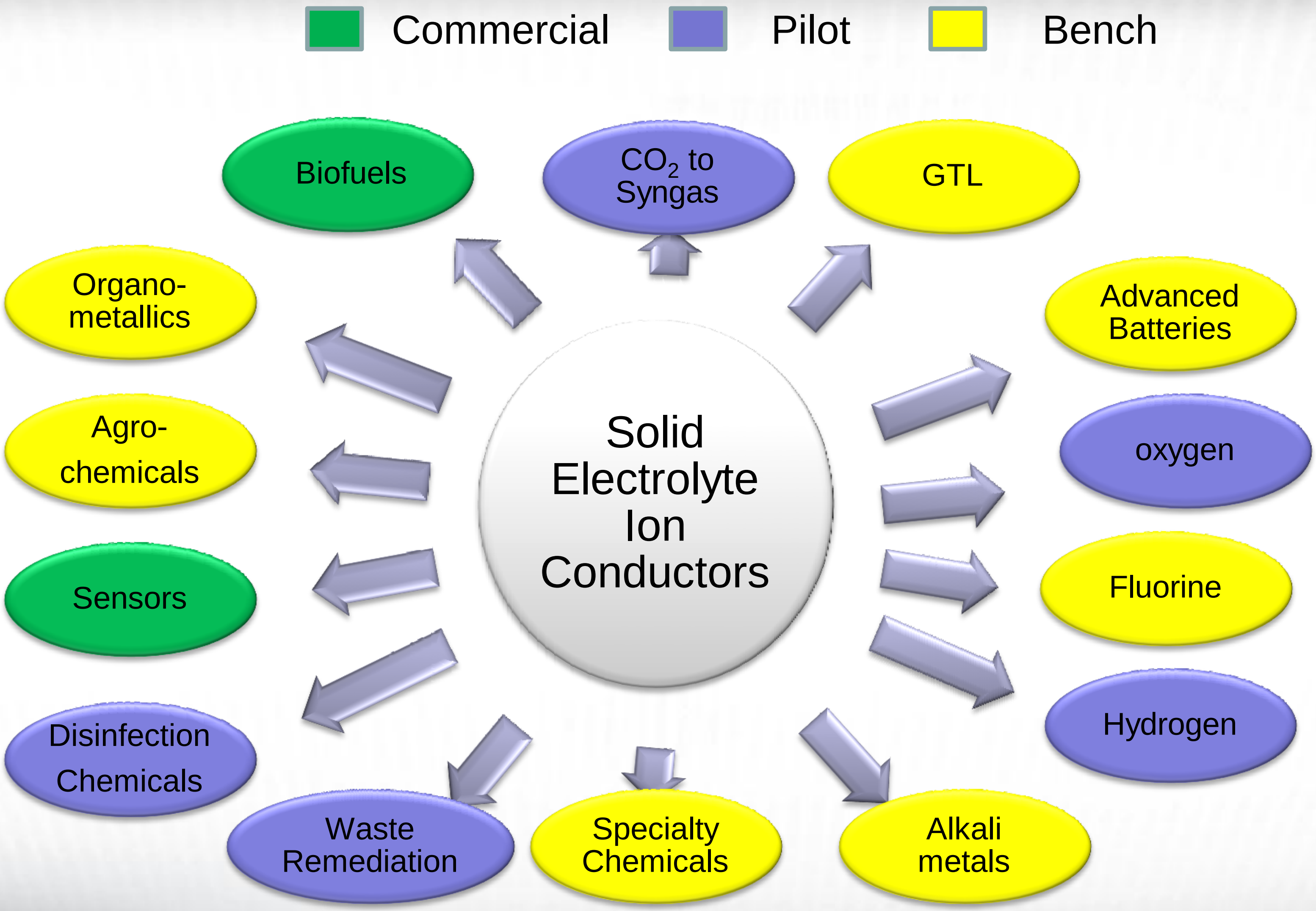
Membrane Applications at Ceramatec



Next Generation – Ceramic membrane devices

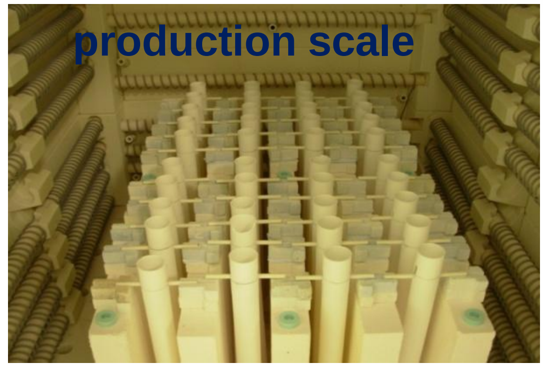
Historical Effort:

- Crystalline alkali ions (Li, K, Na) conducting membranes
  - Selective and conductive at low temperatures (R.T. to 150^{o}C)
  - Material development and engineering
  - Manufacturing and scalability challenges

- Ion Transport Membranes (ITM)
  - Extremely selective and very fast transport for oxygen
  - Operate at high temperatures, typically greater than 700°C
  - Material formulation is complex and dependent upon application

