Helium-Hydrogen PρT-x Measurements and Equation of State

Presenter:

Ian Richardson (WSU)

Co-Authors:

Thomas Blackham (WSU), Jacob Leachman (WSU), Eric Lemmon (NIST)

July 1, 2015

CEC/ICMC 2015

WASHINGTON STATE UNIVERSITY

NIST

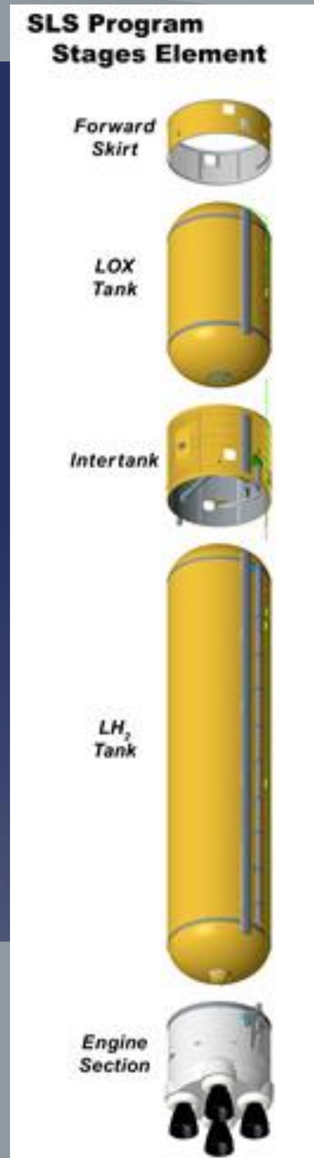
Cryogenic Engineering Conference & International Cryogenic Materials Conference

June 28 - July 2 2015

JW Marriott Starr Pass Resort & Spa

Tucson, Arizona

Liquid Hydrogen as a Rocket Fuel



NASA's Space Launch System: Images from spacenews.com (above) and nasa.gov (right)

- Liquid hydrogen (LH_2) tanks are pressurized with gaseous helium
- Small amounts of helium dissolve into the liquid hydrogen
- Current models assume pure LH_2 properties
- No real fluid helium–hydrogen mixture model exists

Ideal Models

- Dalton's and Amagat's law are **approximations** for real-gas mixtures
- Dalton's law:
  - $P_m = \sum_{i=1}^{k} P_i(Tm, Vm)$
- Amagat's law:
  - $V_m = \sum_{i=1}^{k} V_i(Tm, Pm)$

