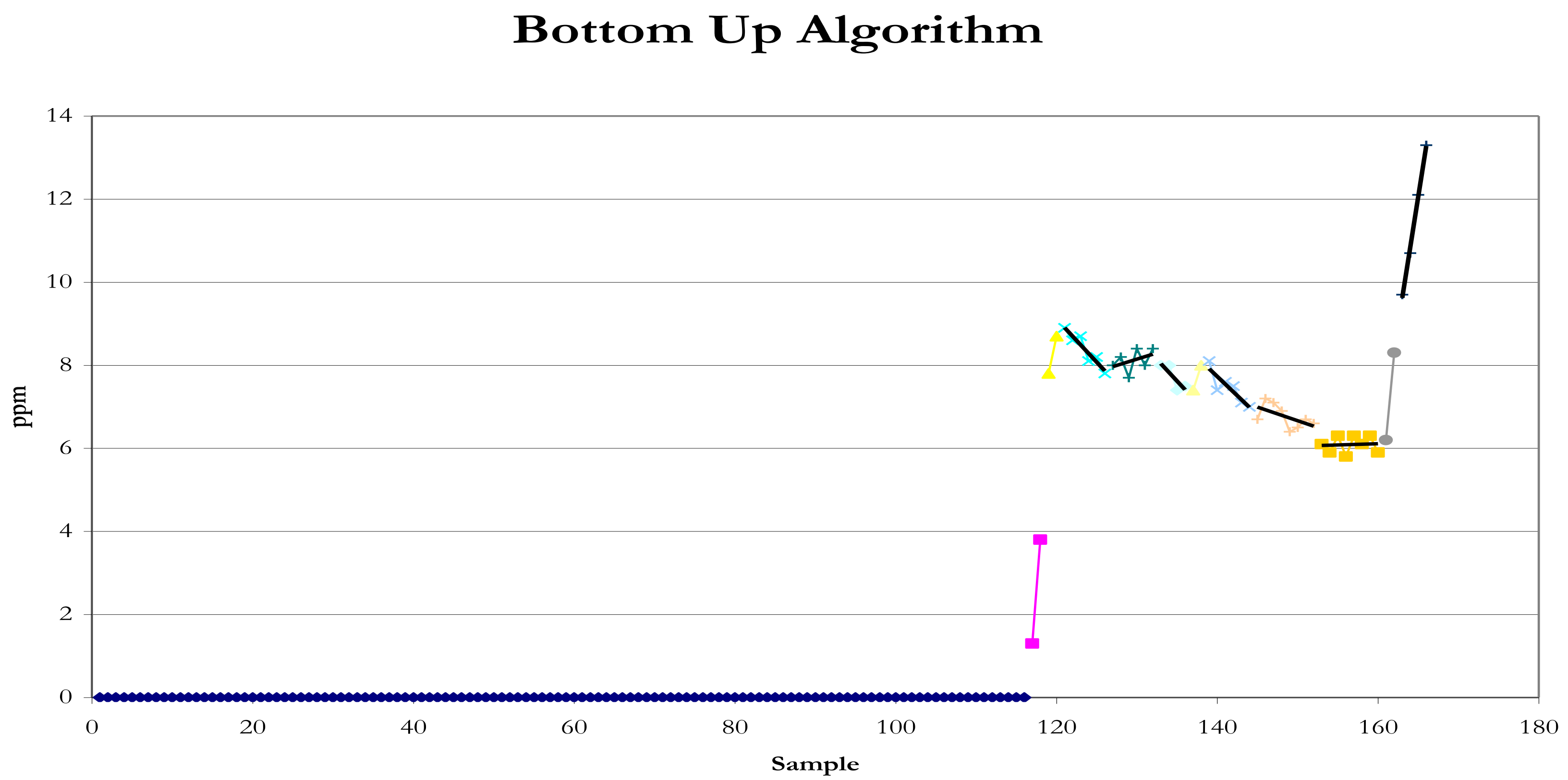
Bottom Up Algorithm
ppm
Sample
0
2
4
6
8
10
12
14
0
20
40
60
80
100
120
140
160
180

Bottom Up Algorithm



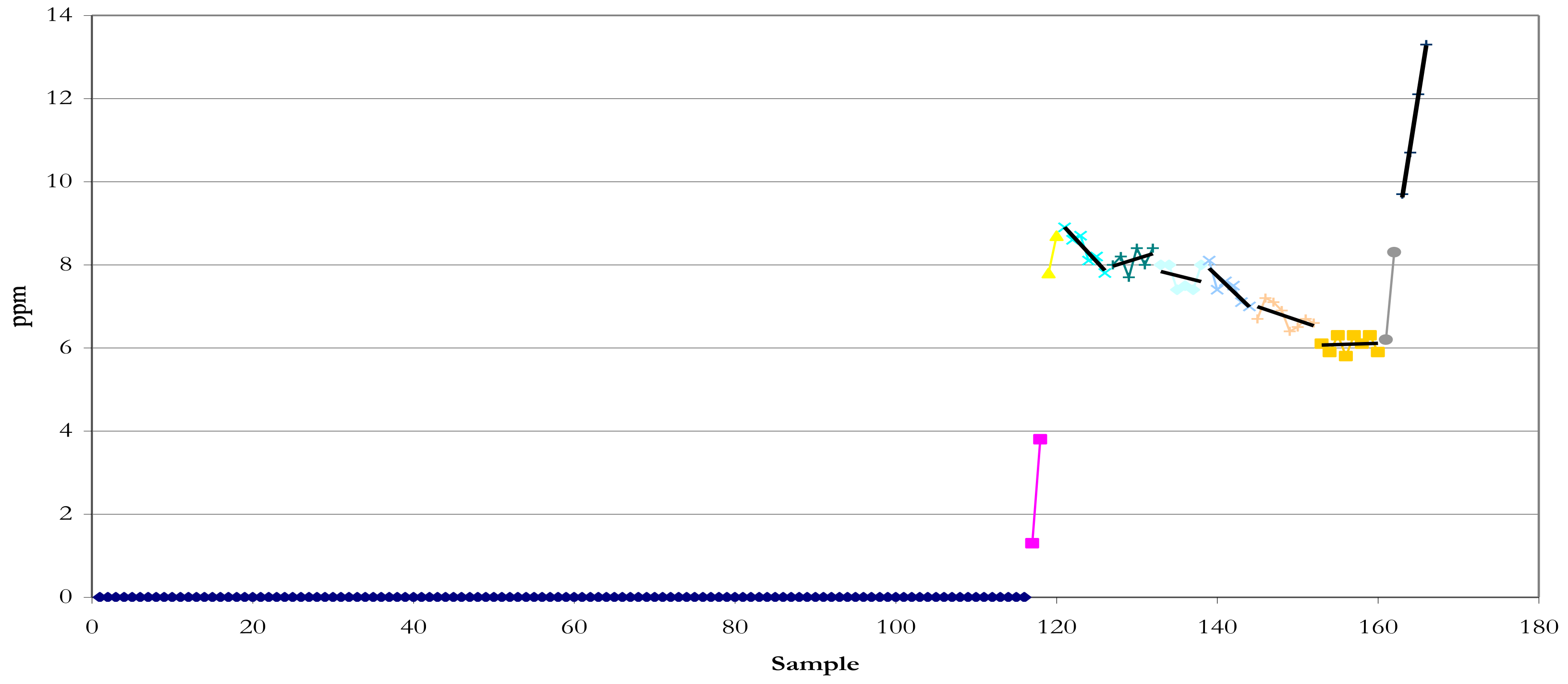


Bottom Up Algorithm
ppm
Sample
0
2
4
6
8
10
12
14
0
20
40
60
80
100
120
140
160
180

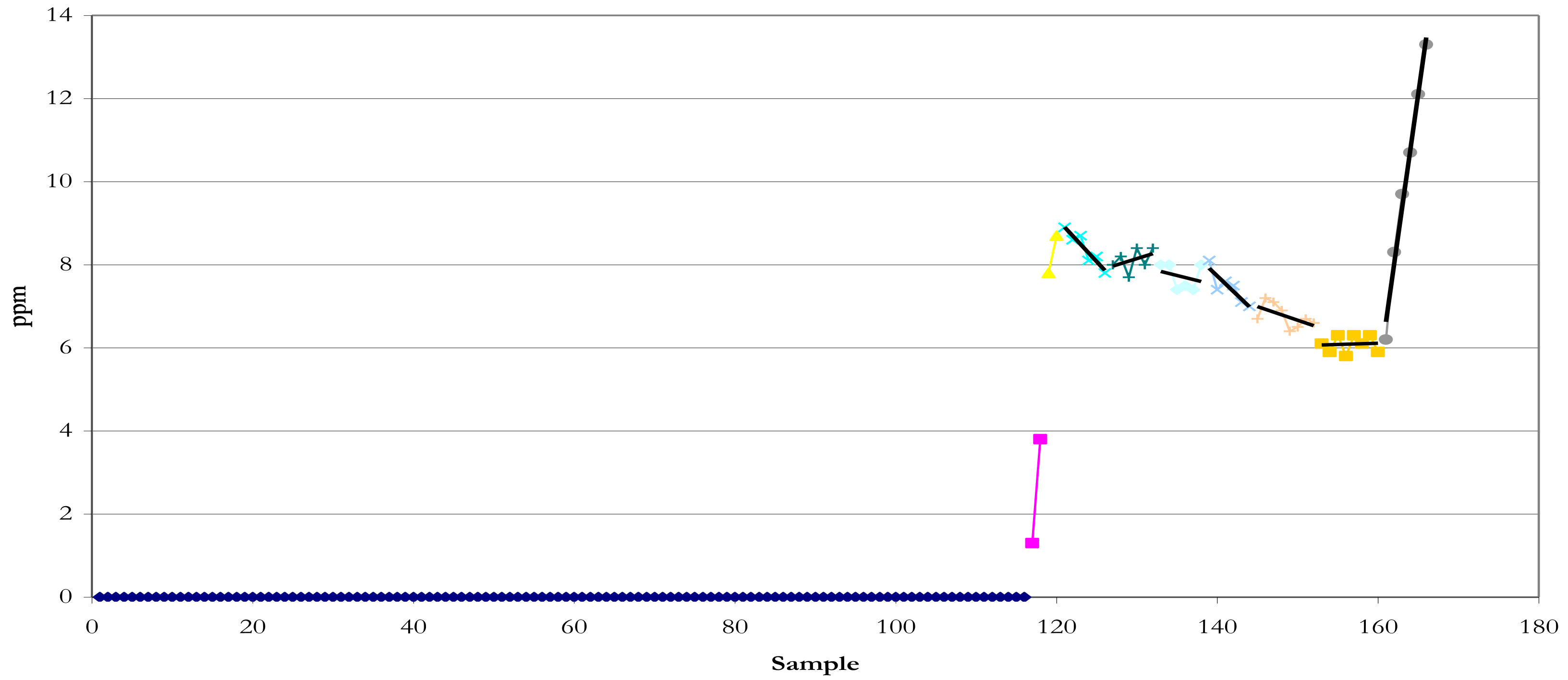


Bottom Up Algorithm
ppm
14
12
10
8
6
4
2
0
0
20
40
60
80
100
120
140
160
180
Sample

