40 YEARS of Innovation

IC Anniversary Seminar Tour

Continual Innovation and Achievement: 40 Years of Ion Chromatography!

2015 Productivity Series

40 Years of Driving Innovation

1975 → 2015

Colloidal, 50 µm, 1-column

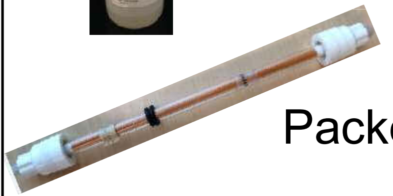
Stationary Phase

Supermacroporous 4 µm, 3 formats 48-columns

Carbonate Eluent

Mobile Phase Chemistry

RFIC



Packed bed

Eluent Suppression

Continuous electrolytic

Dionex Model 10

Instrumentation

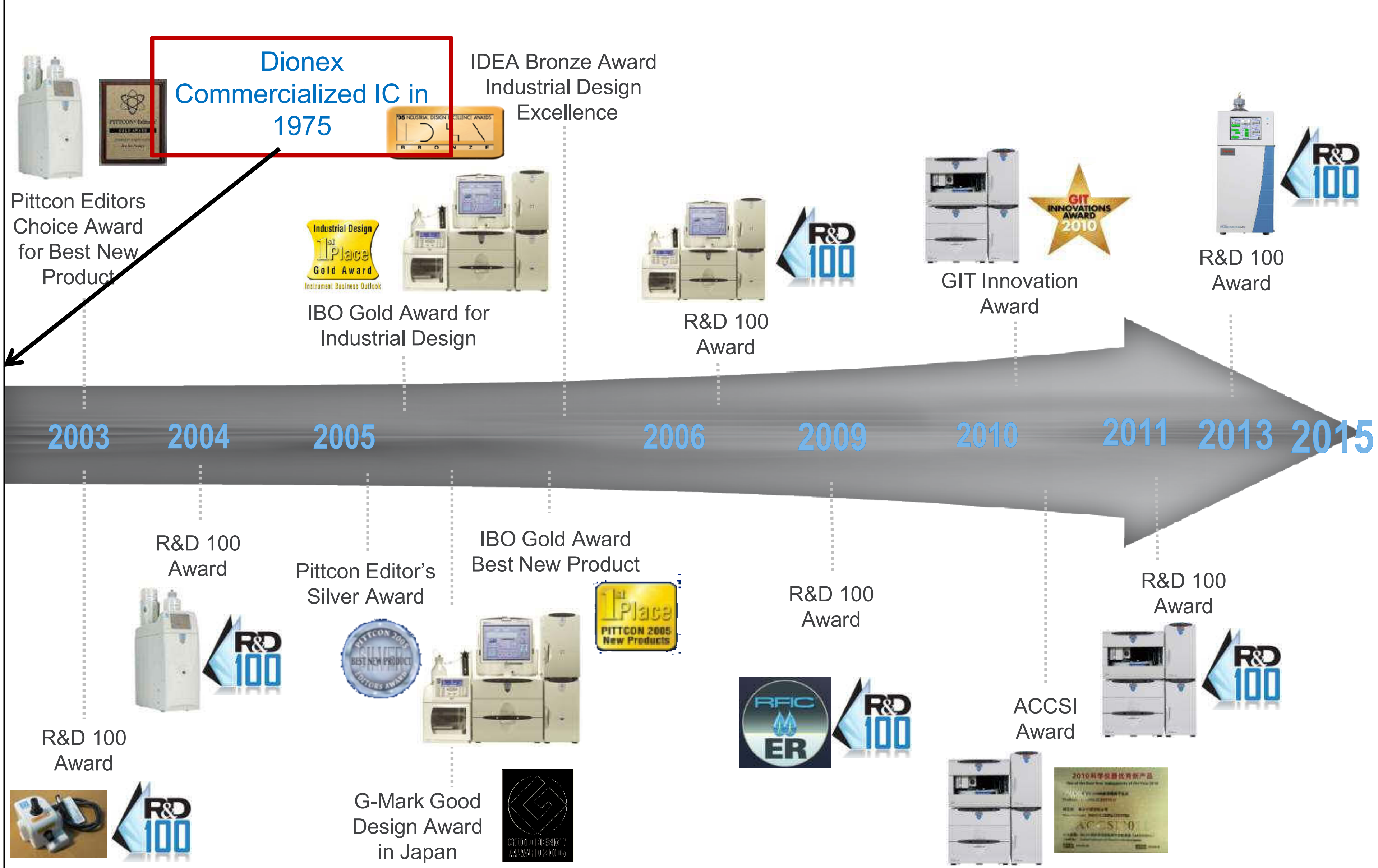
Dionex ICS-4000

Strip Chart recorder

Data/Software

Dionex Chromeleon 7

IC Innovation Awards over the last 10 years



The Landscape Before Ion Chromatography

- Limited automated instrumentation
  - Most ion analysis was colorimetric, turbidimetic or ISE
  - Ion exchange resins were used but only as a sample prep tool for wet chemical analysis methods
  - Data handling: Do you remember “chart recorders” and “integrators”?
  - Reports: Typed with carbon paper on an electric typewriter and mailed with a stamp

Disadvantages of Wet Chemistry Methods

- Large matrix effects, color interference, low sensitivity, labor intensive

Chromatography Goal: Water as a mobile phase

- Tried and discarded

Ionic analysis was a desert, a wet desert

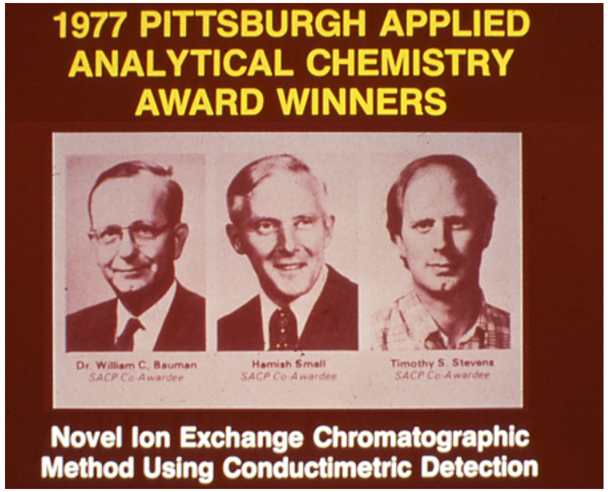
Essential Elements of an Ion Chromatography System

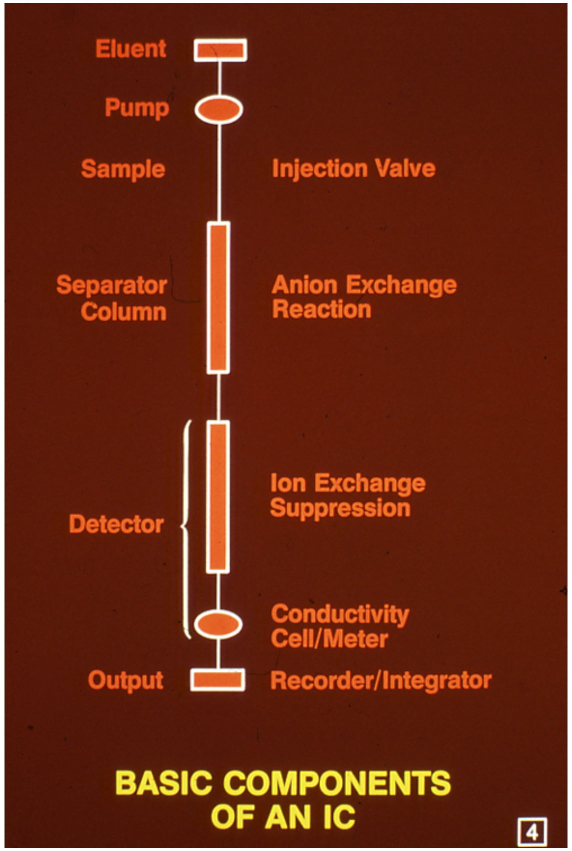
What was missing from today's IC?

- Manufacturing process for ion-exchange stationary phases
- Suitable mobile phase
  - Aqueous solutions had electrical conductance due to high ionic content
- Device to strip ionic content from the mobile phase!
  - Low electrical conductance. Water is the perfect background (goal)
- Detector for analytes that do not have chromophores
  - A conductivity cell for conductivity detection
- Instrument to run the separation and detection methods
- "Integrator" or method to process or present the data

