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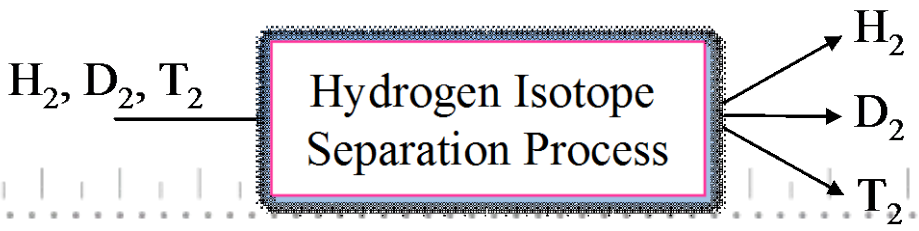

Thermal Cycling Absorption Process Overview

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Savannah River National Laboratory

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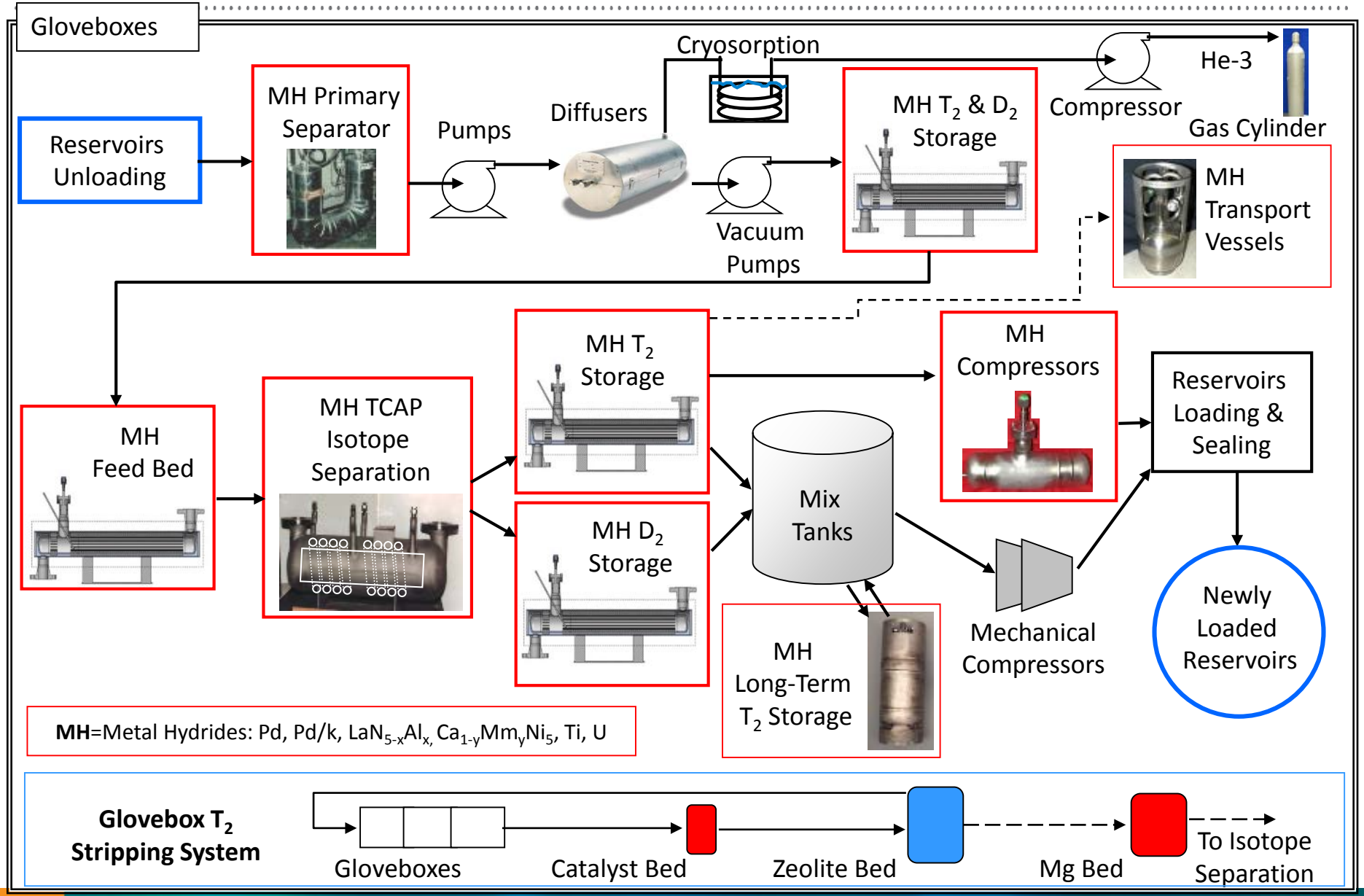
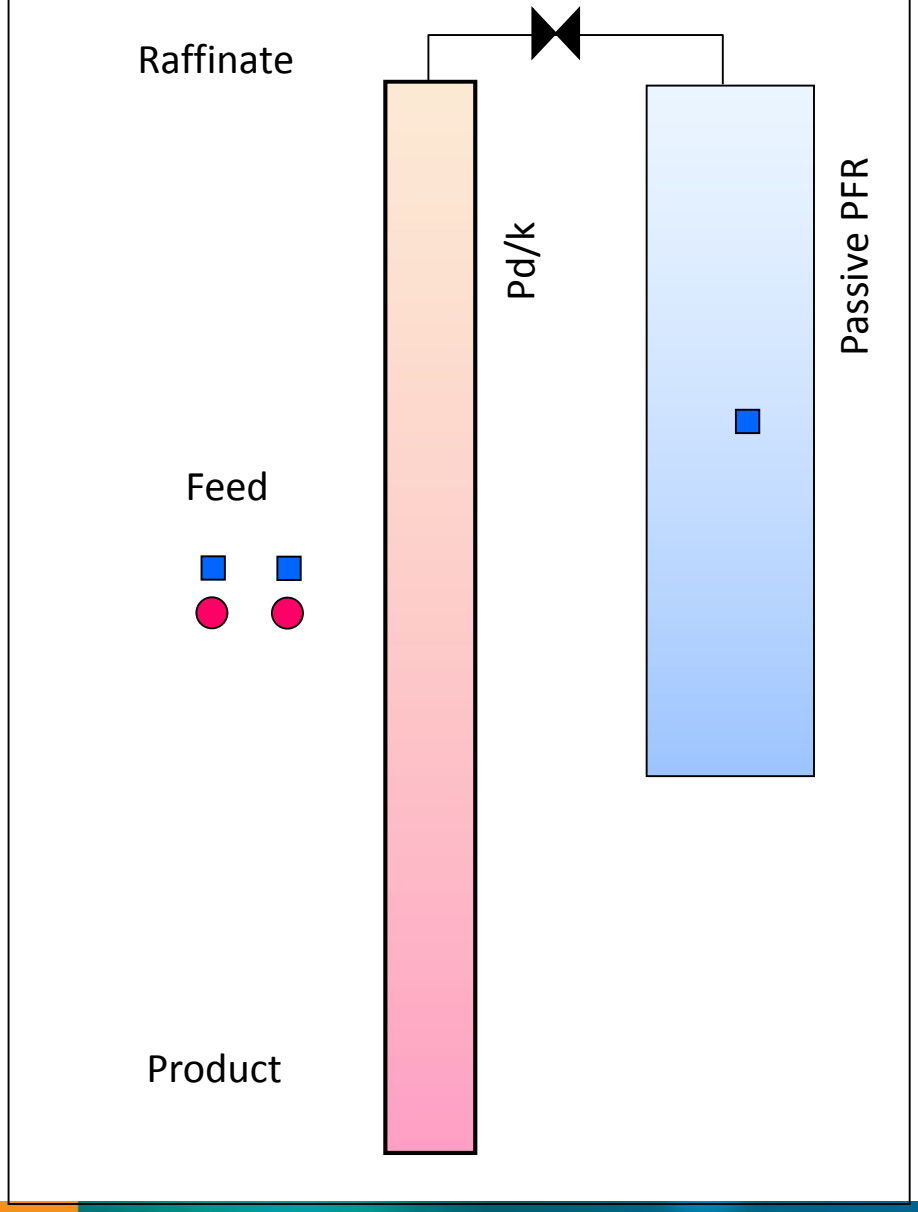
Overview