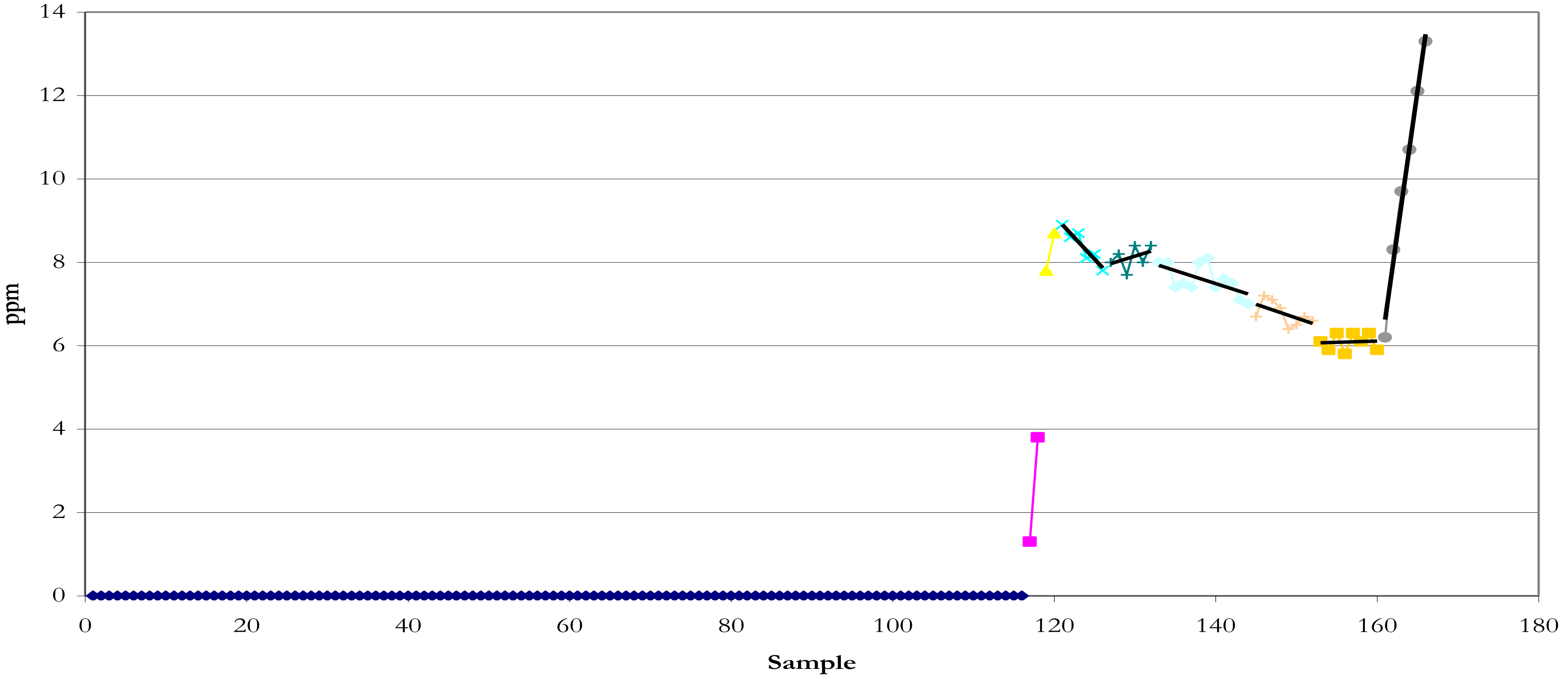
Bottom Up Algorithm



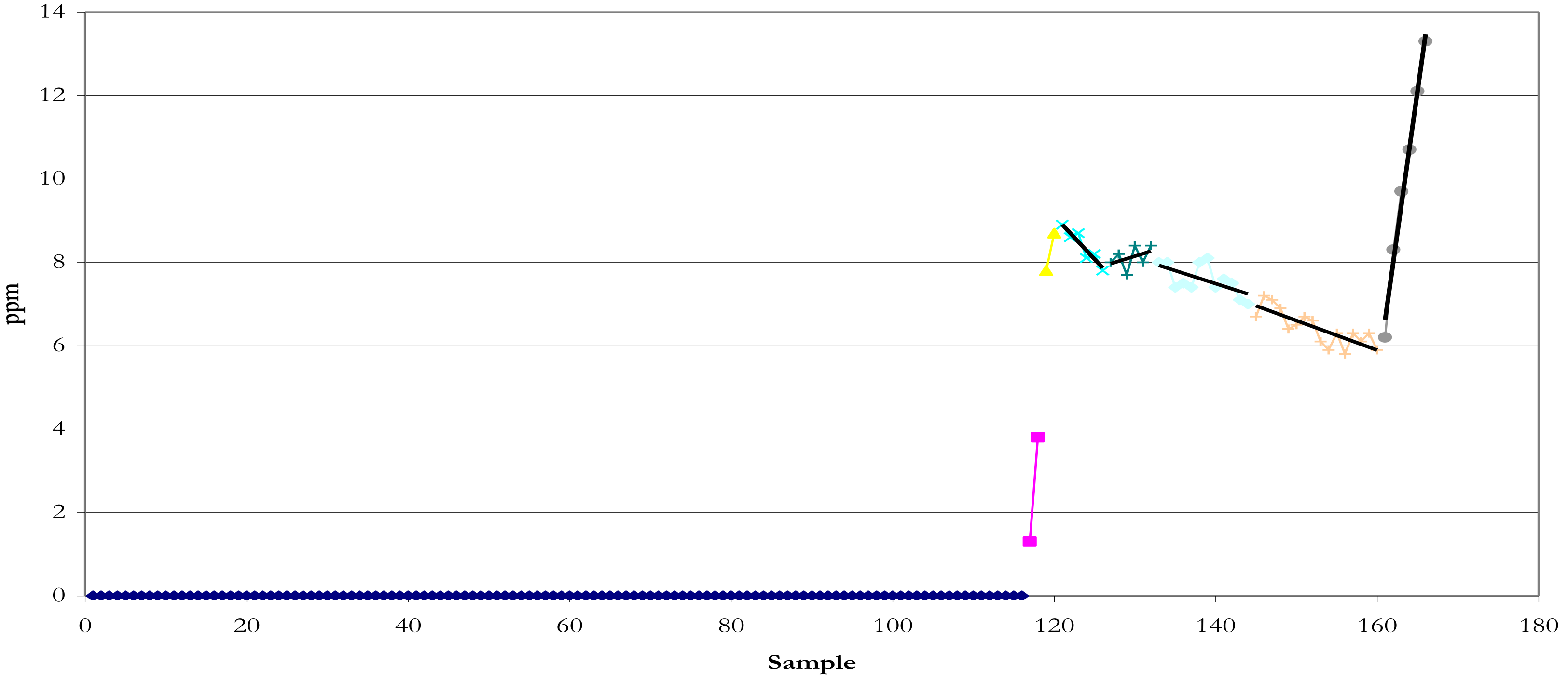
Bottom Up Algorithm



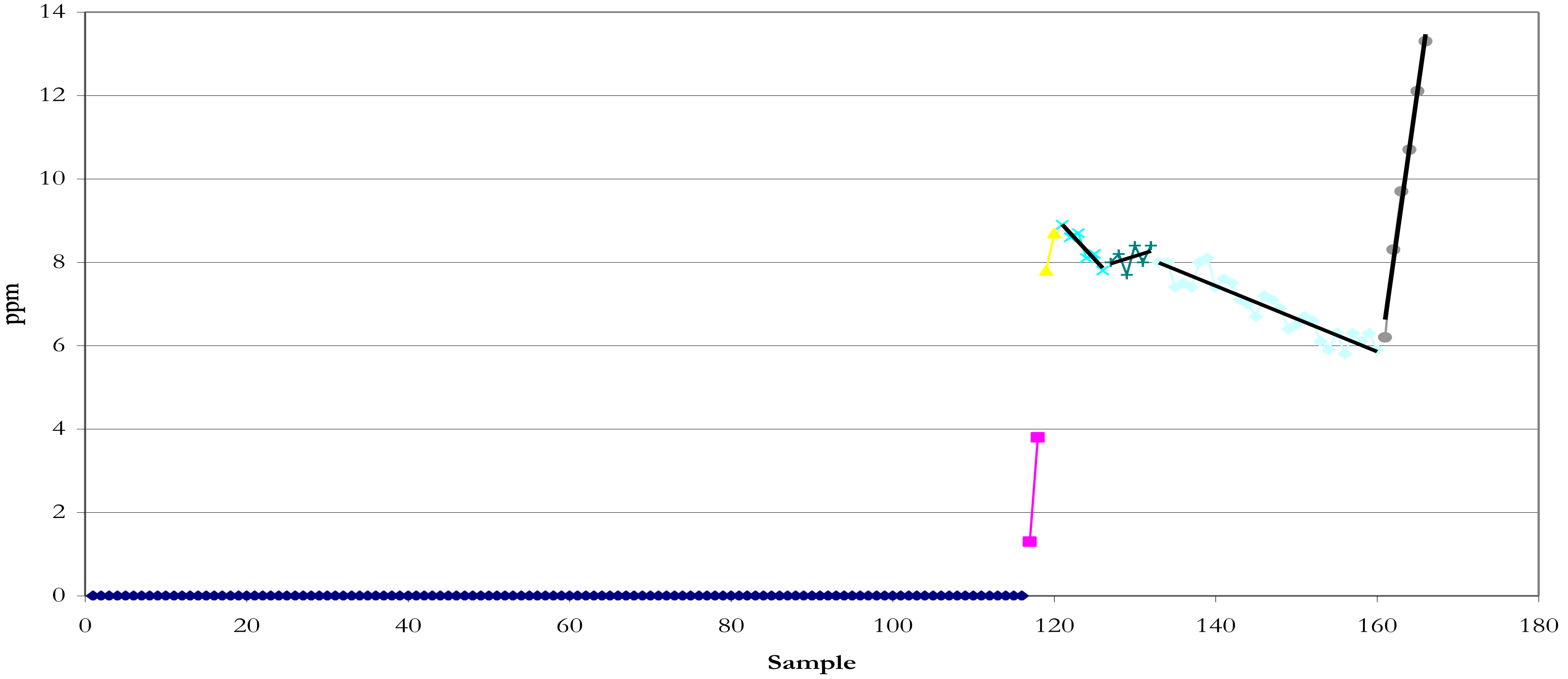
Bottom Up Algorithm

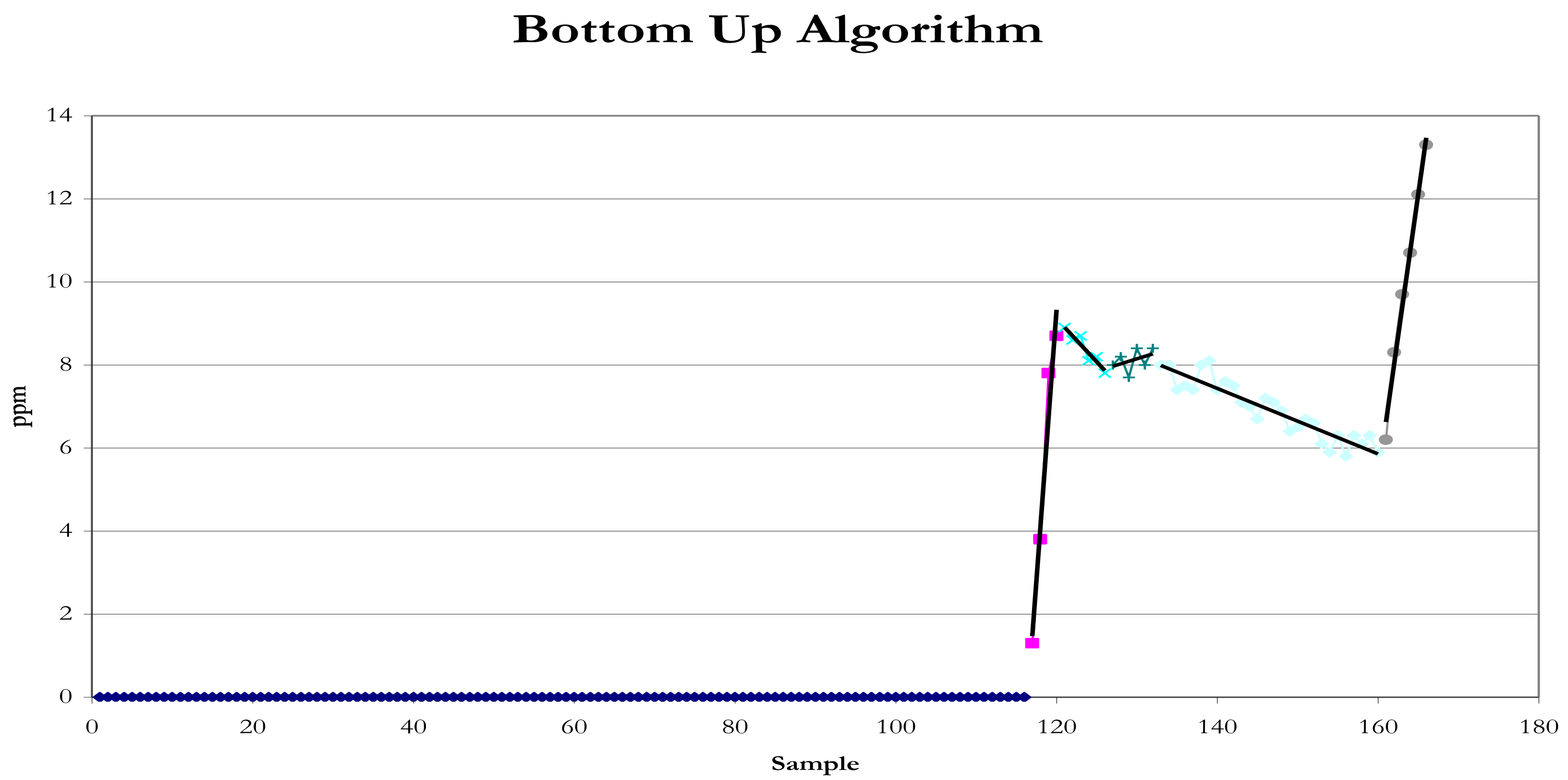


Bottom Up Algorithm

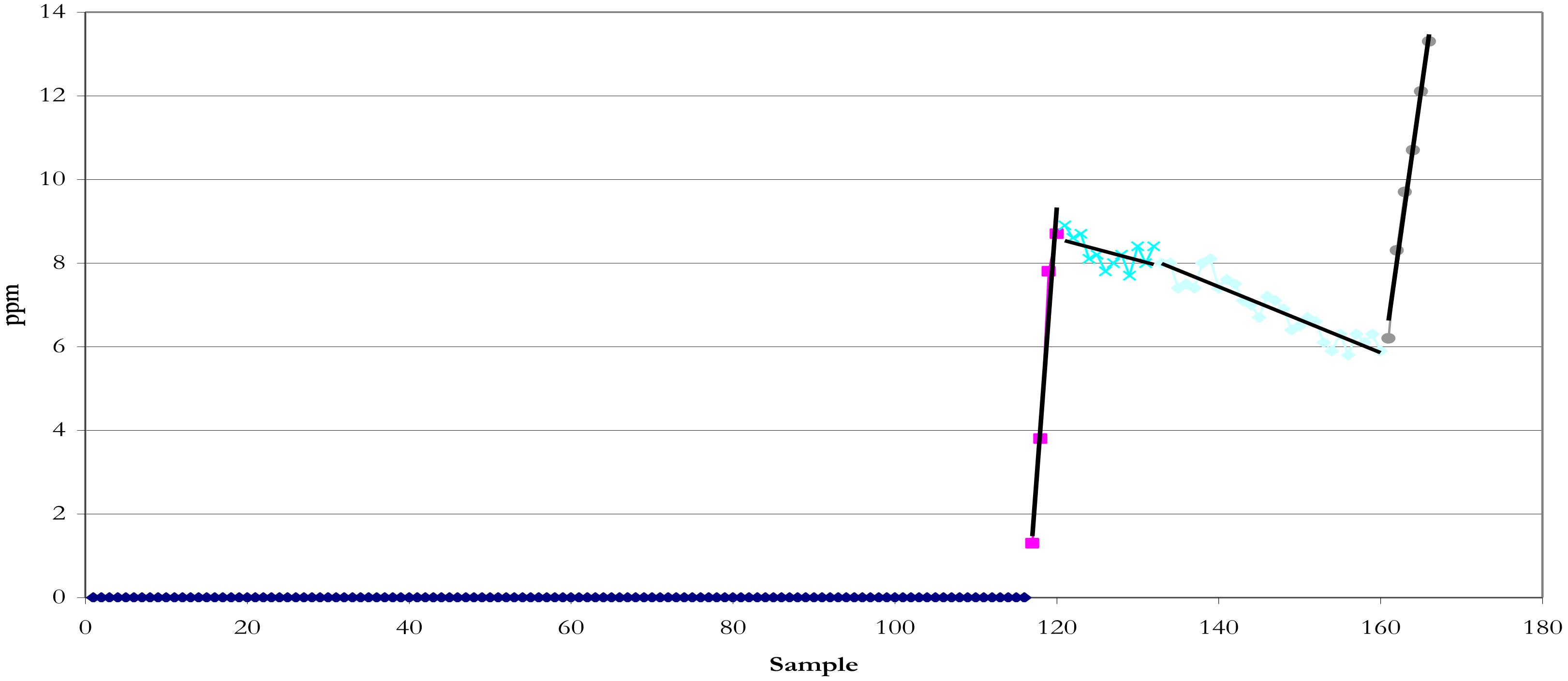


Bottom Up Algorithm

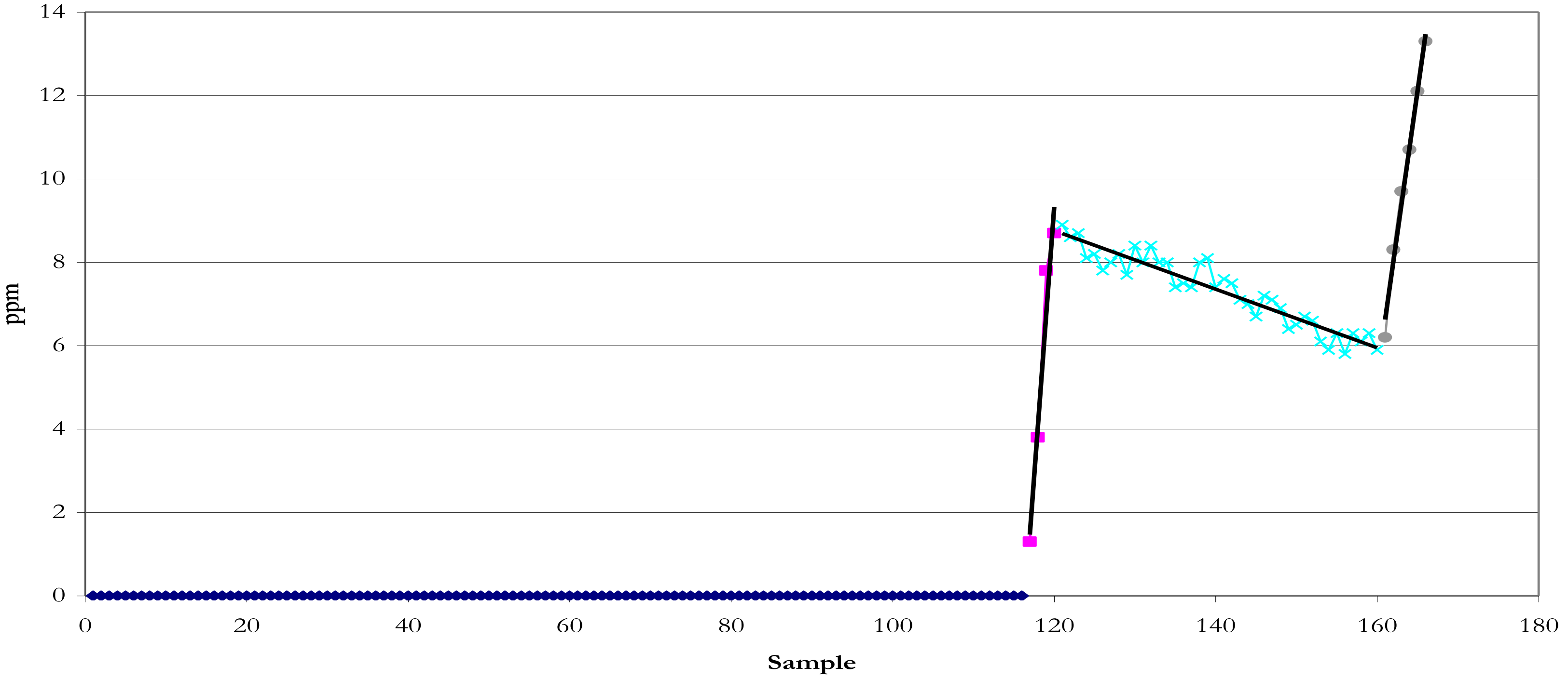


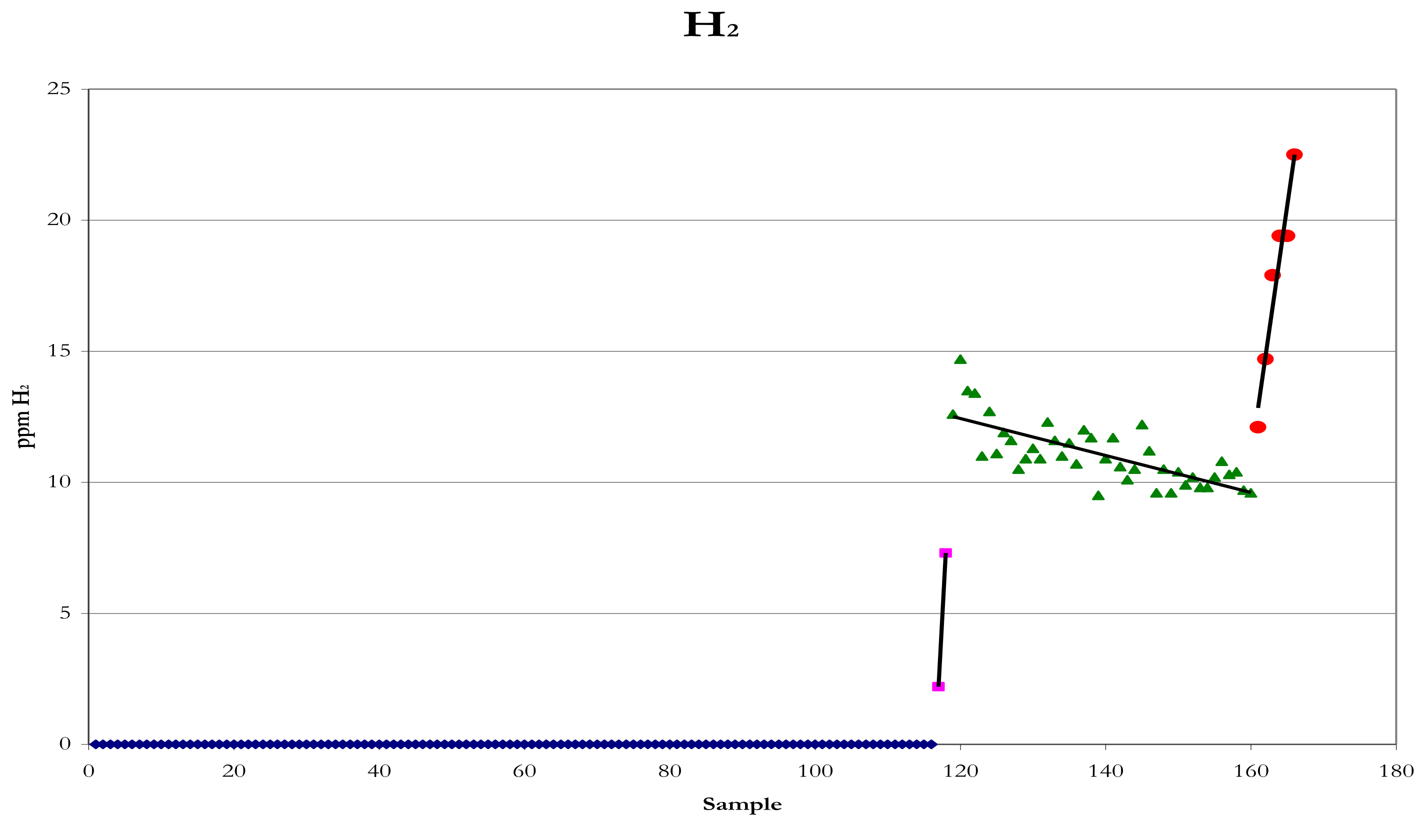

Bottom Up Algorithm
ppm
Sample
0
2
4
6
8
10
12
14
0
20
40
60
80
100
120
140
160
180