Fathers of Ion Chromatography

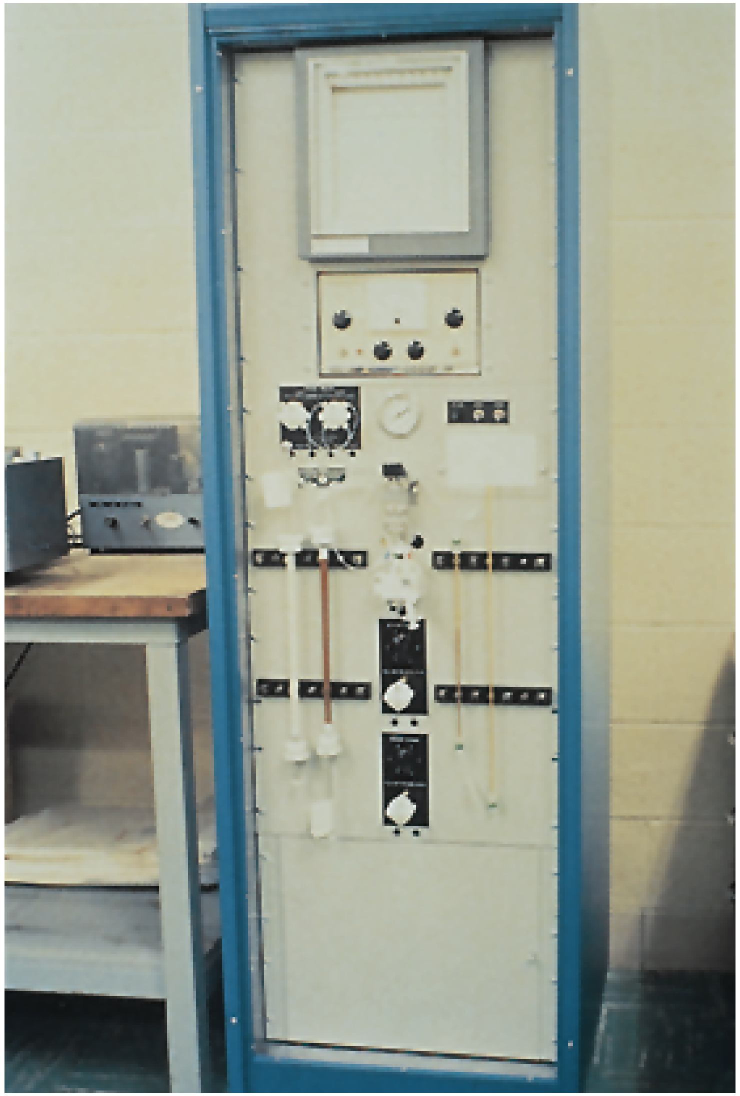
- Hamish Small, Bill Bauman and Tim Stevens (Dow Chemical)

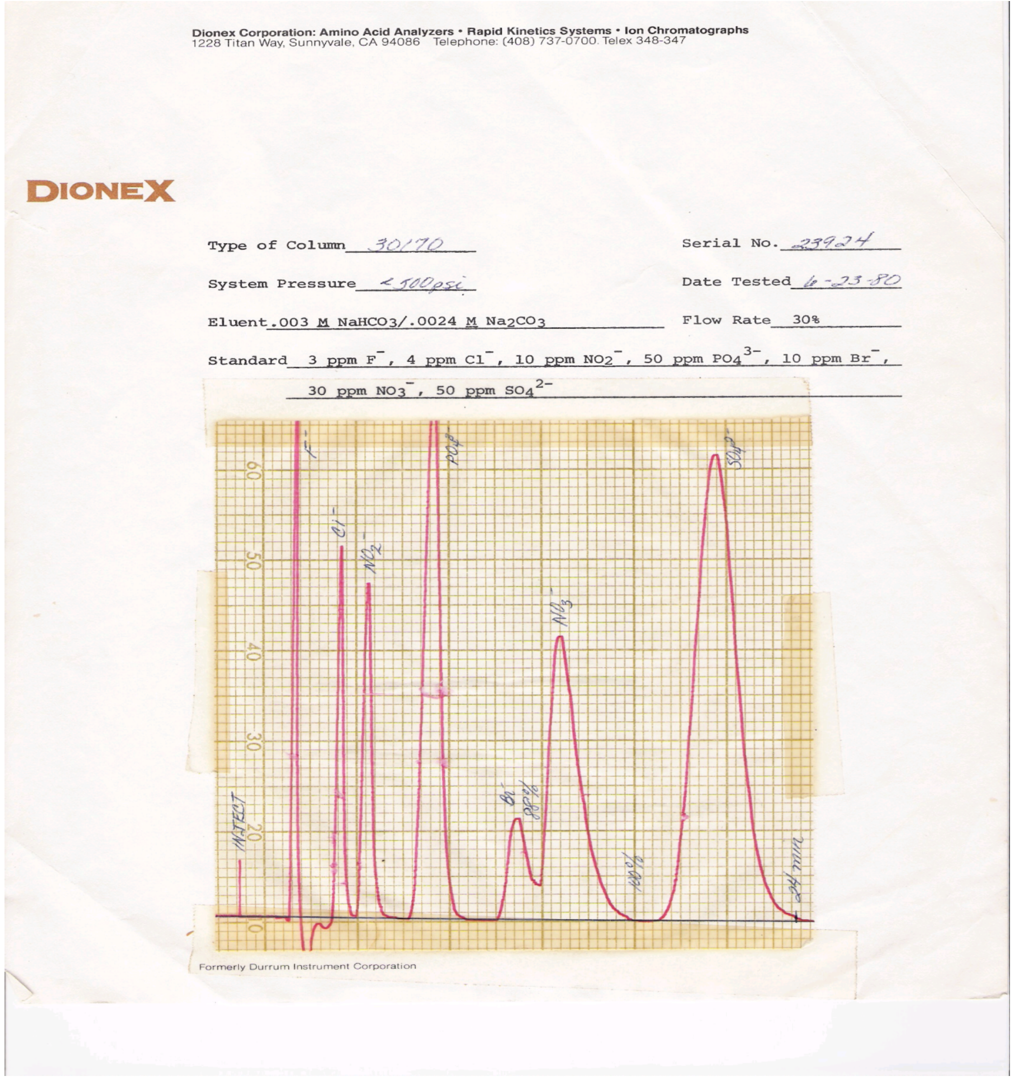




- Defined *"ion chromatography"* exclusively as a combination of
  1) Ion-exchange separation
  2) Eluent suppression
  3) Electrical conductance detection

The Very First Ion Chromatograph – Dow Chemical





Dionex Corporation: Amino Acid Analyzers • Rapid Kinetics Systems • Ion Chromatographs
1228 Titan Way, Sunnyvale, CA 94086 Telephone: (408) 737-0700. Telex 348-347

DIONEX

Type of Column 30170 Serial No. 23924

System Pressure <500psi Date Tested 6-23-80

Eluent .003 M $NaHCO_3$/.0024 M Na_2CO_3 Flow Rate 30%

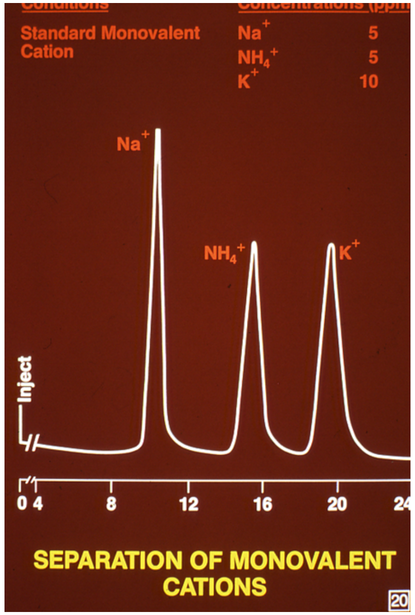
Standard 3 ppm F^-, 4 ppm Cl^-, 10 ppm NO_2^-, 50 ppm PO_4^{3-}, 10 ppm Br^-, 30 ppm NO_3^-, 50 ppm SO_4^{2-}

Formerly Durrum Instrument Corporation

Cations Came First: 26 min for Three Cations!

- 10 mM lithium, sodium, and potassium as chloride salts
- Only monovalent cations
- Column: a lightly sulfonated styrene–divinylbenzene (DVB) polymer, 50 µm

- Eluent: 20 mM HCl
- Injection Vol.: 100 µL
- Dowex 1 "Stripper" (suppressor): (hydroxide form)

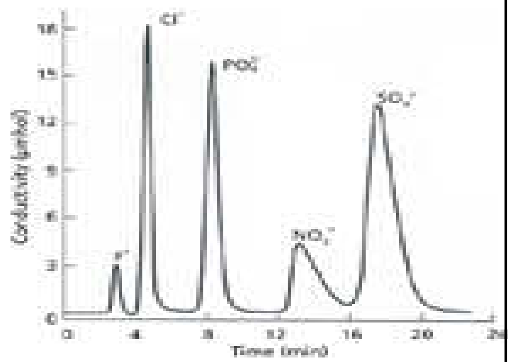


Hamish laboratory notebook, November 9, 1971

Hamish Small, LCGC April 02, 2013

Selection of Eluent Driven by Column Innovations

- Goal: NaOH as anion eluent because it suppresses to water
- Limitations
  - Hydroxide has low affinity for 1970's anion-exchange columns
  - Columns require high eluent concentrations to elute analytes
  - High hydroxide concentrations strain the suppressor capacity
- Compromise: Carbonate eluents
  - Converts to weak and low conducting carbonic acid
  - Compatible with the early suppressors
  - Issue: the baseline conductivity is ~10–22 µSiemens
  - Eluent family for more than 20 yrs



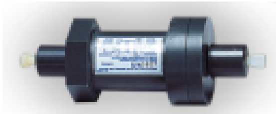
circa 1974

In 1975, Established the Foundations of IC

- Licensing agreements: Dow Chemical and Durrum Instruments
  - Durrum/Dow ION EXchange = DIONEX
- Formation of one company
  – Dionex Corporation (1978)
- Column Process: Surface-sulfonated styrene–DVB resin with a suspension of a colloidal anion-exchange resin
- Eluent system: Carbonate based buffers
- Suppressor: Switching packed bed
- Detector: Suppressed conductivity
- First commercial IC:
  - Dionex Model 10 (single channel system)
  - Dionex Model 14 (dual channel system, but only one detector)