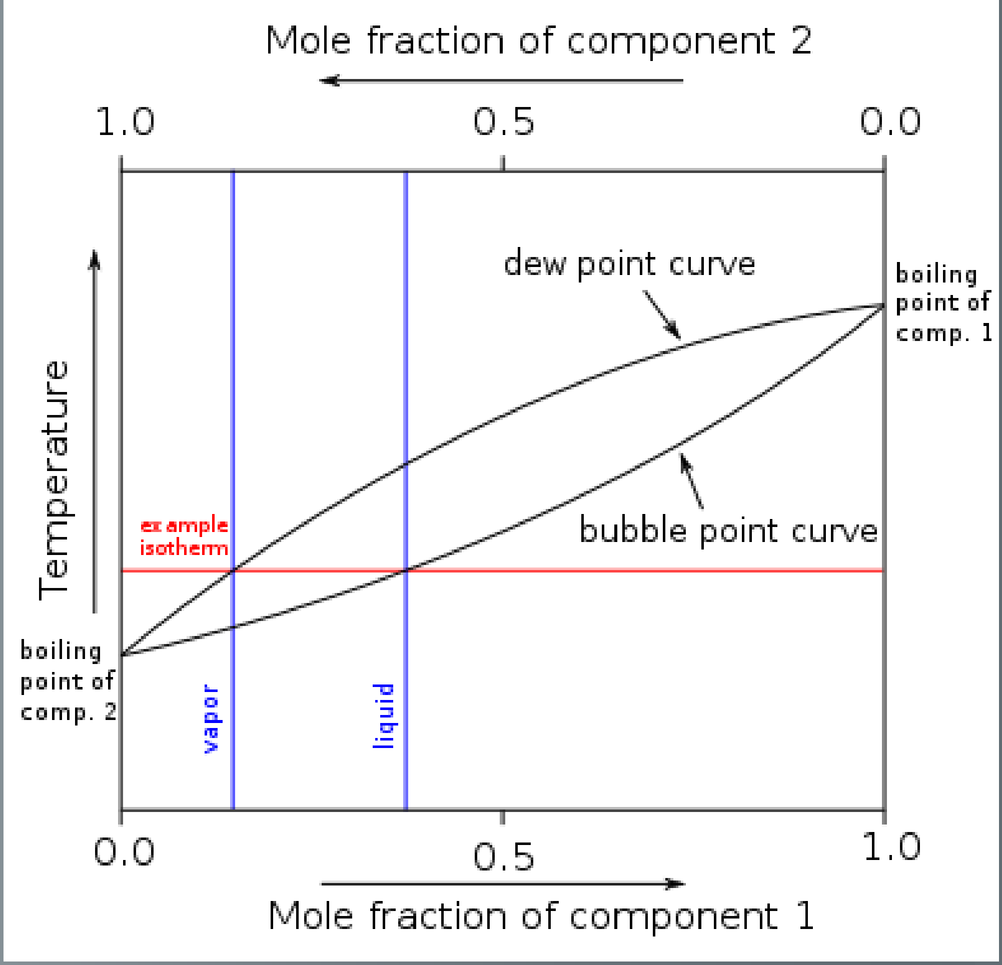
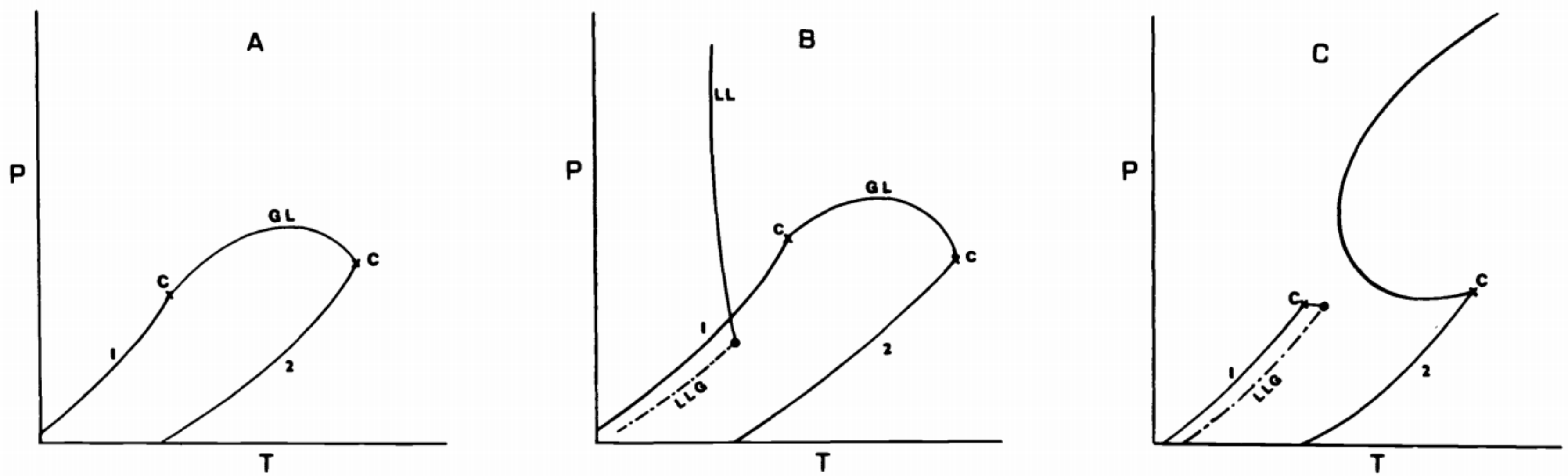