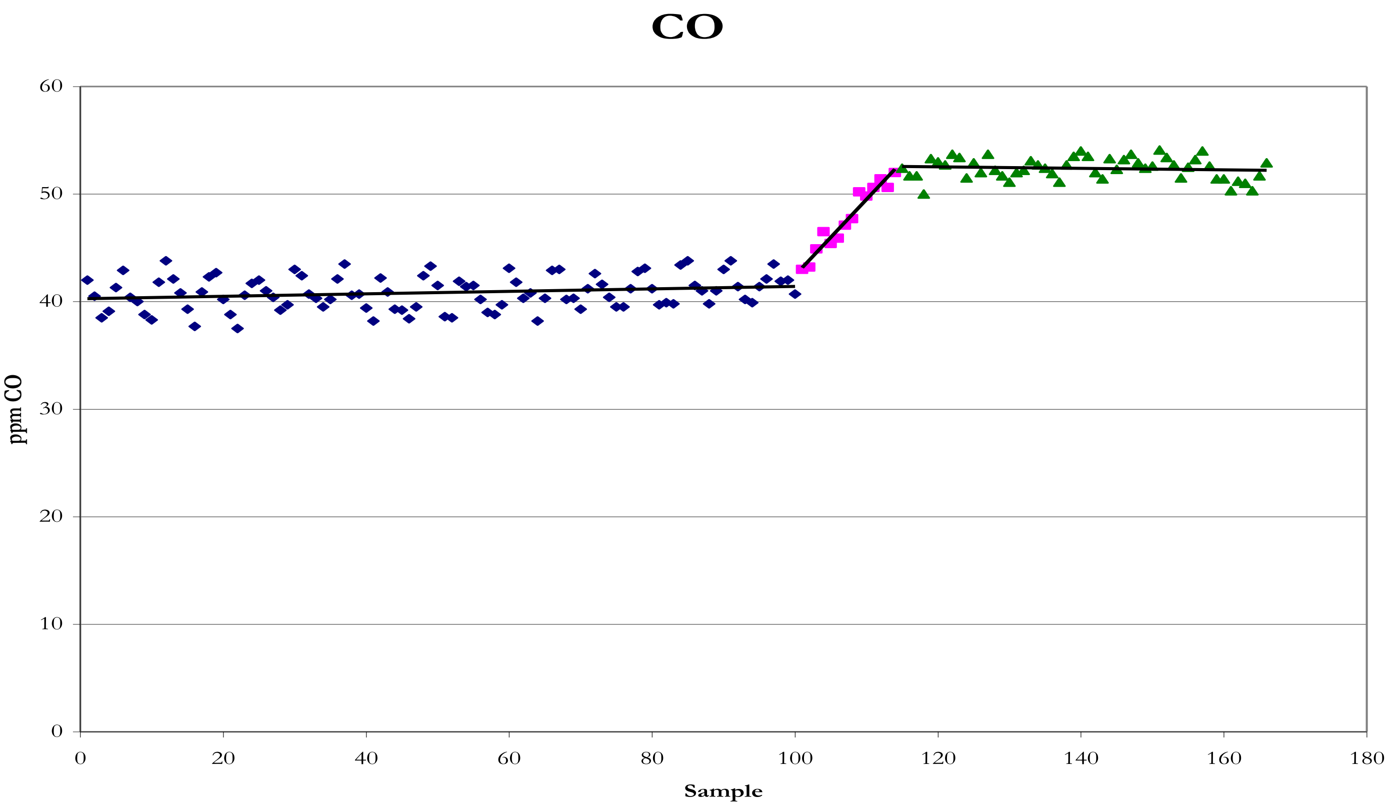
Bottom Up Algorithm



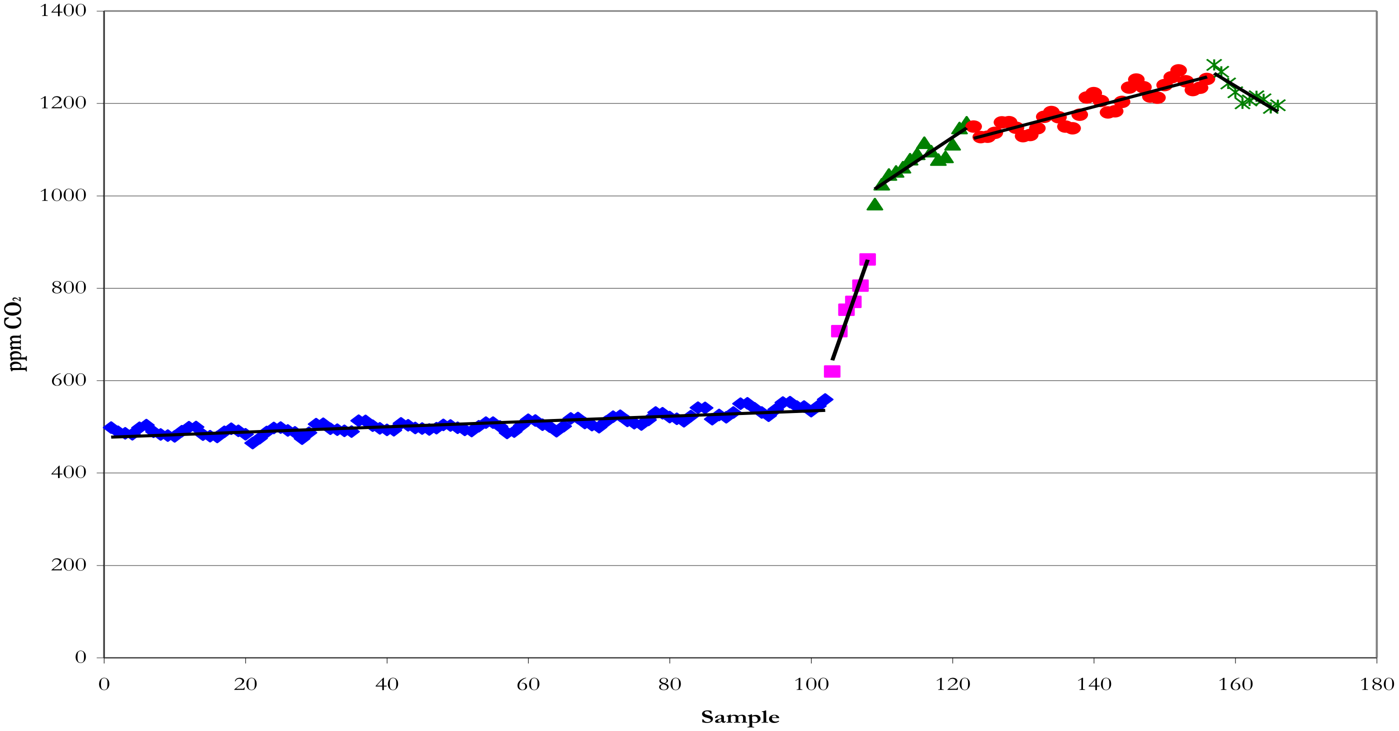
Bottom Up Algorithm



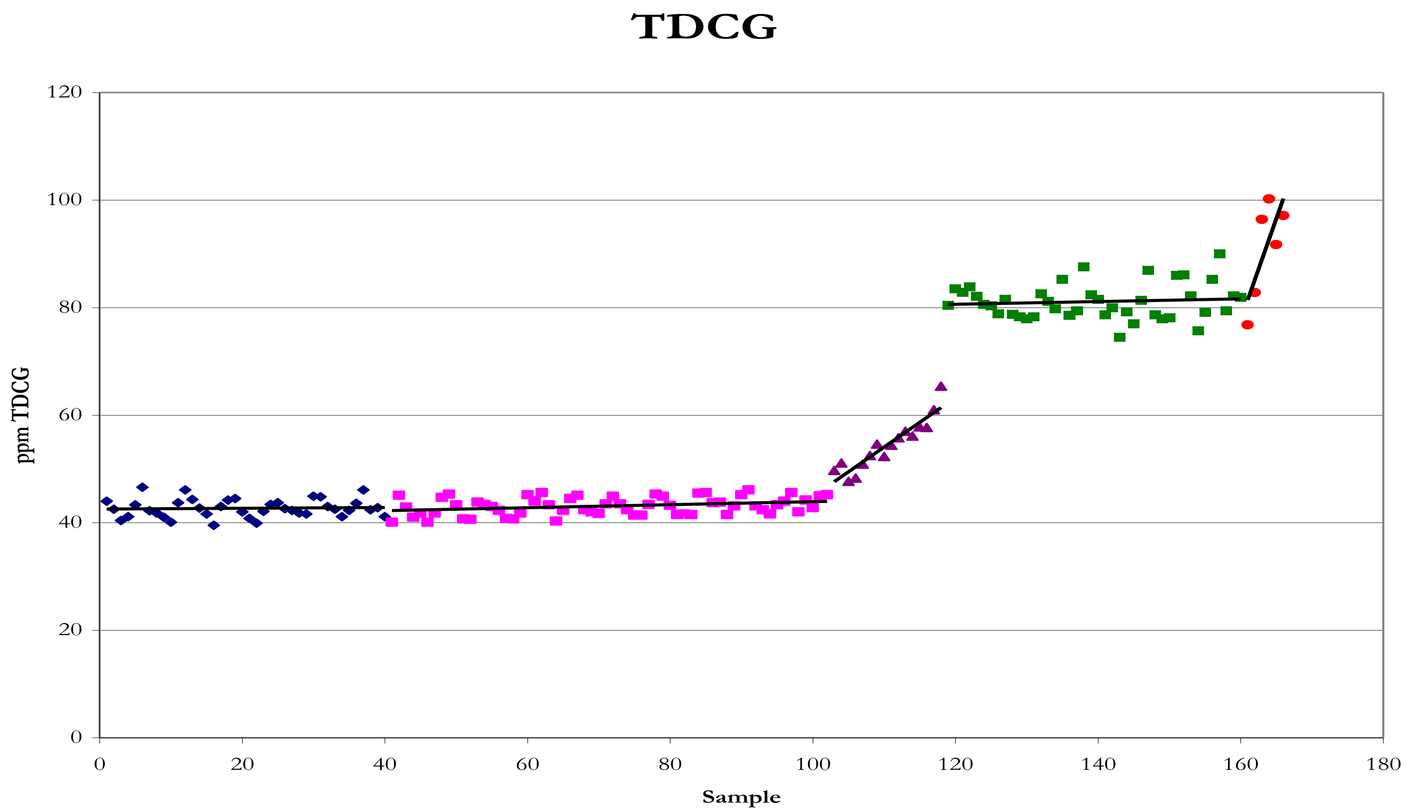

H2
ppm H2
Sample
0
5
10
15
20
25
0
20
40
60
80
100
120
140
160
180


CO
60
50
40
30
20
10
0
ppm CO
0
20
40
60
80
100
120
140
160
180
Sample

CO_2

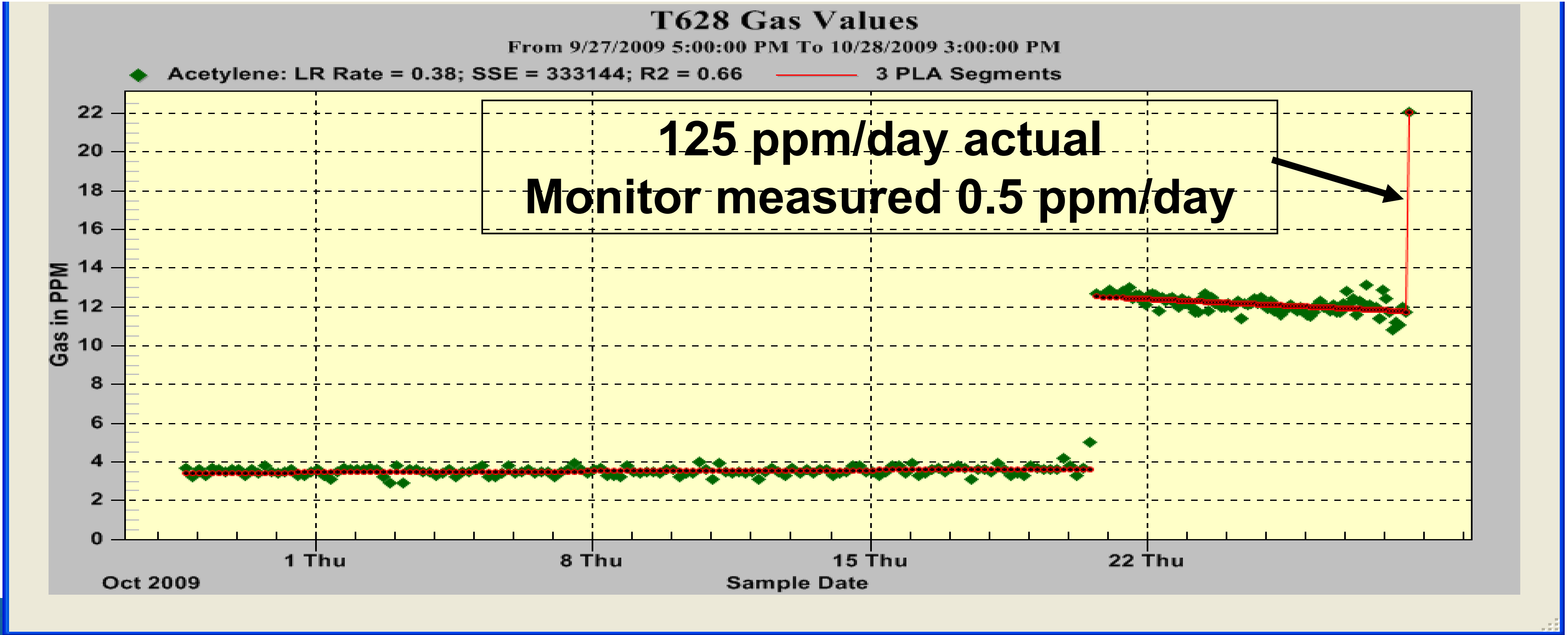


1400
1200
1000
800
600
400
200
0
ppm CO₂
0
20
40
60
80
100
120
140
160
180
Sample



TDCG
ppm TDCG
120
100
80
60
40
20
0
0
20
40
60
80
100
120
140
160
180
Sample

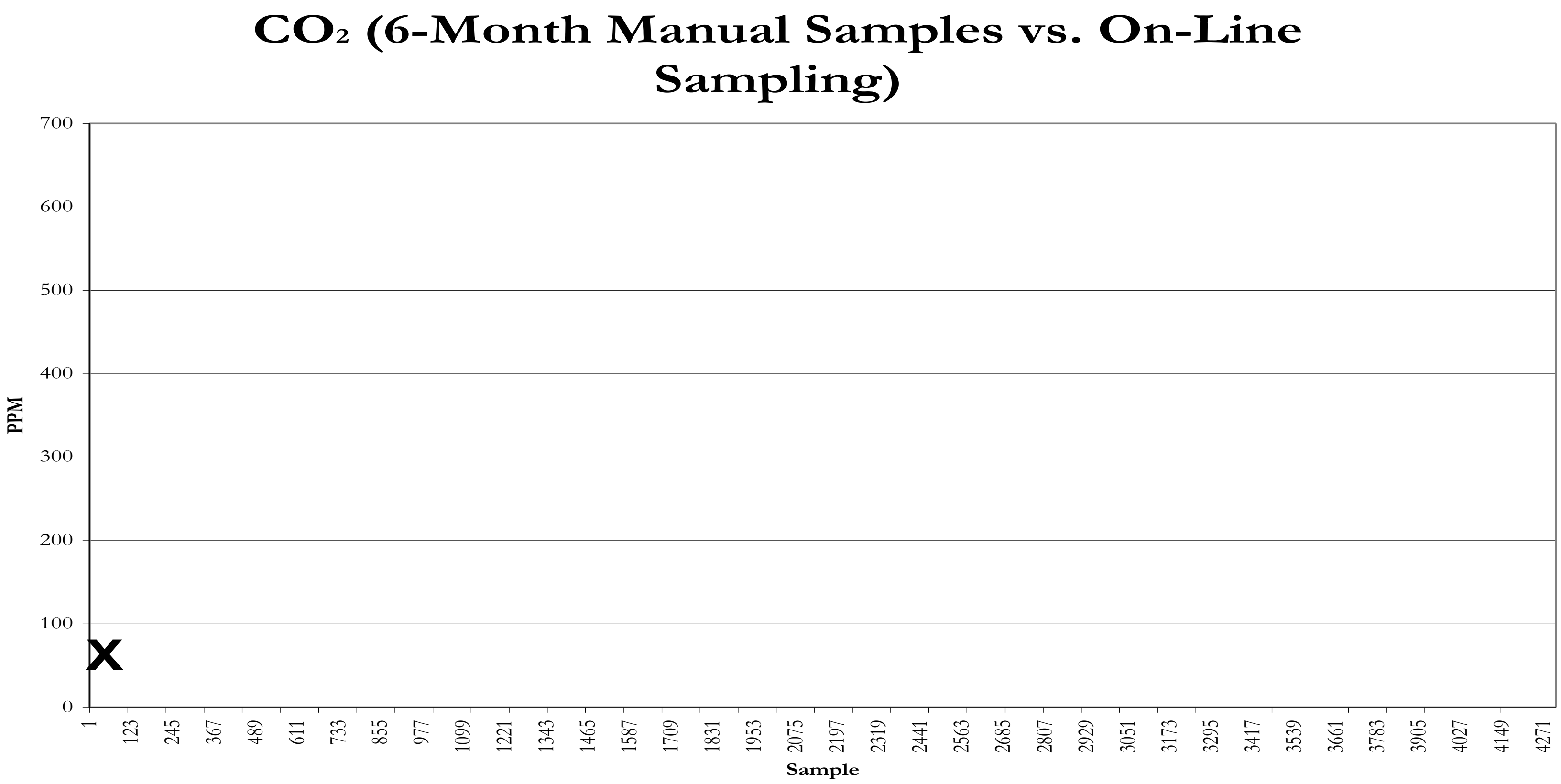
Catastrophic Failure Save Example



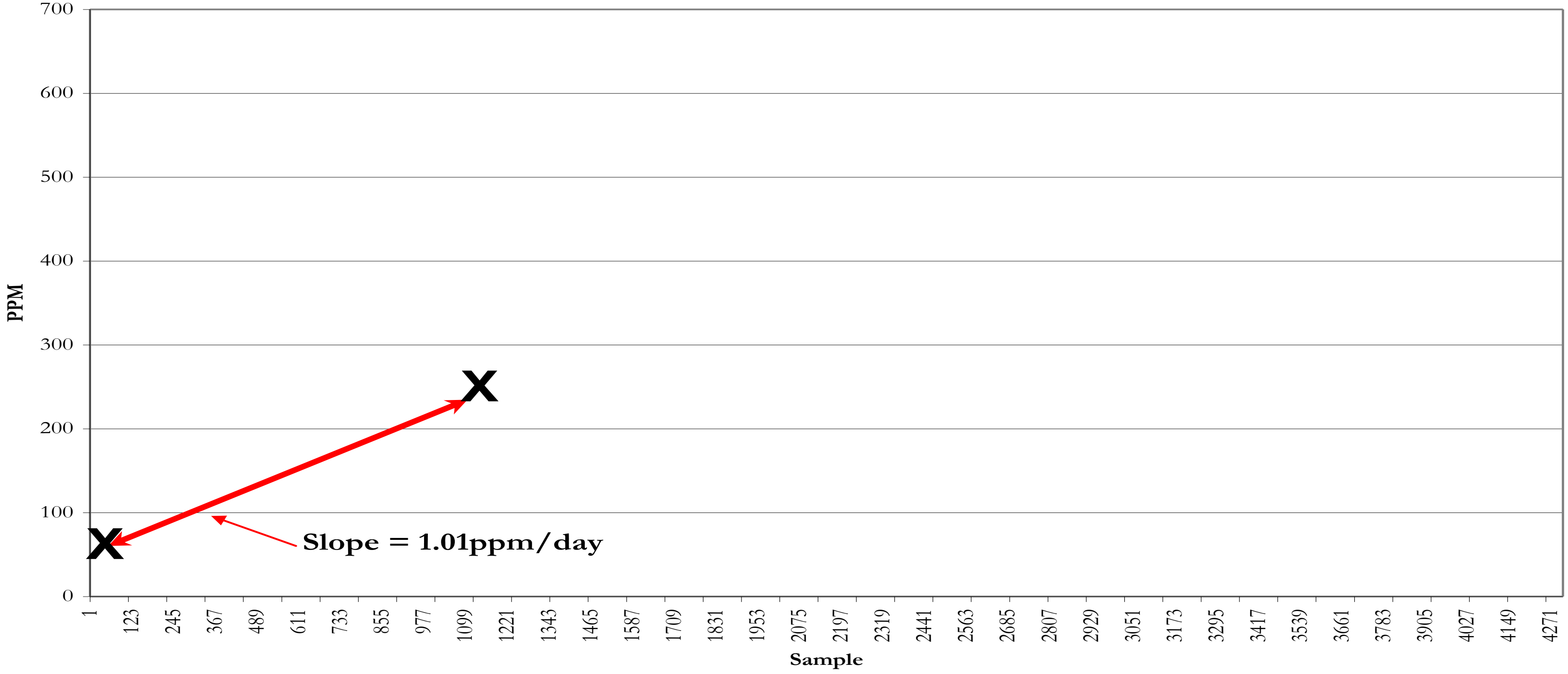