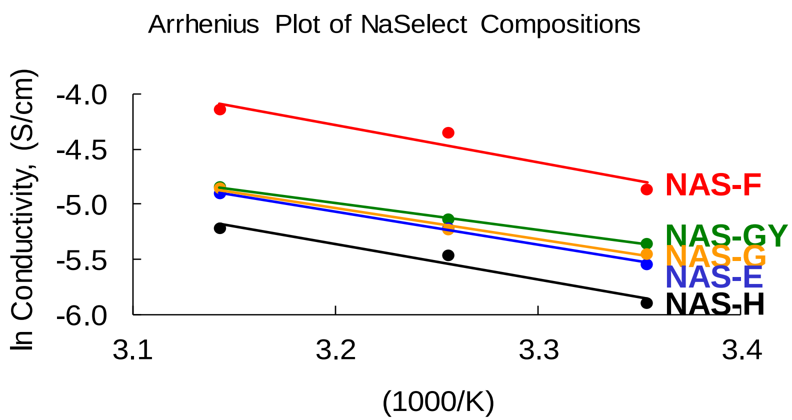
Introduction: NaSelect™ - Membranes

Crystalline alkali ions (Li, K, Na) conducting membranes for chemicals separation processes, batteries and specialty chemicals synthesis



Thin walled ceramic

Withstands 400 psi ΔP



Extrusion

Thin structures (>100 microns)
50% reduction in power consumption

Ionic substitution crystal chemistry approaches

CERAMATEC
TOMORROW'S CERAMIC SYSTEMS

Device Manufacturing

Sodium Methoxide Production units

50 lbs/day

250 lbs/day

1500 lbs/day

<u>Ceramic Manf. Challenges</u>

- Production lot variations
- Large scale processing
- Dimension tolerance
- Impact of machining steps on cost parameters
- Strength and chemical stability
- Geometry benefits: Planar versus tubular ceramics

<u>Pilot Unit</u>

- Packaging of multiple ceramic membranes
- Reliability of seal concept
- Safe operation and lifetime performance

<u>Commercial unit</u>

- Large volume production of ceramics and cell components
- Ceramic reliability
- Servicing of membrane based modular unit on site

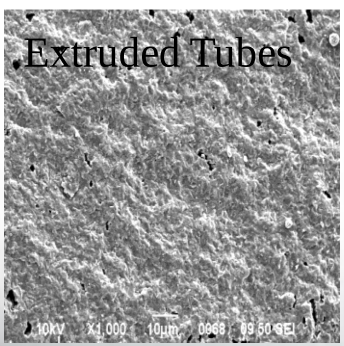
Commercial NaSelect™ production at CoorsTek

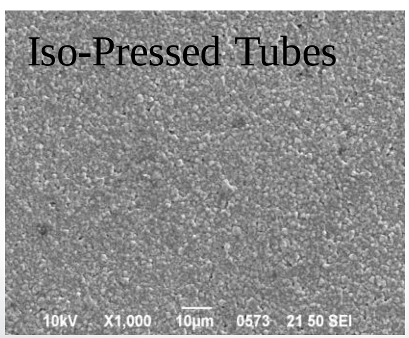
Ceramatec is a subsidiary of CoorsTek, worlds largest technical ceramic manufacturer:

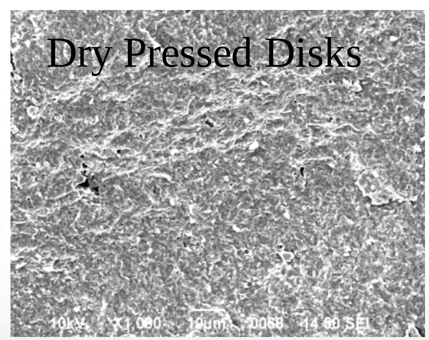
- Develop low cost aqueous processing method (Challenges Addressed)
  - Mill and spray dry of raw materials was extremely problematic due to the solubility, pH effect on leaching and phase segregation
- Due to high pH of the slip (>12), PEG-based binders not suitable. Acrylic emulsions and Aquazol (poly(2-ethyl-2-oxazoline)) were suitable.
- Solubility in water during milling and evaporation of water during spray drying results in a Na-rich “shell” on the spray dried agglomerates.
- Calcination: Agglomerate “shell” decreases crushability and “knitting” at the granular interfaces.
  - Resulted in localized weakness of green compact
  - Large pinholes observed