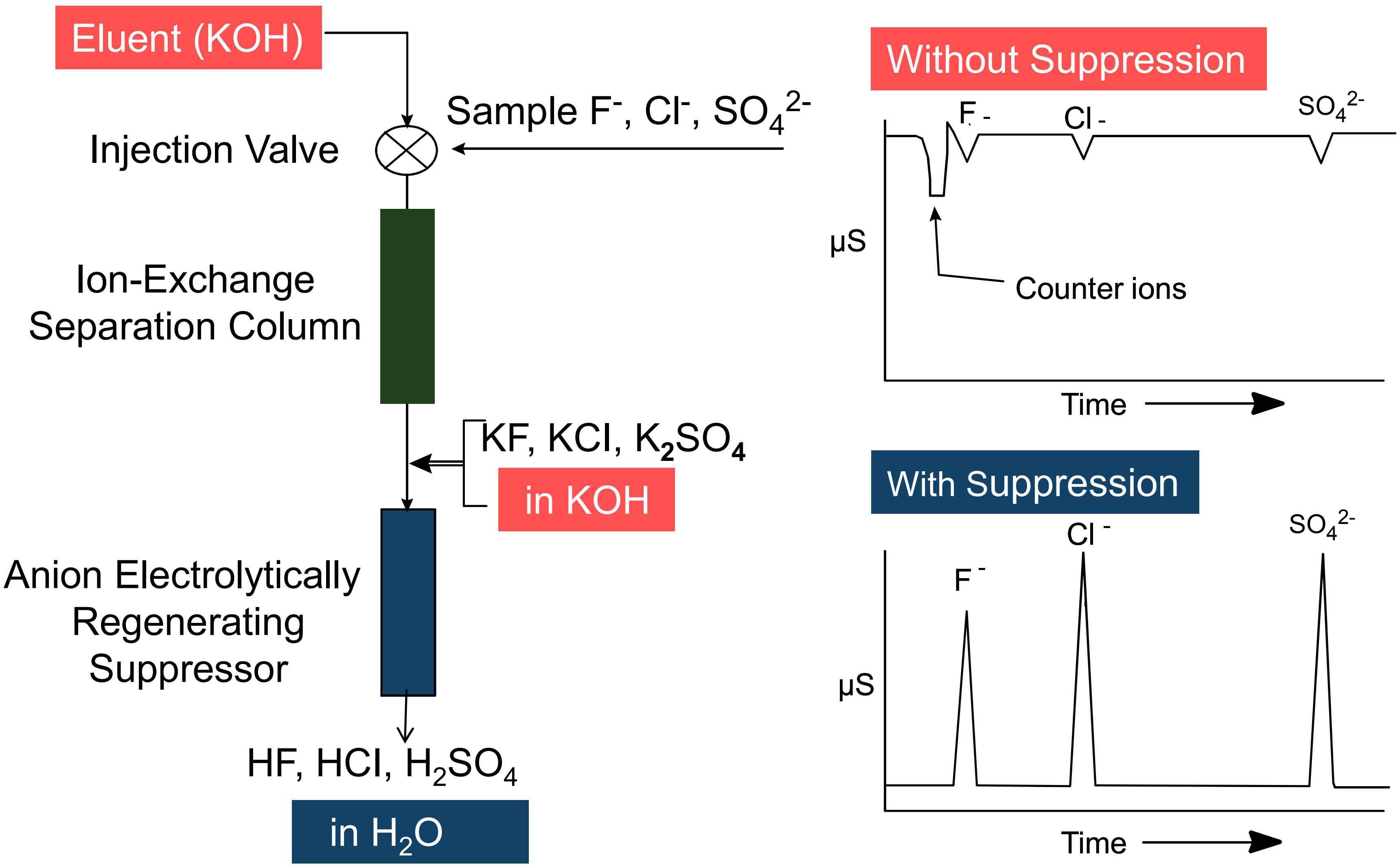
1980's: Developing Continuous Suppression

- Switching packed bed suppressors required periodic regeneration
- Disadvantages: defined capacity (4 to 8 hr)
  - Periodically replace with another suppressor or
  - Wait while suppressor was being regenerated off line
- Led to development of continuous tubular suppressor (Tim Stevens – Dow; Sandy Dasgupta –Texas Tech) "Fiber Suppressor"



- In 1985 Dionex Corp. introduced flat membrane continuous suppressor, the MicroMembrane Suppressor (MMS)

Why Develop Suppressed Conductivity?



Total Conductivity Detection

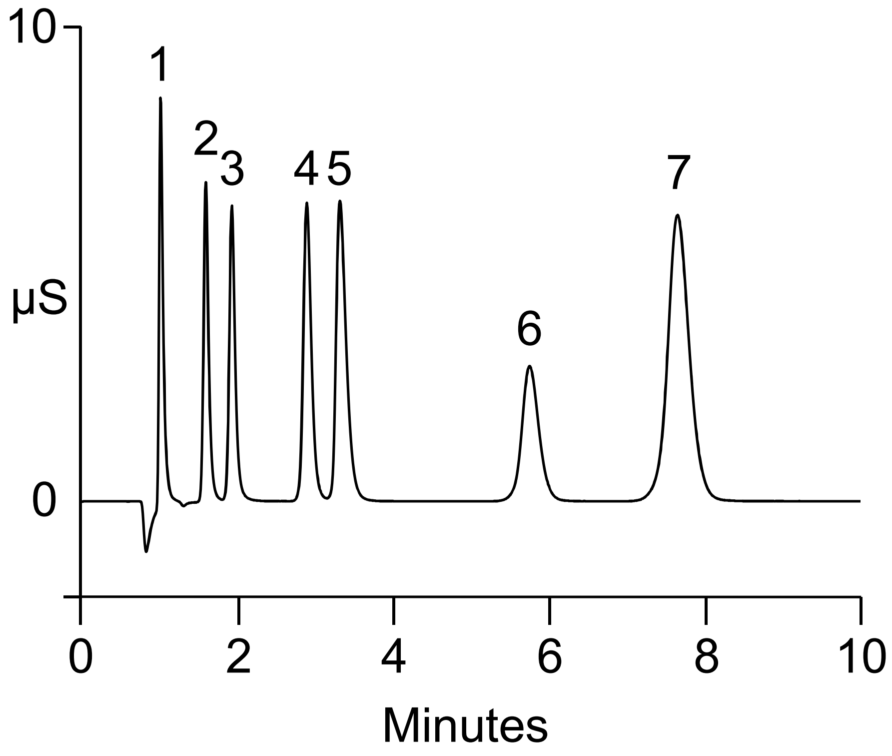
$$\Sigma = \lambda_{anion} + \lambda_{cation}$$

where λ = equivalent conductance

Equivalent Conductances

Anions	$\lambda°$	**Cations**	$\lambda°$
OH^-	198	H^+	350
F^-	54	Li^+	39
Cl^-	76	Na^+	50
NO_3^-	71	K^+	74
Acetate$^-$	41	$CH_3NH_3^+$	58
Benzoate$^-$	32	$N(CH_3CH_2)_4^+$	33

IC Written into EPA Method 300.0 (A) (Drinking Water Analysis)



Column:	Thermo Scientific Dionex IonPac AG4A-SC, AS4A-SC
Eluent:	1.7 mM Sodium bicarbonate/ 1.8 mM sodium carbonate
Flow Rate:	2.0 mL/min
Injection:	50 µL
Detection:	Suppressed conductivity, ASRS™-ULTRA, recycle mode

Peaks:		
	1. Fluoride	2 mg/L
	2. Chloride	3
	3. Nitrite	5
	4. Bromide	10
	5. Nitrate	10
	6. Phosphate	15
	7. Sulfate	15

Dionex instrument, columns and suppressors were written into method

Suppressor Innovations Inspire Column Innovations

- Goal: NaOH as anion eluent because it suppresses to water

√Efficient suppressors to neutralize high concentrations of strong base

- Dionex MMS suppressor has sufficient suppression capacity

Sparking Column Innovations

- Optimized polymer branching in stationary phases to include hydroxide selectivity
- Result: increased selectivity, more control over resolution
- Launched with the introduction of Dionex IonPac AS5A in 1985