Gassing ROC Solution Summary

- PLA algorithm eliminates fixed intervals
- Calculations of gas rates are stabilized through least squares regression
- ***Quickly detects and reports changing gassing rates – no lag time***
- ***Accurately reports gassing rates – no underestimation***

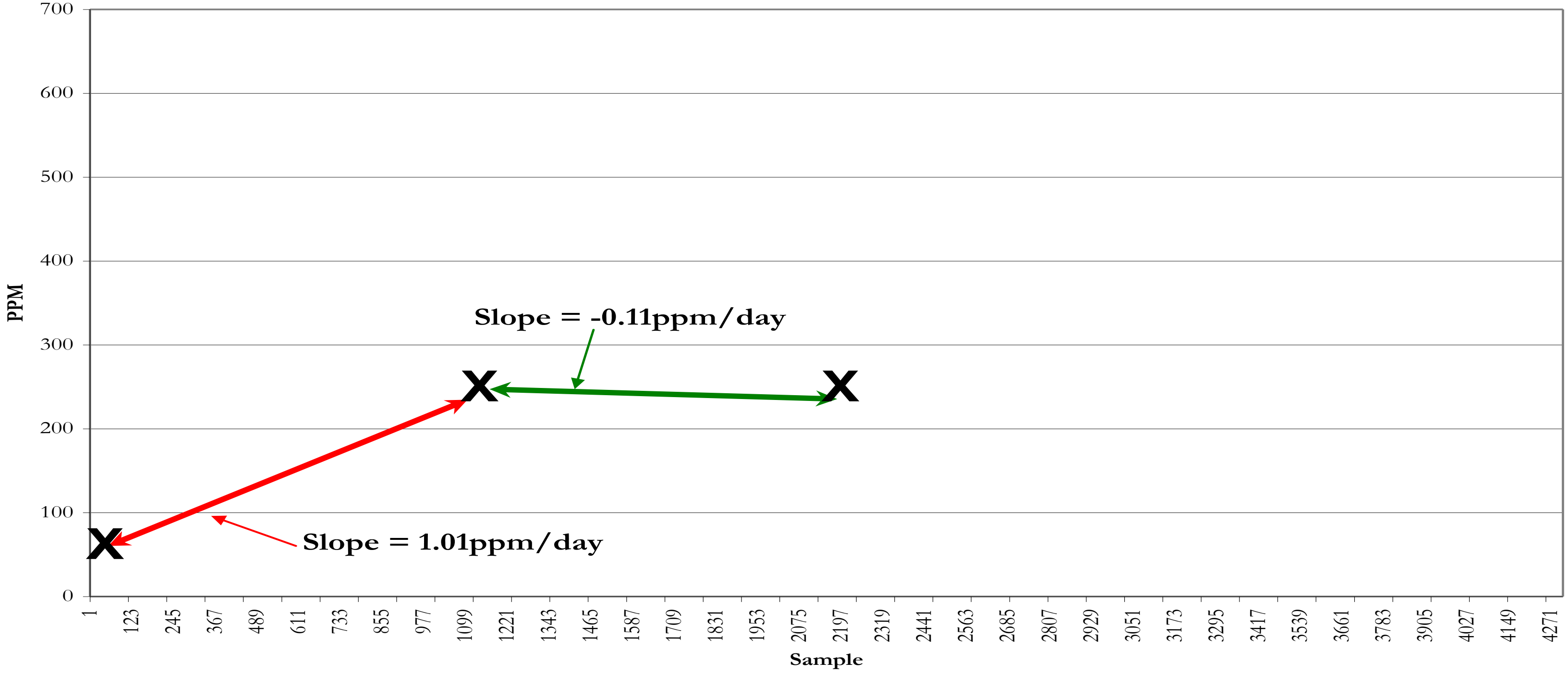
Load Dependent Gassing Analysis


CO2 (6-Month Manual Samples vs. On-Line Sampling)
PPM
700
600
500
400
300
200
100
0
X
1
123
245
367
489
611
733
855
977
1099
1221
1343
1465
1587
1709
1831
1953
2075
2197
2319
2441
2563
2685
2807
2929
3051
3173
3295
3417
3539
3661
3783
3905
4027
4149
4271
Sample

