# Advances in Capillary Column Technology, and Separation Modeling for Comprehensive 2-Dimensional Gas Chromatography

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Restek Corporation
www.restekcorp.com

# Is Comprehensive 2-D Ready for Industrial Use?

- There is not an “agreed” upon method
  - Heated zone modulation
  - Valve-type modulation
  - Cryo-jet modulation
- Technique is confused by other “2-D techniques”
  - Heart-cutting
  - Dean-switching
  - Coupled column techniques
- Limited manufacturers and supplies
  - Technique was considered “research-only tool”
  - Consumables are now behind instrumentation
- Lets not follow 1-D technology…..

# State of Affairs in 1-D GC

- Many users view GC as “separation by boiling point”
- Most of the rest view it as a “black box”
- Column choice has been either mandated or is based on history
- Column choices are few
- Most popular phases are similar in terms of selectivity
- Users look to column manufacturers, and manufacturers are staffed by former users……

# The Reality of the GC Marketplace (the dark side)

- Most Frequent calls/complaints:
  - Installation issues:
    - "Column has one end"
    - "Which side goes into the injector"
    - Improper installations into inlet or detector
    - Leaks and or flow-related issues
    - Press-tight issues!
  - "Which column do you recommend for…_______?"
  - "What conditions do you recommend for…______?"
- Most users do not fully understand the variables that effect separation and how to optimize them.

# Can Comprehensive 2-D GC be Successful in the Marketplace?

- A Few Commercial Manufacturers Now Exist
- Quantitation Software is Available
- Continued Need for:
  - Optimization Software
    - What is the best set of conditions?
  - Support by Consumables Manufacturers
    - What columns do I use?
  - Understanding Where it is/isn't Needed
    - Is this a niche technique?
  - Ease of Use

# Chromatographic Columns

- Press-tight connectors
  - Allow use of dissimilar i.d. columns
  - More flexible
  - Prone to leaks, many customers do not like them
  - Best connection device is glass
- Continuous columns
  - Both columns must be same i.d.
  - Easier to handle and install
  - Can use a restrictor if necessary
  - Can have an uncoated section where modulator is placed

# Typical GCxGC Column Assembly

- First dimension column
- Inter-column transfer line (modulator tube)
- Second dimension column
- Detector transfer line

- **Typically requires up to 3 press-fit connections**

# Press-tight connectors

- Standard press-tights fittings
  - Low cost
  - Low thermal mass
  - Low dead volume
- Metal press tights and unions
  - Higher cost
  - Higher thermal mass
- Vu 2 Union
  - Low thermal mass for chromatographic portion
  - Uses standard press-tights in a housing with back-up ferrules
  - Low cost once holder is purchased

# GCxGC Column Assembly

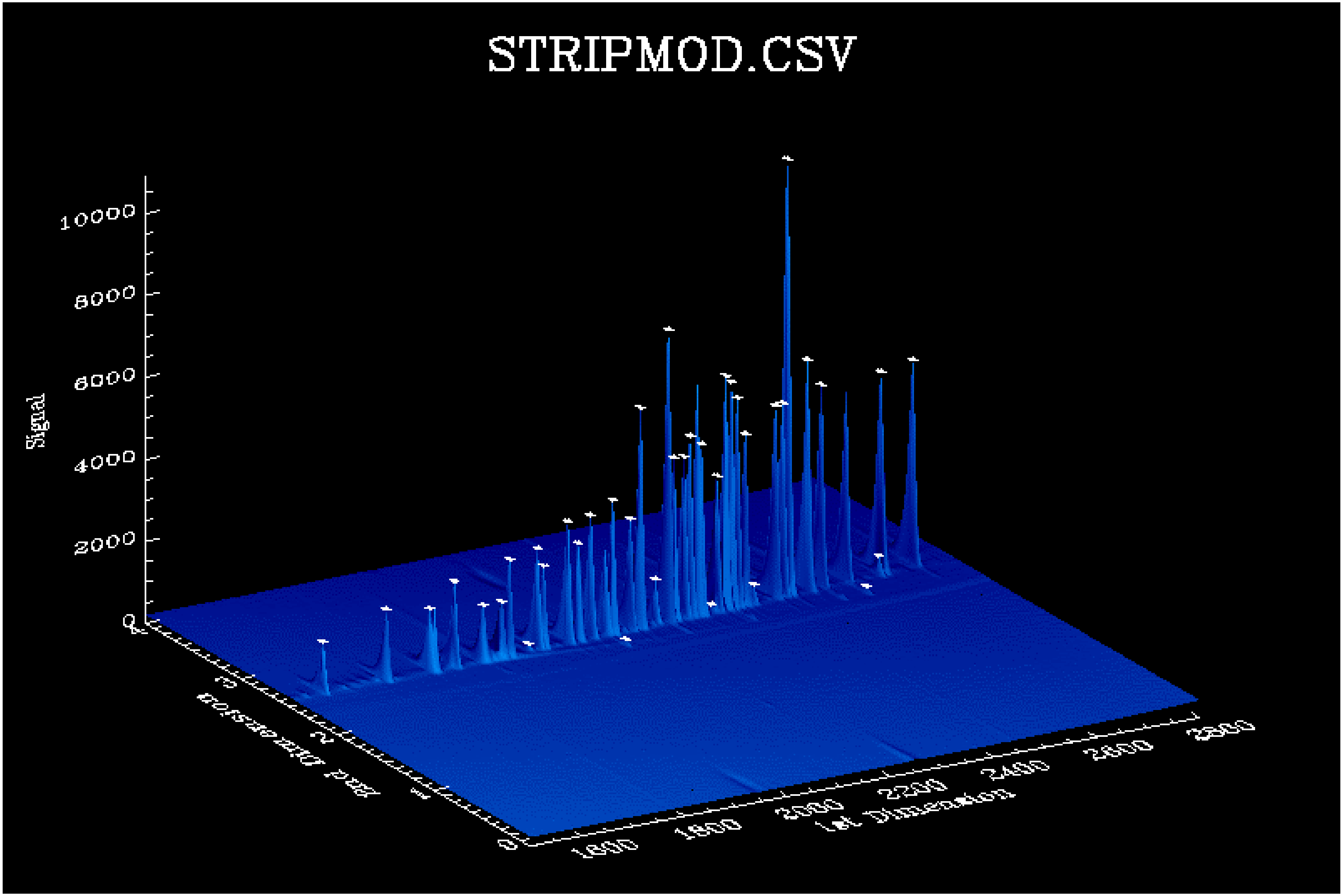
- For R&D purposes, it is preferable to have the ability to change column dimensions at will, and the time involved in preparing the column set is part of the overall task
- For routine laboratory analysis, it is preferable to have ready-made column ensembles, such as is the case in 1D GC.  This insures good column quality and reproducibility

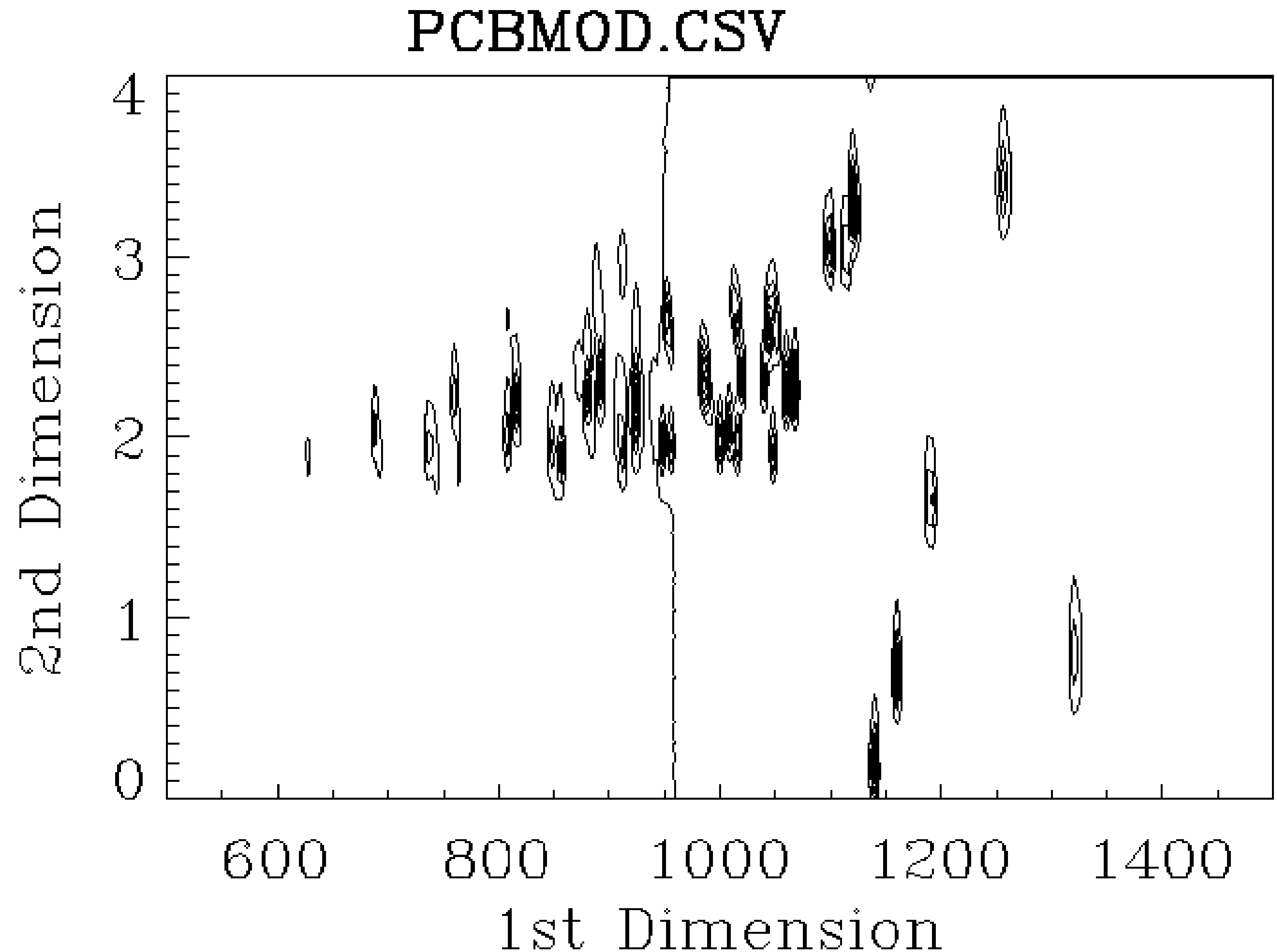
# Goal

- Investigation of a set of continuous column sets for a Jet modulator GCxGC system

# Experimental

- Columns
  - 100 µm set (3m Rtx-1, 1m Rtx-1701)
  - 250 µm set (6m Rtx-1, 2m Rtx-1701)
- Modulator
  - Type: Quad Jet system (Zoex Corporation)
  - Period: 4 seconds
- Detectors
  - FID
  - µ-ECD

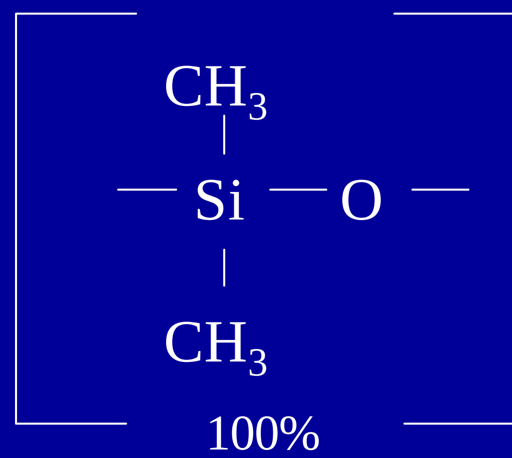

STRIPMOD.CSV
Signal
10000
8000
6000
4000
2000
0
1st Dimension
1600
1800
2000
2200
2400
2600
2800


PCBMOD.CSV
2nd Dimension
0
1
2
3
4
600
800
1000
1200
1400
1st Dimension

# Current continuous 2-D columns

0.25 mm i.d.:
Rtx-1/Rtx-1701 1.0 X 0.1 um d.f. 30 X 5 M
Rtx-1/Rtx-200 1.0 X 0.1 um d.f. 30 X 5 M
Rtx-1/Rtx-50 1.0 X 0.1 um d.f. 30 X 5 M
Rtx-1/Deactivated tubing 1.0 X 0 um d.f. 30 X 5 M
0.18 mm i.d.:
Rtx-1/Rtx-1701 1.0 X 0.1 um d.f. 10 X 2 M
Rtx-1/Rtx-200 1.0 X 0.1 um d.f. 10 X 2 M
Rtx-1/Rtx-50 1.0 X 0.1 um d.f. 10 X 2 M
Rtx-1/Deactivated tubing 1.0 X 0 um d.f. 10 X 5 M
0.10 mm i.d.:
Rtx-1/Rtx-1701 1.0 X 0.1 um d.f. 10 X 2 M
Rtx-1/Rtx-200 1.0 X 0.1 um d.f. 10 X 2 M