Large area ceramic

Commercial Module

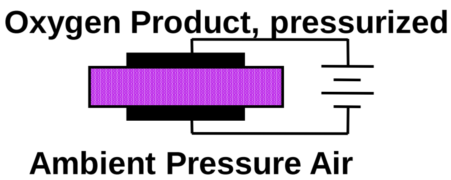


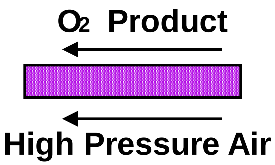


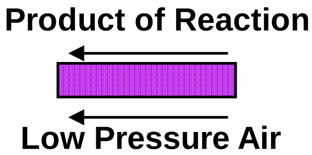


Ion Transfer Membranes (ITM) Technologies

Fundamentals







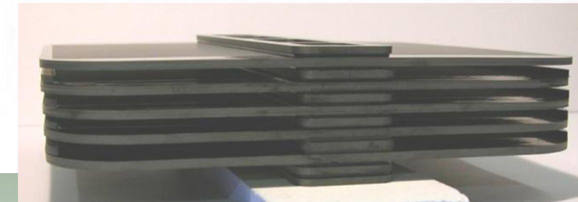
Planar Membrane Design Status

3 liter/min
Ceramic Stack

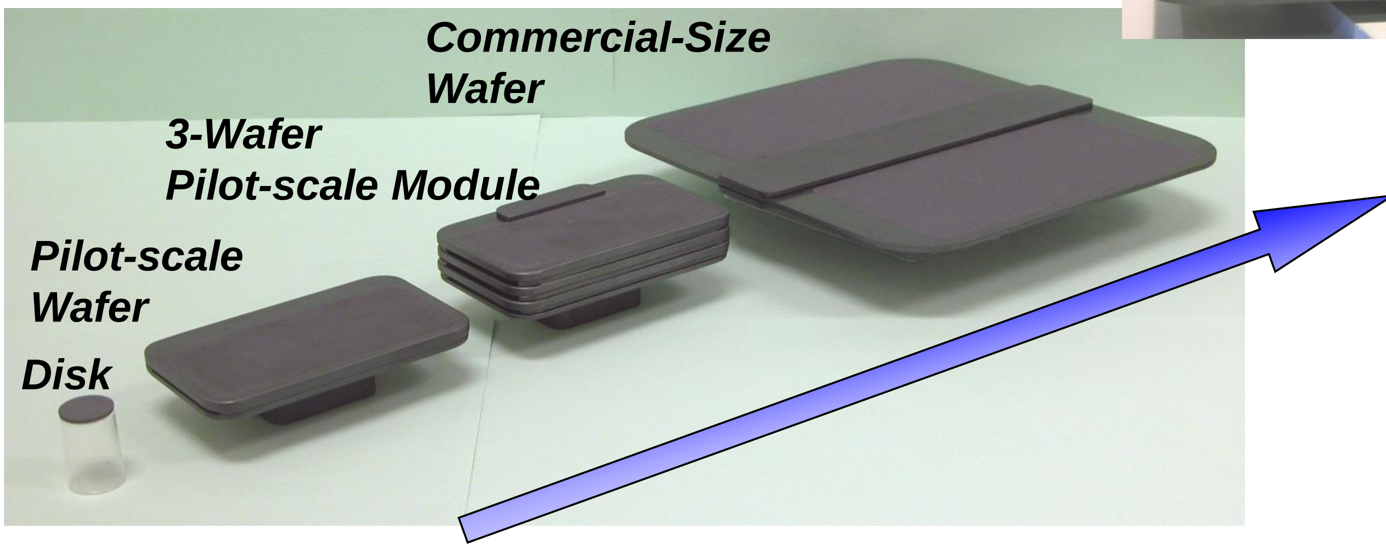
Four 0.5 T/D Ceramic Stacks

16 KSCFD Syngas
Ceramic Stack

Planar Membrane Fabrication Has Advanced Rapidly



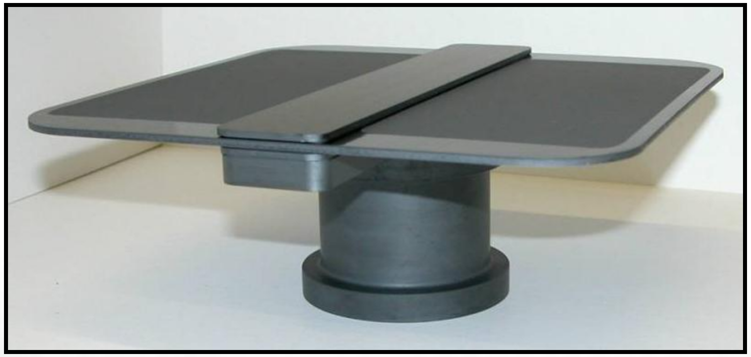
5-Wafer Sub-Module

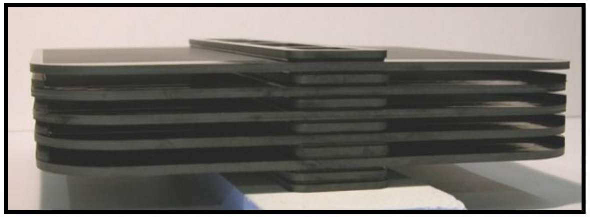


- Scalable ceramic processing methods.
- Internal structures of commercial-size wafer tested in pilot-scale wafer.
- Proprietary all-ceramic joining process is a key enabling technology.
- Same material composition throughout module.

Wafer Stack Joining Method Has Been Developed

- Joining of single membranes into a module is a critical ceramic processing step
- All-ceramic joints* have been demonstrated and have significant benefits
  - Seals meet leak requirements
  - Uniform materials
  - Match expansion behavior and reduce stress
  - Key enabling technology





Membrane Modules with All-Ceramic Joints

AIR PRODUCTS

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