Chris Pohl: Stationary Phases and Suppressors in Ion Chromatography, 1975-2000

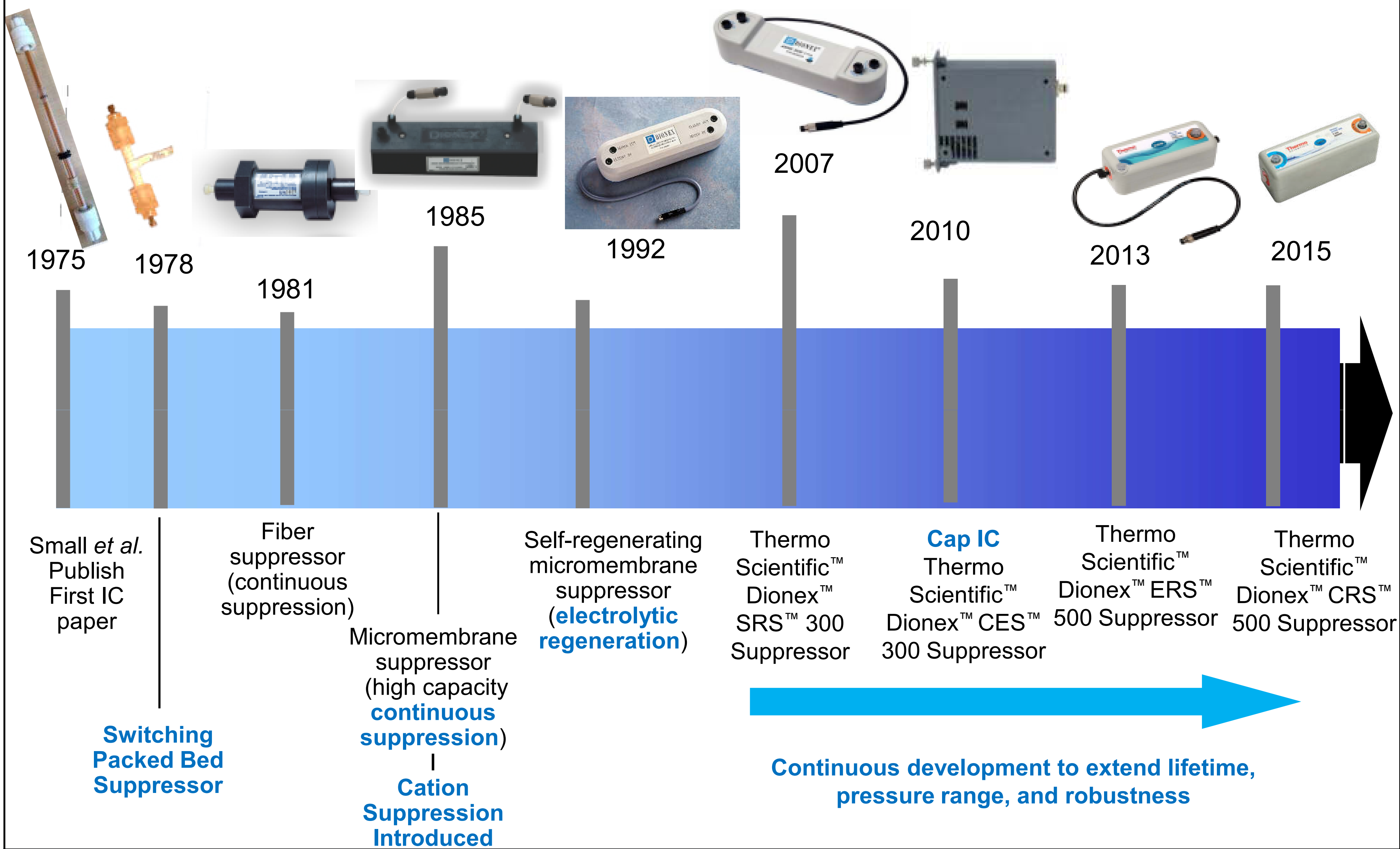
In 1992, Electrochemical Regeneration of Suppressors

- Limitations of chemical regeneration:
  - MMS suppressors require a continuous supply of a chemical regenerant
  - Sometimes chemical regenerants leak into flow path
- Solution: electrochemically regenerated suppression
  - Dionex Self-Regenerating Suppressor (SRS)
  - Continuously regenerated suppression without added chemical reagents
- Why not both?
  - Ion-exchange monolith with ion-exchange membranes continuously regenerated by polarizing the bed

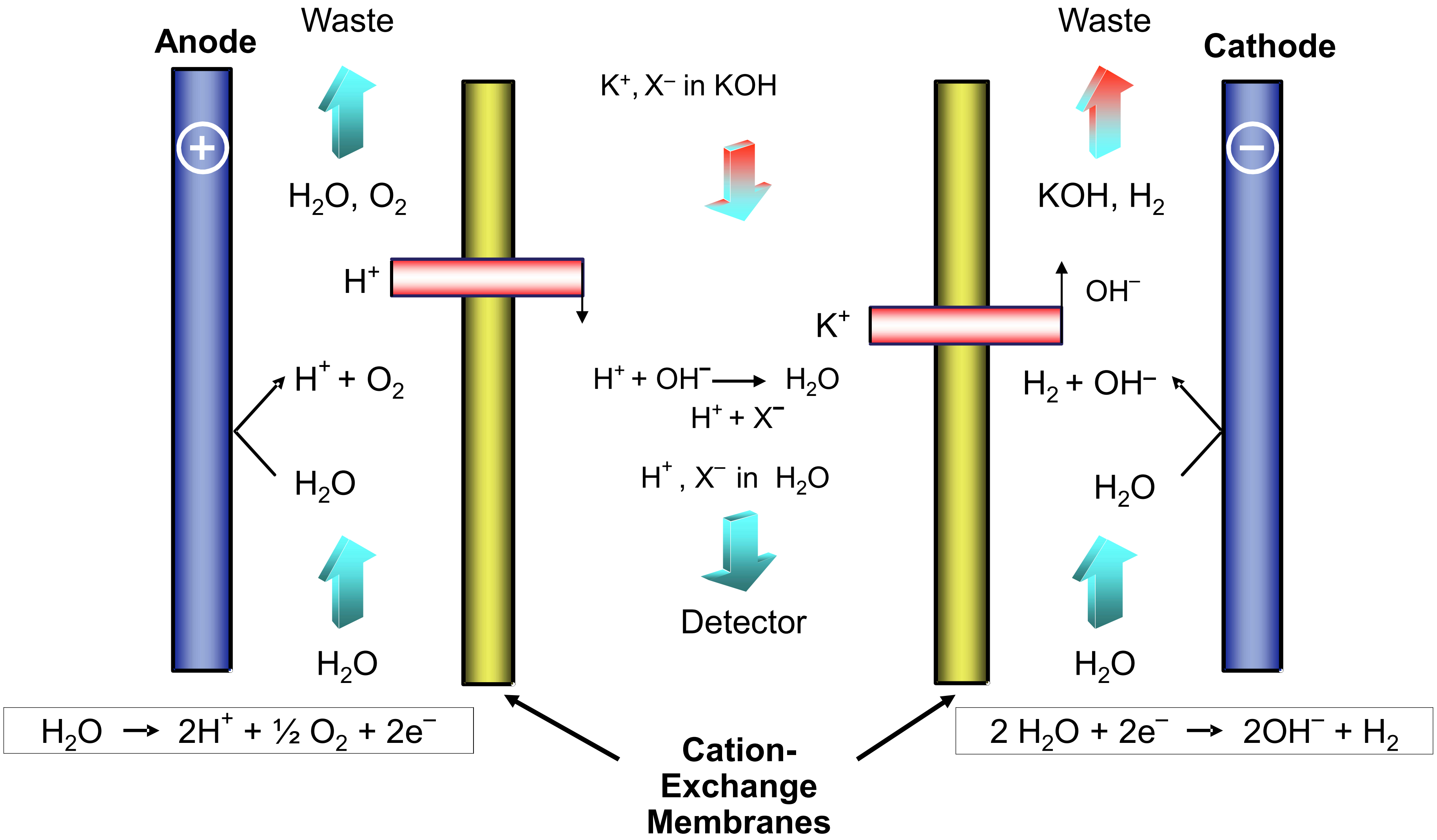
Dionex SRS I suppressor

Dionex Atlas suppressor

Suppressor Development

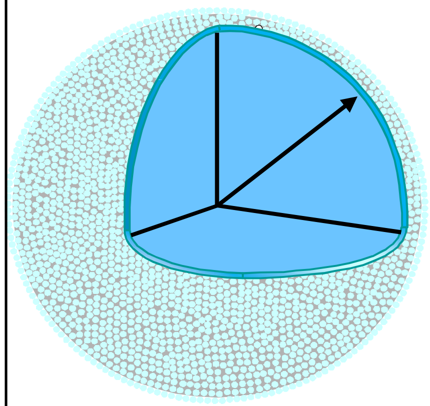


Dionex Electrolytically Regenerated Suppressors

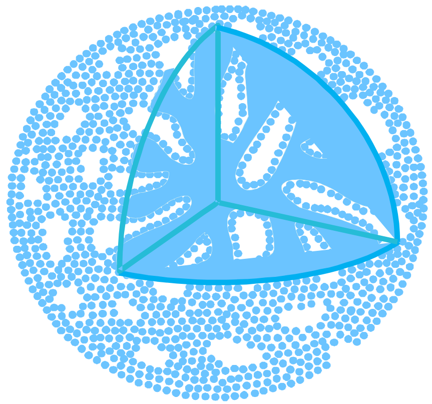


Resin Technology

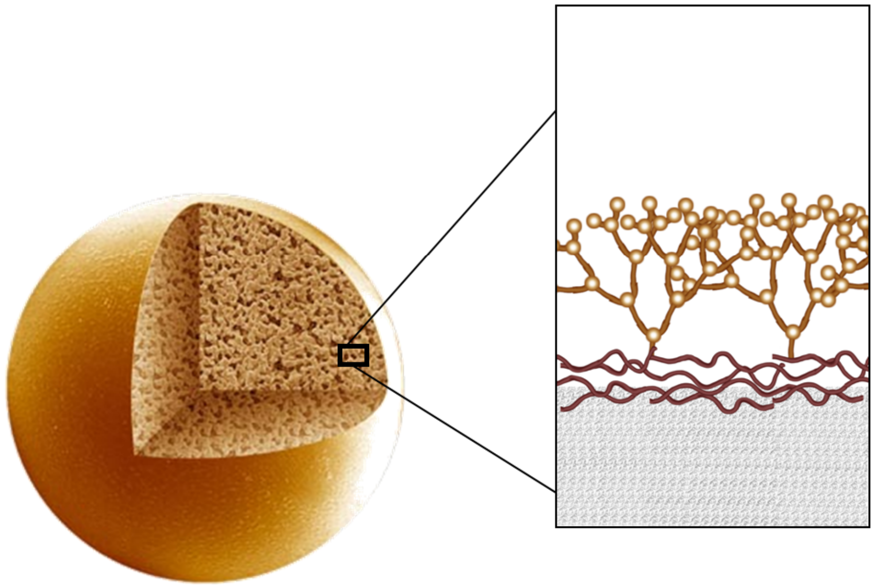
- Resin: polystyrene-divinylbenzene
- Bead type: microporous, macroporous, supermacroporous
- Size: down to 4 µm i.d.