- How does TCAP Work?
- TCAP History
- State of the Art Technology
- Typical Performance
- In House Expertise and Capability
- TCAP Feature Summary

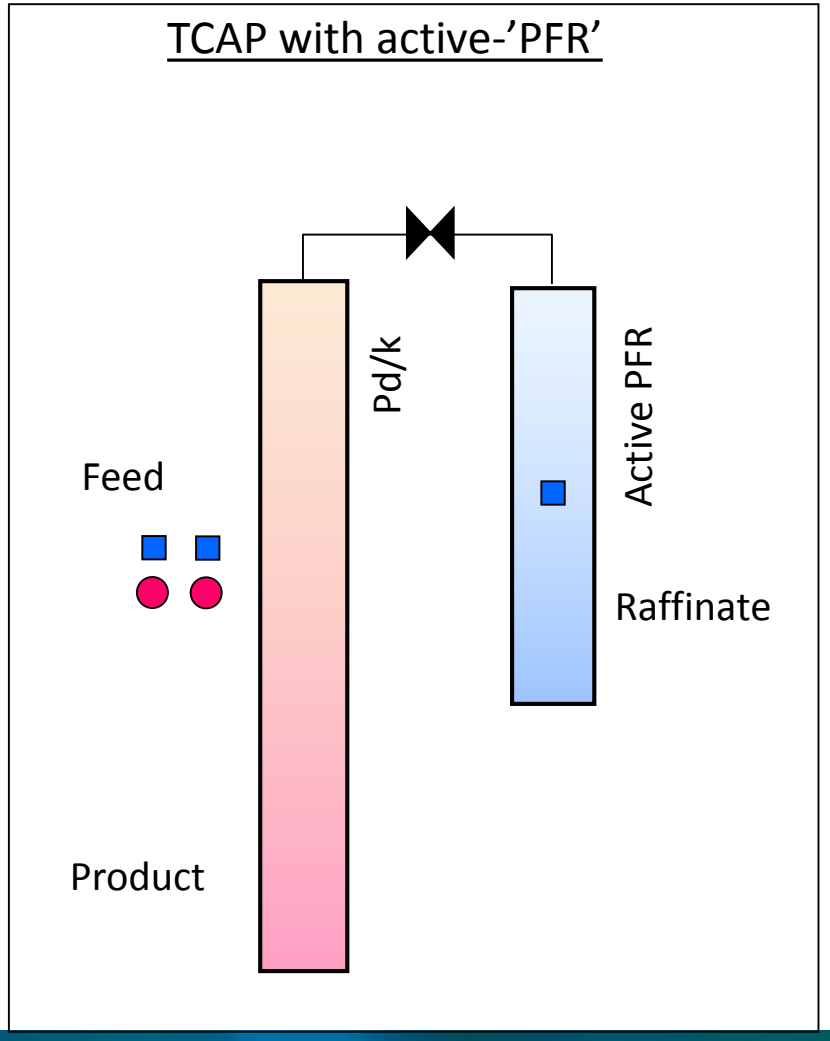
Tritium Processing at SRS - The Largest Metal Hydride Based Tritium Facility in the World



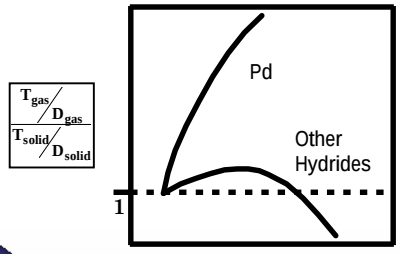
TCAP with passive-PFR

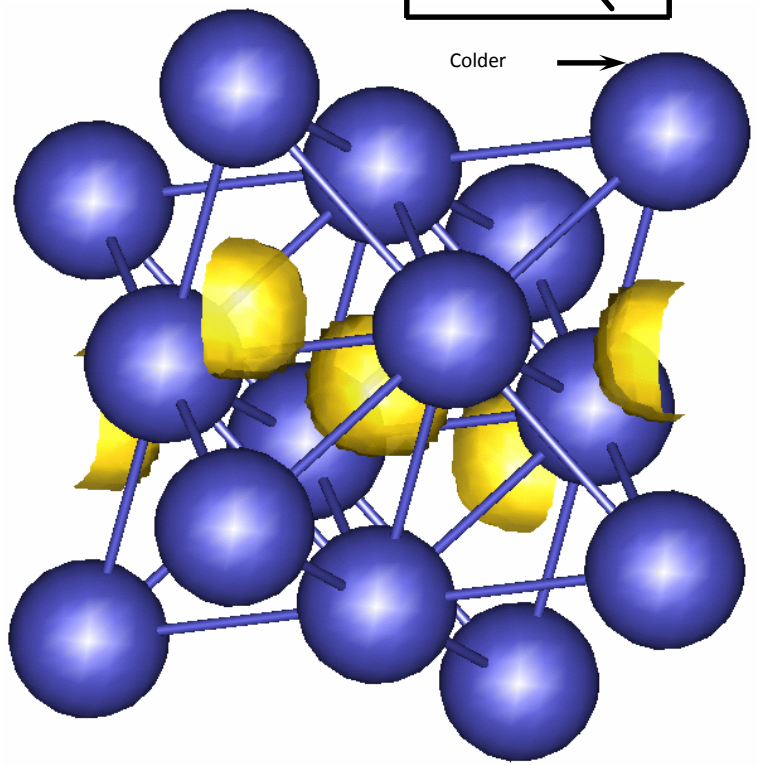


TCAP with active-'PFR'

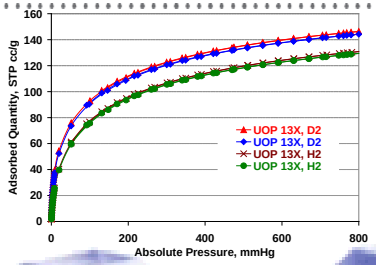


Isotopic Effect Based on Material Property





Palladium favors lighter hydrogen isotope



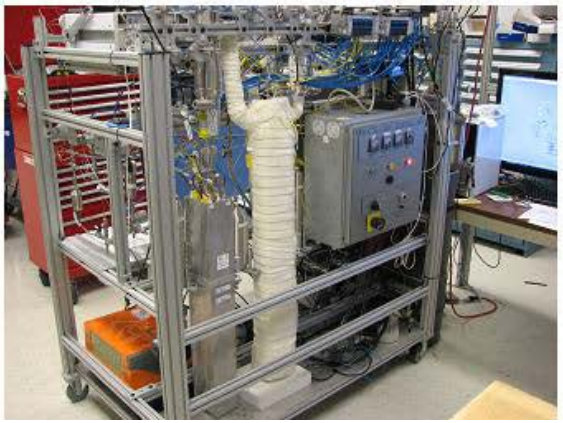
Molecular Sieve favors heavier hydrogen isotope