Image from commons.wikimedia.org

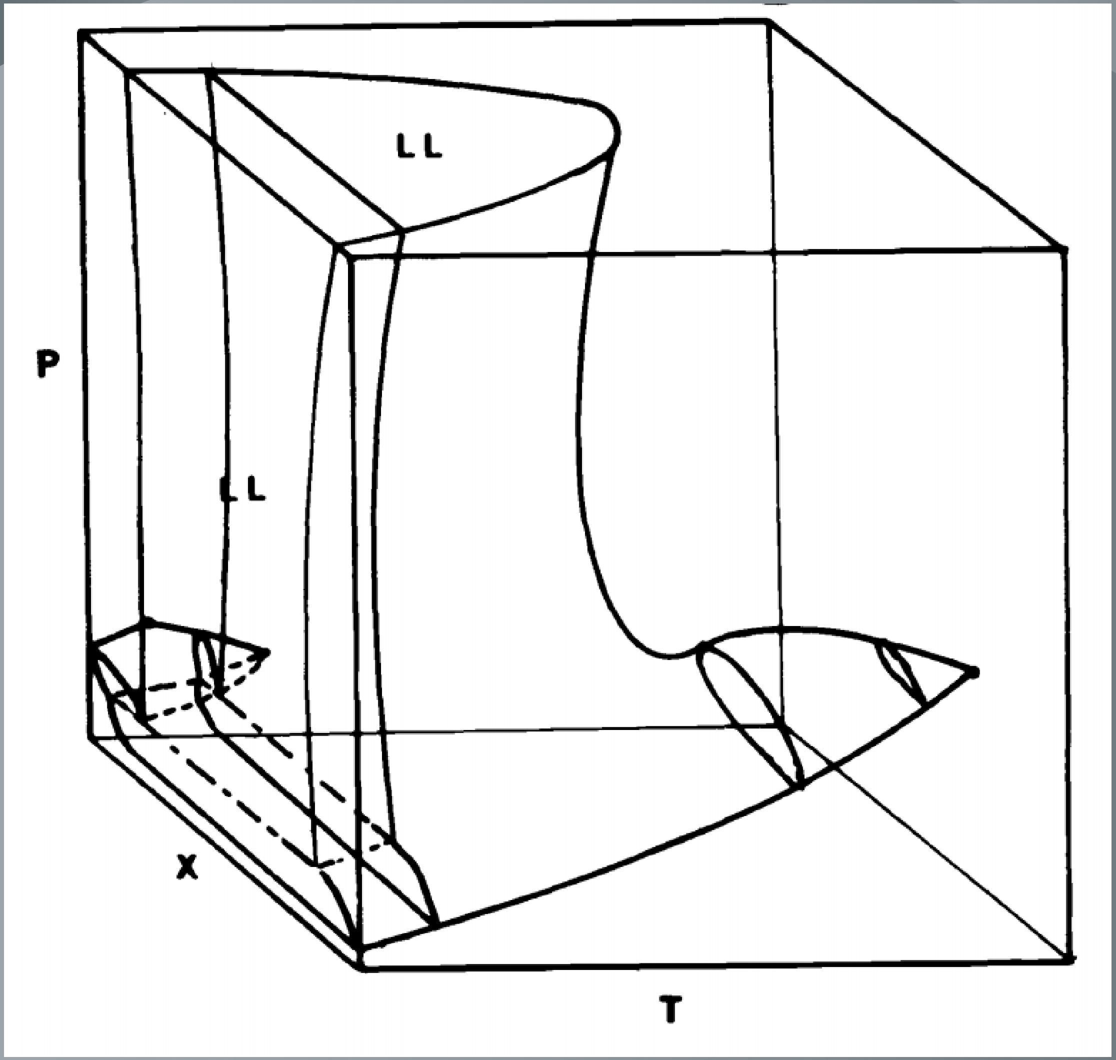
Binary Mixture Fluid Classifications



A – Type I Fluid (methane – ethane) – Simple two phase fluid.
B – Type II (water – phenol) Stable liquid-liquid phase.
C – Type III (helium – hydrogen) – Two distinct critical lines that never meet.

[1] C. L. Young, Pure and Appl. Chem. 68, pp. 1561-1572 (1986).