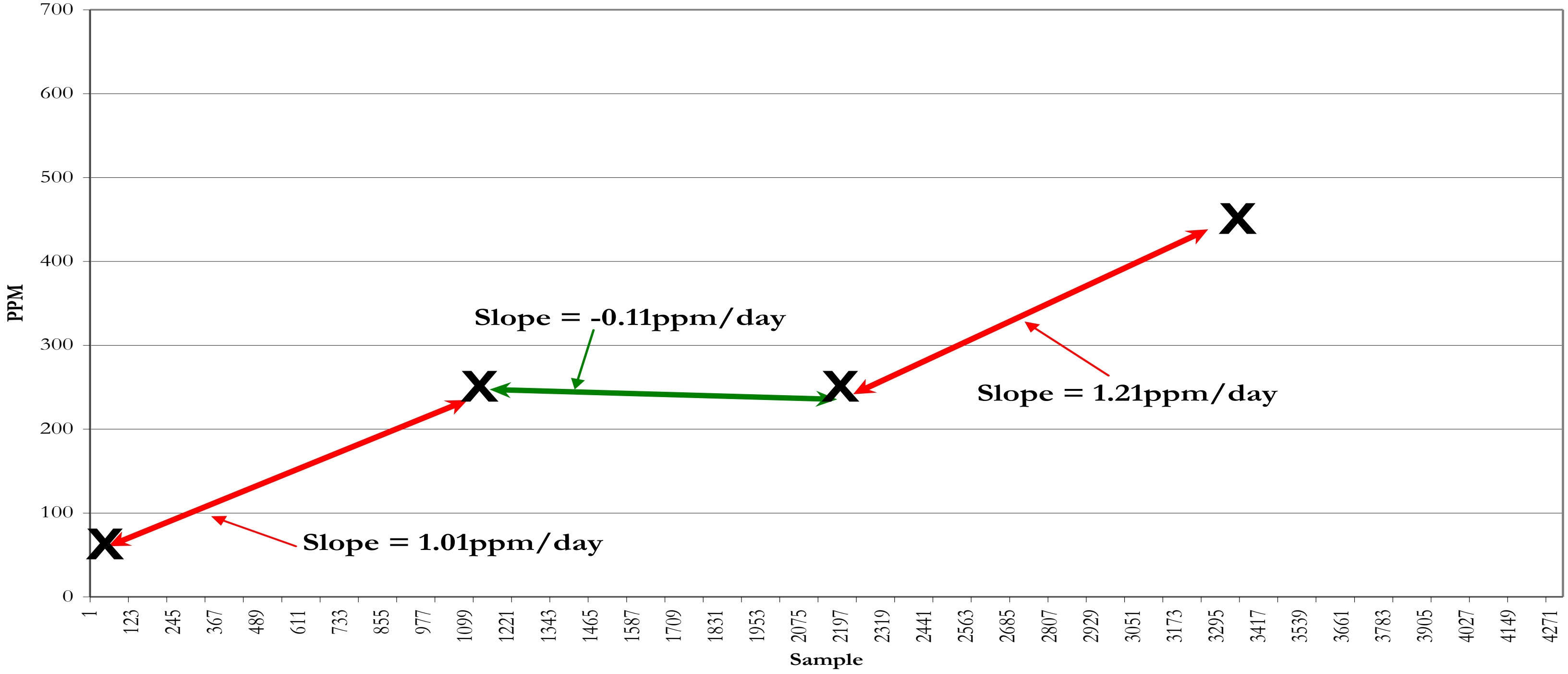
CO_2 (6-Month Manual Samples vs. On-Line Sampling)



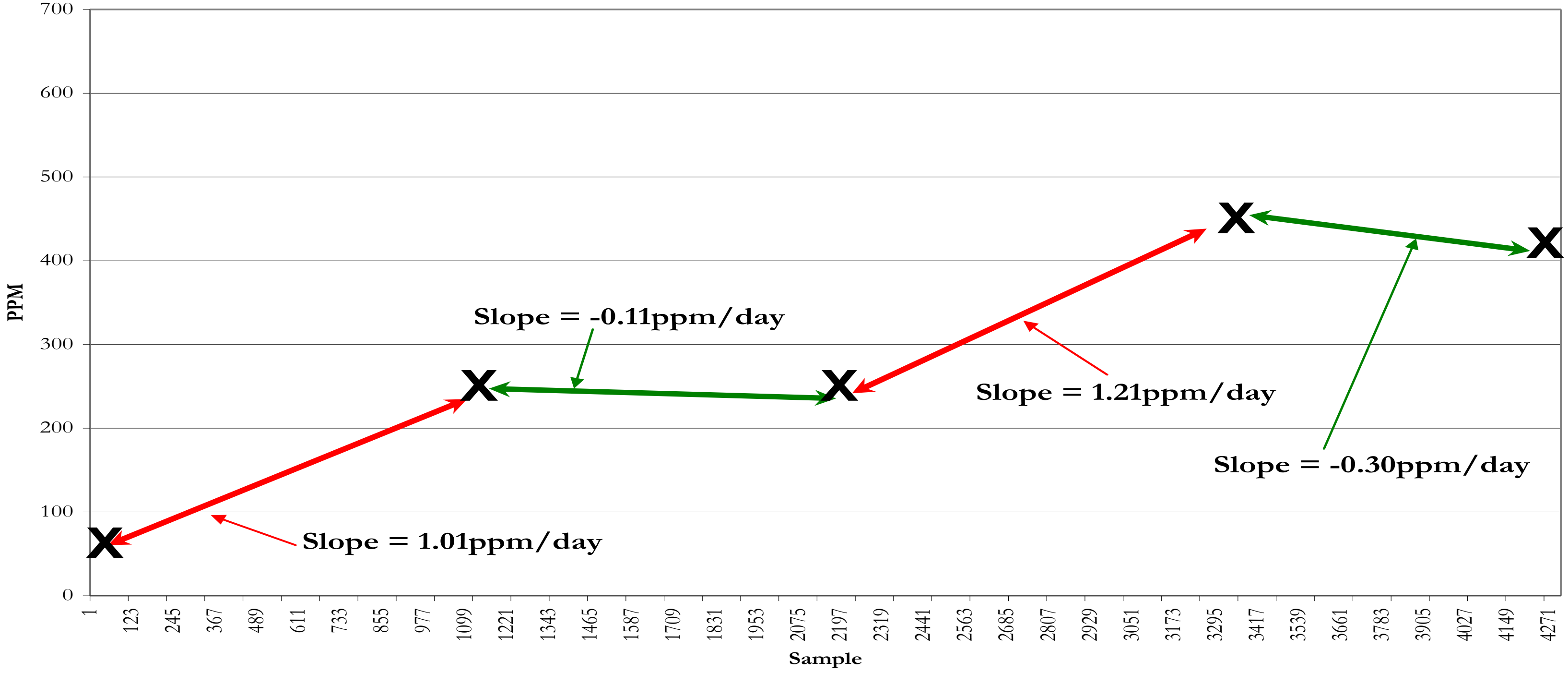
CO_2 (6-Month Manual Samples vs. On-Line Sampling)



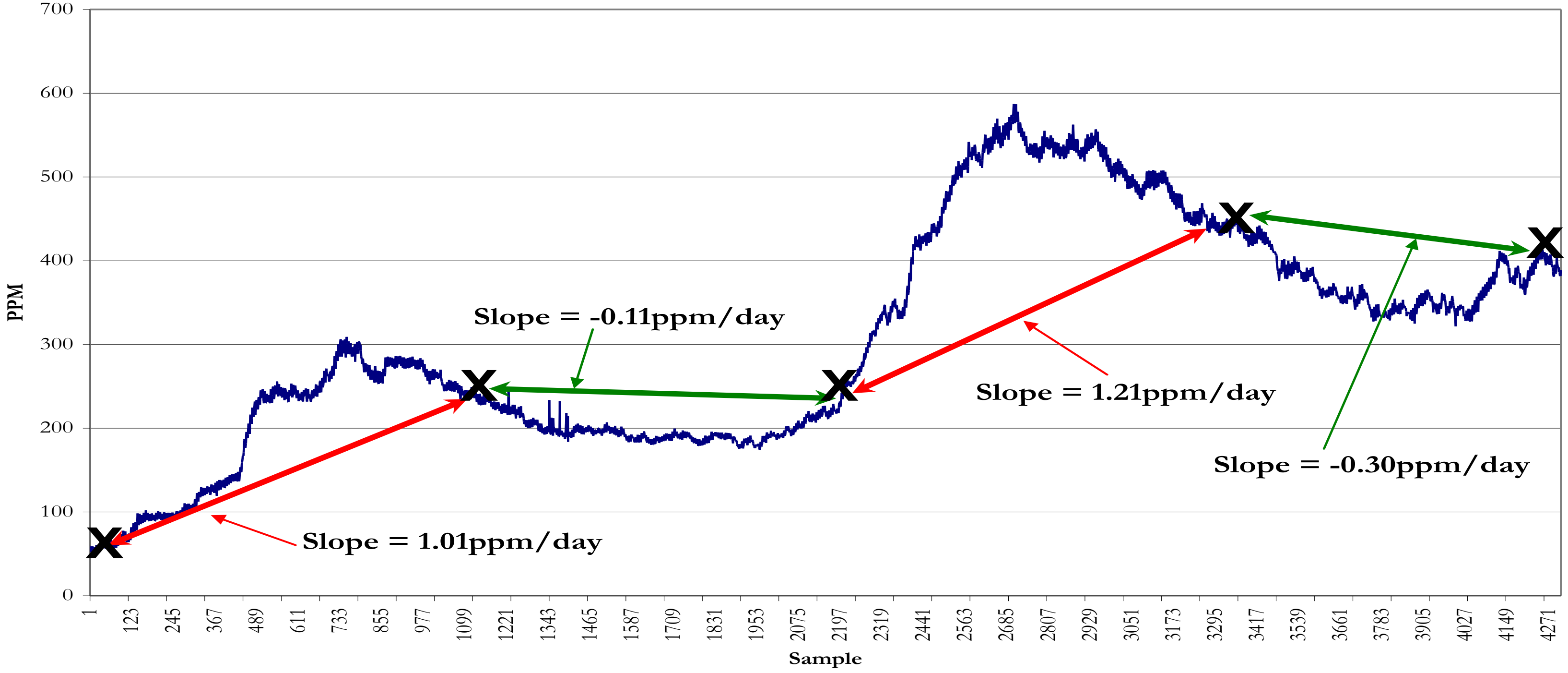
CO_2 (6-Month Manual Samples vs. On-Line Sampling)



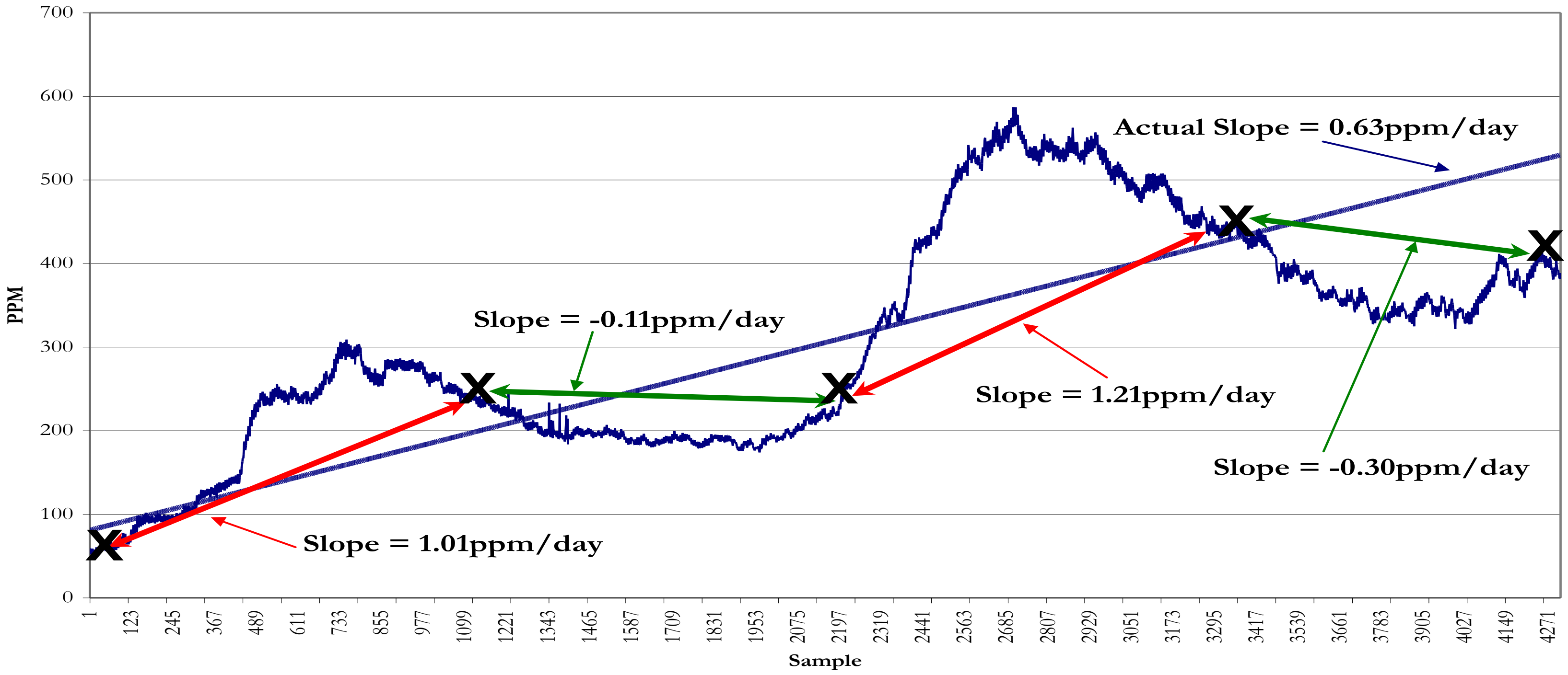
CO_2 (6-Month Manual Samples vs. On-Line Sampling)