TCAP Development History

• TCAP concept invented at SRL	1980
• Experimental TCAP achieved 97% purity (D_2, H_2)	1983
• Prototype TCAP achieved 99% purity (D_2, H_2)	1989
• Pilot TCAP demonstrated (production-configured)	1993
• Production TCAP achieved target T_2/D_2 separation	1994
• Compact TnT design tested at LANL	2001
• Batch Cryogenic distillation column replaced by TCAP	2004
• Comp.-free CTC concept developed, 1/10th footprint	2006
• Comp.-free CTC experiment reached 4,000 cycles	2009
• Inverse Column achieved 2X+ capacity & higher purity	2009
• Mini-TCAP for Shine Medical Technologies	2013
• Micro-TCAP (batch) for LLE (U. Rochester)	2013
• Plant-Configured mini-TCAP reached 8,000 cycles	2018

Representation of TCAP Footprint Reduction

CTC-TCAP (1/10th current footprint)



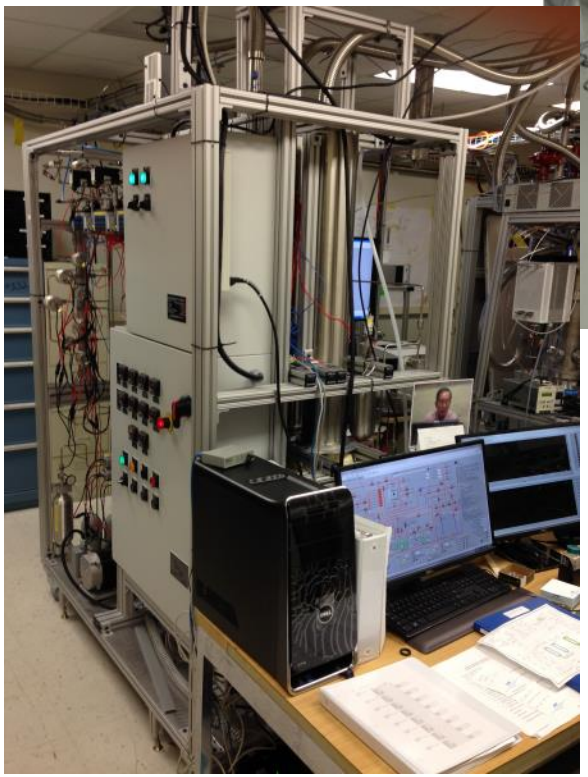
Mini-TCAP

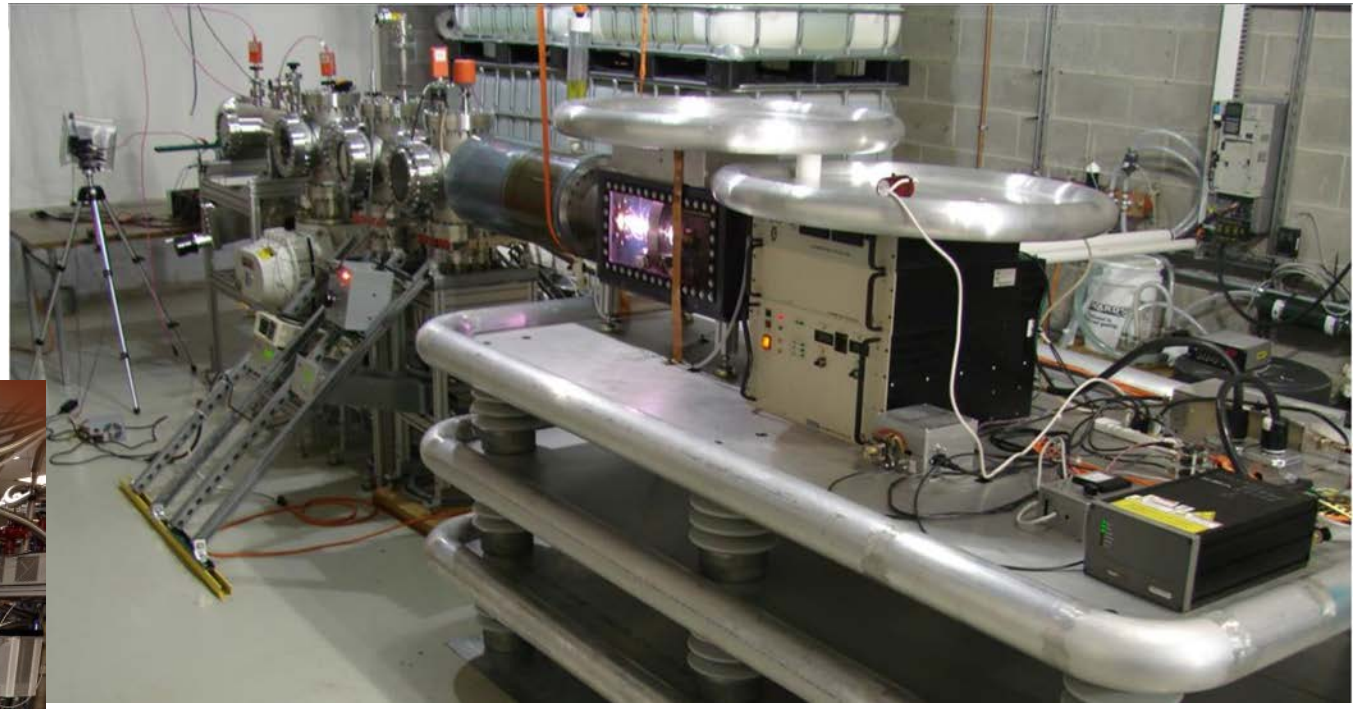
Micro-TCAP

New TCAP technology continues to evolve in miniature designs for diversified applications