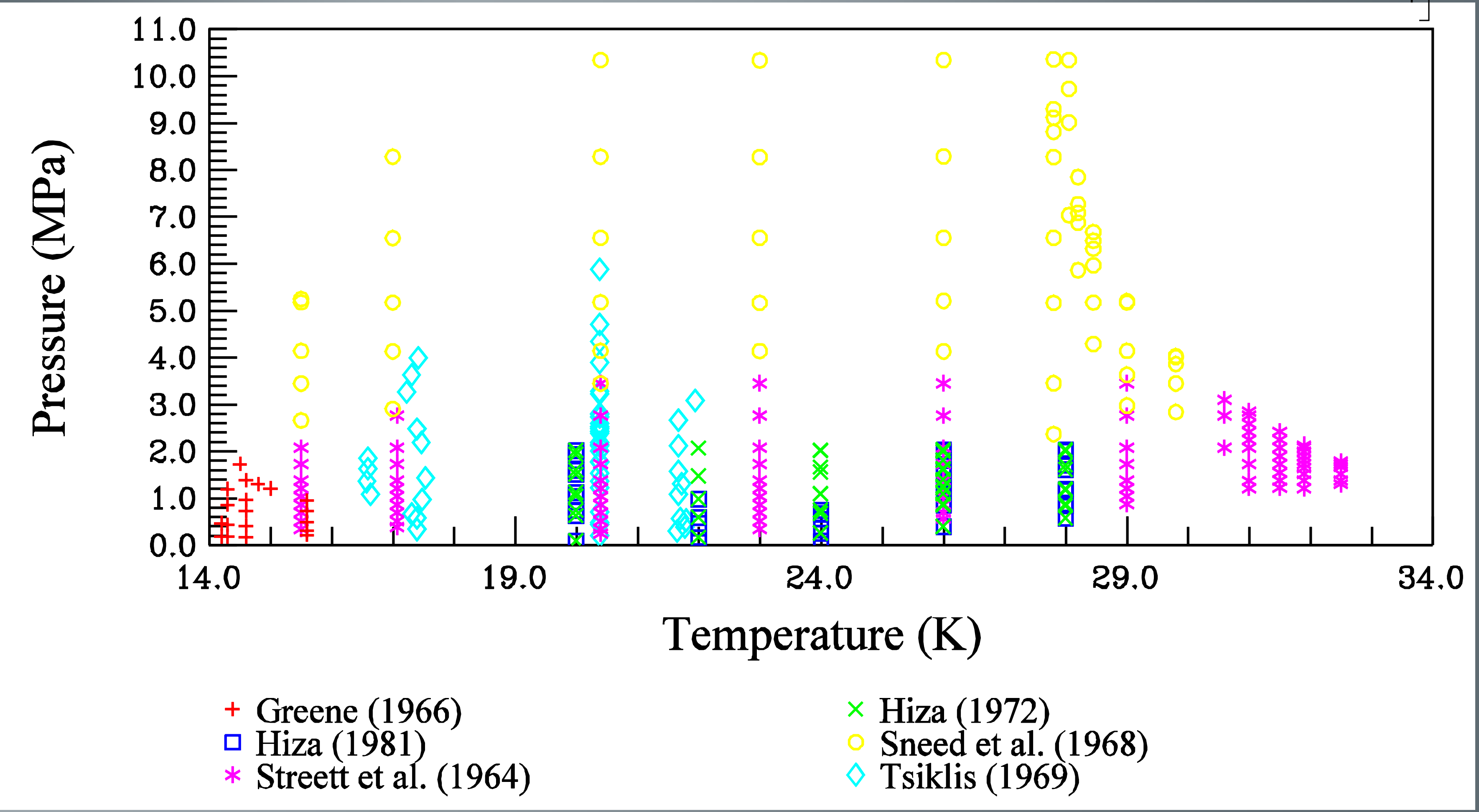
Type III Fluid Surface



- Complex fluid interactions require a real fluid model
- Need VLE and PρT-x experimental measurements

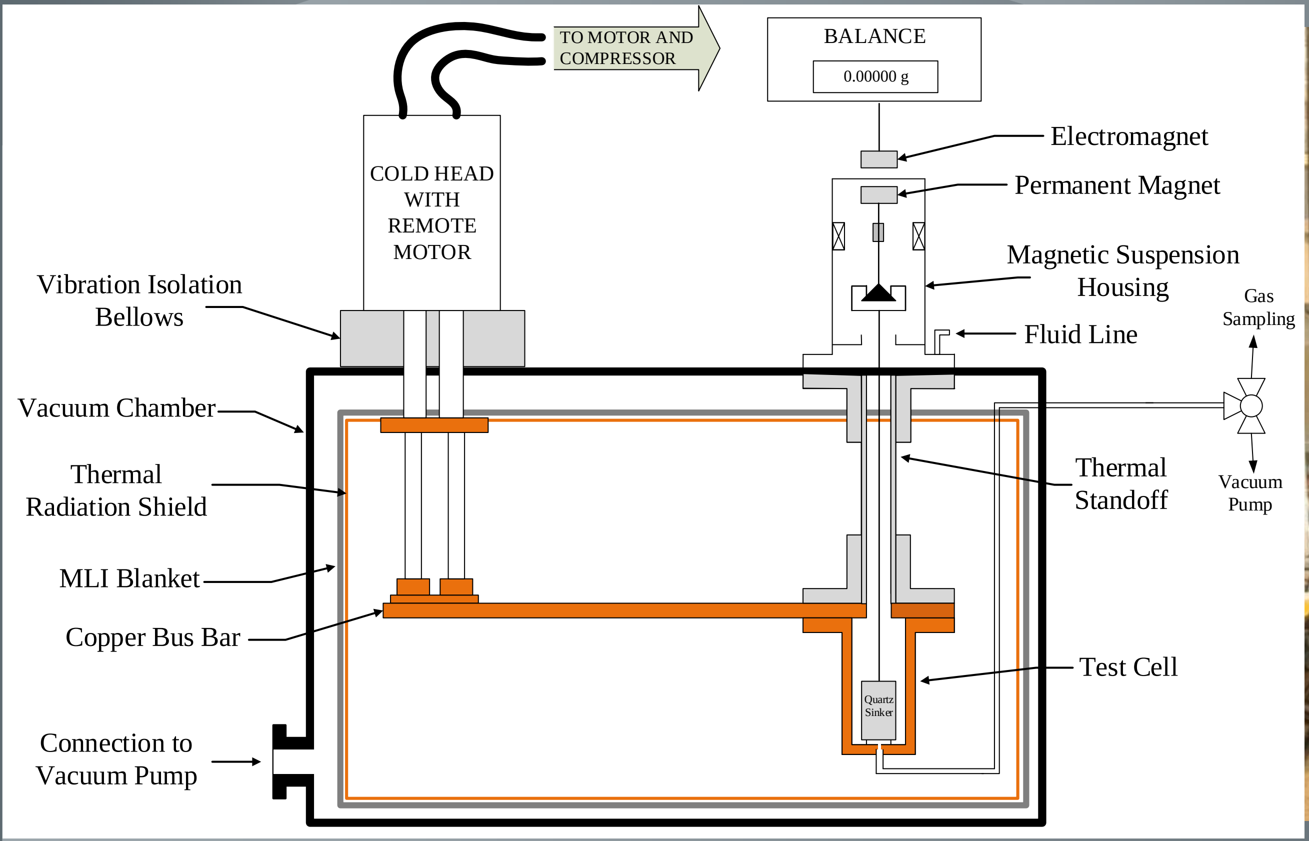
[1] C. L. Young, Pure and Appl. Chem. 68, pp. 1561-1572 (1986).