# Rtx®-1

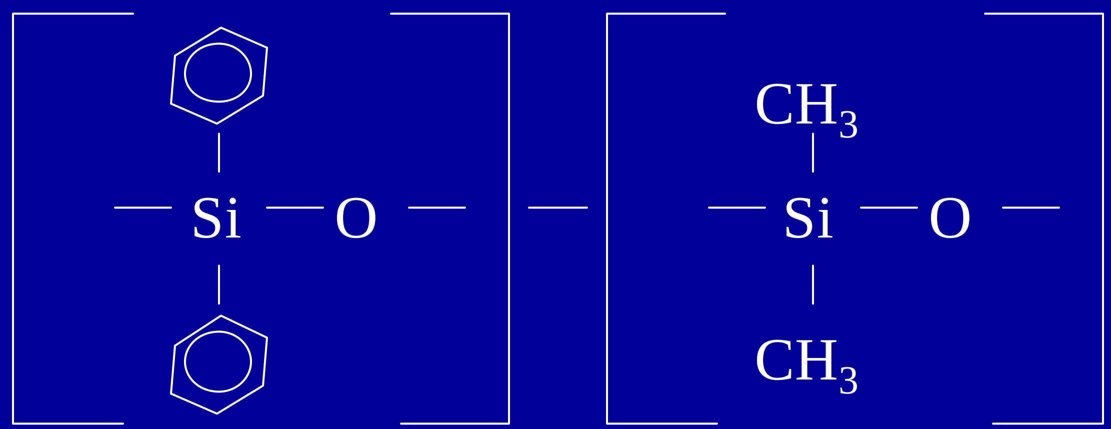



Polarity: least polar bonded phase

Uses: boiling point separations (solvents, petroleum products, and pharmaceuticals)

Properties: min. temp. (-60°C), max. temp. (360°C to 430°C), helix structure

# Rtx®-5, 20, 35, 65



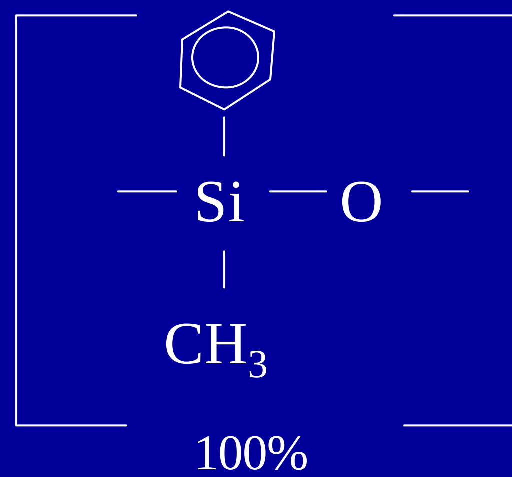

e.g., Rtx-5: 5% diphenyl 95% dimethyl

Polarity: non-polar

Uses: boiling point separations (aromatics, flavors, environmental samples, and aromatic hydrocarbons

Properties: min. temp. (-60°C), max. temp. (340°C)

# Rtx®-50

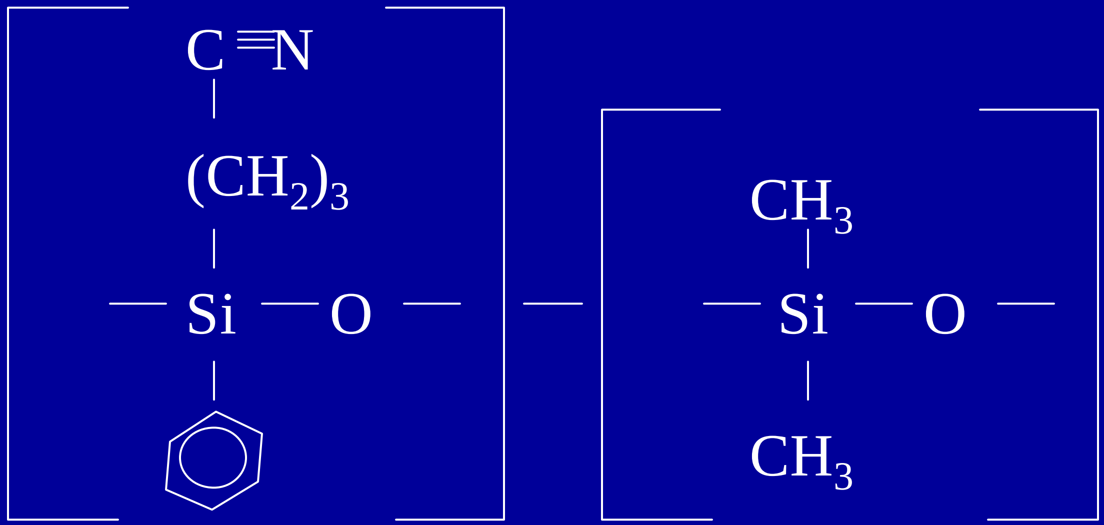



Polarity: intermediate polarity

Uses: triglycerides and phthalate esters

Properties: min. temp. (0°C), max. temp. (340°C)

# Rtx®-1301, 624, 1701

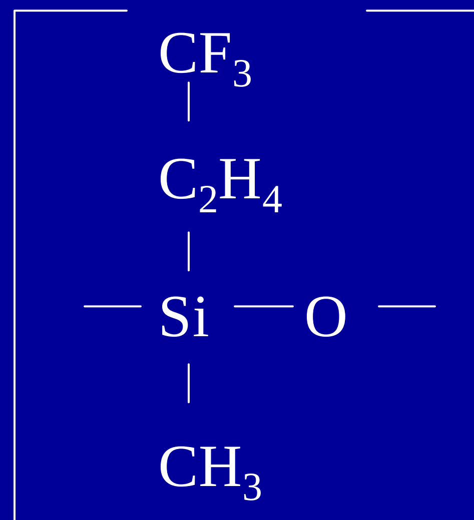



Polarity: intermediate polarity

Uses: pesticides, Aroclor®, alcohols, and oxygenates

Properties: min. temp. (-20°C), max. temp. (280°C)

# Rtx®-200




Polarity: selective for lone pair electrons

Uses: environmental samples, solvents, and Freon®

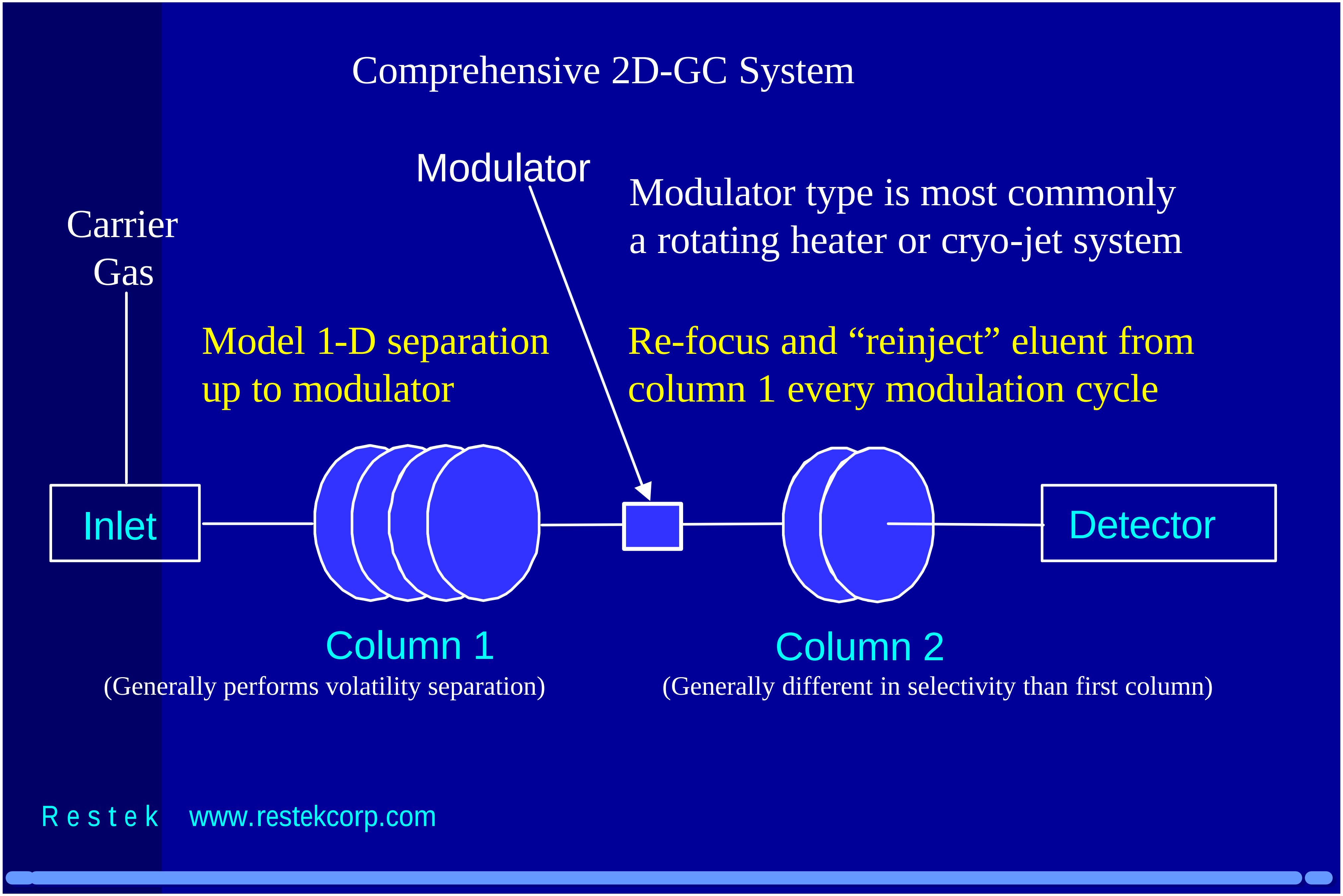
Properties: min. temp. (-20°C), max. temp. (360°C)

# What Phases Do We Need??

Wax Like Phases
Chiral Phases
Liquid Crystal Phases
Others….

# Optimization/Modeling of Separations

- Several approaches have been used for conventional separations
- Allows prediction of optimal conditions for a users column (Pro EZ-GC)
- Allows prediction of optimal stationary phase chemistry and conditions (*Anal. Chem.* **74**(9), 2133-2138 2002)
- Can these be applied to Comprehensive 2-D separations?