TCAP for SHINE Medical Technologies

Mini-TCAP constructed by SRNL

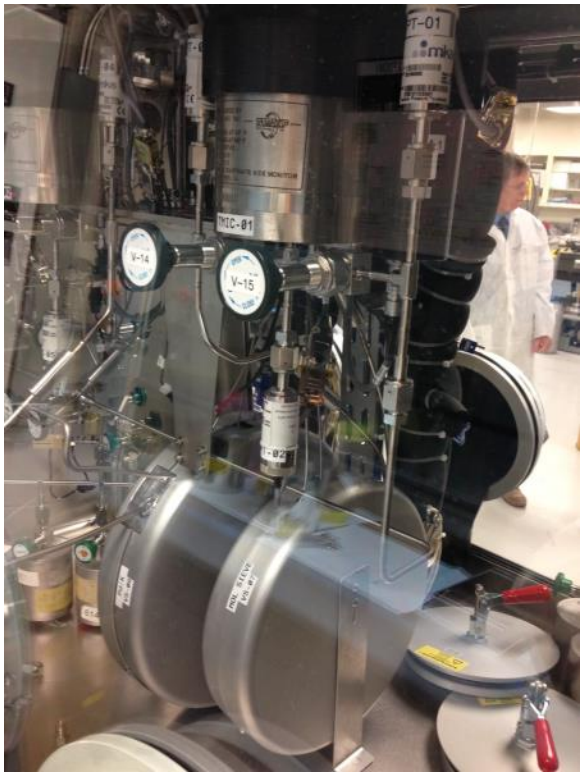




Linear Accelerator in SHINE for medical isotope production

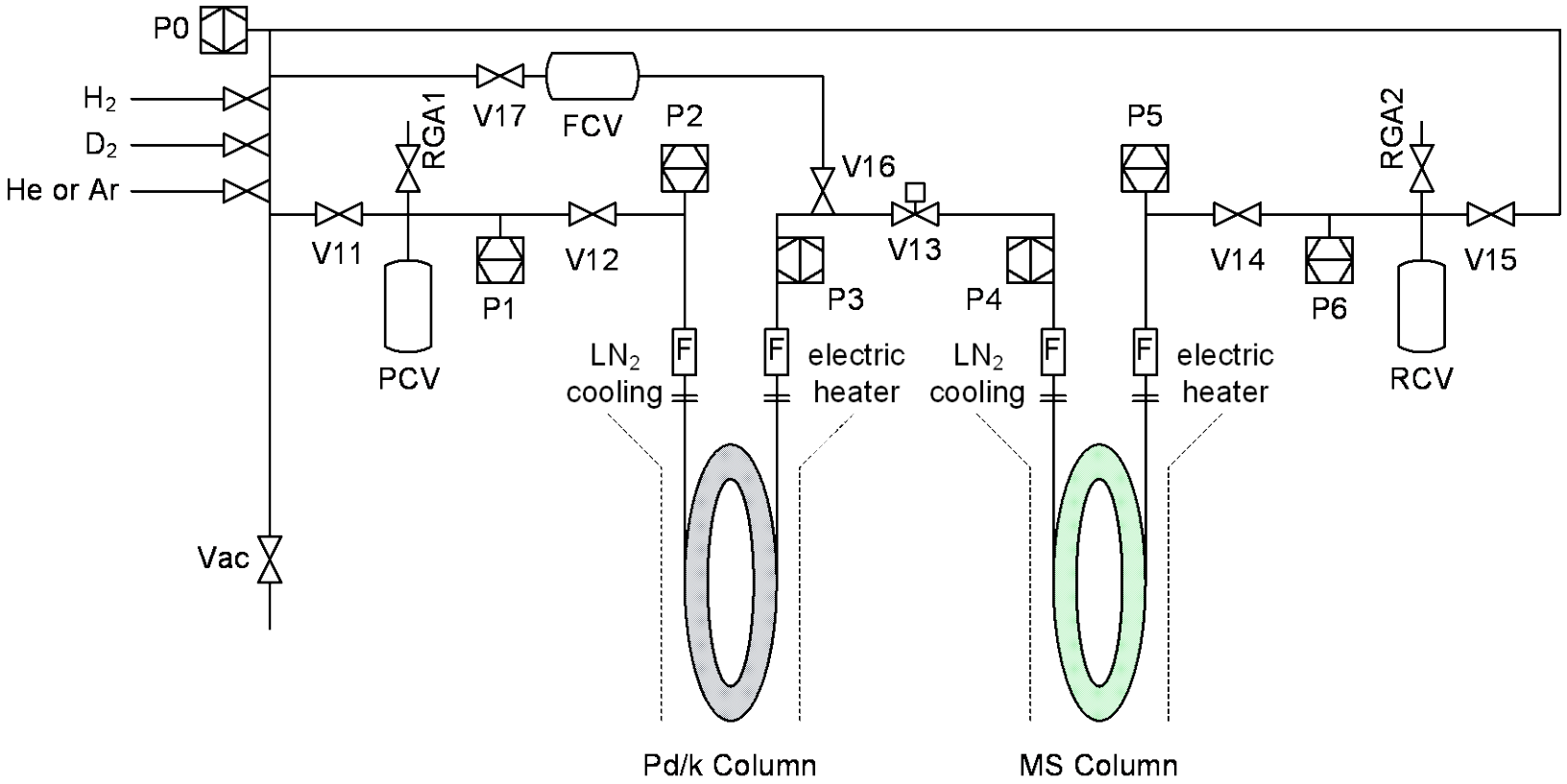
TCAP for LLE, University of Rochester

Micro-TCAP constructed by SRNL

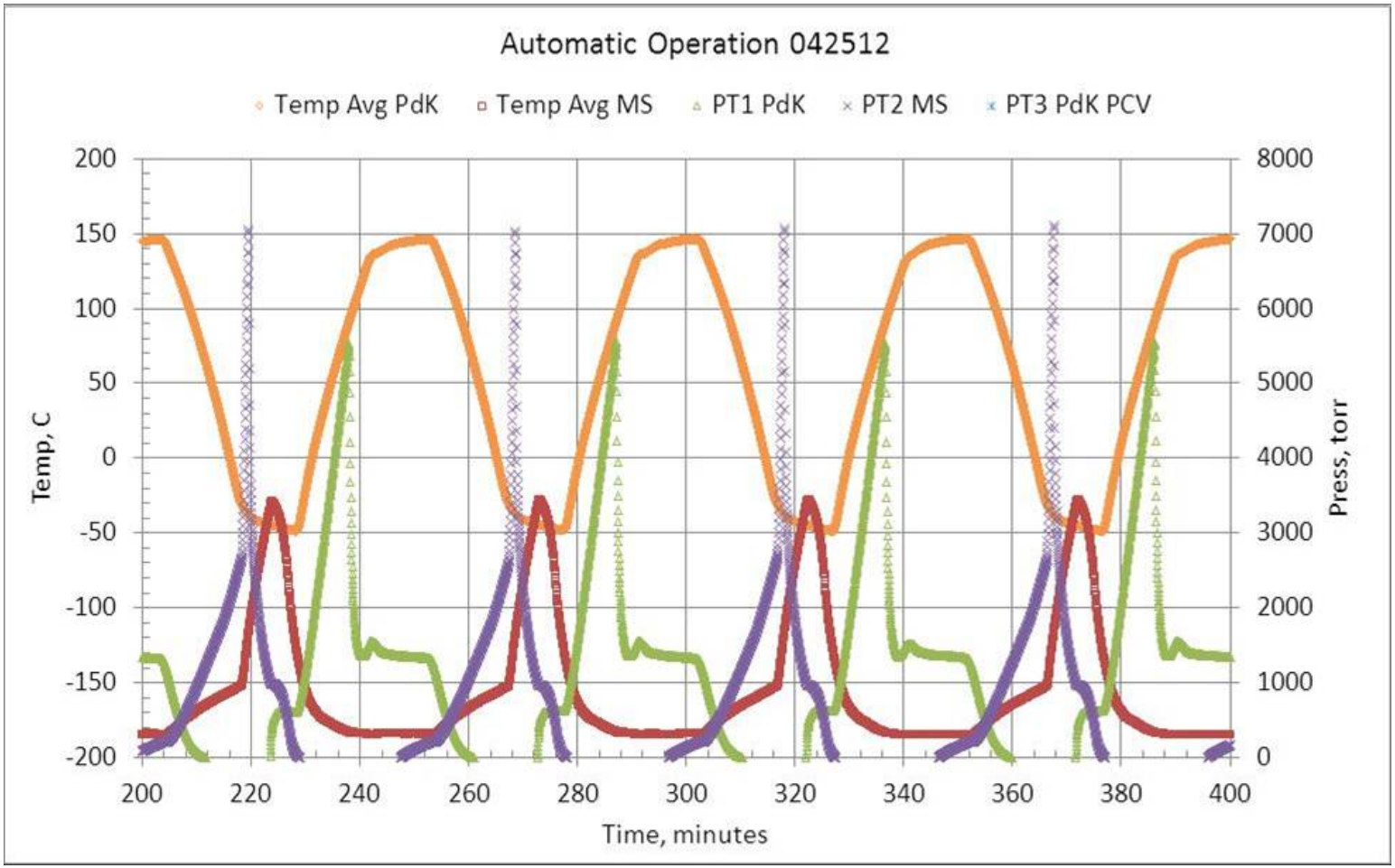