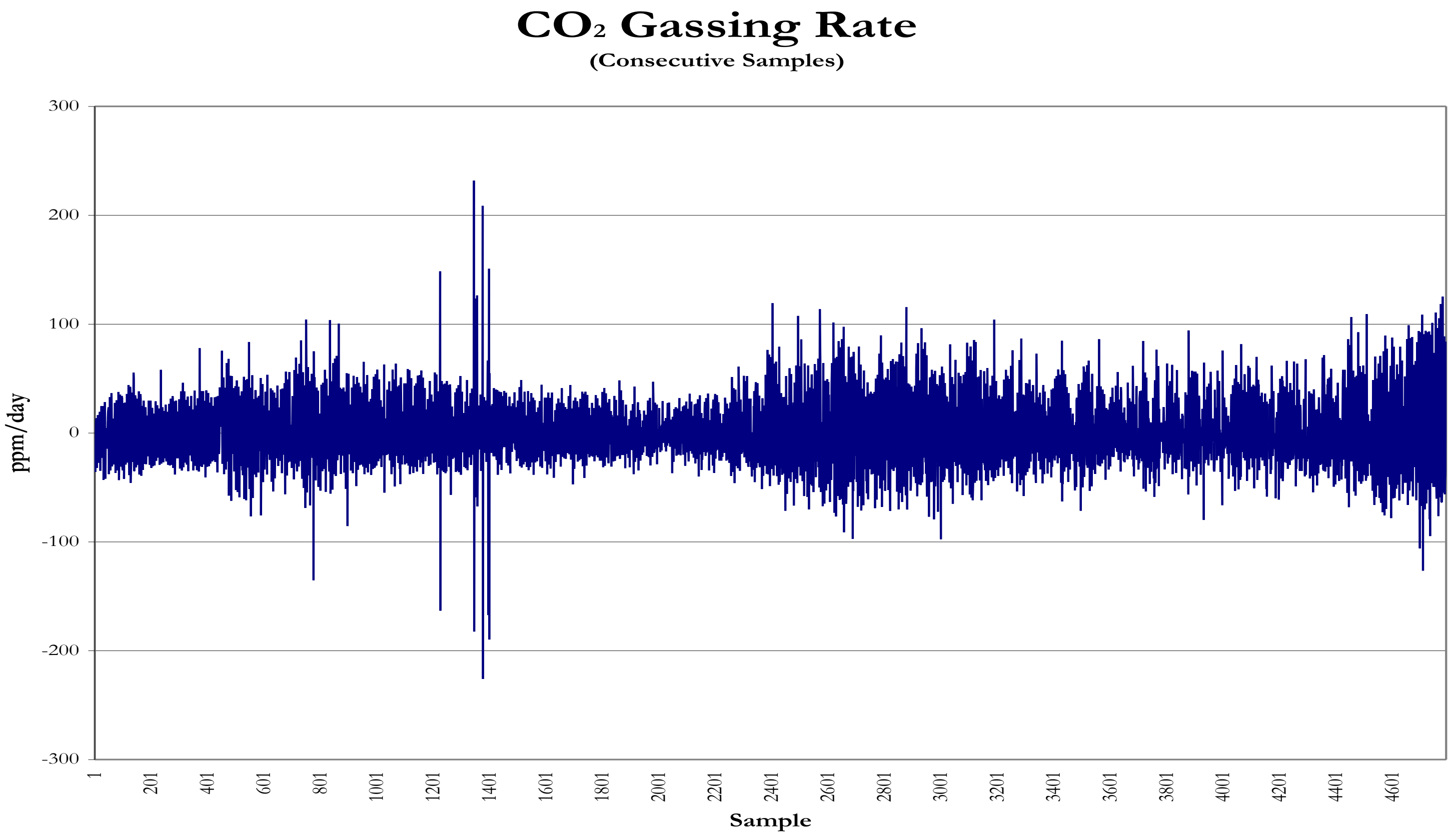


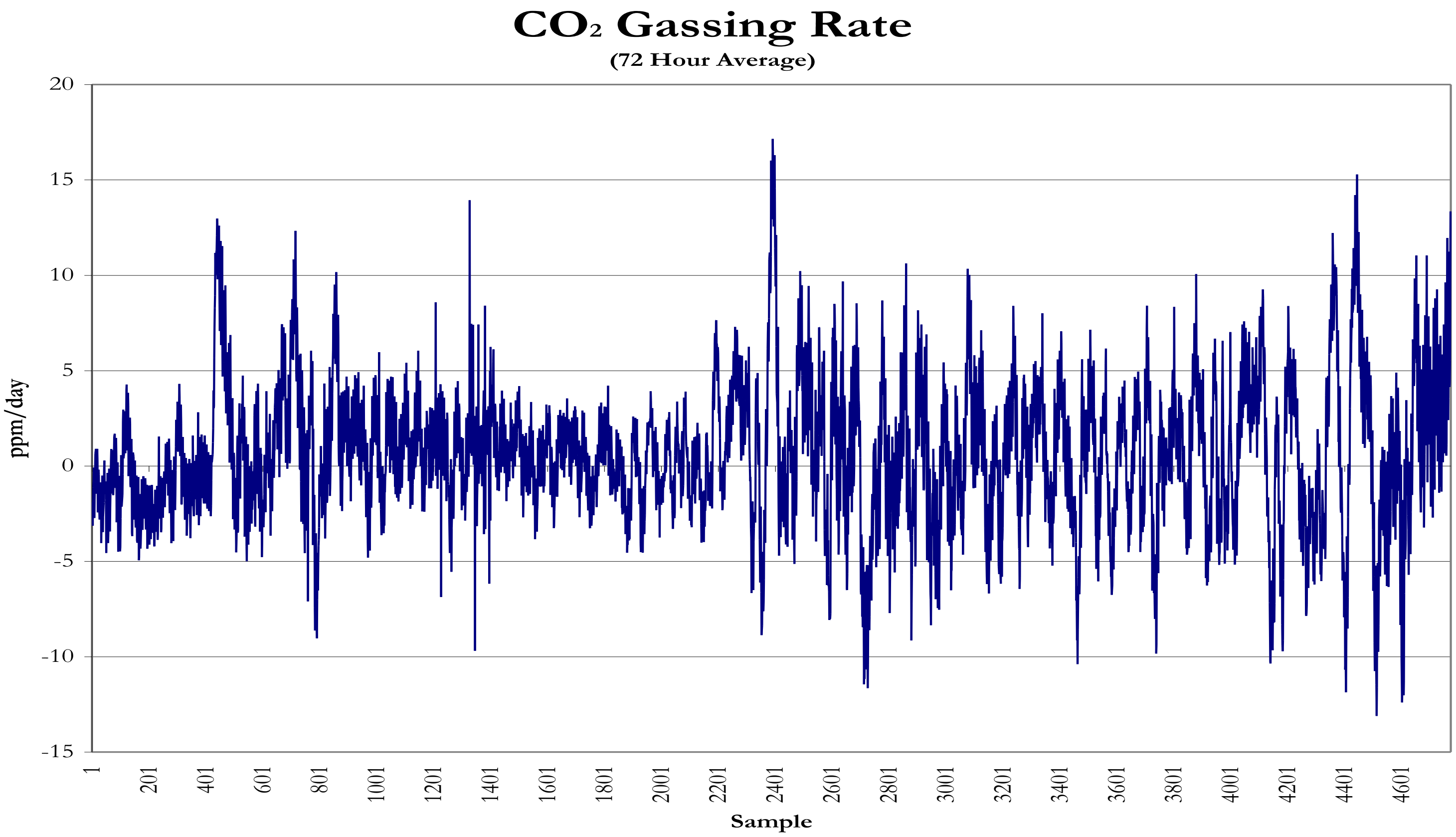
CO_2 (6-Month Manual Samples vs. On-Line Sampling)



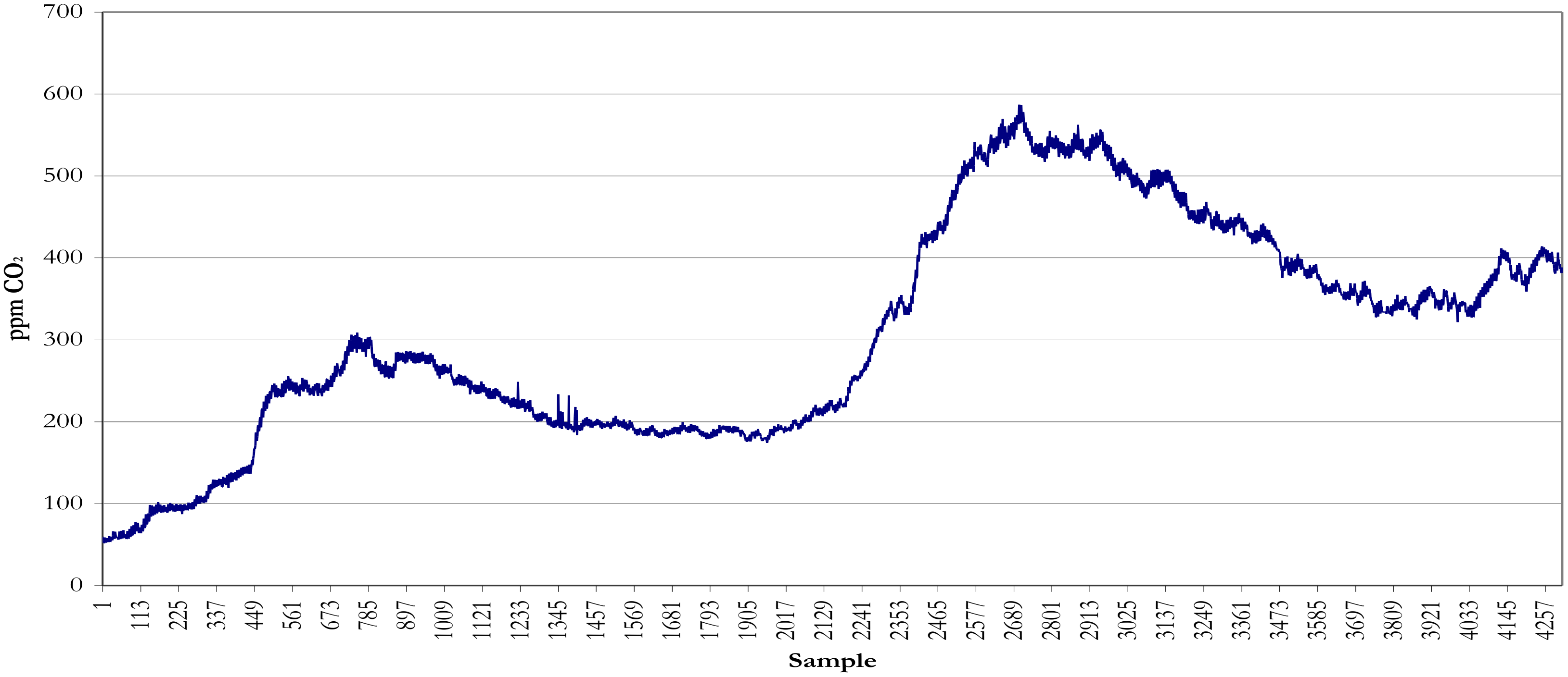
CO_2 (6-Month Manual Samples vs. On-Line Sampling)




CO2 Gassing Rate
(Consecutive Samples)
ppm/day
300
200
100
0
-100
-200
-300
1
201
401
601
801
1001
1201
1401
1601
1801
2001
2201
2401
2601
2801
3001
3201
3401
3601
3801
4001
4201
4401
4601
Sample


CO2 Gassing Rate
(72 Hour Average)
ppm/day
20
15
10
5
0
-5
-10
-15
1
201
401
601
801
1001
1201
1401
1601
1801
2001
2201
2401
2601
2801
3001
3201
3401
3601
3801
4001
4201
4401
4601
Sample

CO_2



700
600
500
400
300
200
100
0
ppm CO_2
1
113
225
337
449
561
673
785
897
1009
1121
1233
1345
1457
1569
1681
1793
1905
2017
2129
2241
2353
2465
2577
2689
2801
2913
3025
3137
3249
3361
3473
3585
3697
3809
3921
4033
4145
4257
Sample

Nonlinear Regression

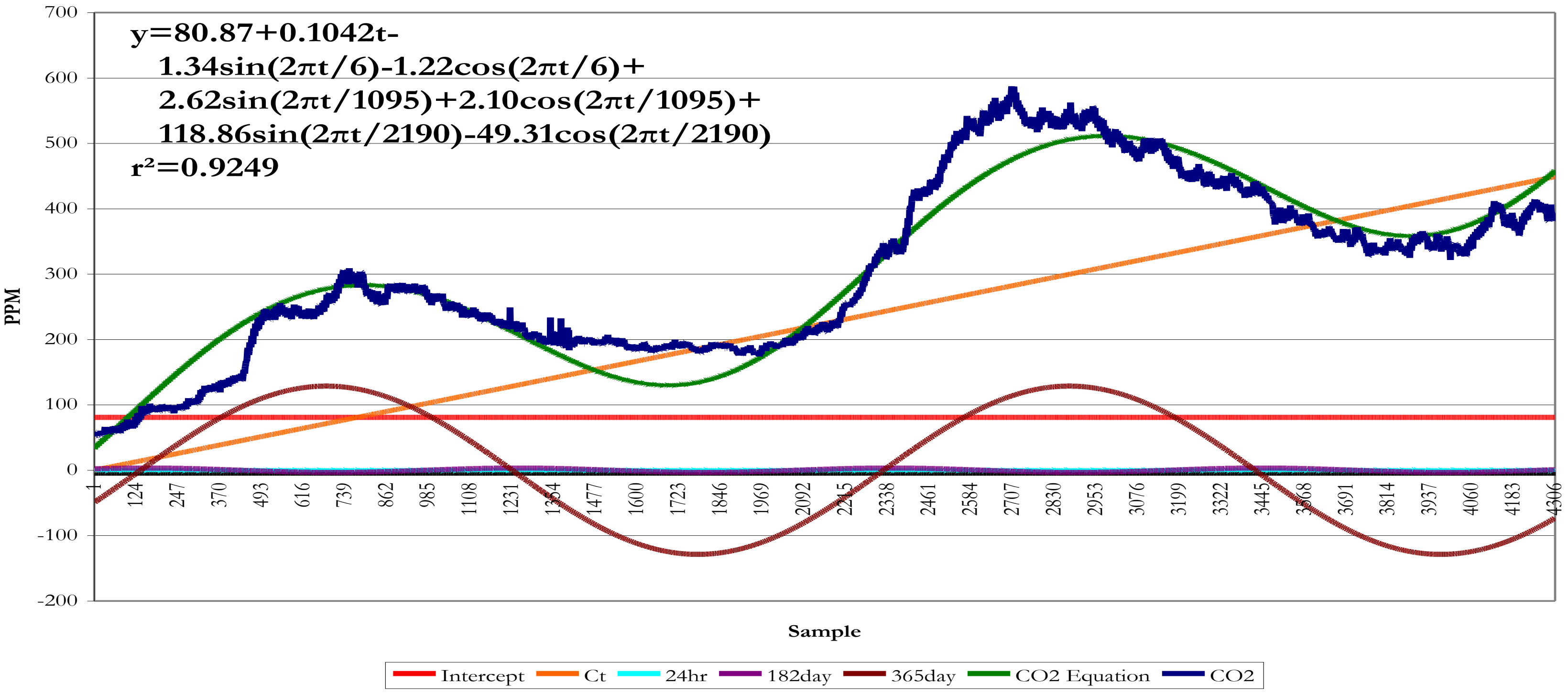
- CO and CO_2 generation is load and temperature dependent
- TOAN's goal is to minimize notification
  - A "steady state" measurement of gassing rate is desired – removal of load and temperature dependency
  - Still need to recognize changing gassing behavior quickly

Calculating Cyclic Behavior

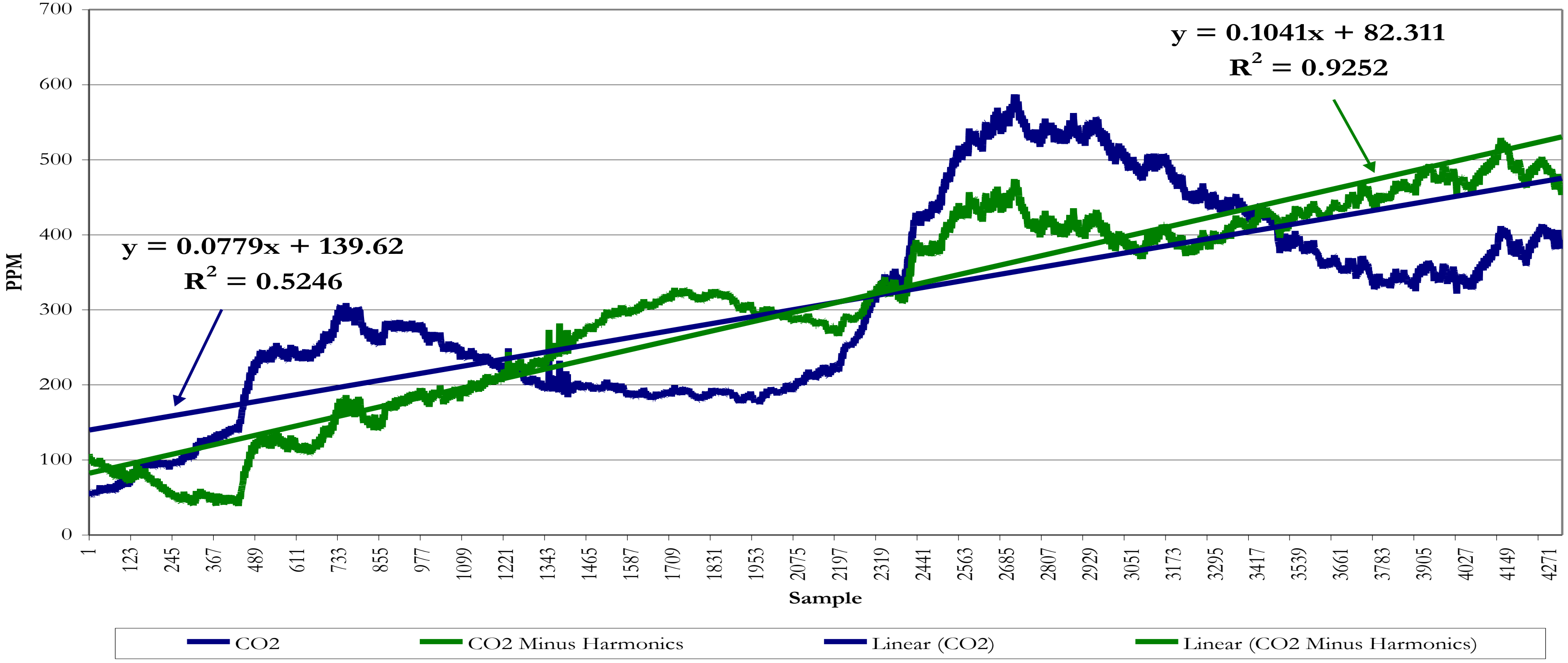
- Need a minimum of 1 year of data for longest periodicity
  - 24 hour (6 samples)
  - 182.5 days (1,095 samples)
  - 365 days (2,190 samples)

$$y = c_1 + c_2 t + \beta_1 \sin \omega_1 t + \beta_2 \cos \omega_1 t + \\ \beta_3 \sin \omega_2 t + \beta_4 \cos \omega_2 t + \\ \beta_5 \sin \omega_3 t + \beta_6 \cos \omega_3 t$$