Comprehensive 2D-GC System
Modulator
Carrier
Gas
Modulator type is most commonly
a rotating heater or cryo-jet system
Model 1-D separation
up to modulator
Re-focus and “reinject” eluent from
column 1 every modulation cycle
Inlet
Detector
Column 1
(Generally performs volatility separation)
Column 2
(Generally different in selectivity than first column)
Restek www.restekcorp.com

# 1-D Modeling

# General Equation for Resolution:

$$R = 1/4 \sqrt{L / h} \times ( k / k+1 ) \times ( \alpha -1 / \alpha )$$

Selectivity Factor (α) – addressed by stationary phase modeling

not commonly done by end user

Capacity Factor (k), and Column Factor – addressed by physical modeling

can be simultaneous with, or independent of stationary phase modeling

# Stationary Phase Optimization Techniques

- Empirical Modeling:
  - Window diagramming approach
  - Computer simulation of phase selectivity, independent of column dimensions (ezGC™)
  - Computer prediction of optimized stationary phase composition and column dimensions, with specific resolution factors (times and peak widths)
- Molecular Modeling:
  - Computer prediction of solute/stationary phase interactions for new polymer designs

# Stationary Phase Optimization

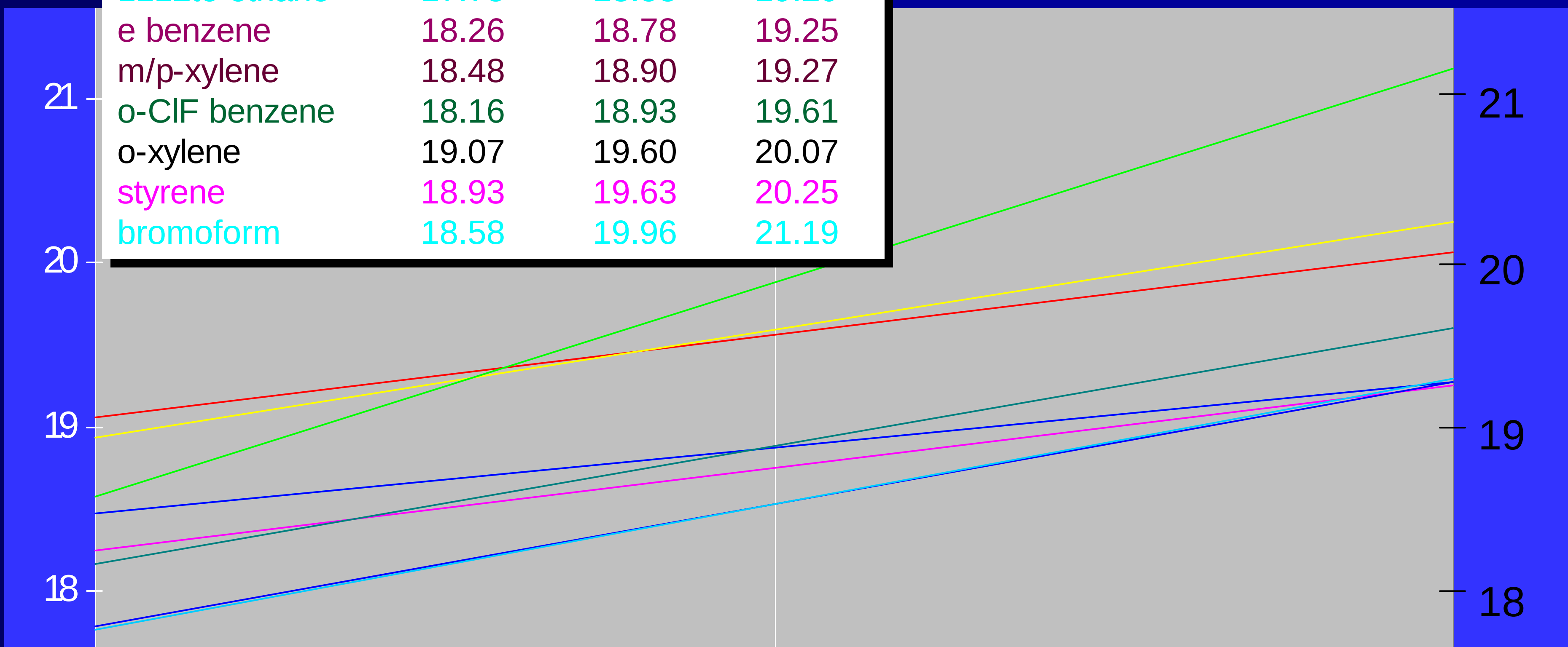
- Window diagramming (Rtx-502.2)
- Computer simulation of selectivity, independent of column dimensions (ezGC™)
  - Rtx®-CLPesticides, Rtx-CLPesticides2
- Computer prediction of optimized stationary phase composition and column dimensions
  - Rtx-TNT, Rtx-TNT2, Rtx-VMS, Rtx-VGC, Rtx-5SilMS, Rtx-VRX
- Computer prediction of  solute/stationary phase interactions for new polymer designs

# Window Diagrams

- Maier and Karpathy ('60's):
  - Demonstrated that mixing phases together could yield unique selectivity for packed column applications
- Laub and Purnell (70's)
  - Mixed phase packed column applications
- Jennings et al (80's)
  - Packed column applications, and capillary work based on lengths of dissimilar columns
  - DB™-1301 developed using DB™-1 and DB™-1701

# Window Diagramming

| | Rtx®-1 | Rtx®-502 | Rtx®-35 |
|---|---|---|---|
| chlorobenzene | 17.79 | 18.57 | 19.27 |
| 1112te ethane | 17.78 | 18.58 | 19.29 |
| e benzene | 18.26 | 18.78 | 19.25 |
| m/p-xylene | 18.48 | 18.90 | 19.27 |
| o-ClF benzene | 18.16 | 18.93 | 19.61 |
| o-xylene | 19.07 | 19.60 | 20.07 |
| styrene | 18.93 | 19.63 | 20.25 |
| bromoform | 18.58 | 19.96 | 21.19 |



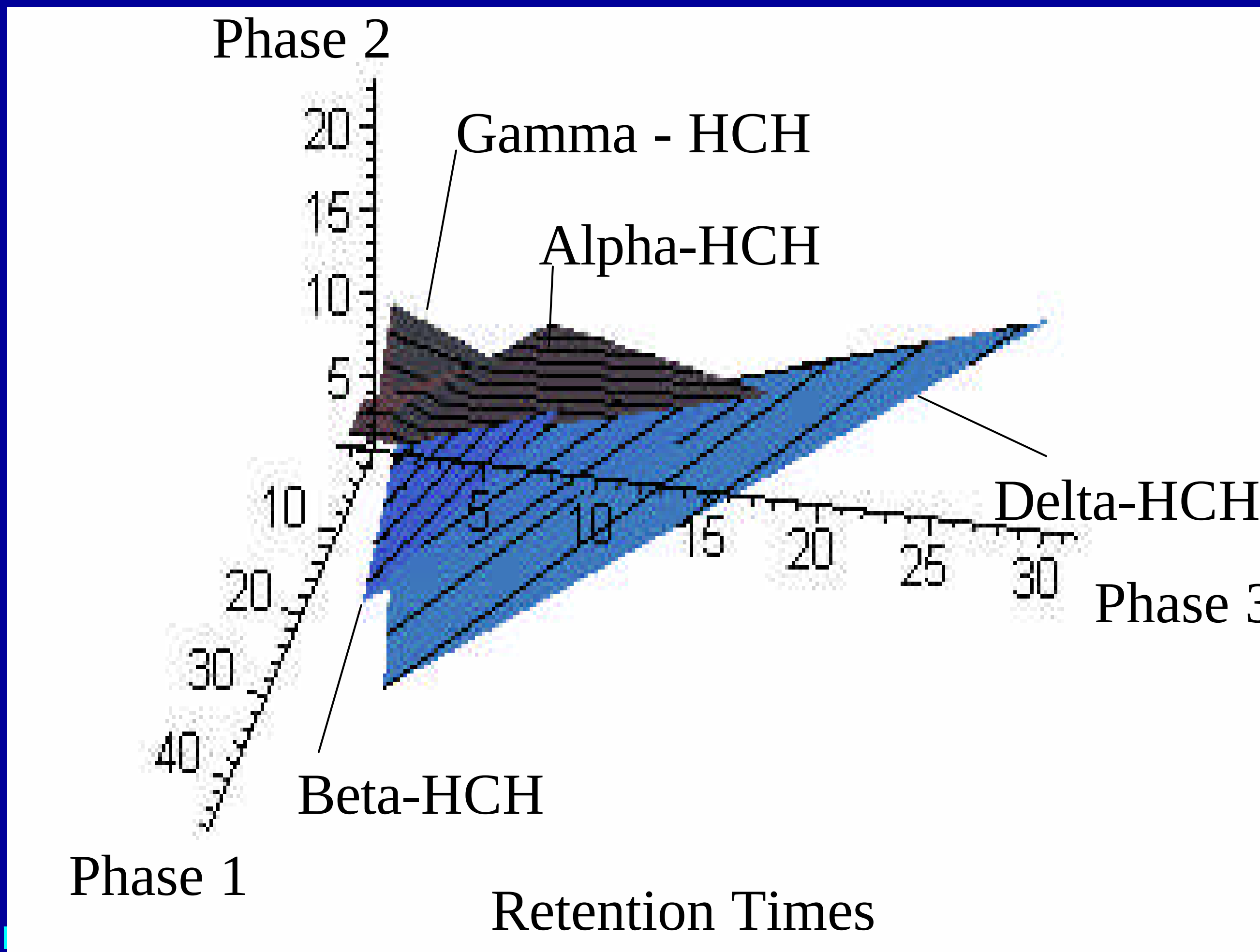
# Stationary Phase Optimization

- Window diagramming
- Computer simulation of phase selectivity, independent of column dimensions (ezGC™)
  - Rtx®-CLPesticides, Rtx-CLPesticides2
- Computer prediction of optimized stationary phase composition and column dimensions
  - Rtx®-CLPesticides, Rtx-CLPesticides2, Rtx-TNT Rtx-TNT2, Rtx-VMS, Rtx-VGC, Rtx-5SilMS, Rtx-VRX
- Computer prediction of solute/stationary phase interactions for new polymer designs

# Computer simulation of phase selectivity, independent of column dimensions (ezGC™)

- "Fix" Run Conditions
- Input data is normalized for column and program parameters
- Search for optimum solution by varying the stationary phase composition
- Program tracks up to 8 dimensions of phase functionalities.
- No solution requires separate re-optimization of input data

# 3-Space Selectivity Surface for 4 Pesticide Compounds

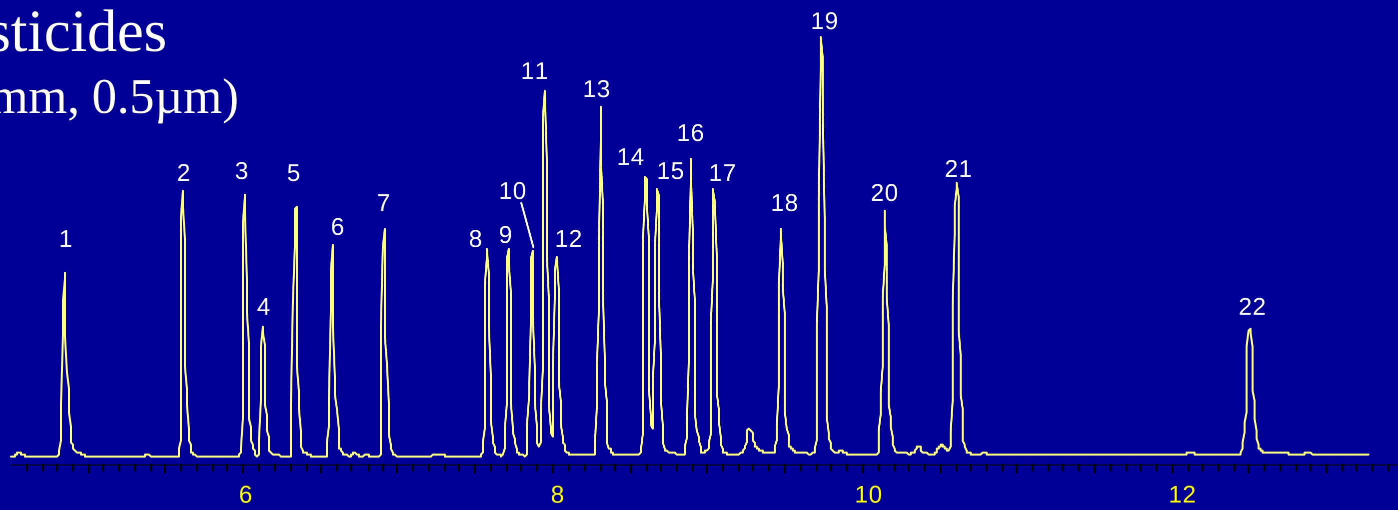


# Rtx®-CLPesticides Column Benefits

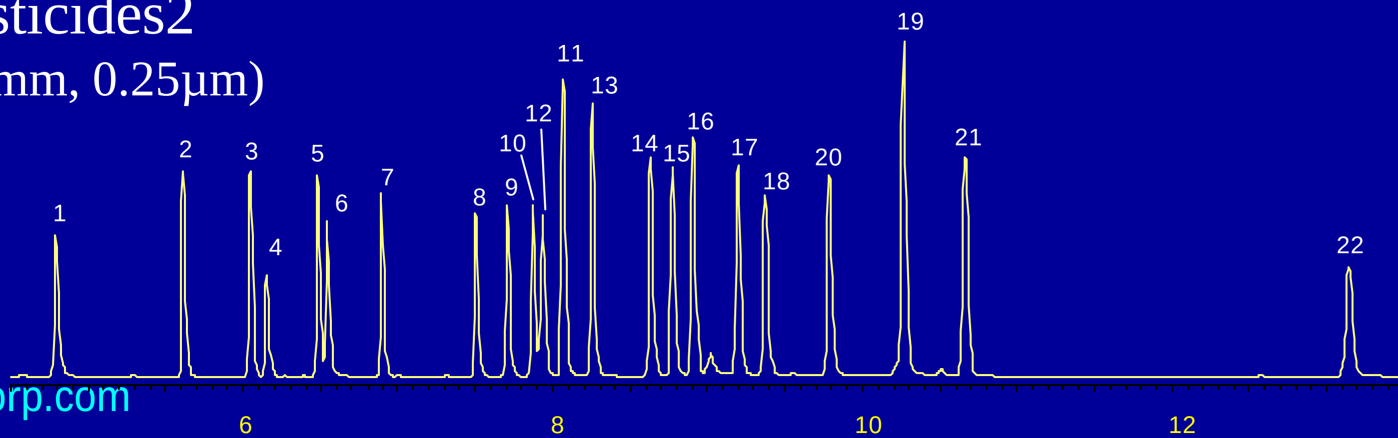
- Baseline resolution of all 22 compounds
- < 25 minute analysis time
- Available in all common dimensions
  - 0.18, 0.25, 0.32 and 0.53mm ODs
- Very low electron capture detector (ECD) bleed levels
- High thermal stability
  - 330°C maximum temperature