Laser Target Shot in Laboratory for Laser Energetics for Fusion Study

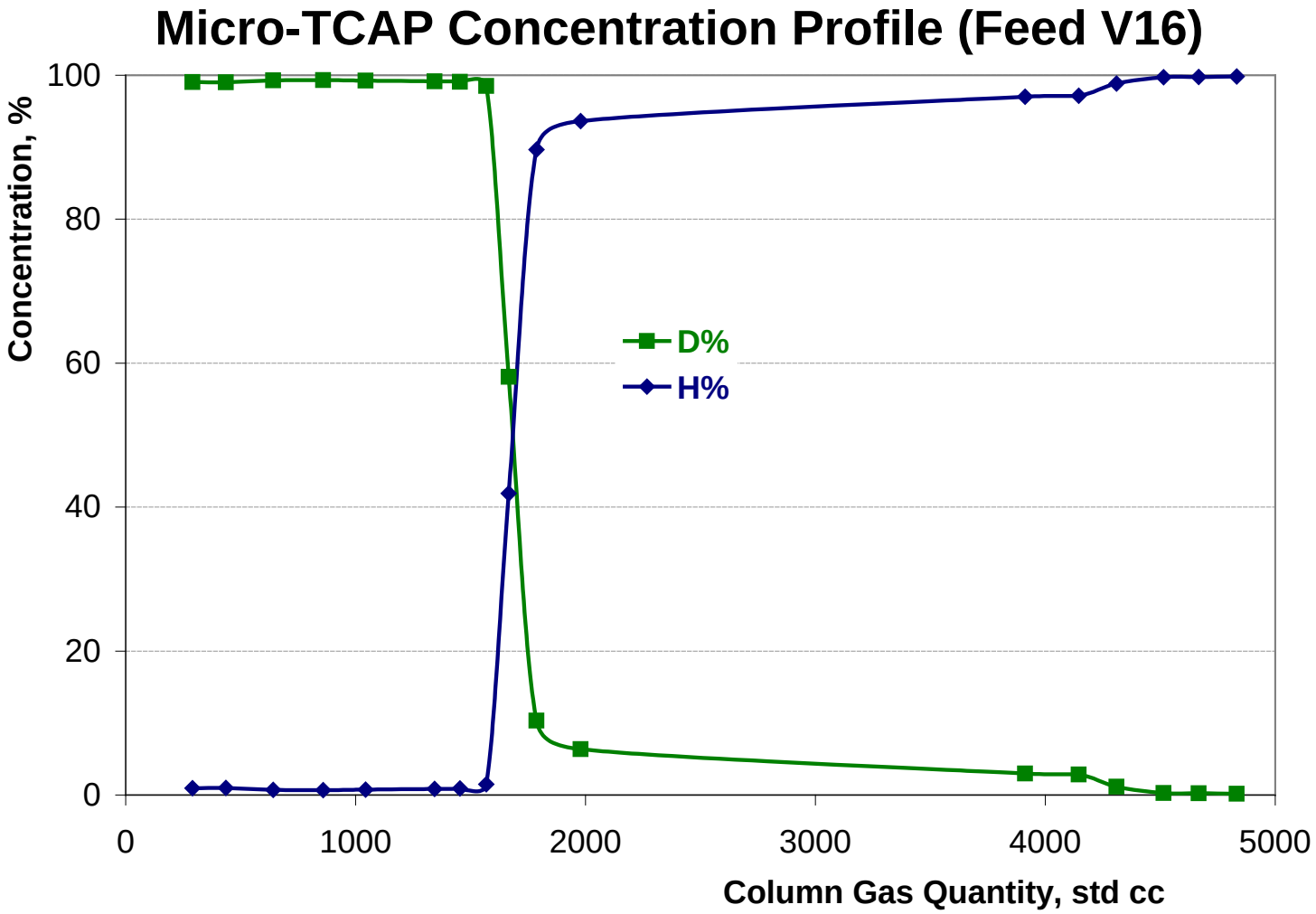
Micro-TCAP Configuration



TCAP Typical T and P Cycles



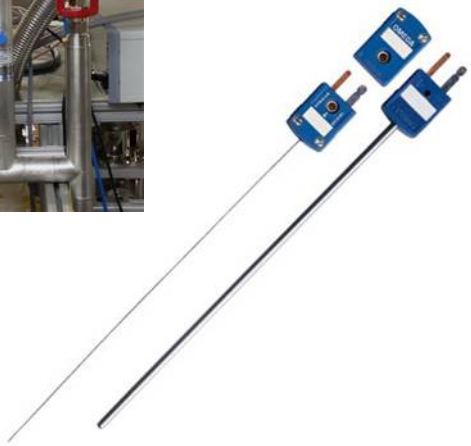
TCAP Concentration Profile



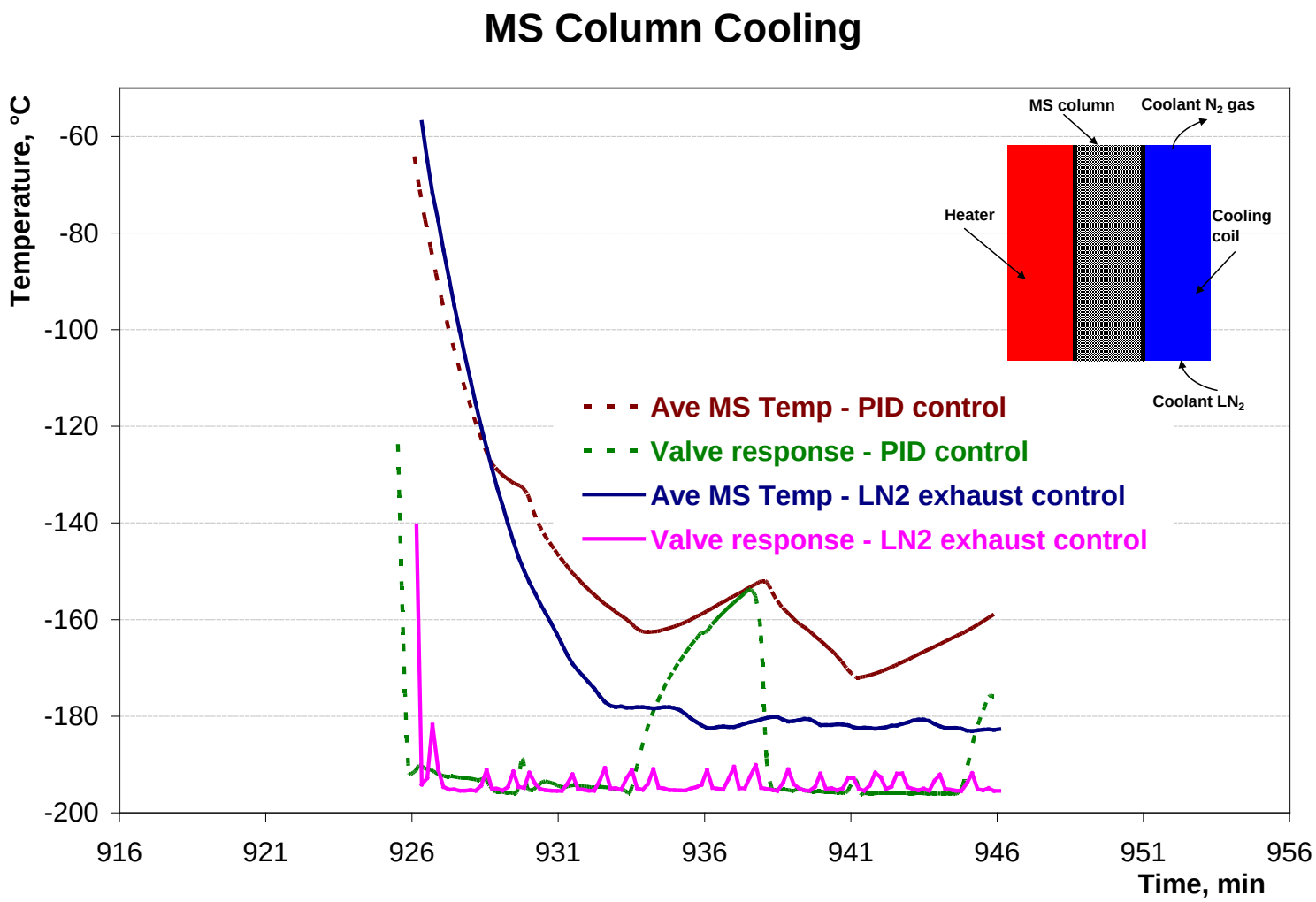
Extensive Evaluation for Component Selection