Literature Review



- Only Vapor-Liquid-Equilibrium (VLE) data available
- Need PρT-x measurements

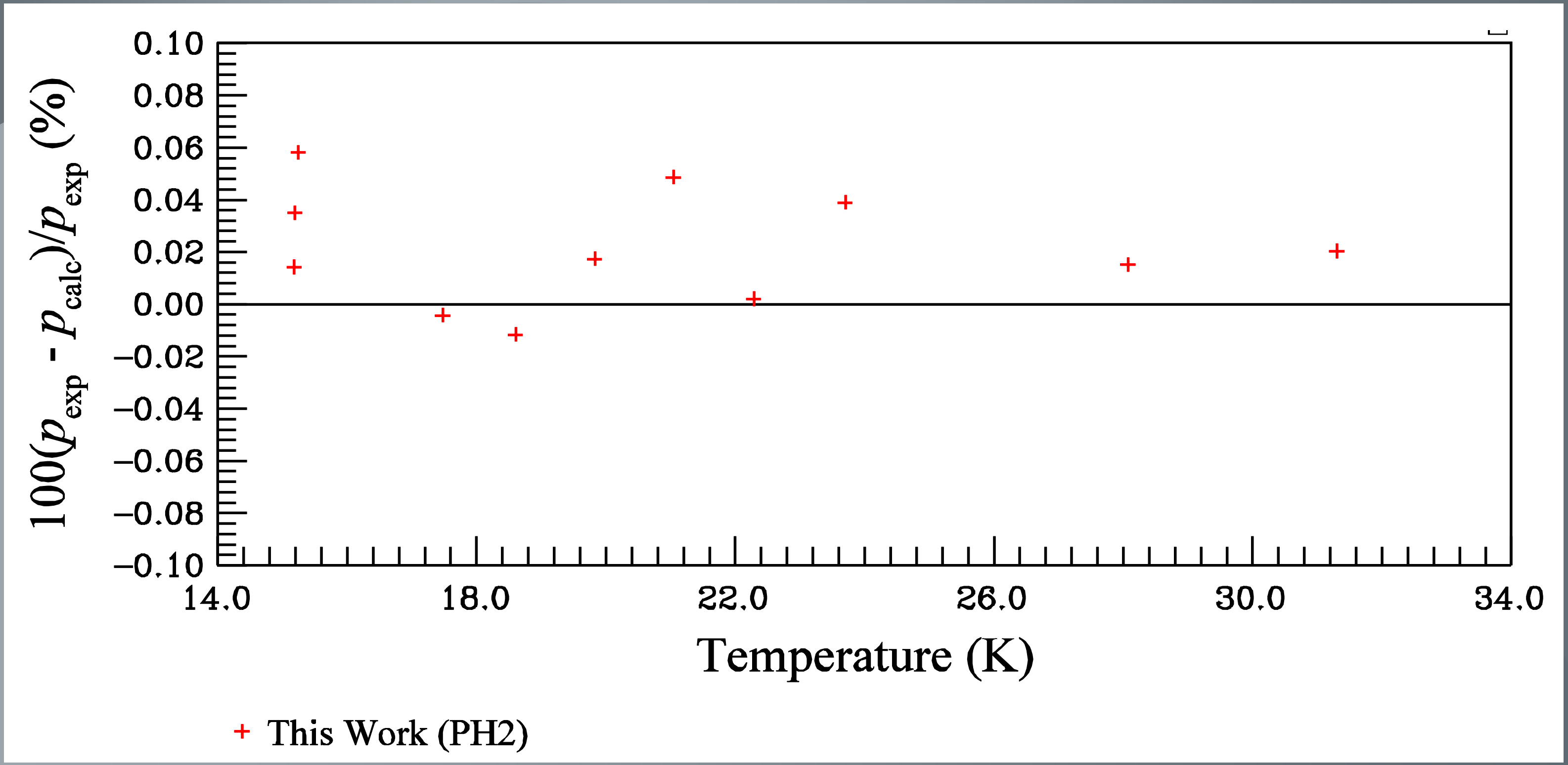
PρT-x Measurements



- Pressure: Paroscientific Digiquartz
- Temperature: Secondary Standard Germanium RTDs
- Composition: Gas Chromatography
- Density: Magnetic Suspension Microbalance

[2] I. A. Richardson, J. W. Leachman, T. M. Blackham, S. G. Penoncello, AIP Conference Proceedings 1573, 1086-1091 (2014).