# Chlorinated Pesticides
# Fast Runs

## Rtx-CLPesticides
(30m x 0.32mm, 0.5µm)




## Rtx-CLPesticides2
(30m x 0.32mm, 0.25µm)



# Chlorinated Pesticides

1 2,4,5,6-tetrachloro-m-xylene
2 alpha BHC
3 gamma BHC
4 beta BHC
5 delta BHC
6 heptachlor
7 aldrin
8 heptachlor epoxide
9 gamma chlordane
10 alpha chlordane
11 4,4'-DDE
12 endosulfan I
13 dieldrin
14 endrin
15 4,4'-DDD
16 endosulfan II
17 4,4'-DDT
18 endrin aldehyde
19 methoxychlor
20 endosulfan sulfate
21 endrin ketone
22 decachlorobiphenyl

# Stationary Phase Optimization

- Window diagramming
- Computer simulation of phase selectivity, independent of column dimensions (ezGC™)
- Rtx®-CLPesticides, Rtx-CLPesticides2
- Computer prediction of optimized stationary phase composition **AND** column dimensions
  - Rtx-TNT Rtx-TNT2, Rtx-VMS, Rtx-VGC, Rtx-5SilMS, Rtx-VRX, Rtx-OPPesticides2, Customer-specific columns
- Computer prediction of solute/stationary phase interactions for new polymer designs

# Achieving Analyte Separation

**Resolution**

$$R = 1/4 \sqrt{L / h} \ \times ( k / k+1 ) \times ( a - 1 / a )$$

**Capacity Factor**

$$k = (t_R - t_0) / t_0$$

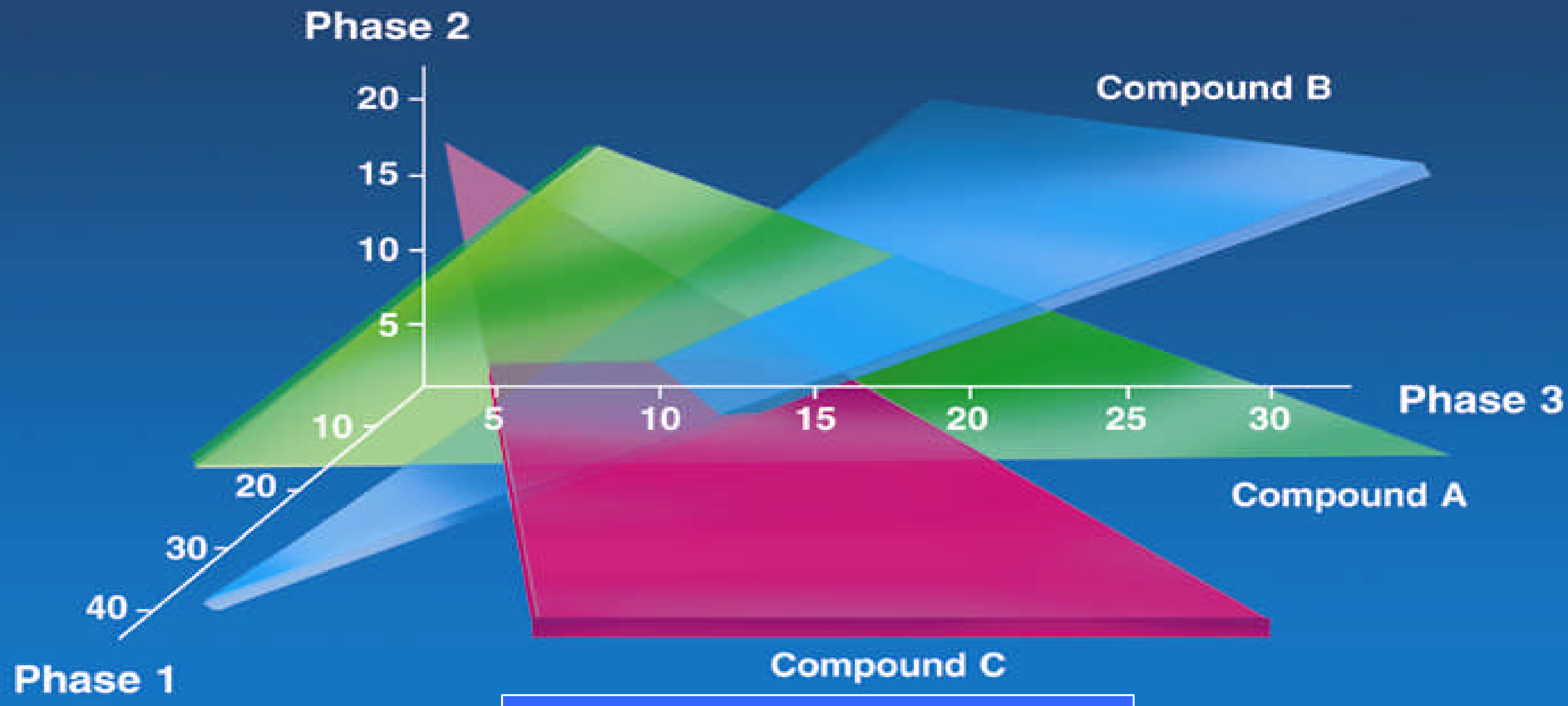
**Selectivity**

$$a = k_2 / k_1$$

**Thermodynamics:**

$$DG = DH - TDS \qquad DG = -RT \ln K_D$$

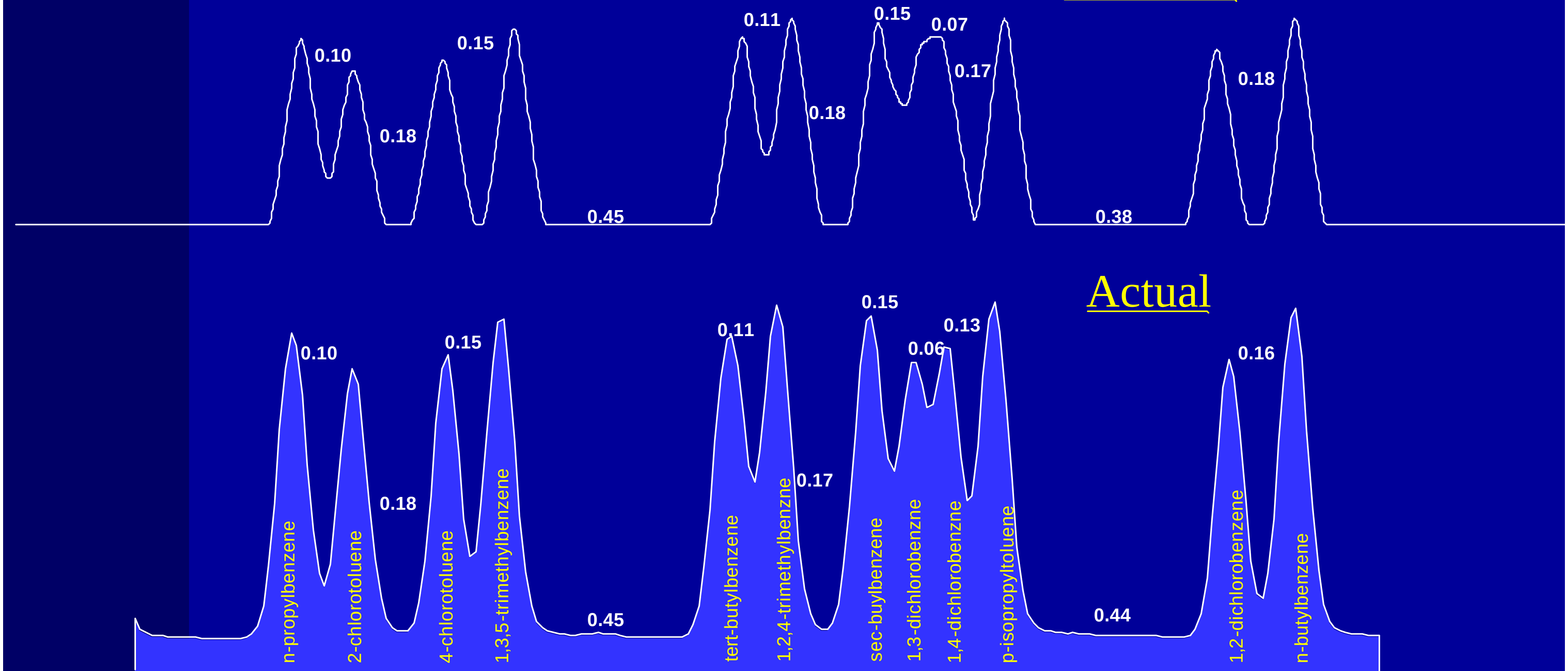
# 3-Space Selectivity Model for 3 Compounds




Surface=FΔHΔS

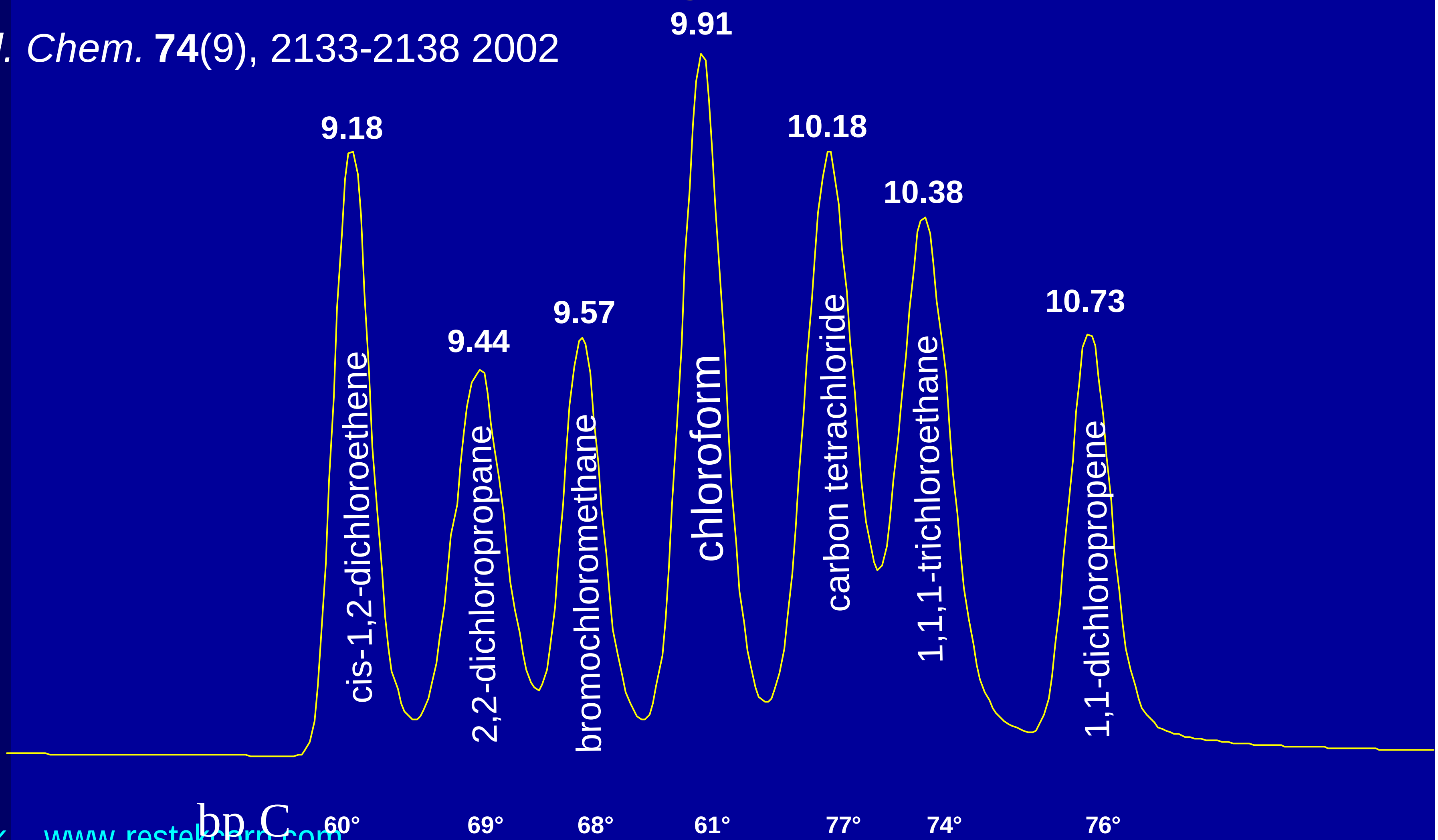
# Volatiles Analysis:
# Predicted vs. Actual 4 Dimensional Phase