- LN_2 control valves
- Process valves:
  - *Tritium compatibility*
  - *Pressure rating*
  - *Performance*
  - *Durability*
- Pressure transducers
- Thermocouples
- Insulation

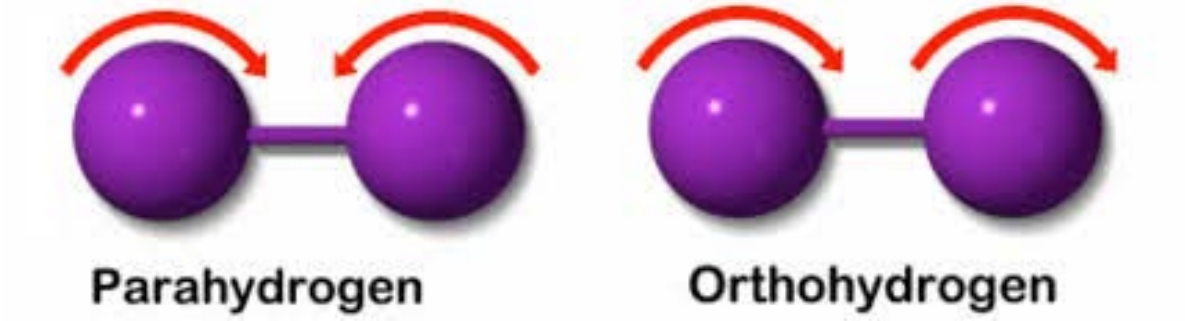
Components meet ASME B31.3 and are tritium compatible



LN_2 Control Algorithm

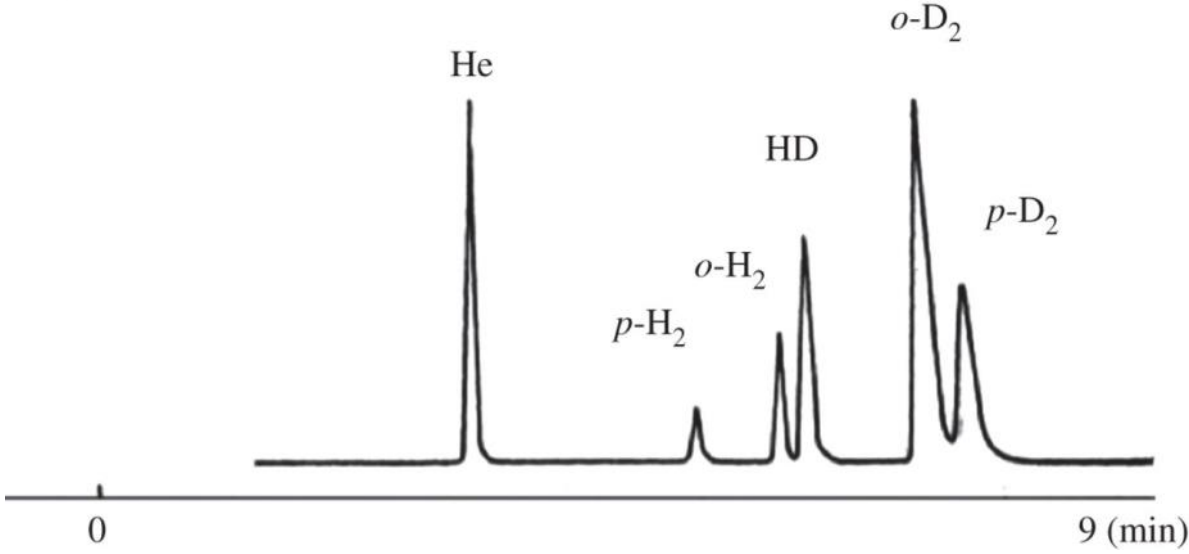


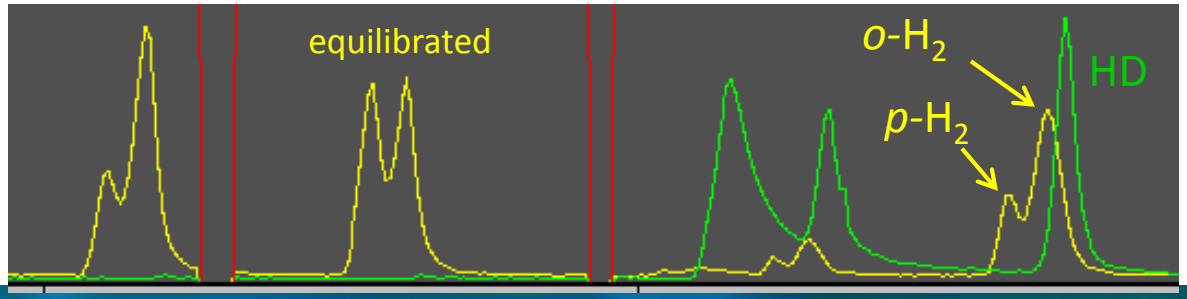
Separation Enhanced by Reactive Equilibrium