Microporous

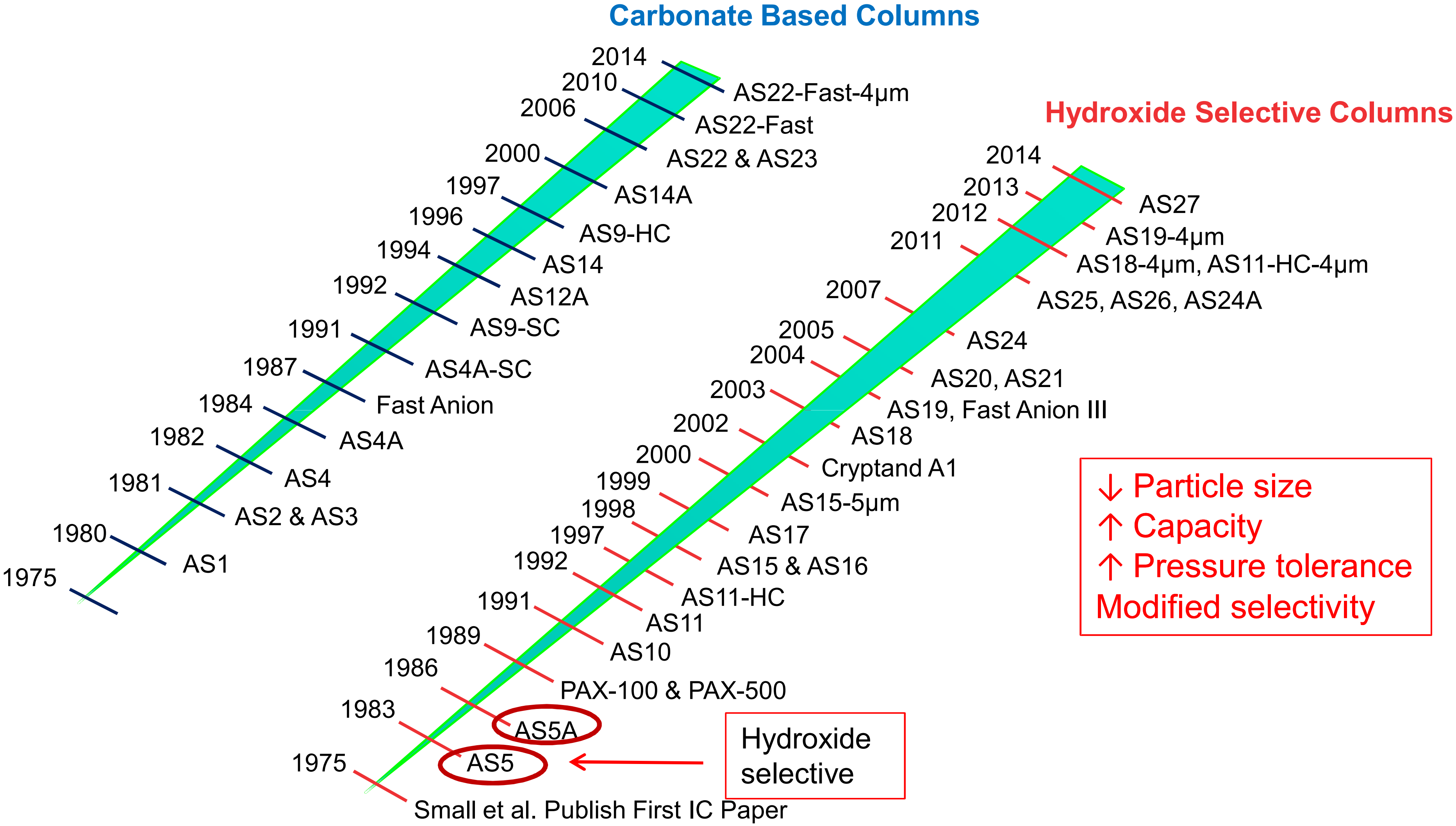


Supermacroporous (SMP)



Hyperbranched Polymer Grafting

History of Anion-Exchange Column Development



1990's: Fixing Carbonate Eluent Limitations

Limitations of carbonate eluent:

- Conductivity is 10–20x higher than pure water which impacts sensitivity
- Nonlinear responses at lower analyte levels
- Gradient separations were difficult
  - Ramping
  - Baseline disturbances
  - Slow buffering

Solution: Hydroxide based eluent

1998: Fixing the Hydroxide Eluent Limitations

Limitations of manually prepared hydroxide based eluent

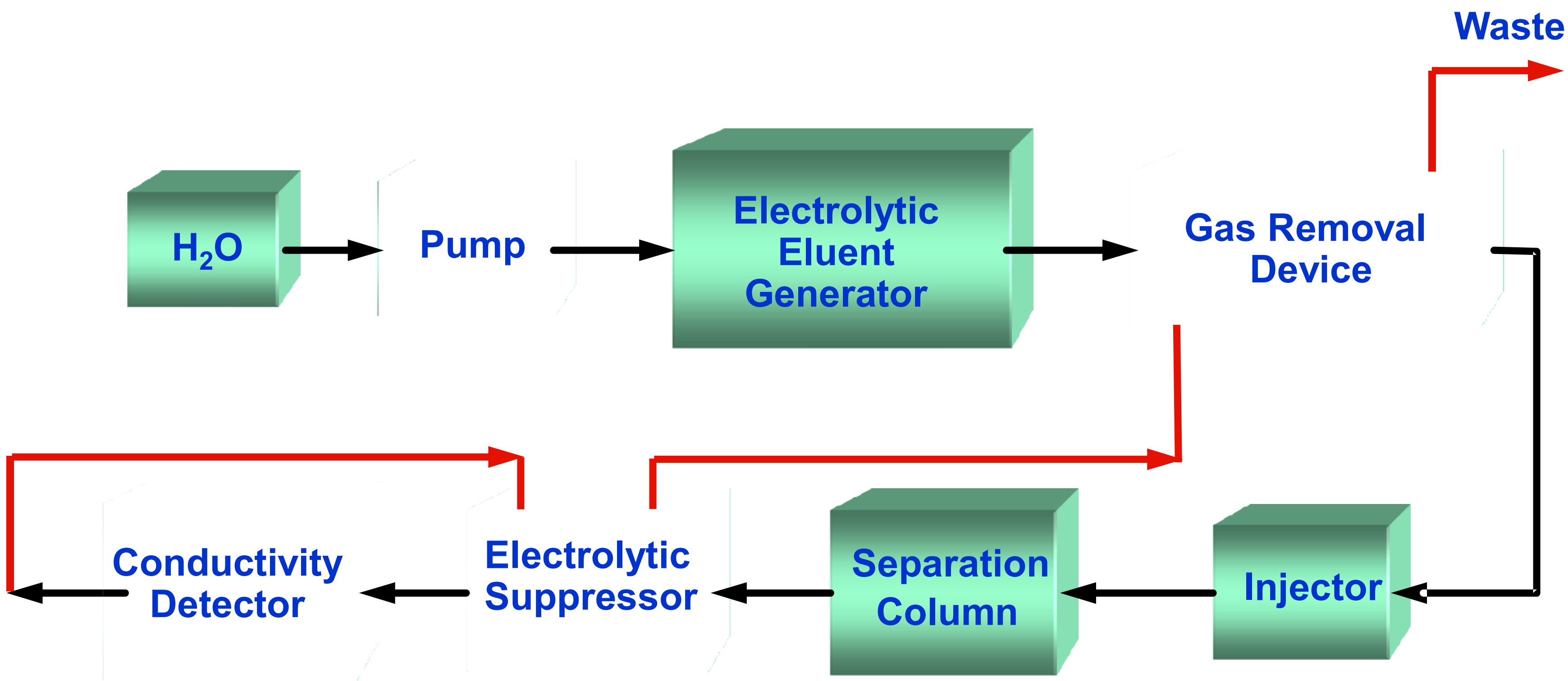
- Absorbance of CO_2 from the air causes instability of retention time, peak area, and baseline
- A gradient pump is needed