*Anal. Chem.* **74**(9), 2133-2138 2002



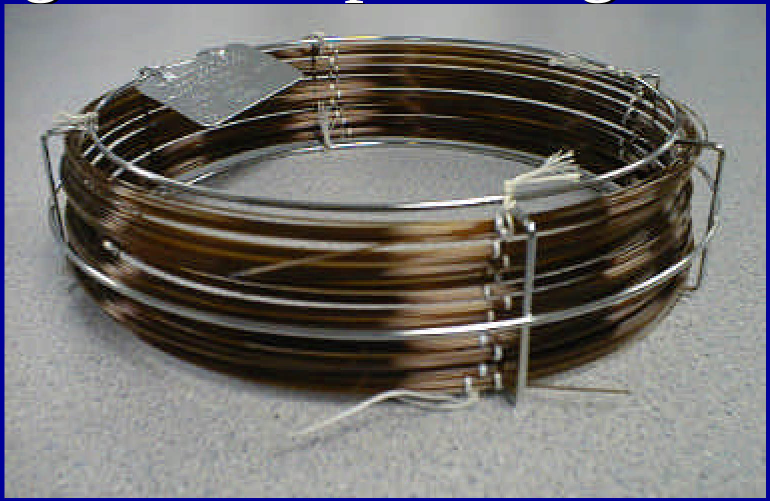
# Volatiles Analysis: Rtx®-VGC

*Anal. Chem.* **74**(9), 2133-2138 2002



# Design Criteria of 2-D Column

- Continuous section of tubing with no press-tight
- Volatility separation 1st
- Alternate selectivity 2nd
- Same i.d. for both columns
- Thicker film on 1st ?
- Maintain higher efficiency on 2nd ?
- Will also work for press-fit columns



# Simultaneous 2-D Modeling
# ---or---
# Why 2D is not 2X 1D GC

1.) Calculation of the pressure at the modulation point is not as straight forward during a “desorption”

2.) Not a normal “injection” onto second column
there is a selective retention of analyte in the phase

3.) There is no “buffer volume” at the modulation point, or a pressure controller to adjust for any pressure surges
at 1 atm a liquid expands 1000X as it vaporizes

# Input Data

- Compounds of interest analyzed in 1-D mode on each stationary phase of interest at two different temperatures or temperature programs
- A separate ΔH and ΔS are calculated for each compound on each stationary phase independent of physical parameters
- Separation is modeled on conditions of 1$^{st}$ column
- Eleuent is re-focused (peak width is re-calculated) and injected onto 2$^{nd}$ column
- Final elution from second column is reported as a function of both 1$^{st}$ and 2$^{nd}$ dimension – tabular report

# Modeling Accuracy on Continuous 2D column - LECO Pegasus 4D system Conditions

180 um i.d. continuous 2D column:

10M Rtx-1, 1.0 um d.f.

50C (0.2 min), 5C/min to 200C (0.8 min)

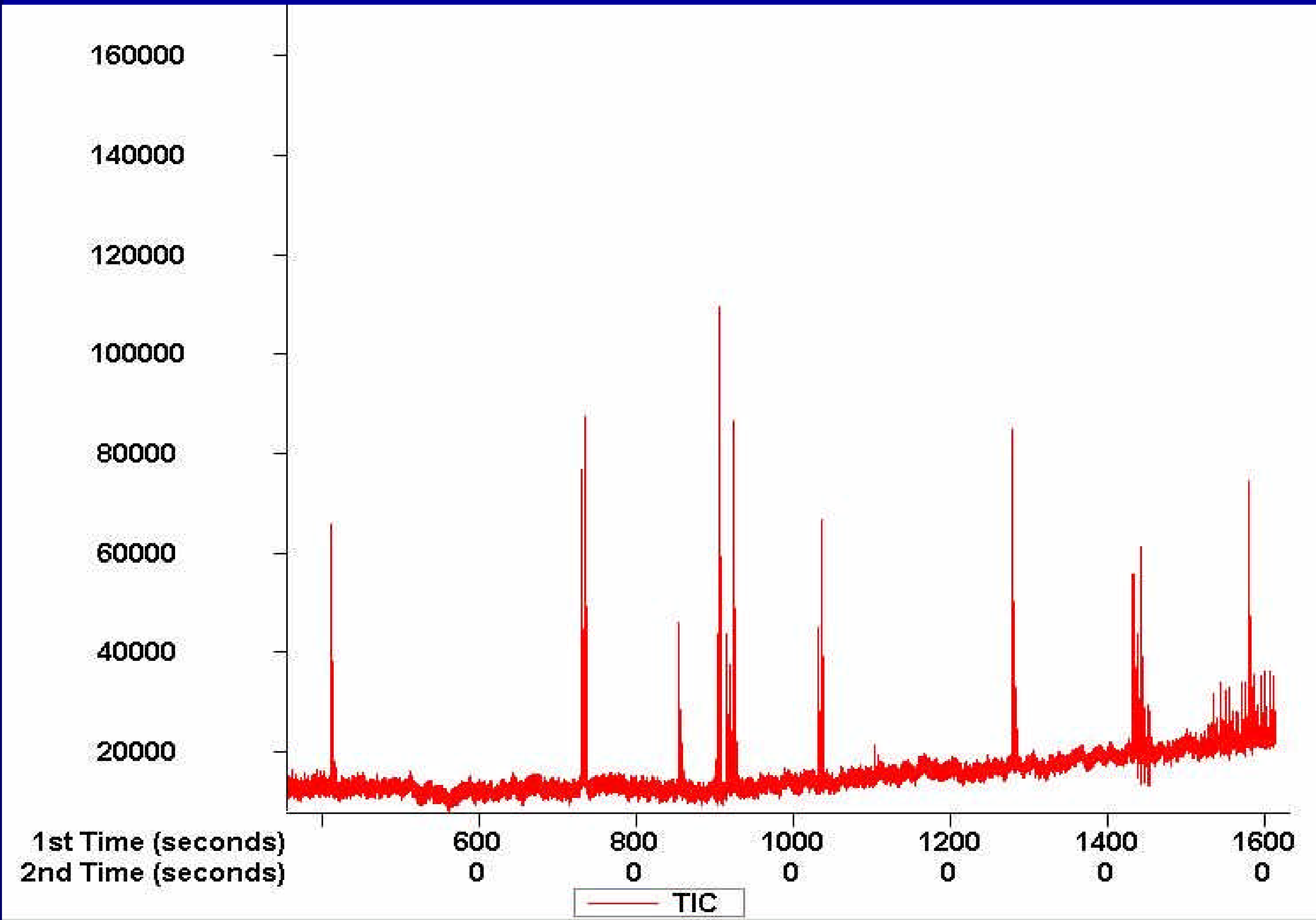
0.8M Rtx-1701, 0.1 um d.f.

55C (0.2 min), 5C/min to 205C (0.8 min)