Validating Measurements with Parahydrogen



- Liquid pH_2 PρT measurements agree with pH2 EOS[3] within 0.06% (above), early LN_2 agreed within 0.1%[4].
- Conducted PρT-x measurement on helium-hydrogen mixtures from 17 K to 29 K for pressures up to 2 MPa.

[3] J. W. Leachman, R. T. Jacobsen, S. G. Penoncello and E. W. Lemmon, J. Phys. Chem Ref. Data 38, 721-748 (2009).
[4] R. Span et al. J. Phys. Chem. Ref. Data 29, 1361-1433 (2000).

Mixture Equations of State

Helmholtz Free Energy Equation

$$\alpha(\delta,\tau,\boldsymbol{x}) = \alpha^0(\rho,T,\boldsymbol{x})+\alpha^r(\delta,\tau,\boldsymbol{x})$$

Reduced Density

$$\delta = \frac{\rho}{\rho_\mathrm{c}(\boldsymbol{x})}$$

Ideal Equation

$$\alpha^0(\rho,T,\boldsymbol{x})=\sum_{i=1}^{N} x_i(a^0{}_{0i}(\delta,\tau) + \ln(xi))$$

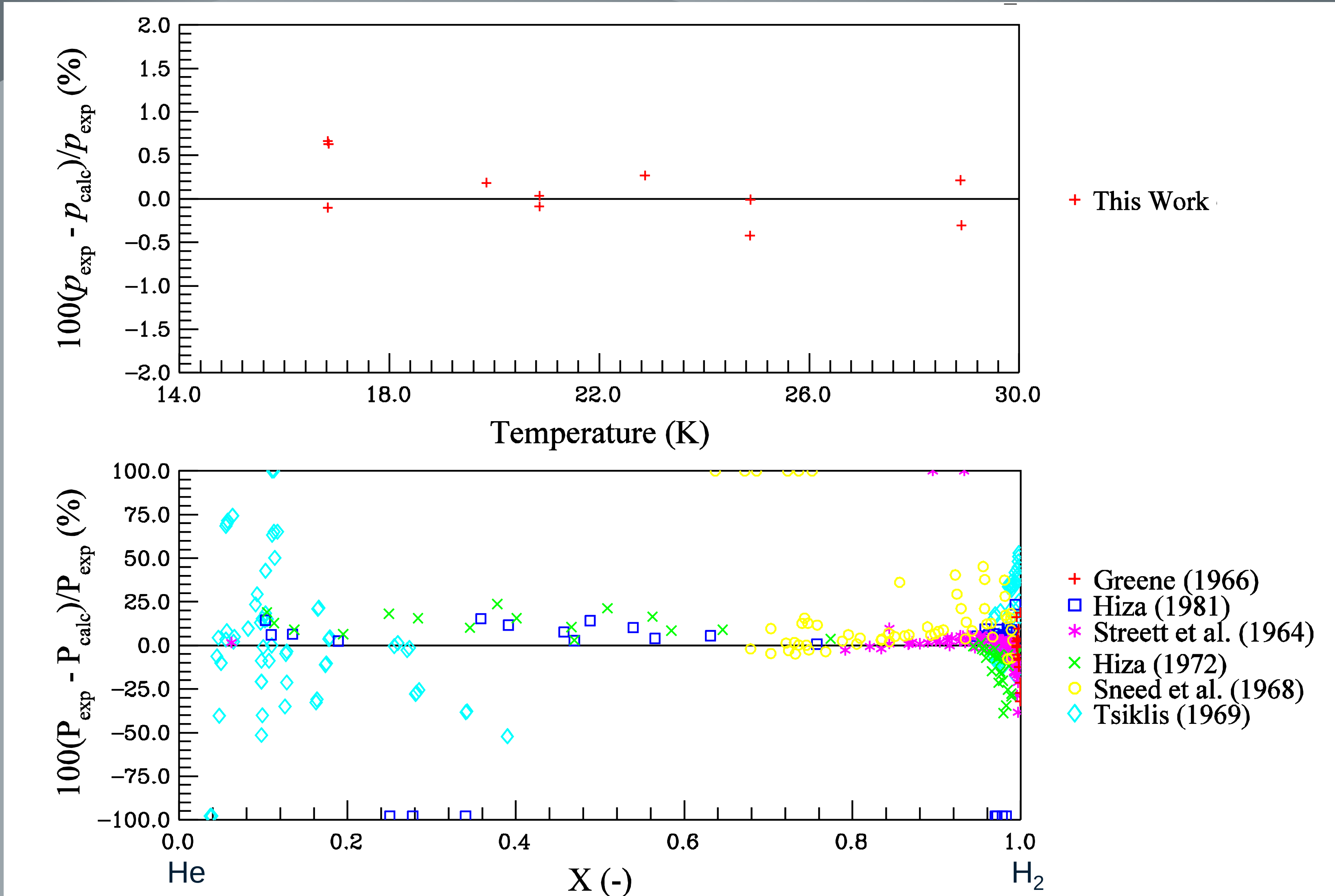
Reduced Temperature

$$\tau = \frac{T_\mathrm{c}(\boldsymbol{x})}{T}$$

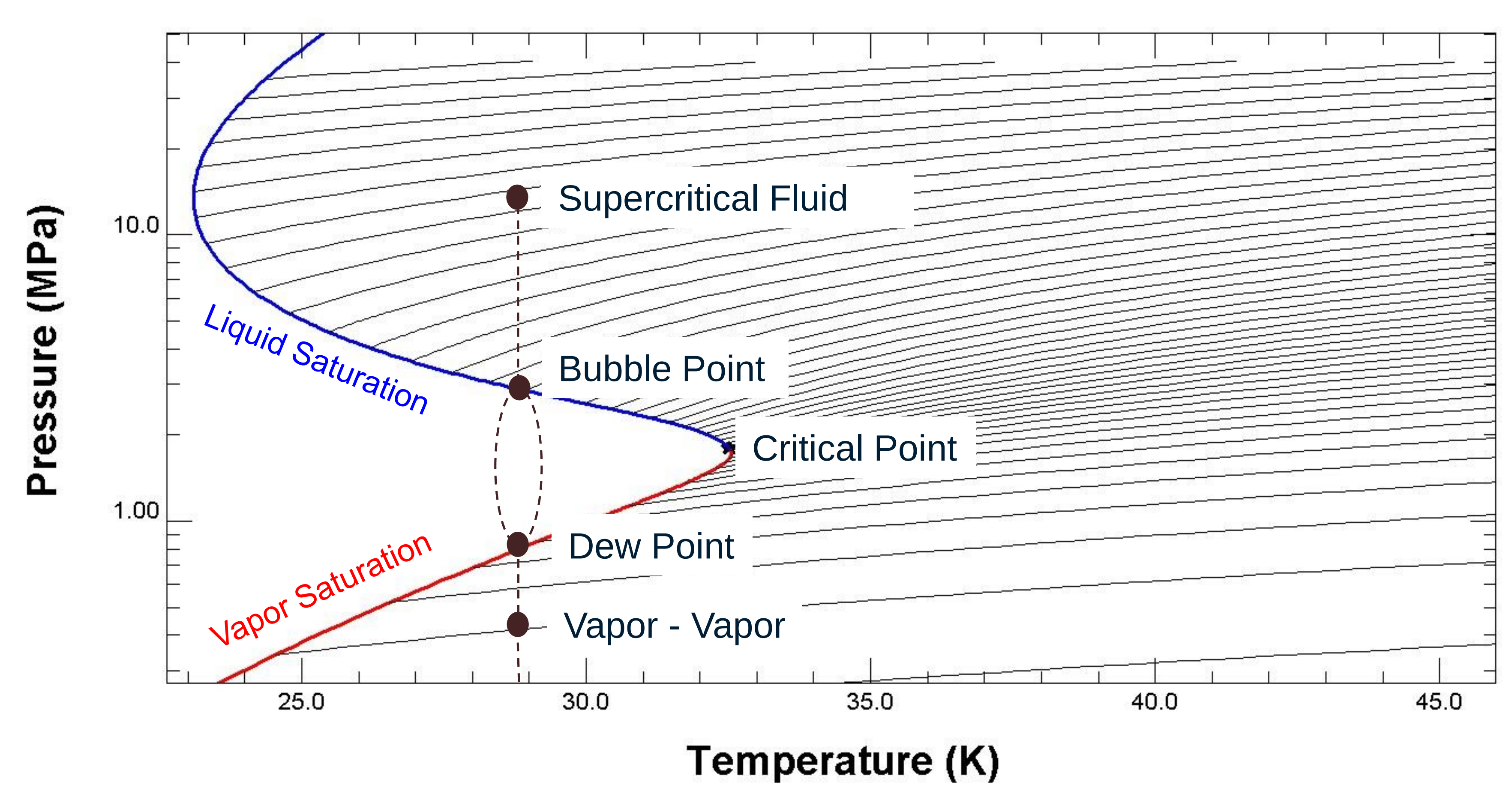
Residual Equation

$$\alpha^r(\delta,\tau,x) = \sum_{i=1}^{N}\left(x_i a^r{}_{0i}(\delta,\tau)\right) + \sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\left(x_i x_j F_{ij} a^r{}_{ij}(\delta,\tau)\right)$$