Solution: Electrolytic eluent generation

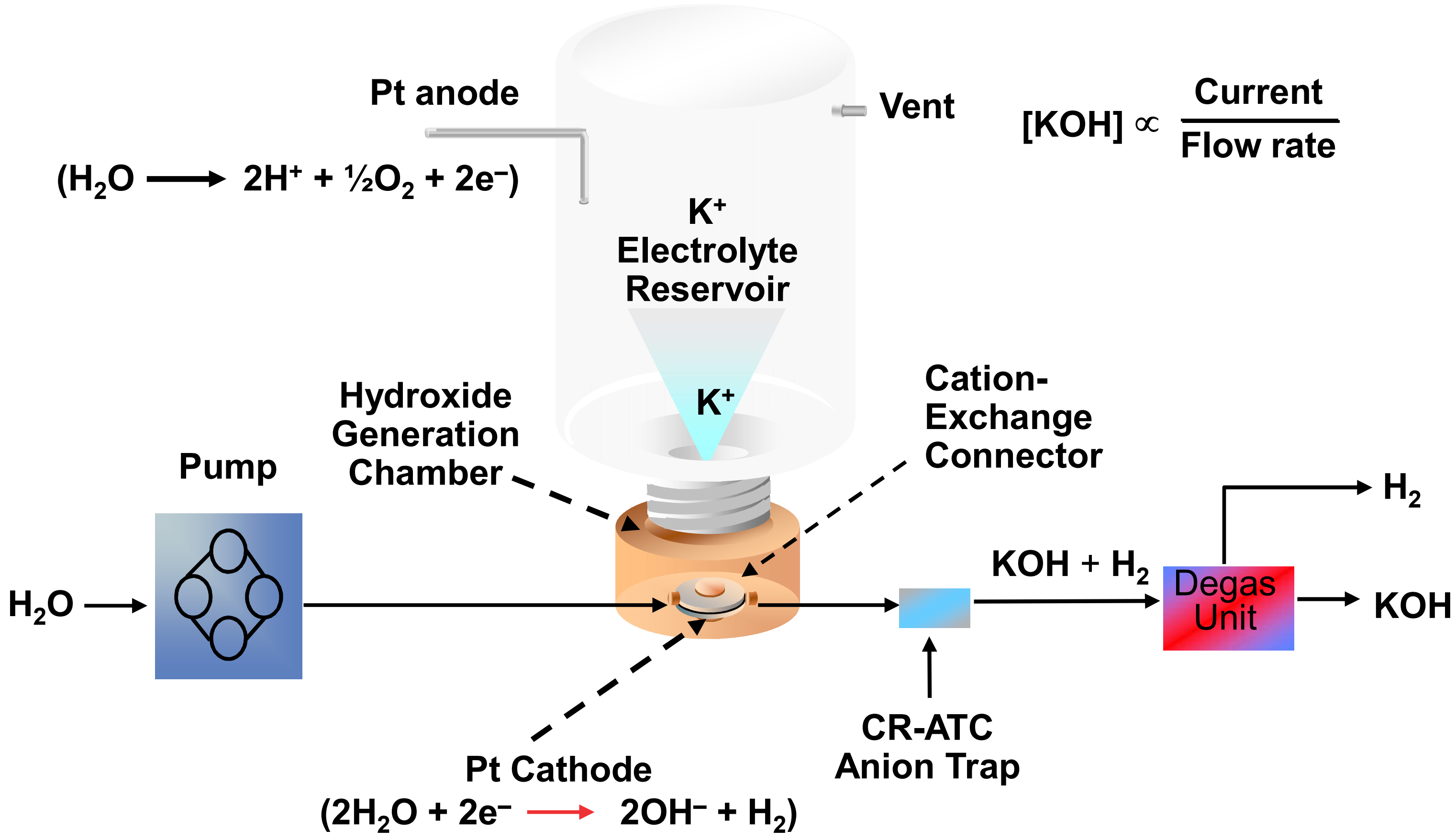
- Adapted membrane-based suppressor technology into an electrochemical eluent generator
- Result: precise and accurate eluent and gradients (from an isocratic pump)

Just Add Water

RFIC-EG™ System Schematic



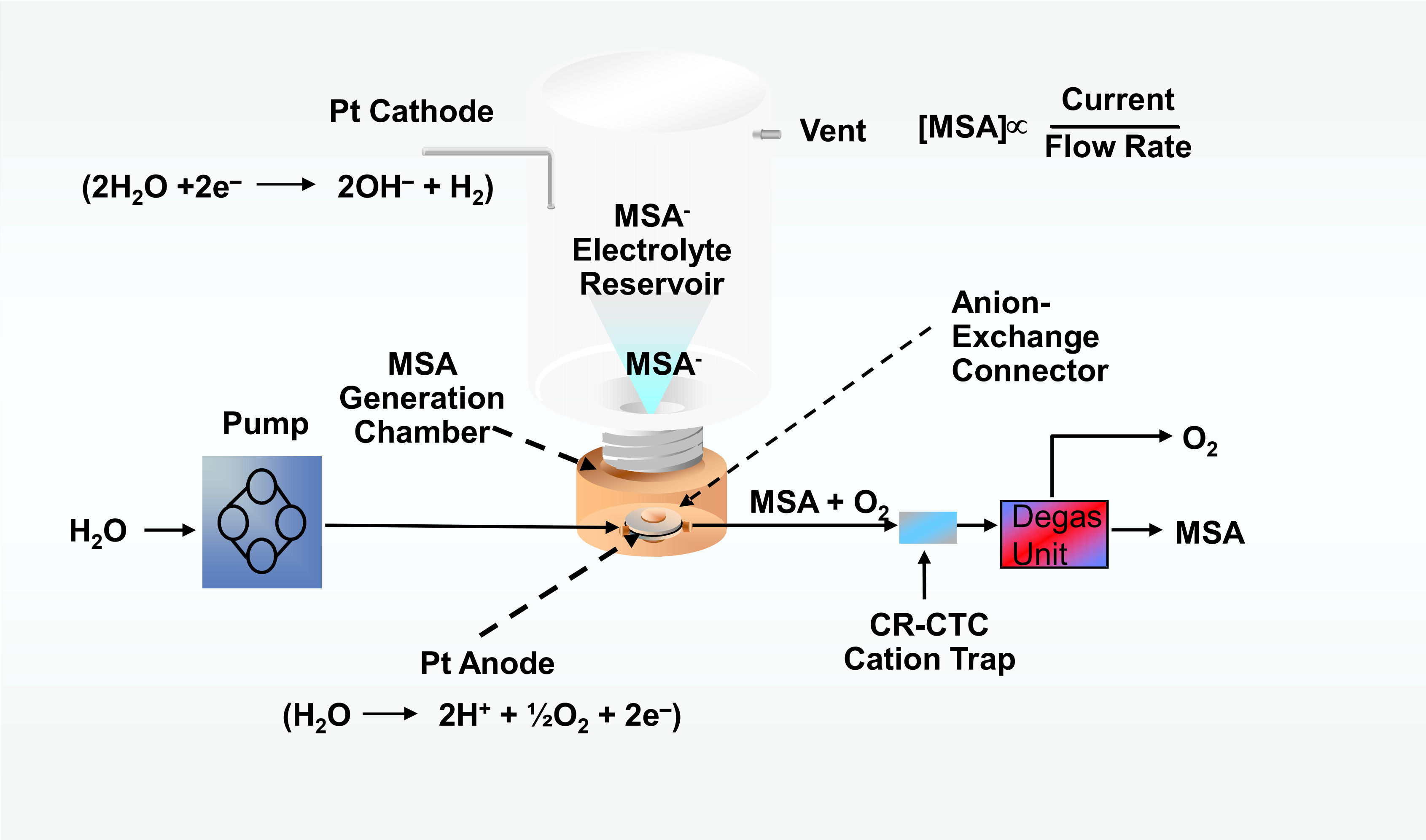
Electrolytic Generation of KOH Eluents



$$[KOH] \propto \frac{Current}{Flow\ rate}$$

ThermoFisher SCIENTIFIC

Electrolytic Generation of Methanesulfonic Acid (MSA)



Eluent generation requires further development

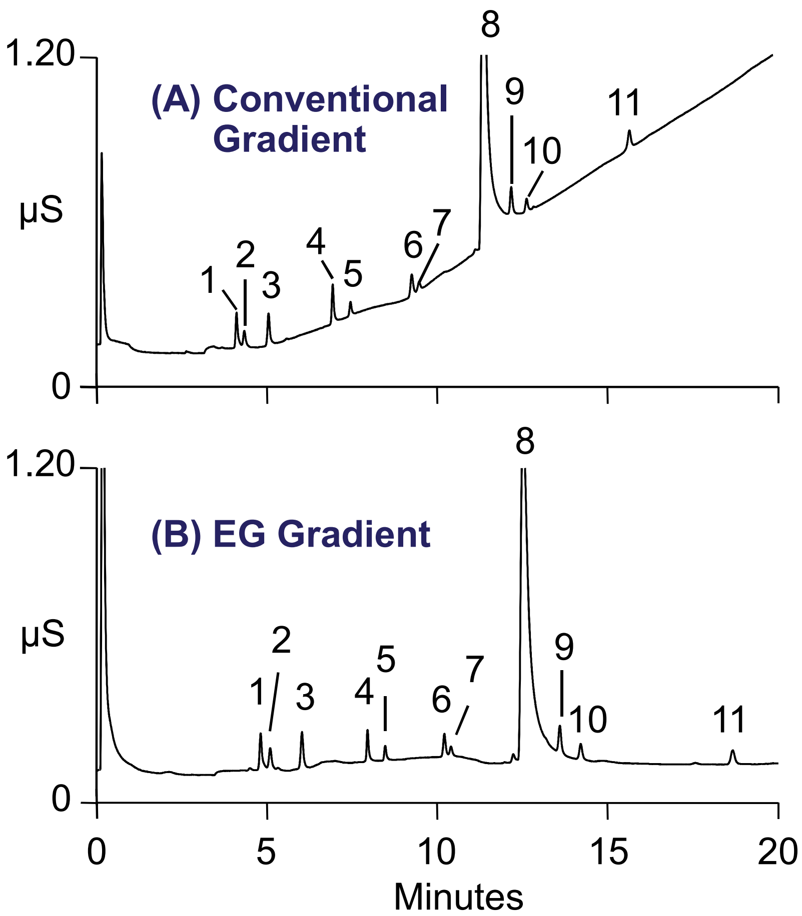
√ Efficient suppressors to neutralize high concentrations of strong base (MMS and ASRS suppressors)