Helium Carrier, 1mL/min constant flow

1uL injection, 200/1 split

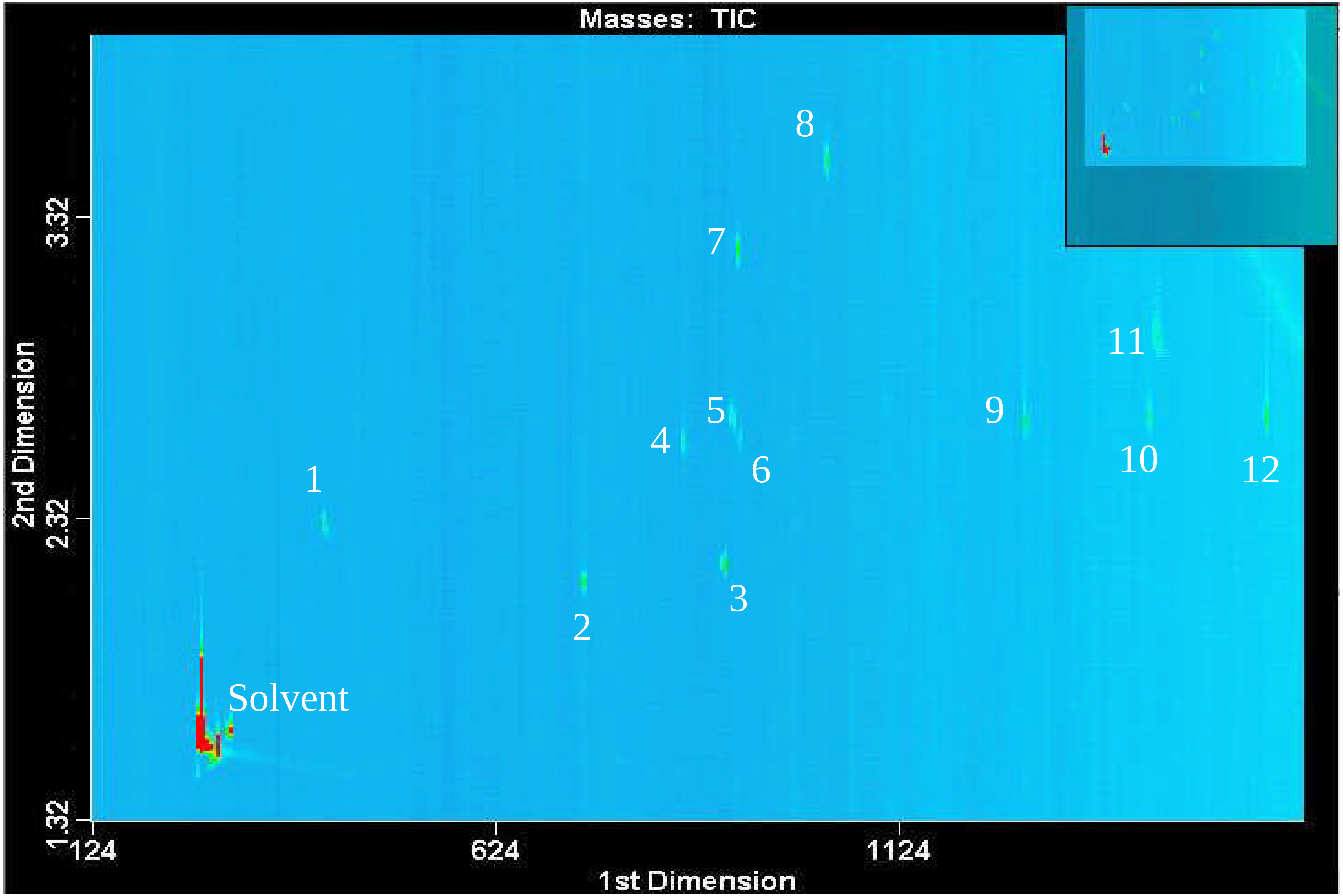
Modulator Period = 4 sec

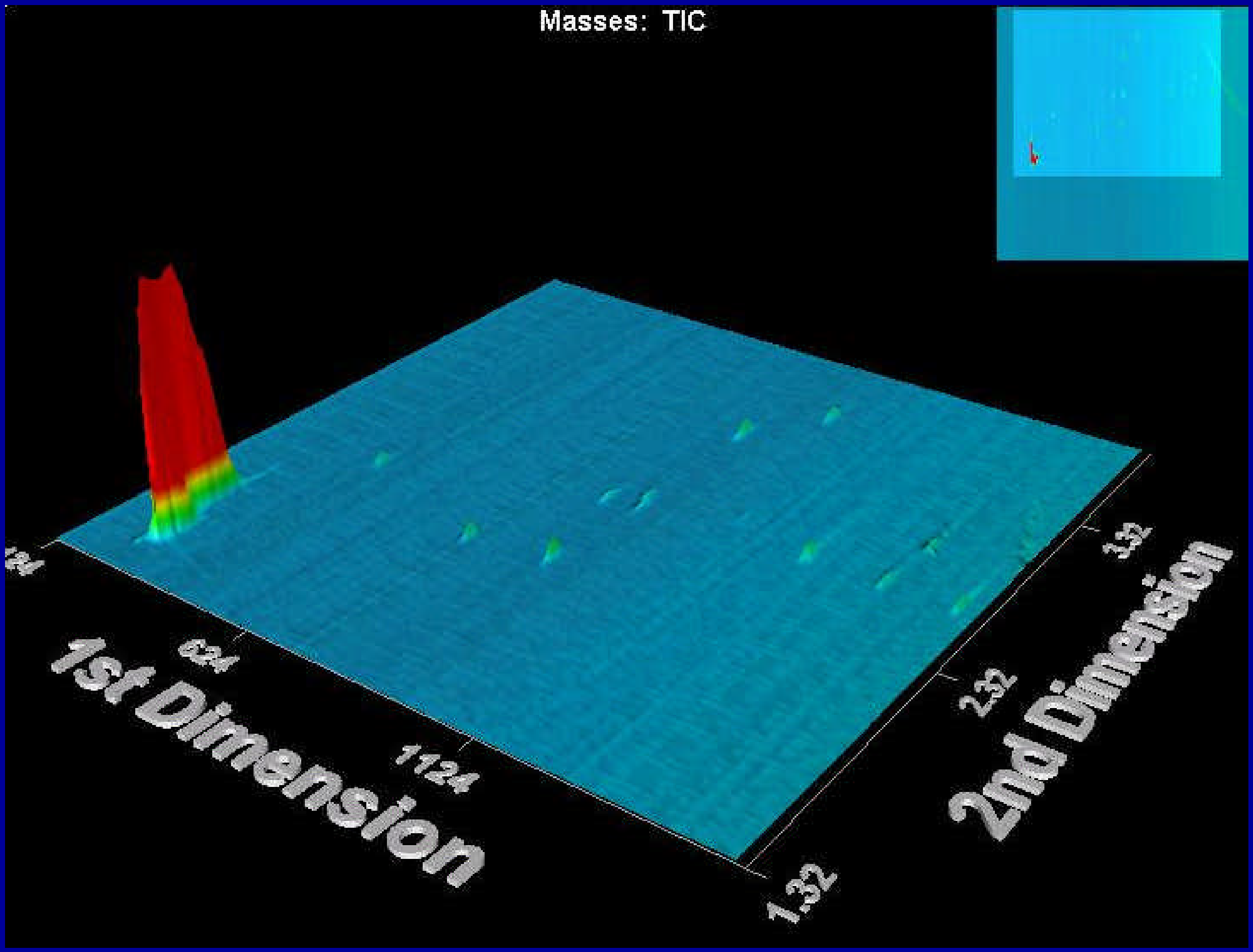

160000
140000
120000
100000
80000
60000
40000
20000
1st Time (seconds)
2nd Time (seconds)
600
0
800
0
1000
0
1200
0
1400
0
1600
0
TIC

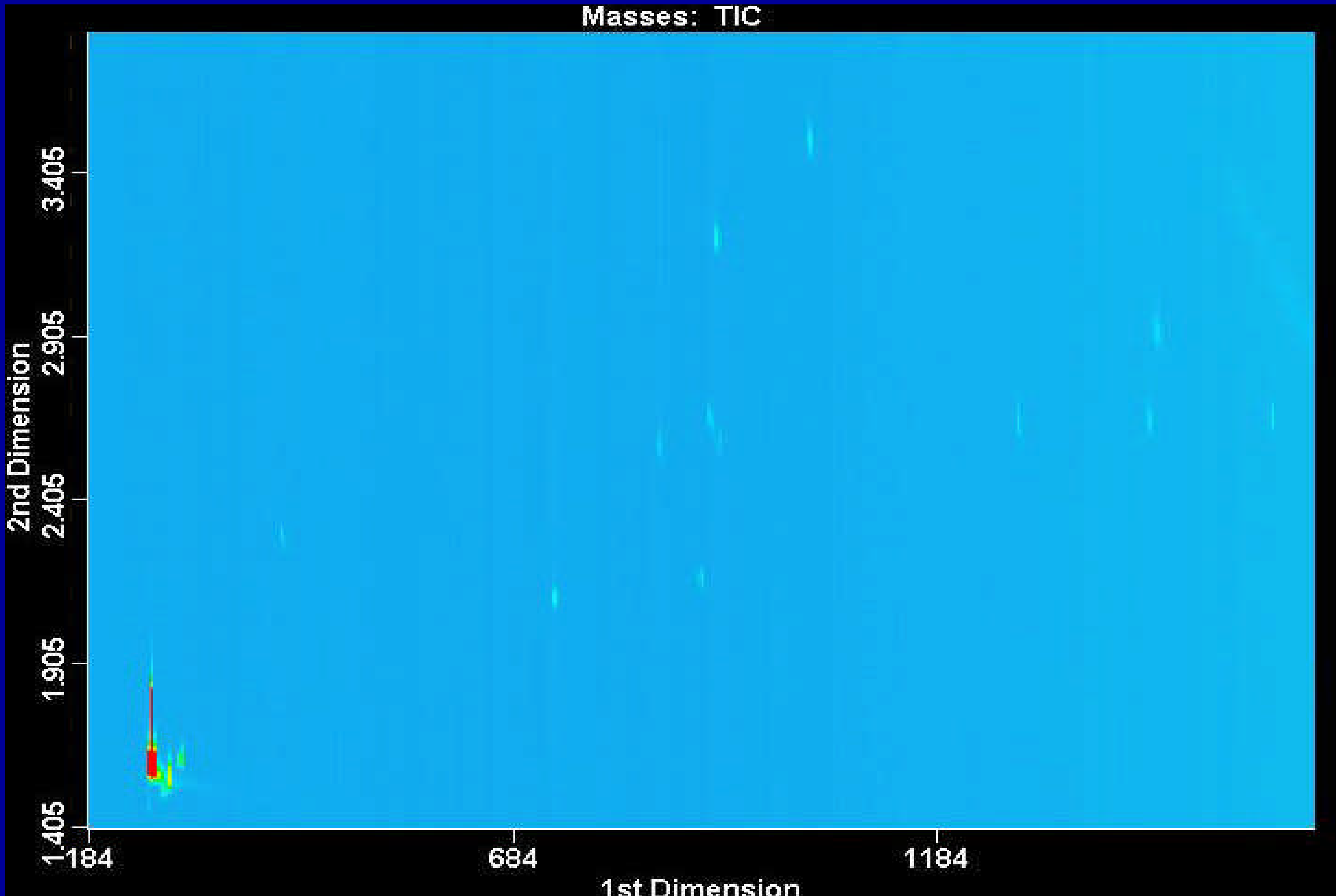
# Grob Test Mixture

## As numbered on 2D Chromatogram

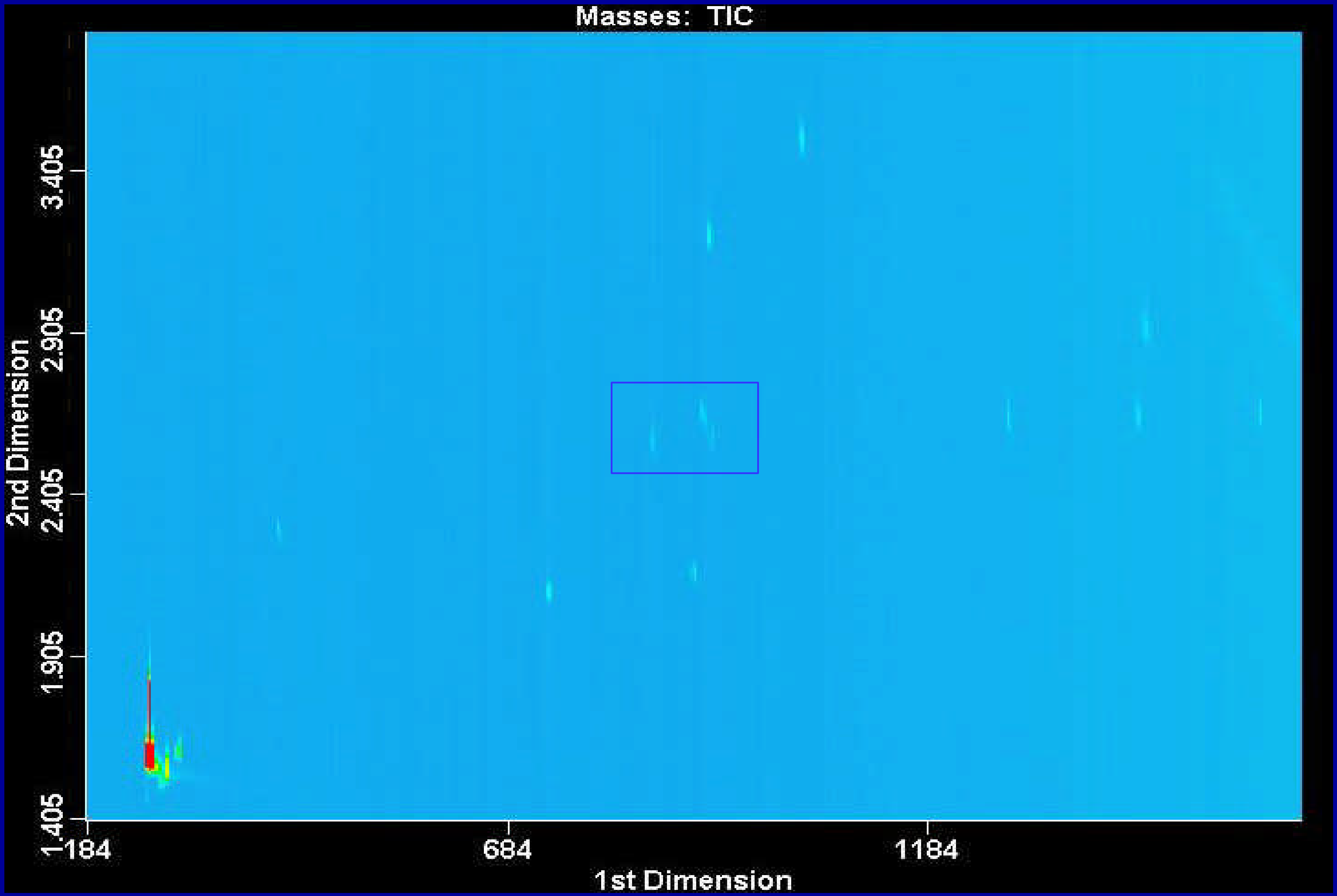
- 1.) 2,3-butanediol
- 2.) decane
- 3.) undecane
- 4.) 1-octanol
- 5.) 1-nonanol
- 6.) 2-ethylhexanoic acid
- 7.) 2,6-dimethylphenol
- 8.) 2,6-dimethylaniline
- 9.) C10 FAME
- 10.) C11 FAME
- 11.) dicyclohexylamine
- 12.) C12 FAME


Masses: TIC
2nd Dimension
3.32
2.32
1.32
1st Dimension
124
624
1124
Solvent
1
2
3
4
5
6
7
8
9
10
11
12