He-H_2 Equation of State Comparisons to Experimental Measurements



He-H_2 EOS Saturation Region

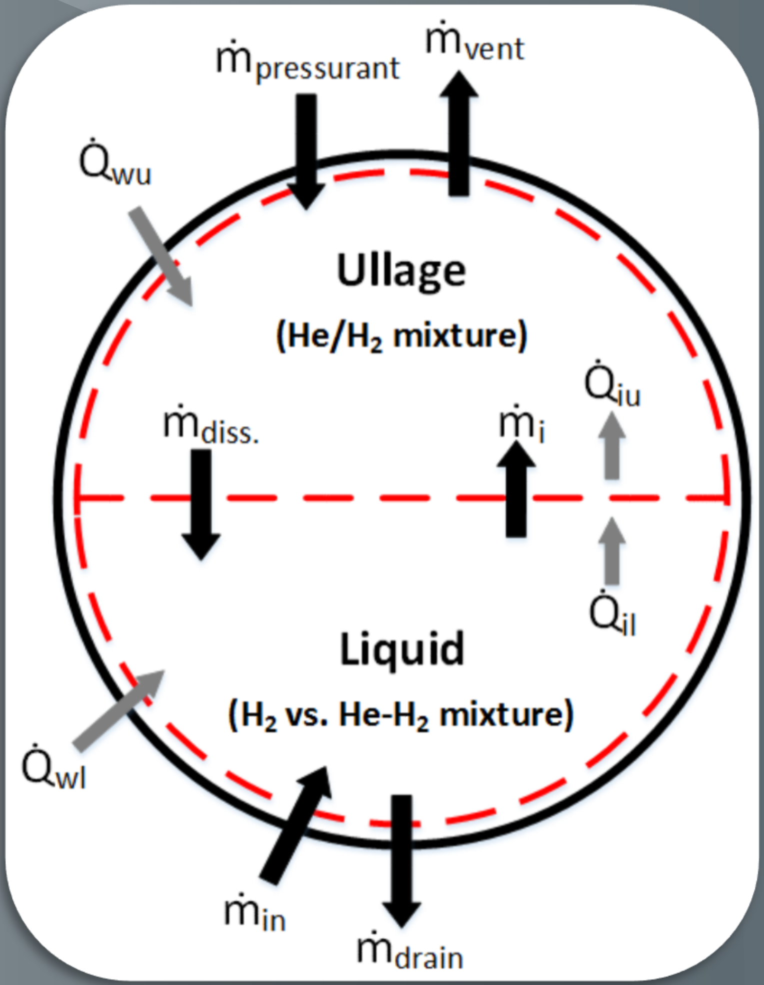


HYPER

Future Work

- Does dissolved helium affect system level design and operation decisions?
  - Compare system performance assuming no helium dissolution and using the new He-H_2 EOS.
- Use new capabilities to develop mixture models for other cryogens (neon-helium, neon-hydrogen, hydrogen-deuterium etc.)

LH_2 storage tank model



Summary

- Conducted the first ever PρT-x measurements of He-H_2 mixtures.
- Developed a reference quality mixture equation of state.
- This EOS will be used to determine if dissolved helium affects system level decisions.
- This work will be continued for other cryogenic mixtures.

Acknowledgements

NASA

- Dr. Stephen Barsi

(NASA – GRC)

National Institute of Standards and Technology

- Dr. Mark McLinden

(NIST – Boulder)

NSTRF Grant NNX14AL59H


THANK
YOU

PρT-x Measurements

Sample #	Temperature [K]	Pressure [PSI]	Density [kg/m^3]	% He [mol %]	% H2 [mol %]
2.1	16.83	141.6	76.34	0.76	99.24
2.2	20.86	159.0	72.18	1.33	98.67
2.3	24.88	154.0	66.63	1.33	98.67
2.4	28.88	156.3	58.81	0.74	99.26
2.5	16.83	310.0	77.30	1.42	98.58
2.6	20.86	303.7	74.05	2.64	97.36
2.7	24.87	311.8	69.17	3.62	96.38
2.8	28.9	305.2	62.04	3.35	96.65
2.9	16.84	44.4	75.43	0.44	99.56
2.10	19.85	51.8	71.96	0.29	99.71
2.11	22.87	55.0	68.21	0.25	99.75