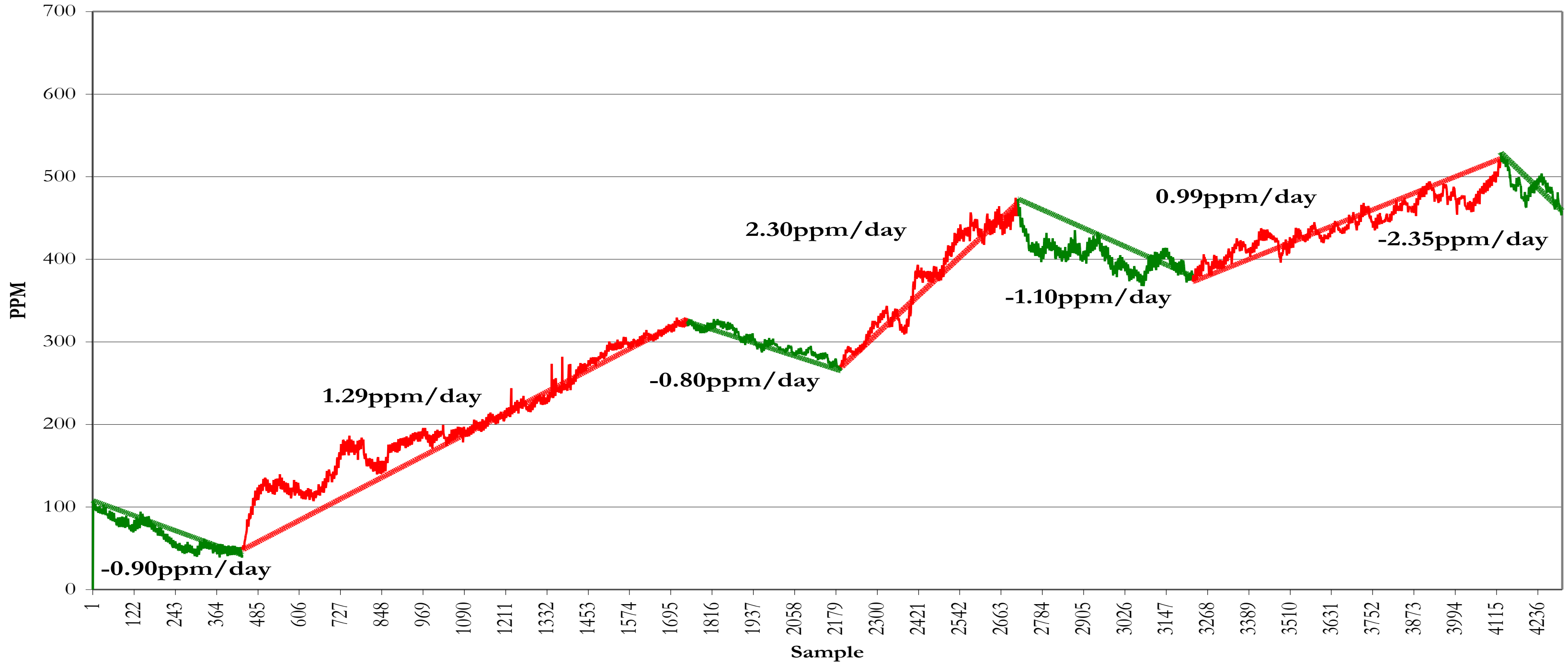
Harmonic Equation Components of CO_2 Gassing



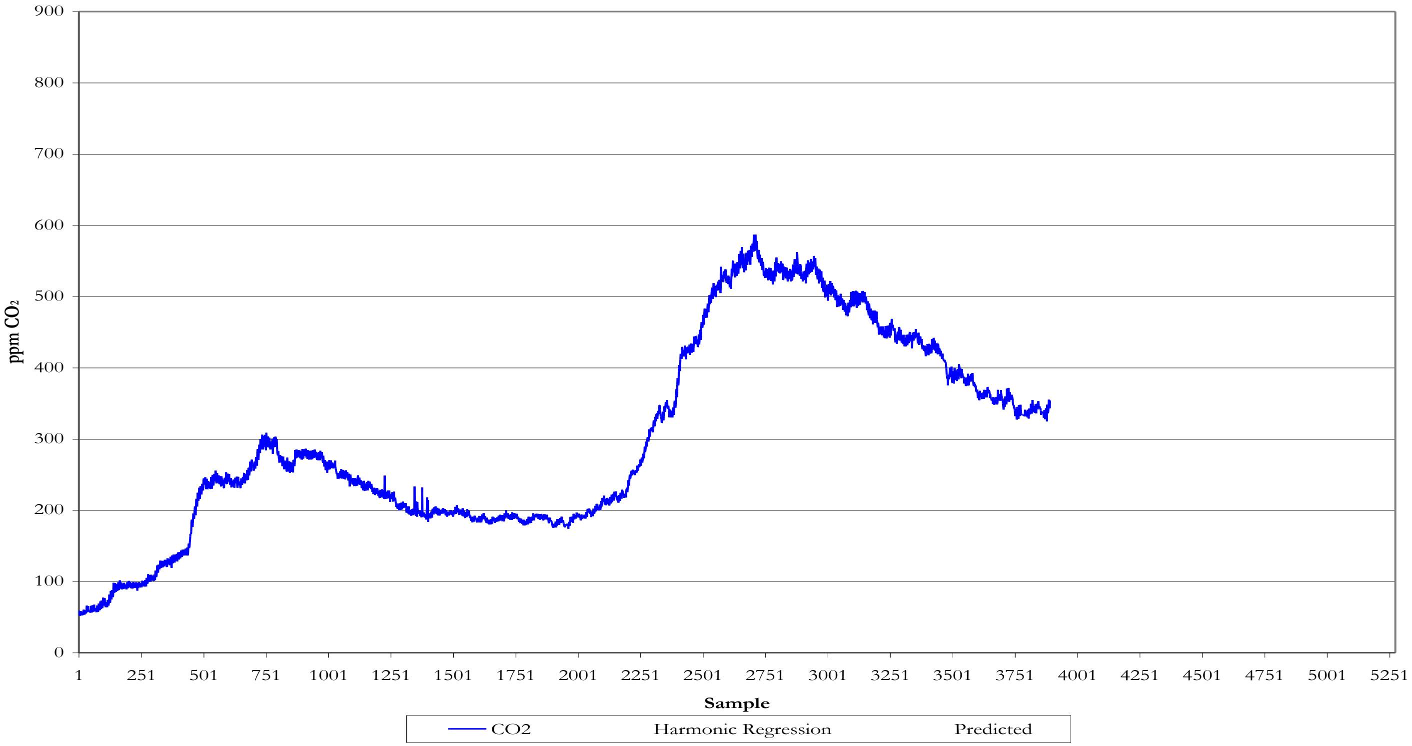
CO_2 Gassing with and without Harmonic Components



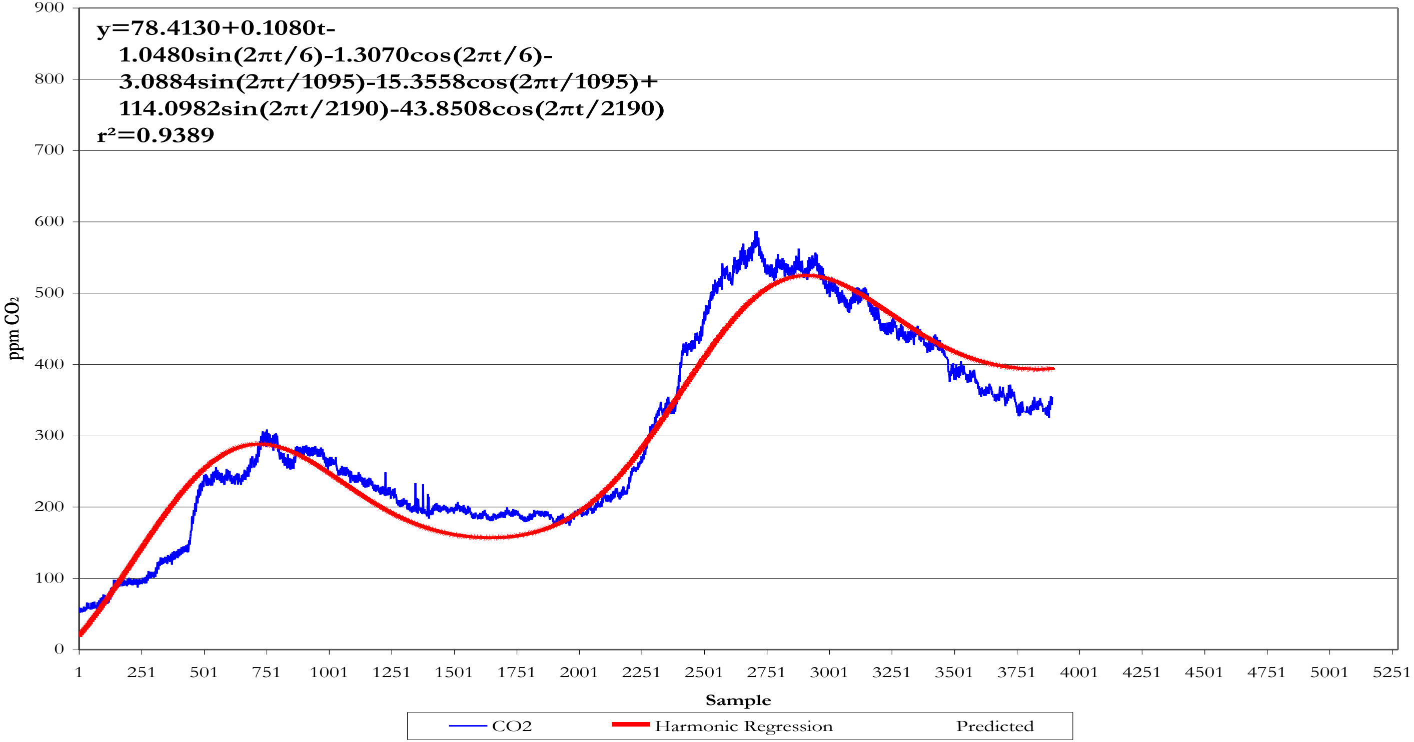
Piecewise Linear Approximation of CO_2 Gassing



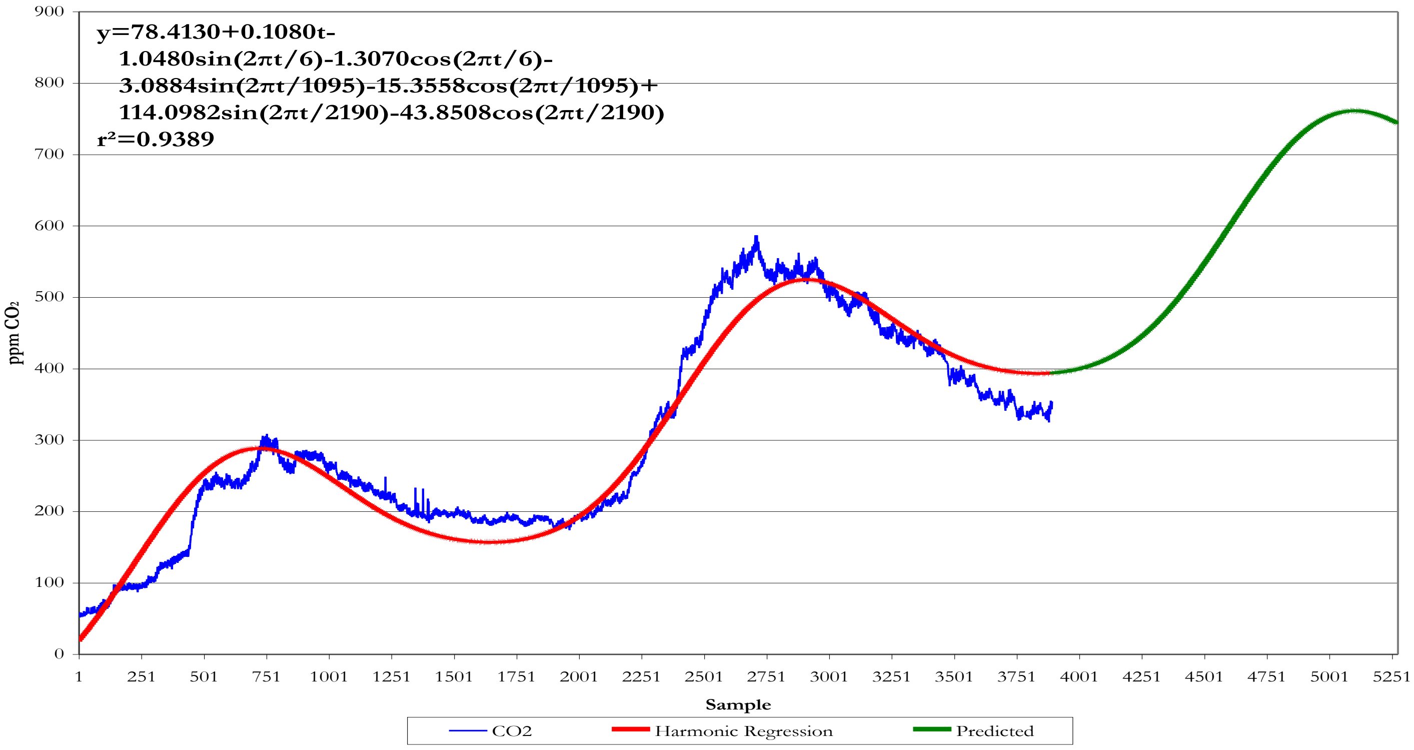
Predicted CO_2 230 Days Forward vs. Actual