√ Hydroxide selective columns (Dionex IonPac™ AS5, AS5A)

- New devices to clean eluent and remove gases (Dionex CR-TC)
- Instrumentation to support eluent generation (Reagent-Free™ systems)

Chris Pohl: Stationary Phases and Suppressors in Ion Chromatography, 1975-2000

Precise and Accurate Carbonate-Free Eluent Delivery

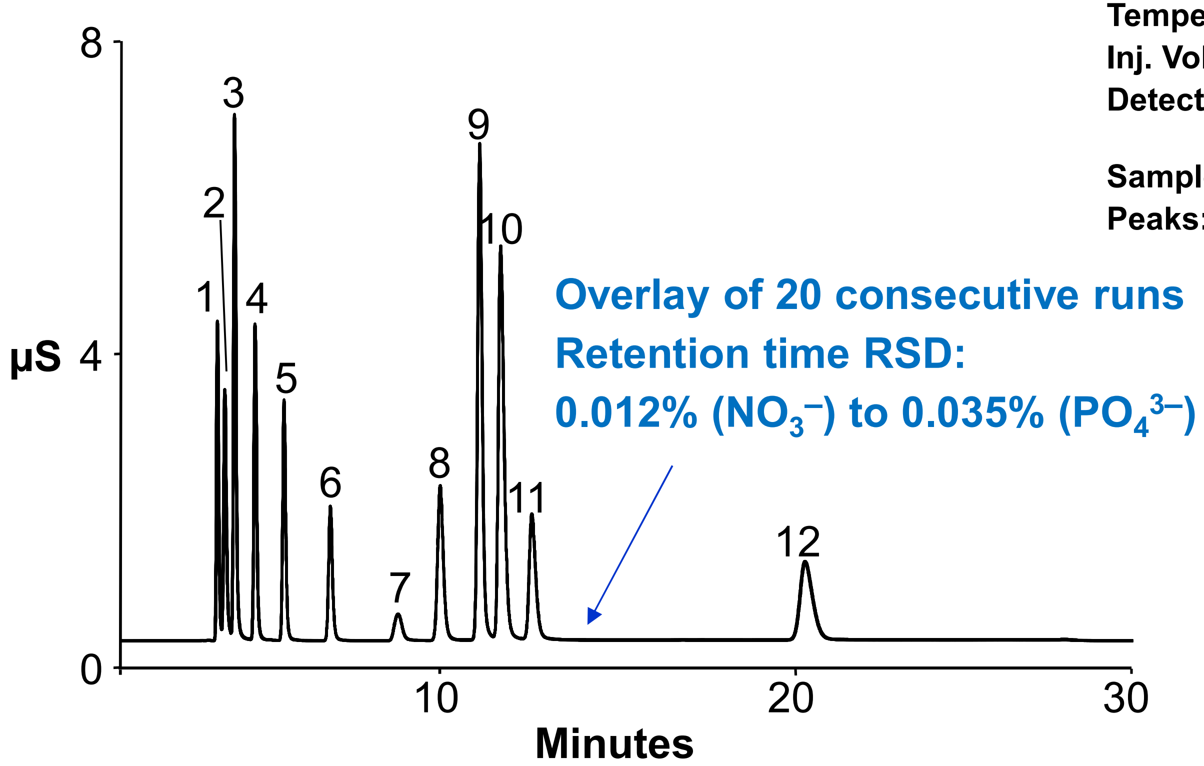


Column:	Dionex IonPac AG11, AS11, 2 mm
Eluent:	(A) NaOH (B) KOH (EGC-KOH as the source) 0.5 mM to 2.5 min, to 5.0 mM at 6 min, to 26 mM at 20 min
Flow Rate:	0.5 mL/min
Inj. Volume:	1.0 mL
Detection:	Suppressed conductivity, Electrolytic suppression, External Water Mode

Peaks:		
	1. Fluoride	0.37 µg/L (ppb)
	2. Acetate	1.0
	3. Formate	0.93
	4. Chloride	0.44
	5. Nitrite	0.27
	6. Bromide	1.0
	7. Nitrate	0.33
	8. Carbonate	–
	9. Sulfate	0.64
	10. Oxalate	0.39
	11. Phosphate	1.1

Flat Baselines, Improved Peak Integration, Increased Sensitivity

Reproducibility of an RFIC-EG™ Anion System

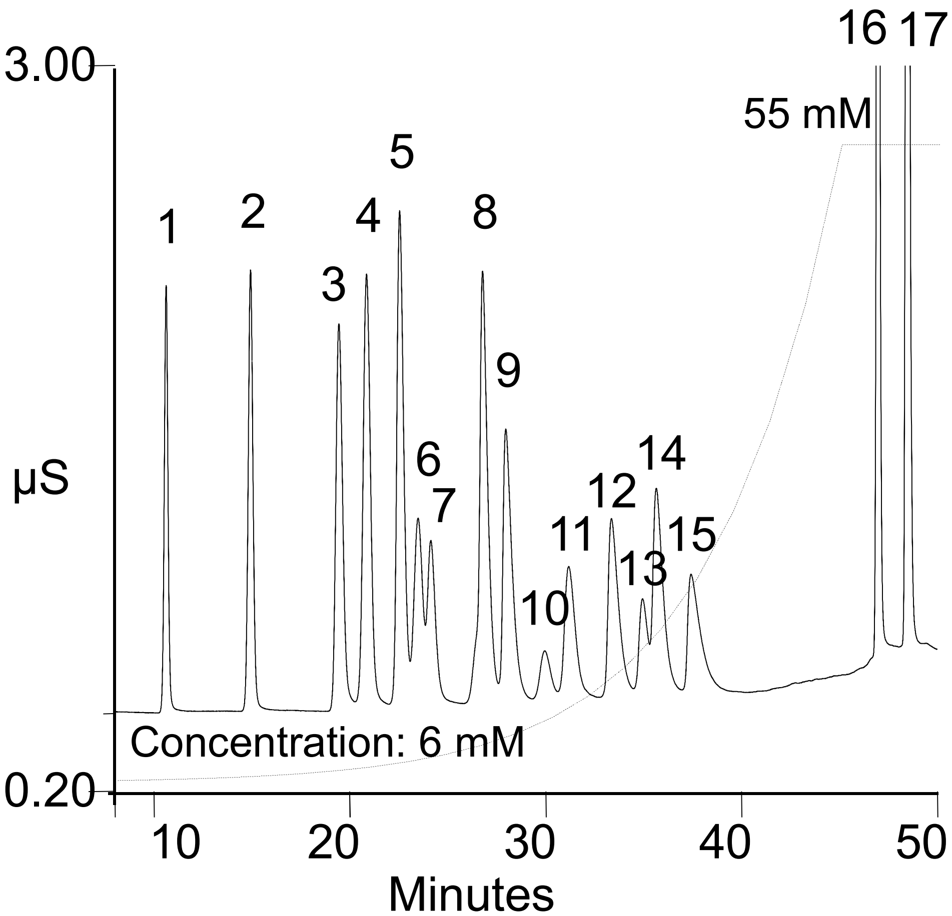


Column: Dionex IonPac AS18, 4 mm
Eluent Source: Dionex EGC-KOH cartridge with Dionex CR-ATC trap column
Eluent: 22–30 mM KOH: 7–8 min
Flow Rate: 1.0 mL/min
Temperature: 30 °C
Inj. Volume: 25 µL
Detection: Suppressed conductivity, Electrolytic suppression
Sample: Anion Standard
Peaks:

1. Fluoride	2.0	mg/L
2. Acetate	10	
3. Formate	10	
4. Chlorite	10	
5. Chloride	3.0	
6. Nitrite	10	
7. Carbonate	—	
8. Bromide	10	
9. Sulfate	15	
10. Nitrate	10	
11. Chlorate	10	
12. Phosphate	15	

Improved Reproducibility and Reporting Accuracy

Separation of Anticorrosion Amines and Cations



Column:	**Dionex IonPac CG16, CS16, 3 × 250 mm**
Eluent:	**MSA (EGC gradient)**
Temperature:	**60 °C**
Flow Rate:	**0.5 mL/min**
Inj. Volume:	**10 µL**
Detection:	**Suppressed conductivity, Electrolytic suppression, Recycle mode**

Peaks:

1. Lithium	**0.5 ppm**
2. Sodium	**2**
3. Ammonium	**2.5**
4. Monoethanolamine	**1**
5. Methylamine	**0.5**
6. Diethanolamine	**1**
7. Ethylamine	**1.5**
8. Potassium	**5**
9. Dimethylamine	**1**
10. Triethanolamine	**1**
11. Methyldiethanolamine	**1**
12. Dimethylethanolamine	**1**
13. Morpholine	**5**
14. 1-Methoxypropylamine	**1**
15. Dimethylamino-2-propanol	**1**
16. Magnesium	**2.5**
17. Calcium	**5**

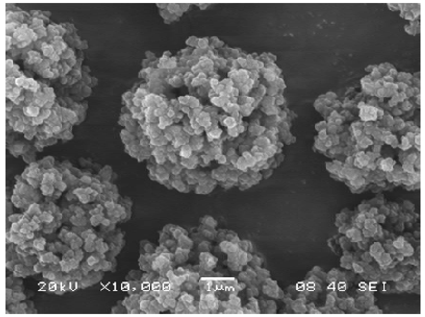
Eluent Generation has the same benefits for cations

Dionex IonPac 4 µm IC Columns Driving Innovation

In 2012, Dionex IonPac Ion-exchange columns with 4 µm particle-size resin were developed