$$p\text{-}H_2 \xrightleftharpoons{Fe_2O_3} o\text{-}H_2$$

$$H_2 + D_2 \xrightleftharpoons{Pt/z} HD$$



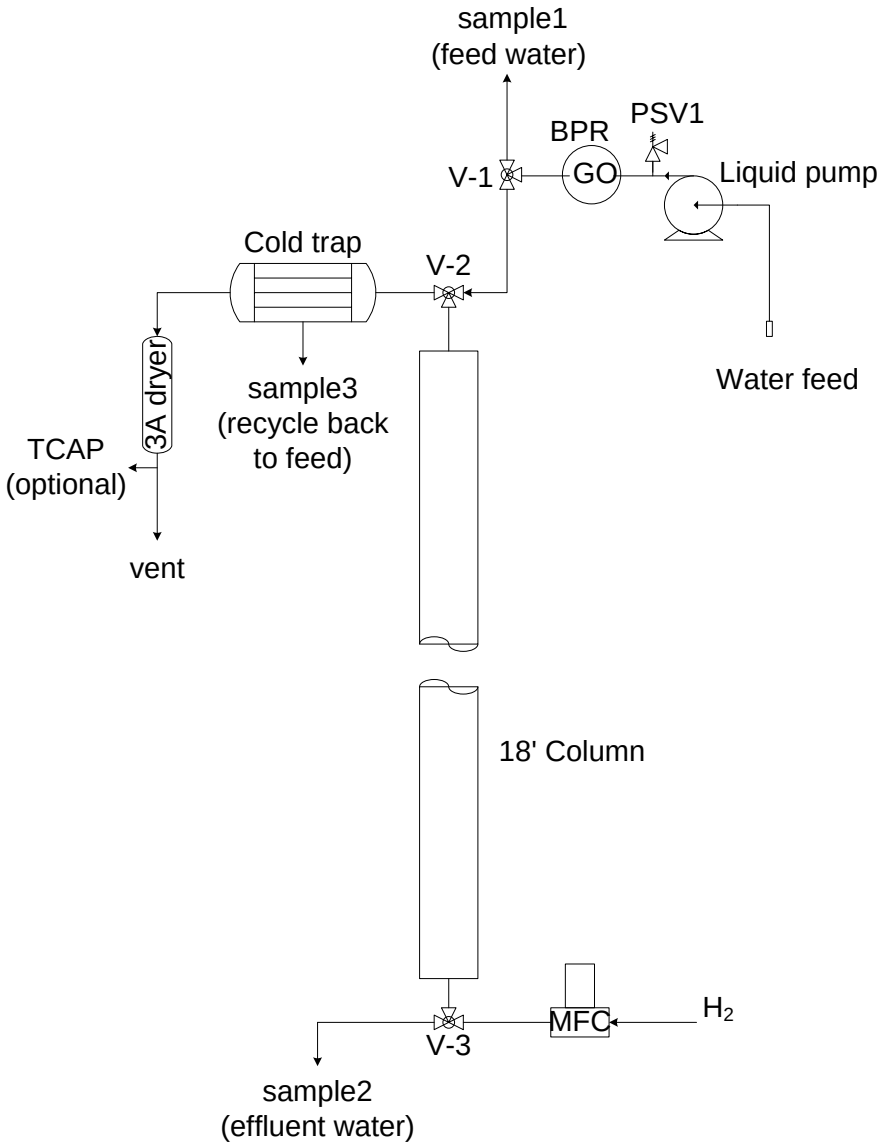


Why Us? - Team with Track of Records and Expertise

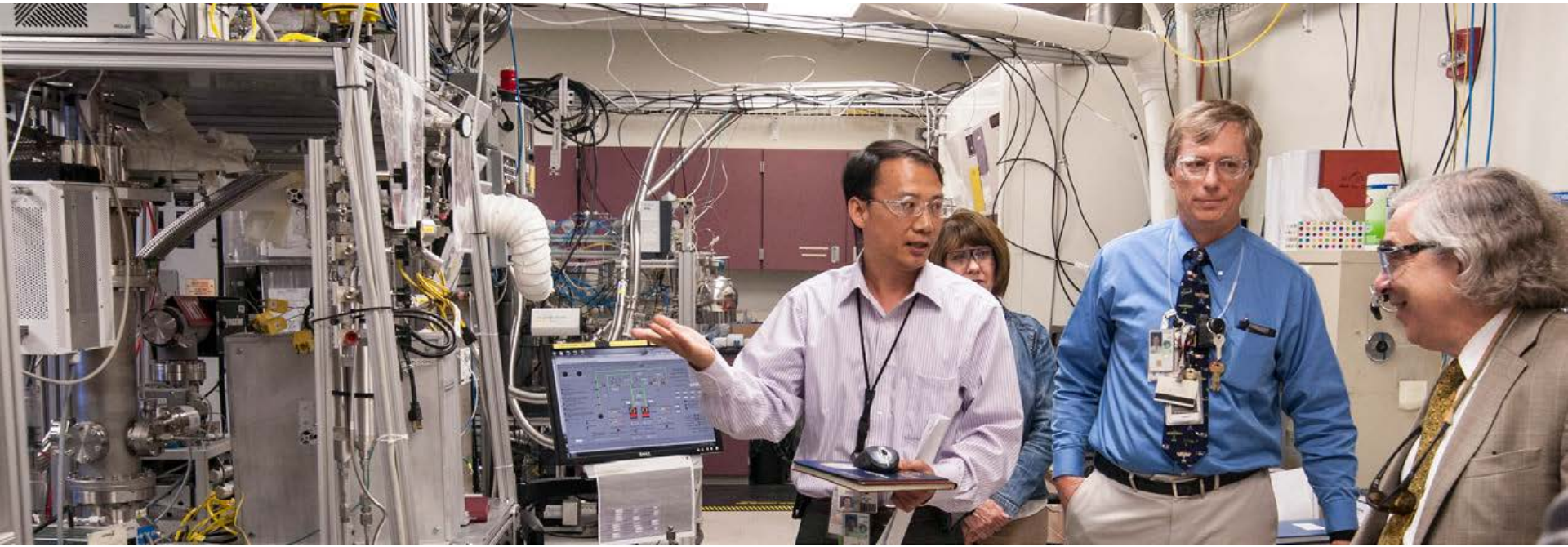
- Discovery of deuterium 1931
- Discovery of tritium 1934
- TCAP concept invented at SRL 1980
- SRS Isotope Separation
  - Thermal diffusion 1957-1986
  - Fractional absorption1964-1968
  - Cryogenic distillation 1967-2004
  - TCAP 1994- present