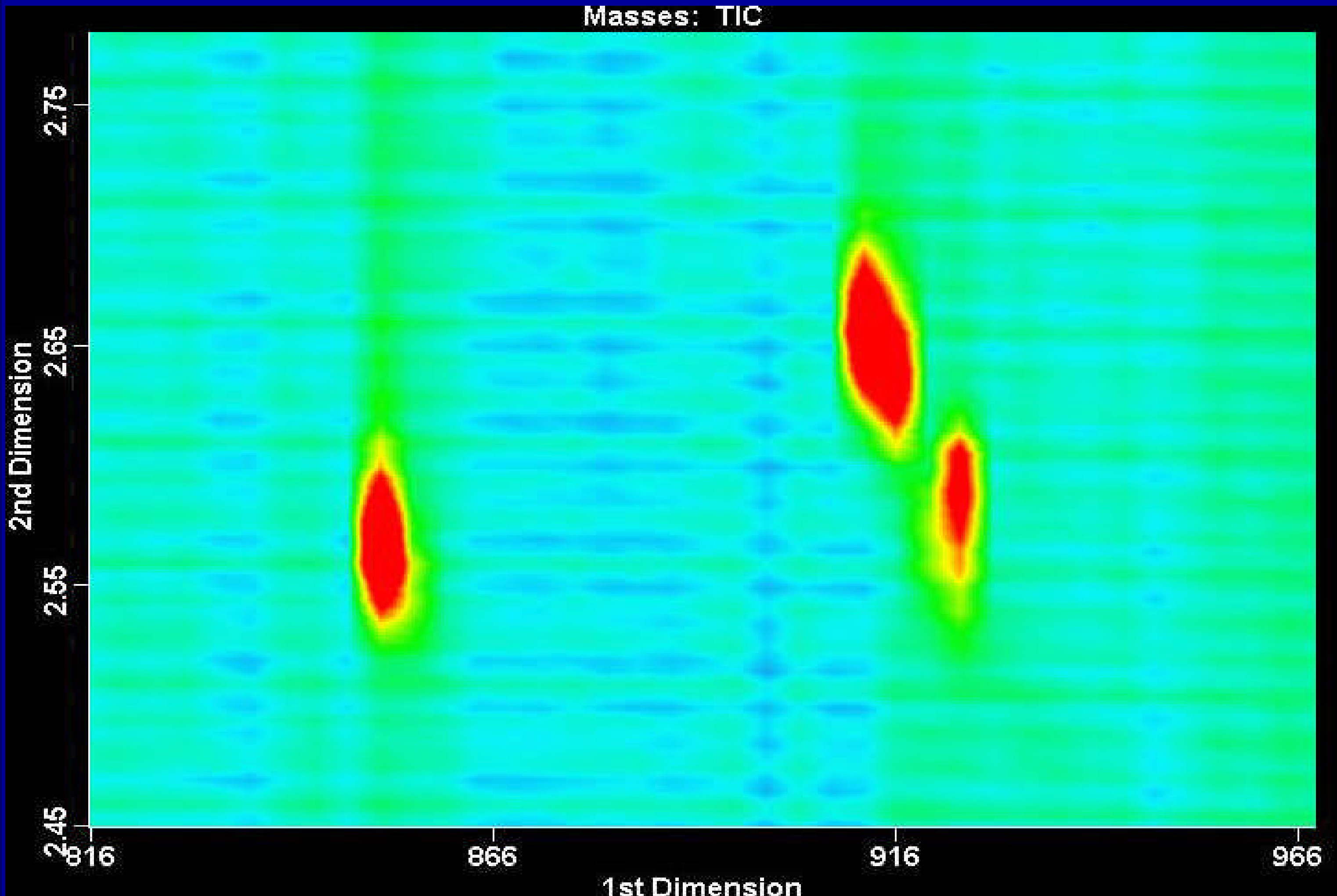

Masses: TIC
624
1124
1st Dimension
3.32
2.32
1.32
2nd Dimension

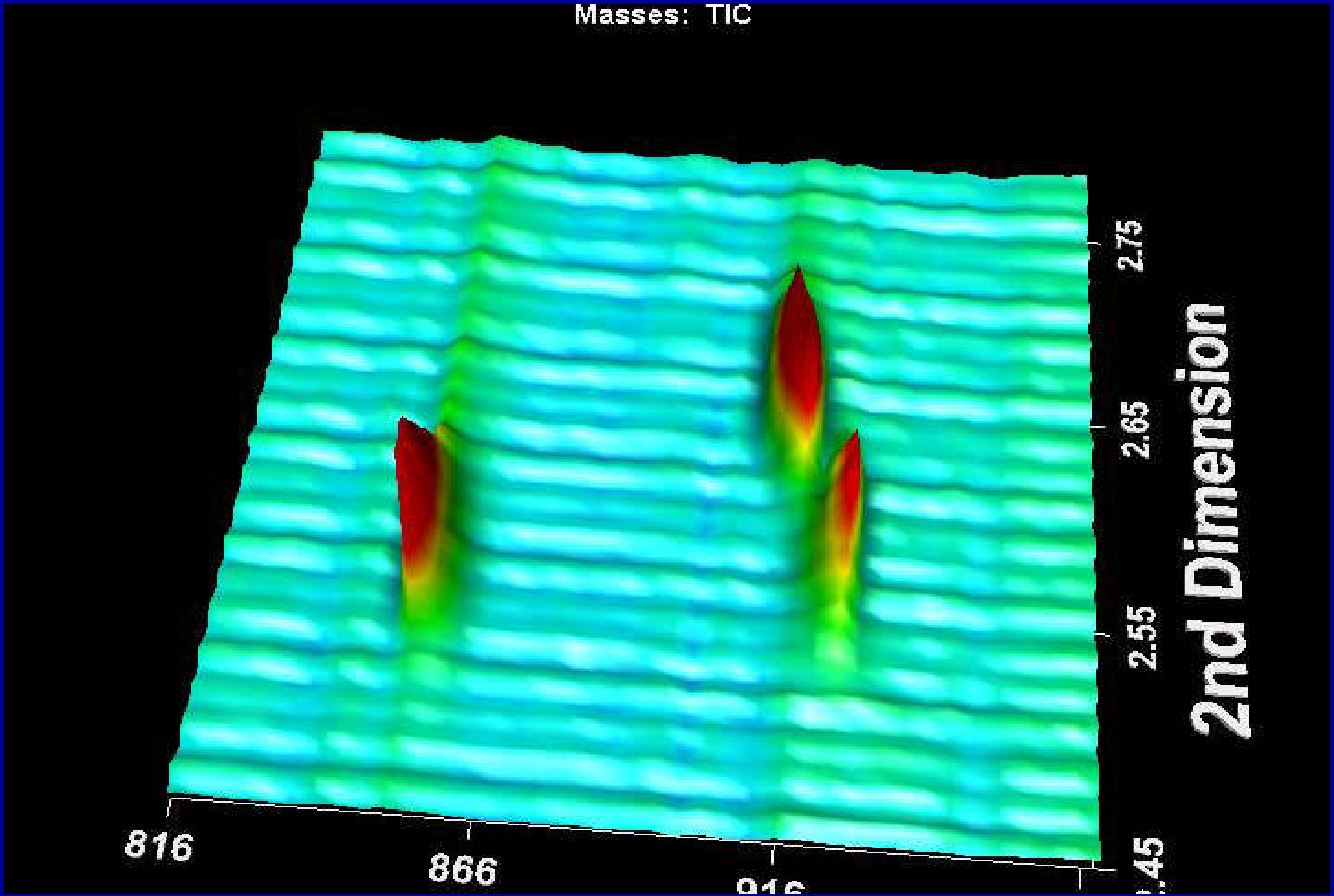


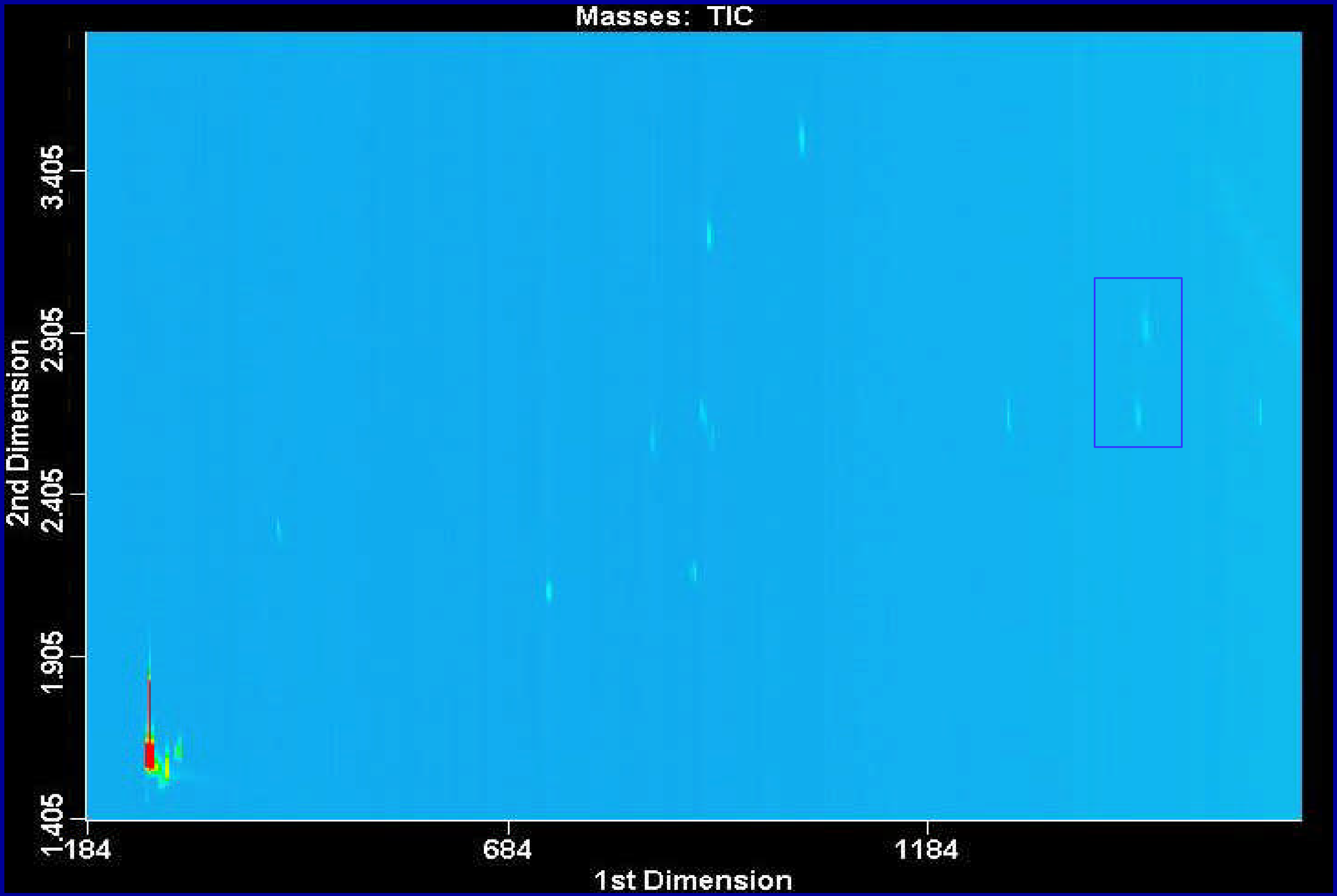
Masses: TIC
2nd Dimension
3.405
2.905
2.405
1.905
1.405
184
684
1184
1st Dimension