Benefits

- Smaller particles provide better performance
- Faster run times at higher flow rates (150 mm)
- Better resolution at standard flow rates (250 mm)



SEM Image of 4 µm Supermacroporous Bead

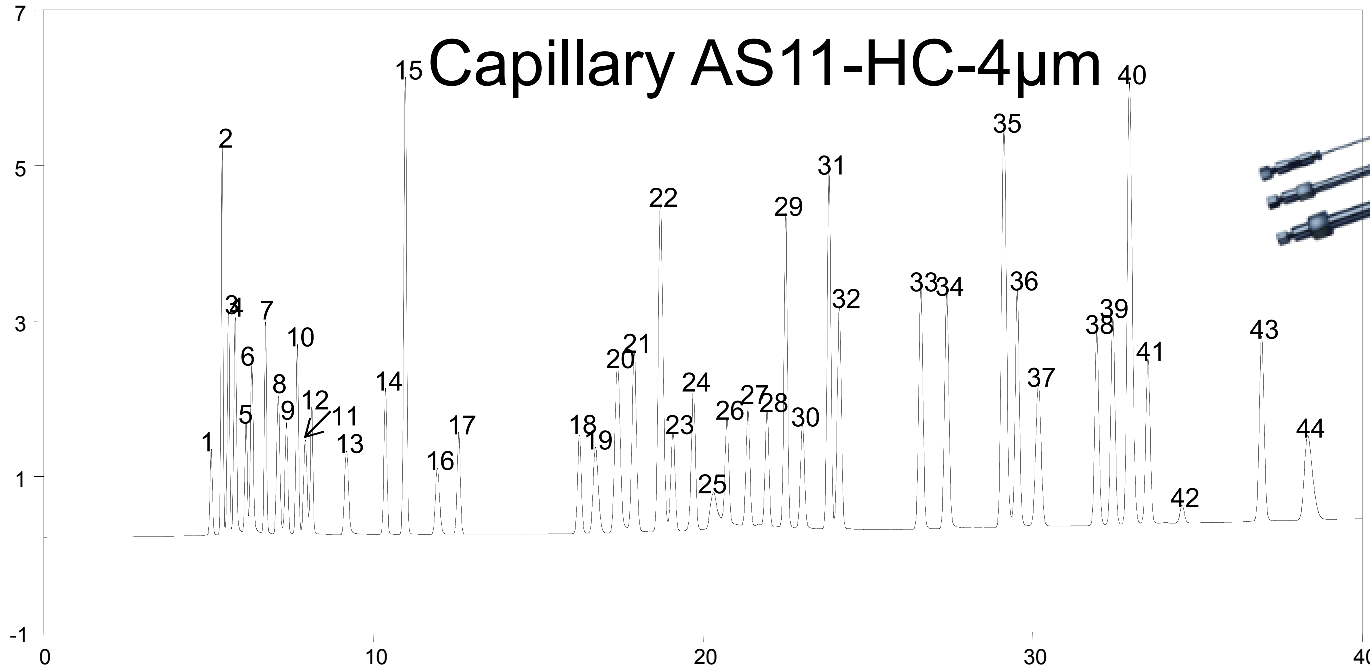
Limitations

- Many of the 250 mm length columns have operating pressures above the pressure tolerances of the 2011 RFIC devices

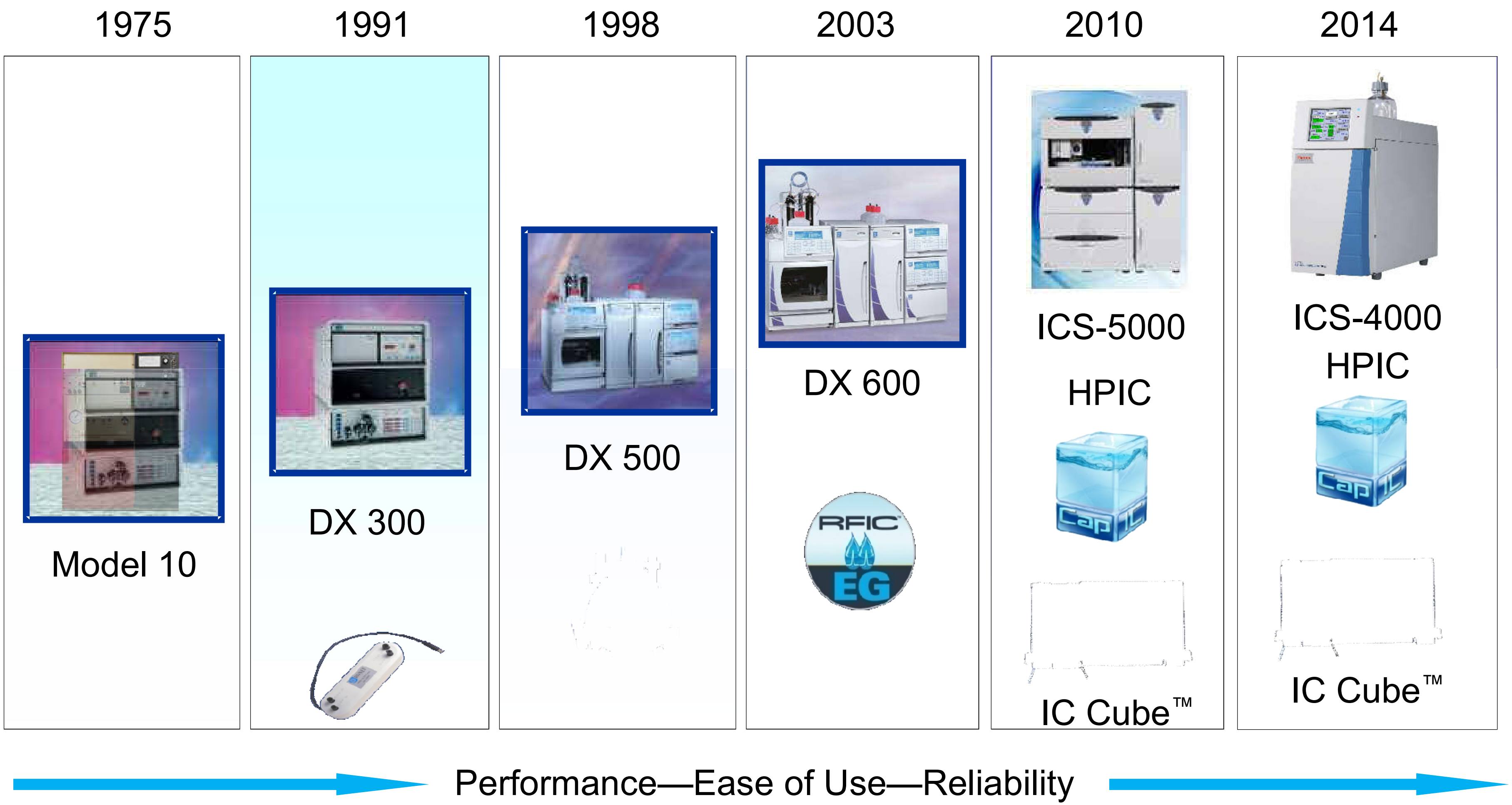
Solutions: Redesign IC and RFIC devices into high pressure capable devices

- Results: higher efficiency and resolving power especially with critical peak pairs and disparate concentrations, improved reporting

Miniaturization: 2 mm i.d., then 0.4 mm i.d. Columns



Evolution of Ion Chromatography Systems



The Dionex Integrated Systems

- Wide Range of Capabilities
- Reagent-Free™ (RFIC™) with ICS-2100, ICS-4000
- CapIC with ICS-4000
- Dedicated Performance
- Ease of Operation

The Dionex ICS-5000^{+} Universal HPIC System

- Versatile, Modular Design
- Microbore, standard, and capillary flow rates
- HPIC and Reagent-Free™ (RFIC™) Capabilities
- Detection Options (Conductivity, Electrochemical, Absorbance, MS)
- Single and Dual-System Configurations
- Advanced Application Support

HPIC - High Resolution, Fast Analyses

Practical Solutions from Advanced Capabilities

- HPIC delivers more information in less time
  - Quicker turnaround of sample results
  - Better resolution with smaller particles
  - Provides the optimal combination of speed and resolution
- Capillary IC delivers more with less
  - Always Ready to run samples
  - System performance more stable
  - Reduced costs from less eluent use, less waste generation, and less maintenance
  - Stable pressures extend consumables lifetime
  - Increased sensitivity provides reliable data with limited sample volumes

Analysis: Riding the Electronics Wave

Strip Chart Recorders

Integrators on thermal paper printers

2000i

1994, AI 300 (Analog-DX LAN)

1998, Dionex Chromeleon™

2013, Dionex Chromeleon 7.2

Continuous improvement of data management, instrument control, and ease of use

Summary

- Only 40 years ago, IC was commercialized. Defined as:
  - Ion-exchange separations using ionic eluents
  - Eluent suppression and conductivity detection
- Since then, …continuous IC innovation starting from Dow Chemical + Durrum Instrumentation, then Dionex Corp., and now Thermo Fisher Scientific
- We introduced and to this day, continue to develop IC methods supporting regulatory needs
- Each new innovation drives *(or necessitates)* complimentary improvements in columns and resin technology, suppressors, eluents, instrumentation, and software technology

"IC would not be the IC of today without the suppressor technology," Art Fitchett, circa 1980

What’s Next?

Thermo
SCIENTIFIC

Transform Your Science