TCAP (Thermal Cycling Absorption Process) for hydrogen isotope separation

Water Isotope Separation Under Development



Energy Secretary Ernest Moniz in the TCAP Lab

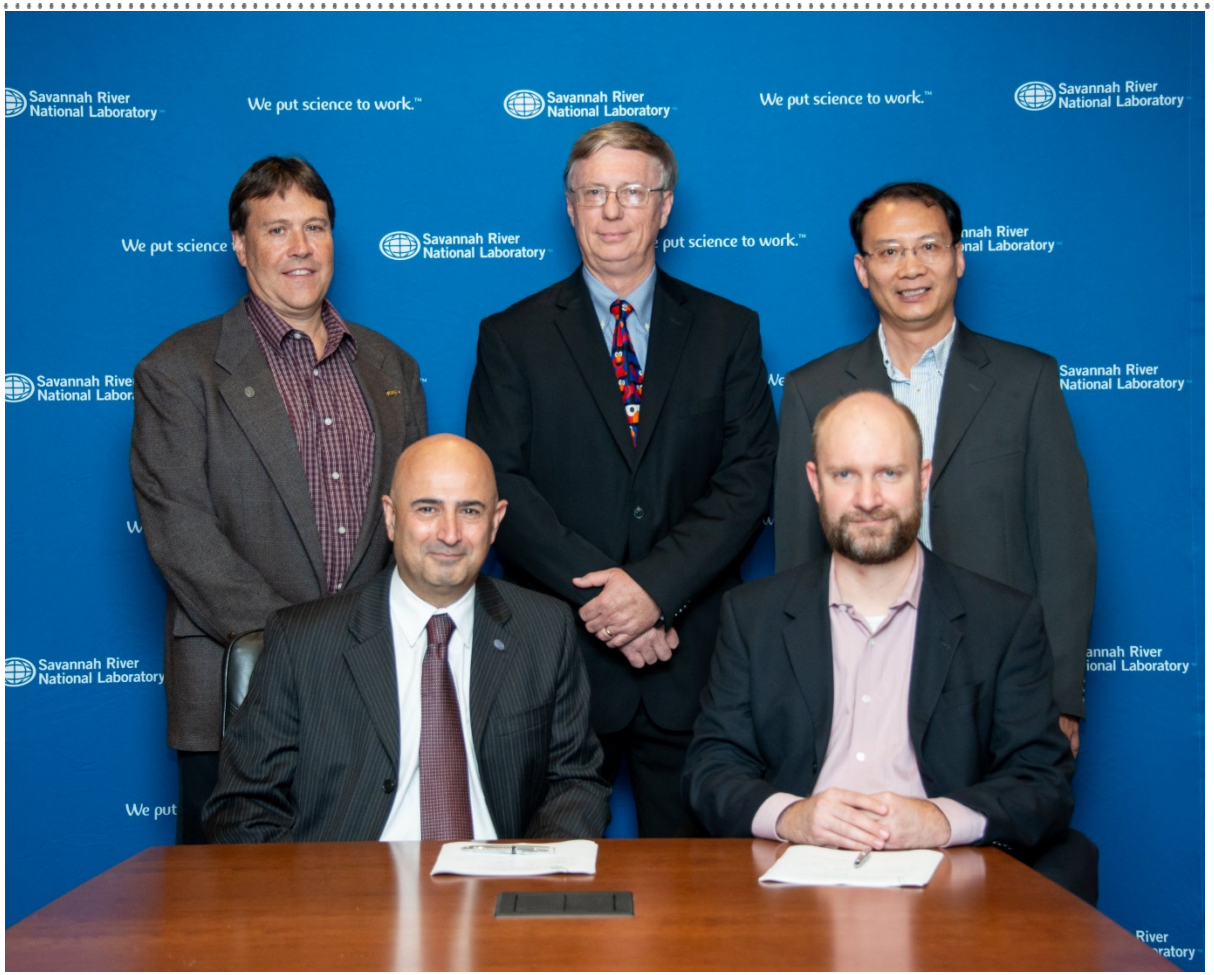


SRNL's Steve Xiao (from left), Sharon Redd and Tommy Sessions explain the research and development process behind SRNL's Thermal Cycling Absorption Process (TCAP) for Secretary Moniz in July 2014. SRNL has continually improved TCAP's ability to enrich tritium gas in a smaller space, and in a more cost-effective process.

Energy Secretary Rick Perry in the TCAP Lab

Savannah River National Laboratory (SRNL) Director of Defense Programs Science and Technology David Babineau explains the Thermal Cycling Absorption Process (TCAP) to Energy Secretary Rick Perry in February 2018. TCAP has reduced the footprint needed to separate hydrogen isotopes by up to 10 times while saving operational costs and improving performance.

TCAP Technology Licensed to Greenway Energy



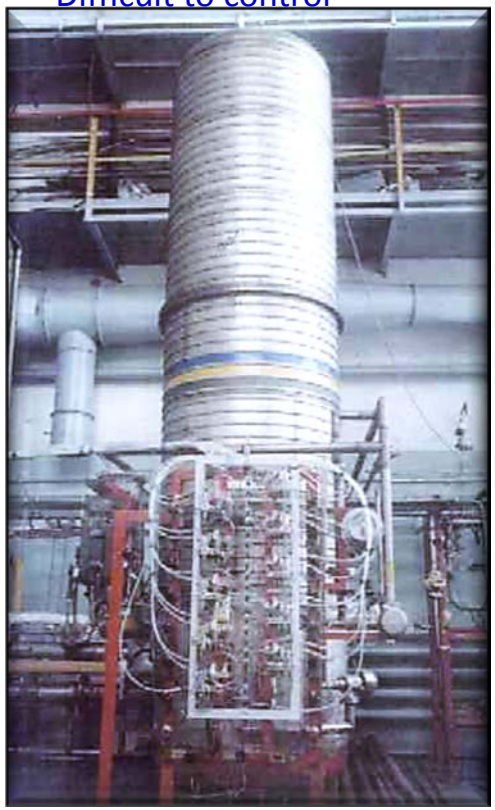
Savannah River National Laboratory (SRNL) Director Vahid Majidi and President of Greenway Energy Scott Greenway signed TCAP license agreement. Standing in the Backrow are Director of Defense Programs David Babineau, inventors Henry T. Sessions and Steve Xiao.

Isotope Separation for Tritium: Past, Present and Future

Past

Cryogenic Distillation

- 23 Feet Tall
- Significant Supporting Infrastructure
  - Helium refrigeration
  - Liquid nitrogen cooling jacket
- Large inventory of tritium
- Batch mode operation
- Difficult to control

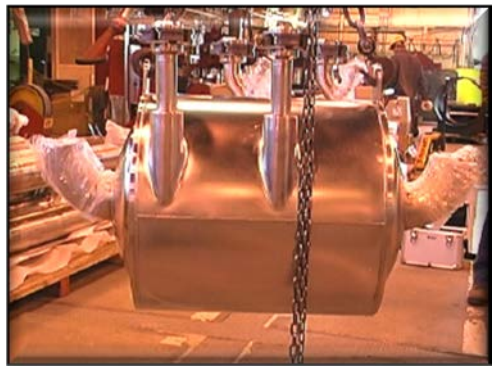


Past: 23 ft. Cryogenic Distillation Column

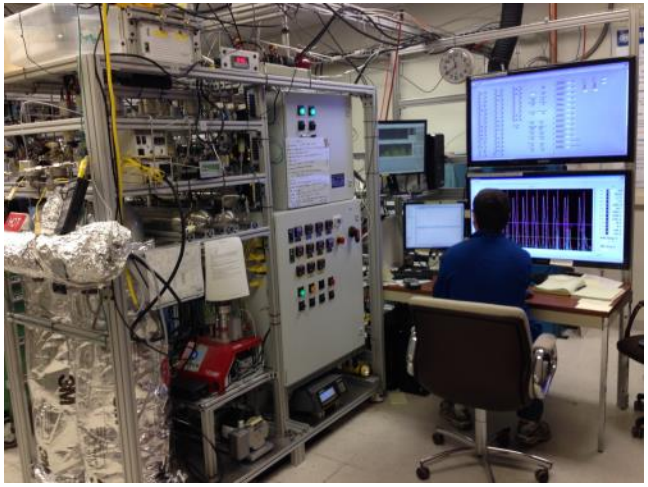
Present

Thermal Cycling Absorption Process

- About three feet in length and diameter
- Small enough to be placed in glovebox
- Reduced material-at-risk by 27X
- Reduced tritium environmental emissions by 1000X
- Continuous mode operation
- Reduction in supporting infrastructure
- Hot and cold nitrogen refrigeration system



Present: Thermal Cycling Absorption Process



Future: Mini-TCAP

Future

Mini-TCAP

- < 1/10th footprint of present TCAP
- ¼ heat load
- Further reduces tritium at risk by 2/3
- Once through liquid nitrogen cooling
- Electric heating

Summary: TCAP Features

- Pressure swing
- Temperature Swing
- Hydride vacuum pump
- Hydride pressure pump
- Hydride interim storage

- Separation by chromatography
- Hydrogen itself as carrier gas
- Excellent radioactive confinement
- Reprocess gas in column repeatedly
- HD re-equilibrium / separation

- Versatility
- Scale by throughput
- Impurity rejection
- Energy efficient

- Simple design & advanced control logic
- No mechanical moving parts besides valves
- Inherently safe / extra long life
- Robust and fault proof

- Easily beat deuterium natural abundance (~ 150 ppm)