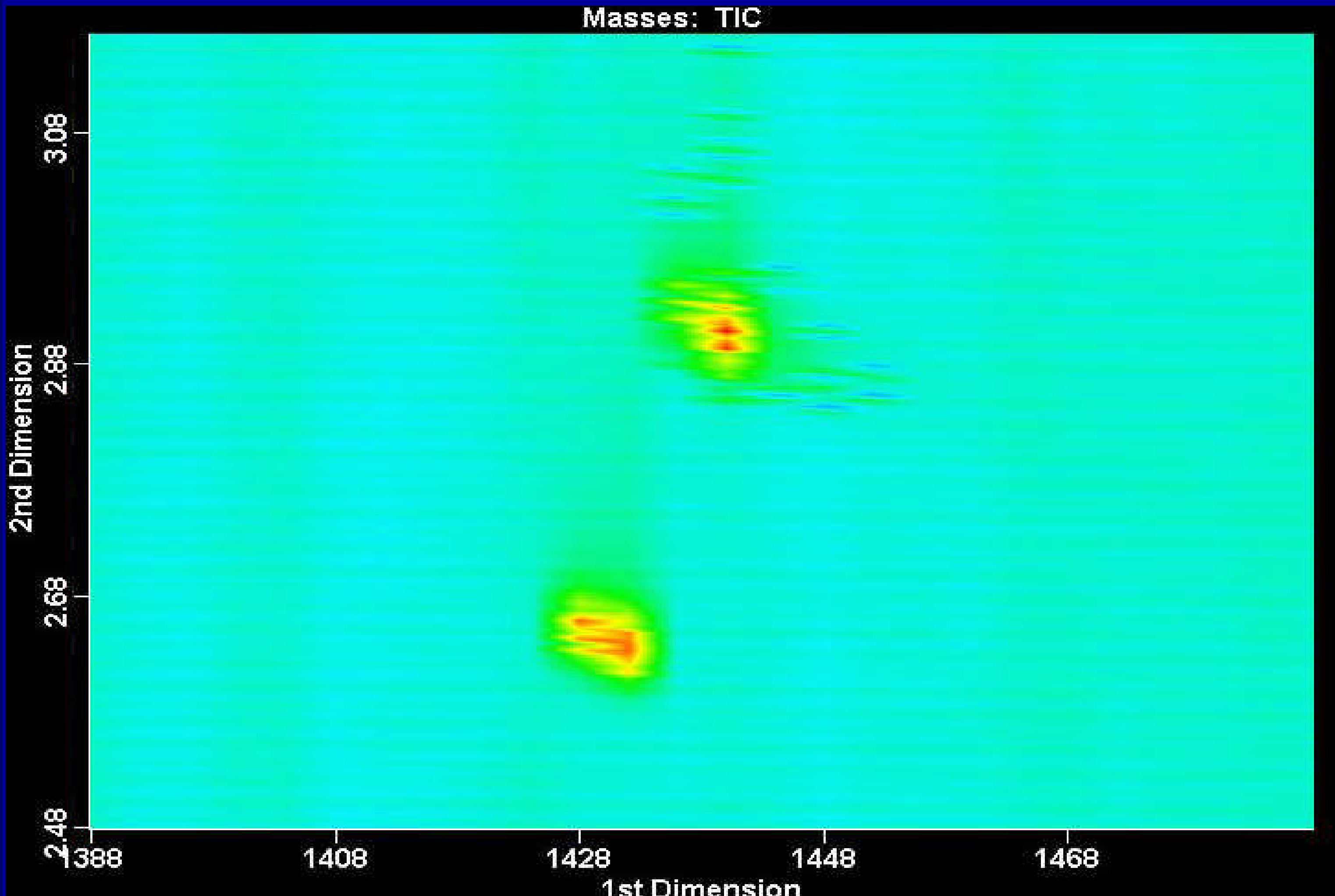


Masses: TIC
2nd Dimension
3.405
2.905
2.405
1.905
1.405
184
684
1184
1st Dimension


Masses: TIC
2nd Dimension
2.75
2.65
2.55
2.45
816
866
916
966
1st Dimension

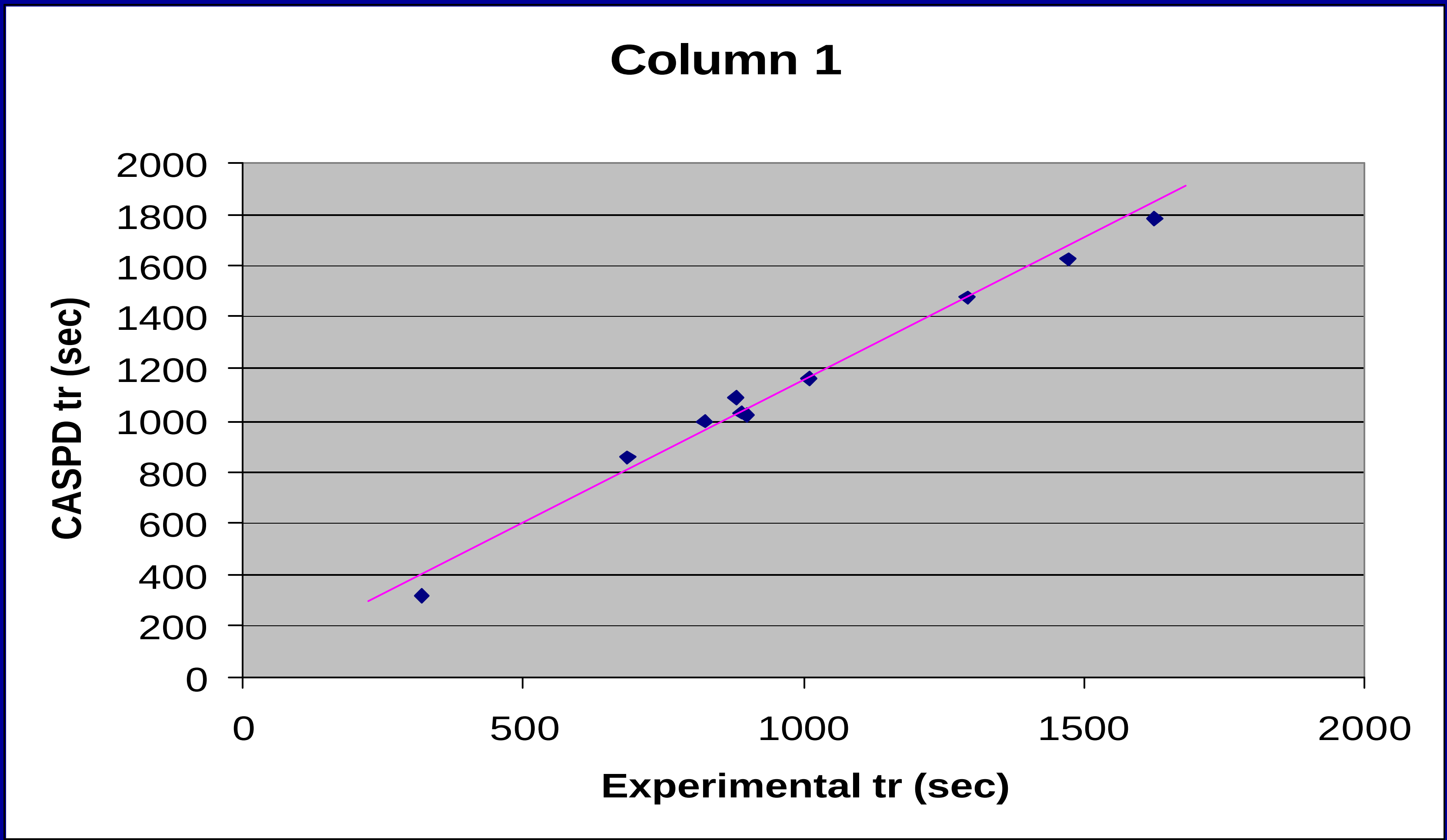

Masses: TIC
2.75
2.65
2.55
2nd Dimension
816
866


Masses: TIC
2nd Dimension
3.405
2.905
2.405
1.905
1.405
184
684
1184
1st Dimension

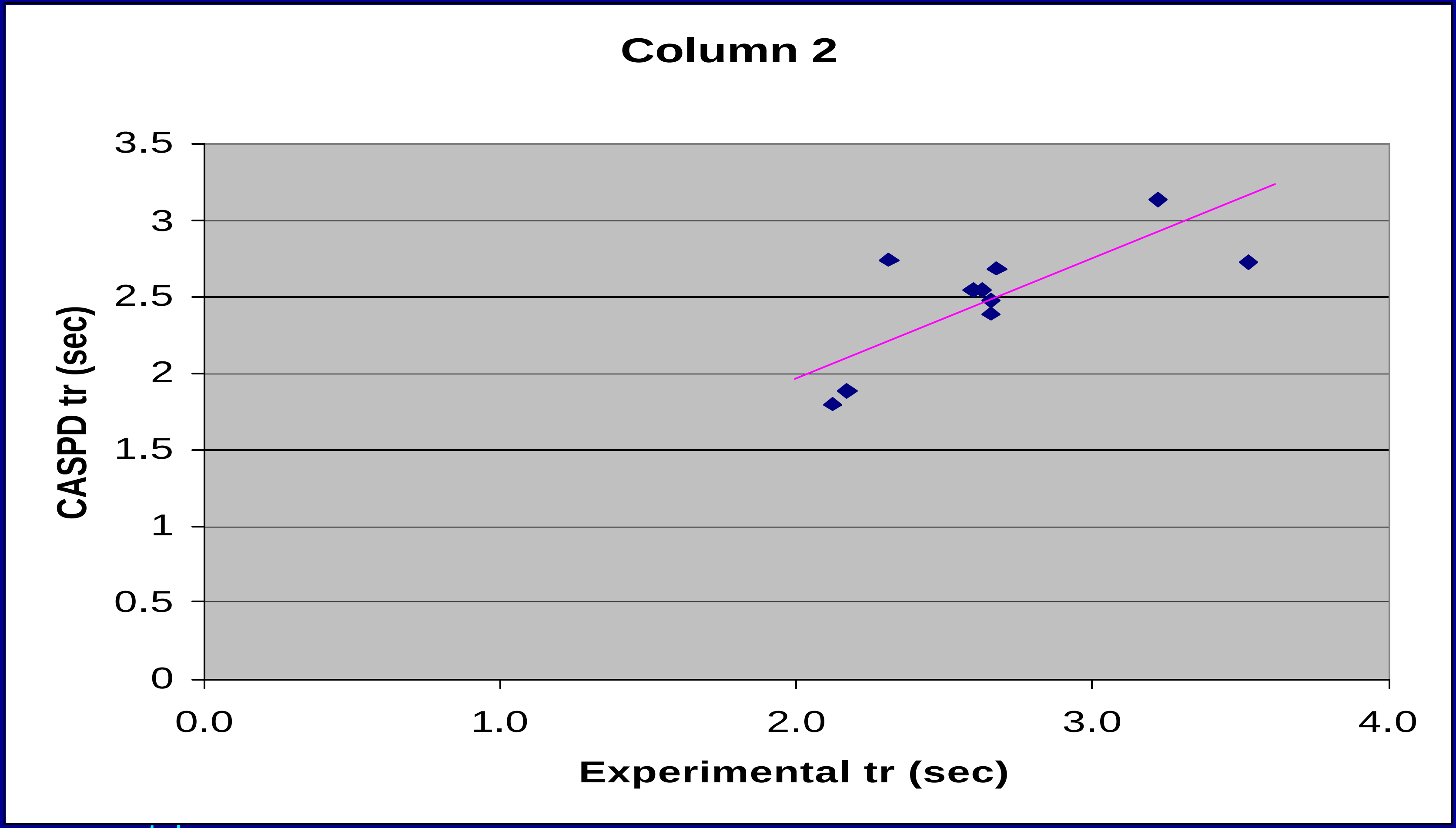

Masses: TIC
2nd Dimension
3.08
2.88
2.68
2.48
1388
1408
1428
1448
1468
1st Dimension

| | | | Column 1 | | | Column 2 | |
|---|---|---|---|---|---|---|---|
| | | | Exp | Model | | Exp | Model |
| Compound Name | # | tr1 cm | **tr1 sec** | **tr1 sec** | tr2 cm | **tr2 sec** | **tr2 sec** |
| Calibration | 0 | 17.35 | **1124** | | 12.85 | **2** | |
| 2,3 Butanediol | 1 | 4.9 | **317** | **318** | 6.4 | **2.3** | **2.74** |
| decane | 2 | 10.55 | **683** | **858** | 5.15 | **2.1** | **1.8** |
| undecane | 3 | 13.55 | **878** | **1088** | 5.5 | **2.2** | **1.89** |
| 1-octanol | 4 | 12.75 | **826** | **995** | 8.2 | **2.6** | **2.54** |
| 1-nonanol | 5 | 13.75 | **891** | **1032** | 8.7 | **2.7** | **2.68** |
| 2-ethylhexanoic a | 6 | 13.9 | **900** | | 8.25 | **2.6** | |
| 2,6 dimethylpheno | 7 | 13.85 | **897** | **1018** | 12.25 | **3.2** | **3.13** |
| 2,6-dimethylaniline | 8 | 15.55 | **1007** | **1160** | 14.2 | **3.5** | **2.73** |
| C10-FAME | 9 | 19.95 | **1292** | **1476** | 8.6 | **2.7** | **2.39** |
| C11-FAME | 10 | 22.7 | **1471** | **1627** | 8.6 | **2.7** | **2.47** |
| dicyclohexylamine | 11 | 22.85 | **1480** | | 10.25 | **2.9** | |
| C12-FAME | 12 | 25.1 | **1626** | **1784** | 8.4 | **2.6** | **2.55** |

# Actual –vs.- Theoretical for Column 1



# Actual –vs.- Theoretical for Column 2



# Conclusions

- Columns performed successfully
- Modeling is not yet correct
- Future work
  - Investigation of the best column ratios for general use
  - Vu-2 Union developed for applications requiring press-tight connections
  - Role of modulator in “injection” onto second column
  - Modeling refinements for column ensemble developments and technical service
  - Commercially-available Optimization program?

# Summary

- Continuous 2-D columns eliminate need for press tights.
  - Distinct advantage for commercial users
- Modeling optimization software can save large amount of R&D time for column ensemble development
- Physical optimization work on hold
- Additional research needs to be done for prediction of second column elution

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