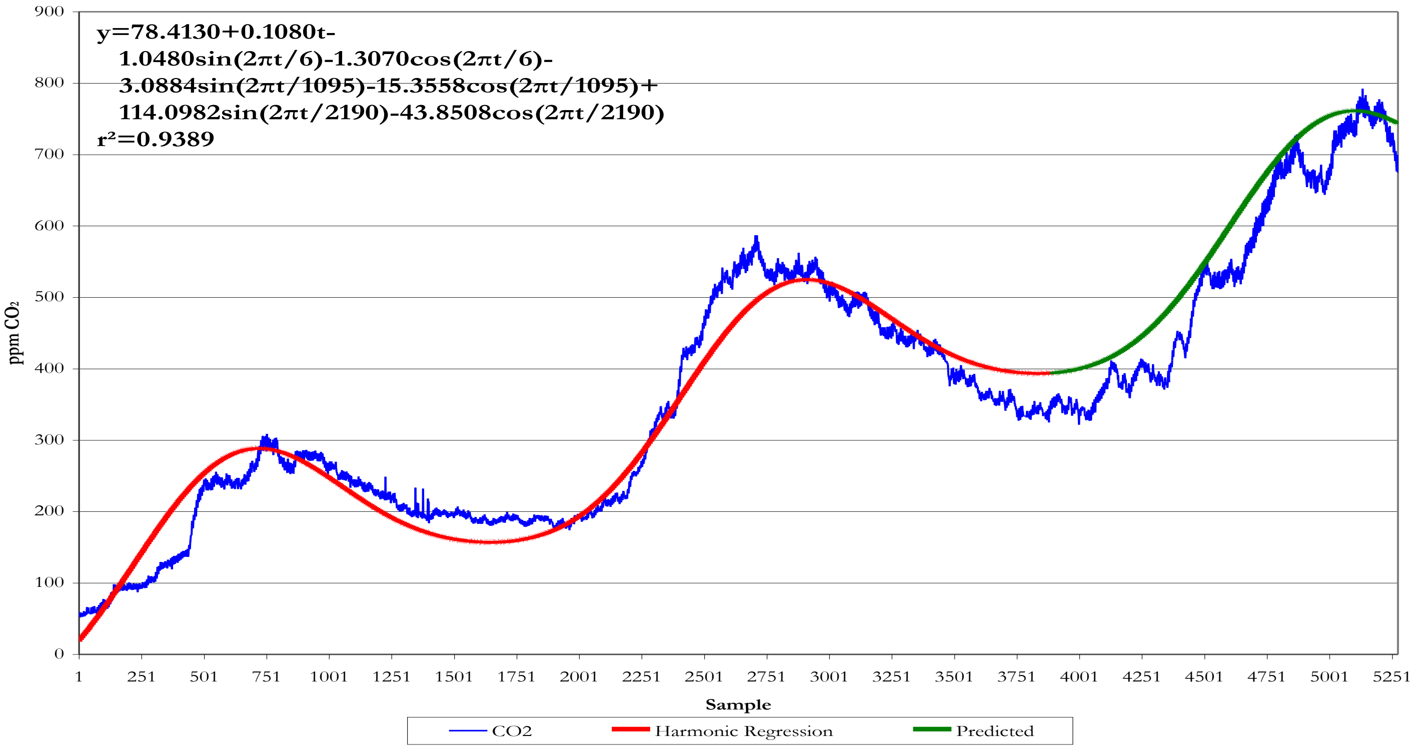
Predicted CO_2 230 Days Forward vs. Actual



Predicted CO_2 230 Days Forward vs. Actual



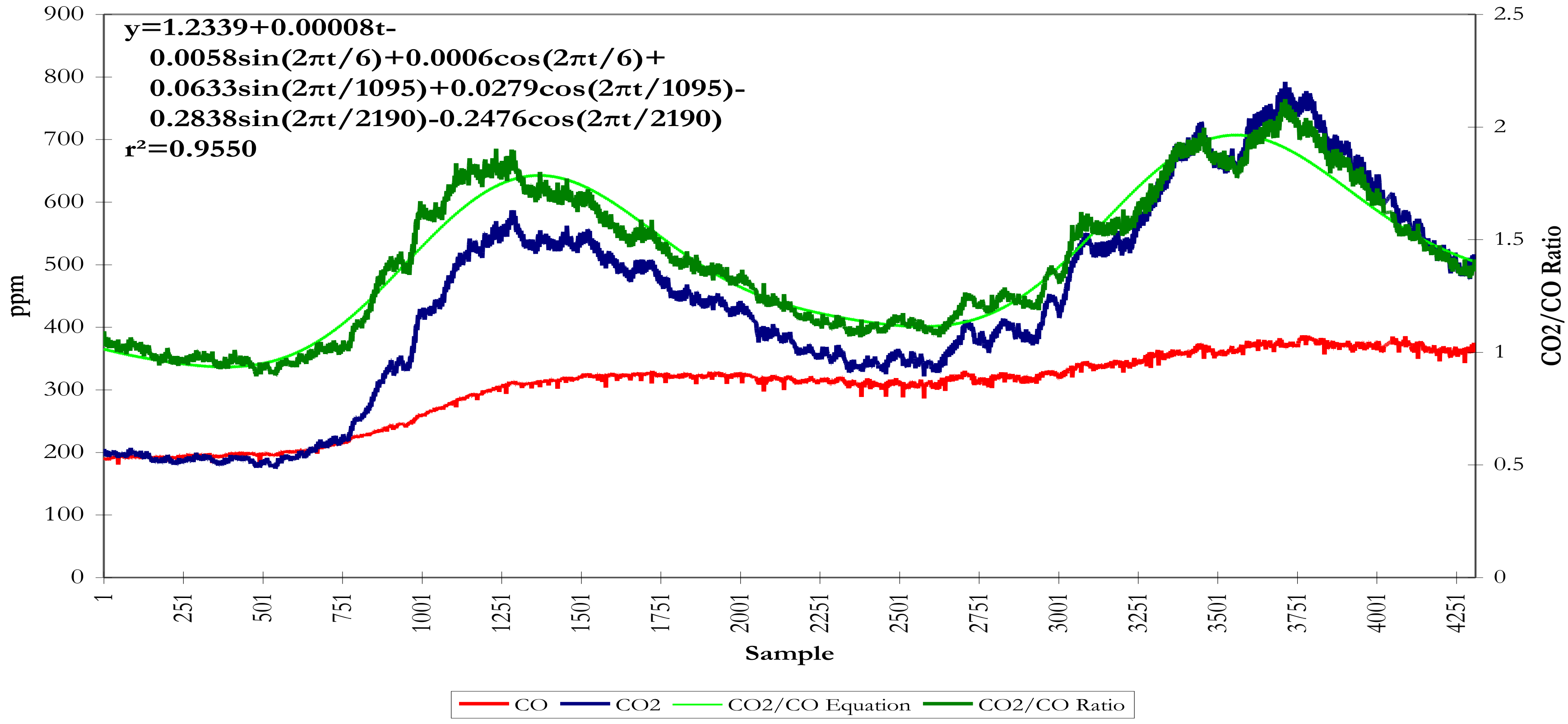
Predicted CO_2 230 Days Forward vs. Actual



CO_2/CO Ratio

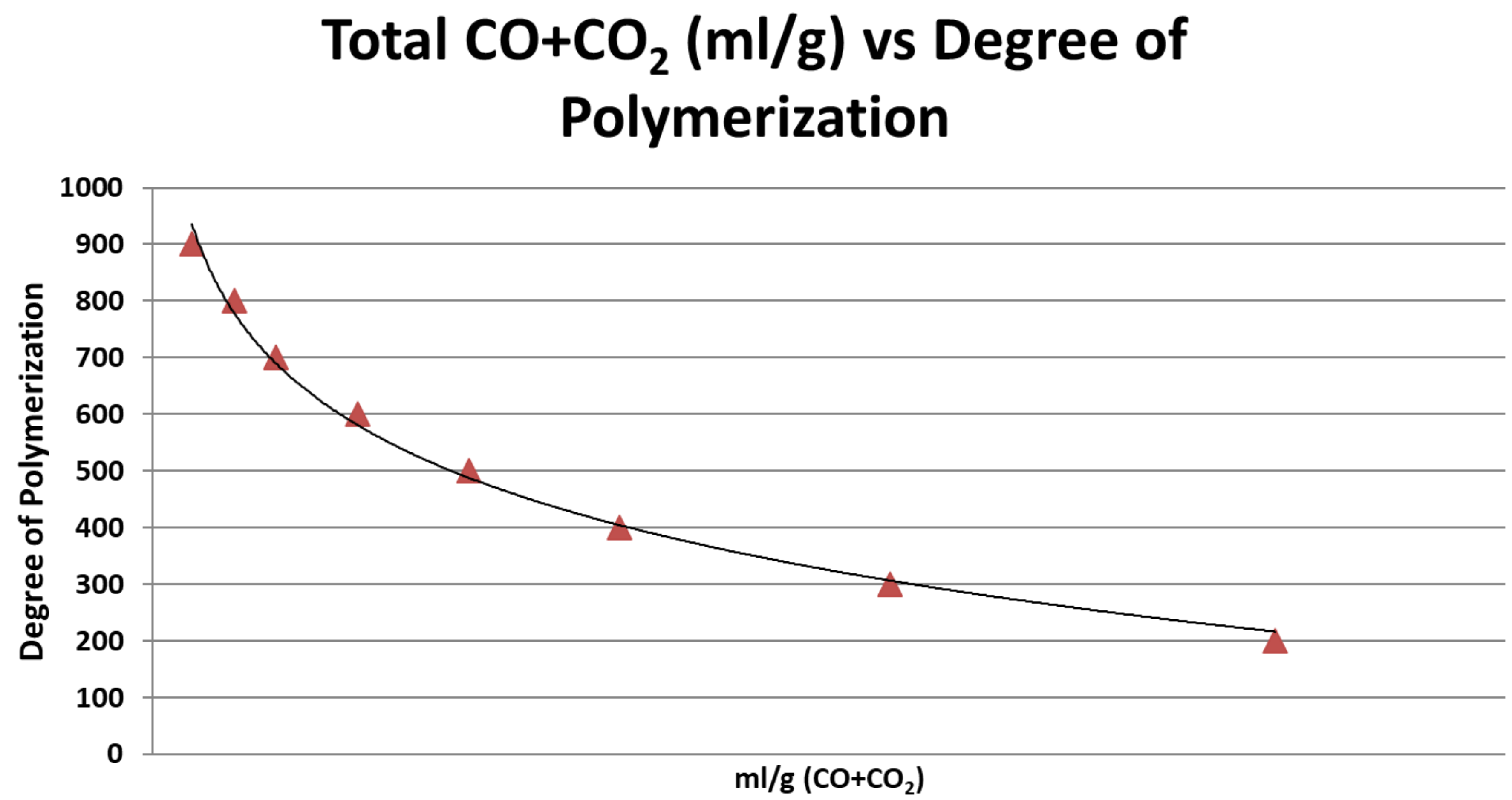
- Used to detect excessive insulation cellulose degradation
- Previous industry guidance - between 3 and 10
- However, there is a strong harmonic behavior overriding the data
- No industry guidance on how to deal with the load dependency

CO_2/CO Ratio

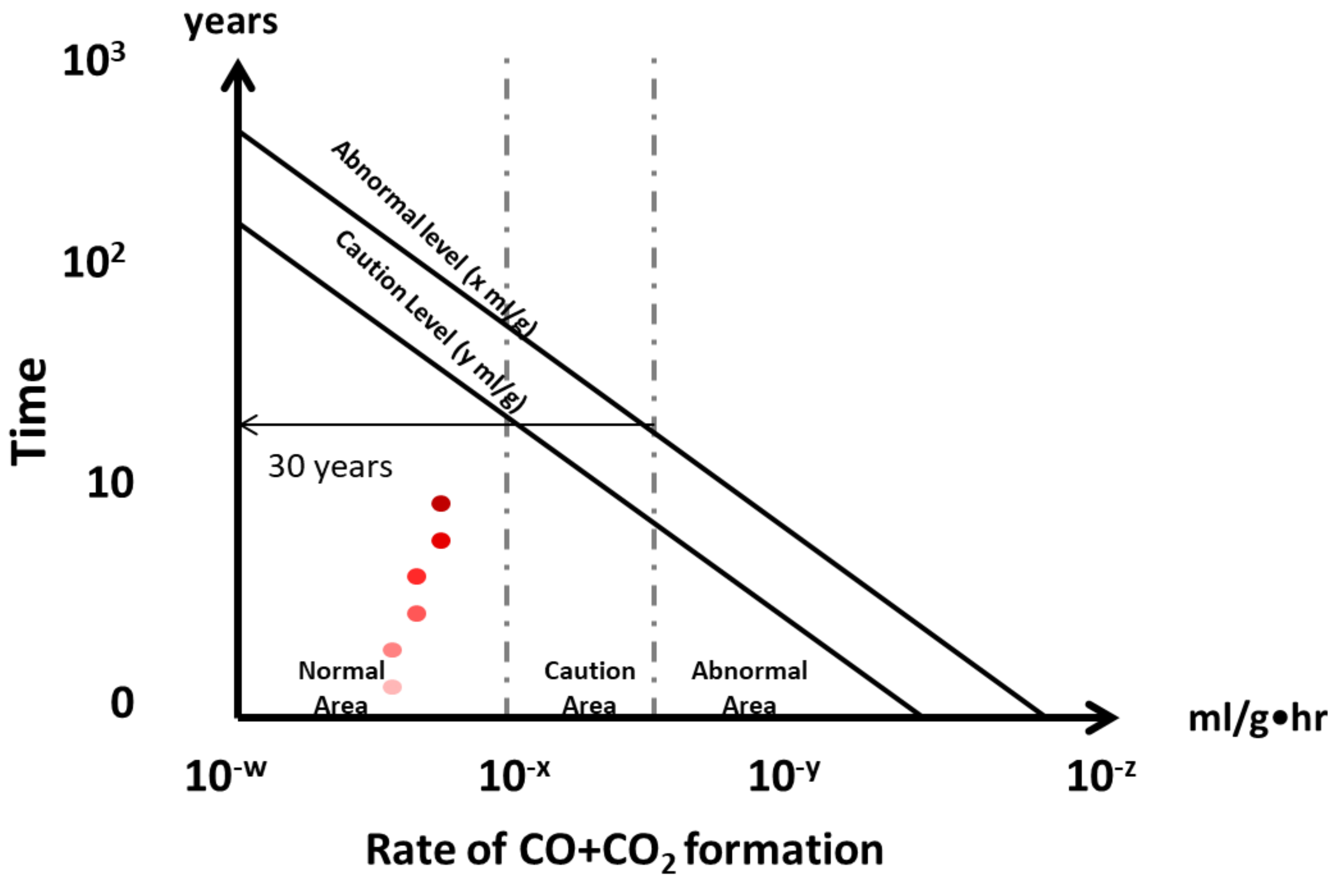

y=1.2339+0.00008t-
0.0058sin(2πt/6)+0.0006cos(2πt/6)+
0.0633sin(2πt/1095)+0.0279cos(2πt/1095)-
0.2838sin(2πt/2190)-0.2476cos(2πt/2190)
r²=0.9550
ppm
900
800
700
600
500
400
300
200
100
0
CO2/CO Ratio
2.5
2
1.5
1
0.5
0
1
251
501
751
1001
1251
1501
1751
2001
2251
2501
2751
3001
3251
3501
3751
4001
4251
Sample
CO
CO2
CO2/CO Equation
CO2/CO Ratio

Insulation Aging

- Leverage on-line DGA monitor data.
- Paper degradation creates CO and CO_2.
- $CO+CO_2$ created during the transformer's life is related to degree of polymerization (DP).
- Need to also know steady state gassing rate to estimate time to end of life.
- Need to track gas removed by maintenance
- Need to track through fault damage



Total $CO+CO_2$ (ml/g) vs Degree of Polymerization
Degree of Polymerization
1000
900
800
700
600
500
400
300
200
100
0
ml/g ($CO+CO_2$)


years
10^3
10^2
10
0
Time
Abnormal level (x ml/g)
Caution Level (y ml/g)
30 years
Normal Area
Caution Area
Abnormal Area
ml/g•hr
10^{-w}
10^{-x}
10^{-y}
10^{-z}
Rate of $CO+CO_2$ formation

Load Dependent Gassing Analysis Solution Summary

- Load and temperature dependencies can be "nulled out" through non-linear regression
- Non-harmonic components can be analyzed with PLA to identify changes
- Used to accurately predict future gas values and insulation effective life measurement

Summary

- Met our goal in building an “exception based” system with better than “Ivory Soap” performance.
- Classification accuracy of ANNs is excellent (96%) and exceptioning > 99.9%.
- Data Mining (PLA) and Non-linear Regression techniques are a must to correctly analyze the data.

Summary

- Since the incorporation of the PLA algorithm, 100% of transformers (over 800 being monitored) experiencing winding arcing events have been successfully de-energized prior to catastrophic failure.

Questions?