Task 1A: Transport Property Measurements of Pressurized Liquid Oxygen and Liquid Hydrogen

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Start Date = 6/2002
Planned Completion Date = 12/2006

Research Goals and Objectives

- Establish the capability to perform precision (accuracy < 1%) measurements of the transport properties (thermal conductivity & viscosity) and density of cryogenic liquids.
- Conduct transport property measurements on LO_2 and LH_2 in the subcooled liquid regime where the data are sparse or non-existent ($T_{tp} < T < T_{NBP}$ and pressure up to ~ 1 MPa).
- Compare results with existing property data bases (REFPROP)
- Where appropriate, develop improved correlations to describe fluid properties
- Investigate related physical conditions that can affect transport properties

Relevance to Current State-of-the-Art

- Transport property data on LO_2 and LH_2 in the literature are quite old (1960s and 1970s)
- FSU program is the only current effort on measuring cryogen transport properties
- Higher precision in the data sets through improved instrumentation and measurement techniques

Relevance to NASA

- NASA uses LO_2 and LH_2 for propulsion systems for which transport properties are of critical importance
- Many systems use subcooled liquid to increase density, but available data are very limited
- FSU measurement capability could be used for property measurements of other fluids of interest to NASA and other groups

Budget, Schedule and Deliverables

Milestones: (Bold tasks are complete)

• **Complete LH_2 density measurements**	**3/31/05**
• **Attend NASA Review**	**5/10/05**
• **Presented paper at the Space Cryogenics Workshop**	**8/25/05**
• **Complete LO_2 viscosity measurements**	**10/30/05**
• Attend NASA Review	11/1-4/05
• Modify viscosity apparatus for LH_2 measurements	12/1/05
• Complete LH_2 thermal conductivity measurements	12/1/05
• Preliminary LH_2 viscosity data	12/31/05
• Complete LH_2 viscosity data	mid-2006
• Final report	12/31/06

Deliverables:

- Report containing data and analysis of transport properties of subcooled LH_2 & LO_2.
- Description of test apparatus and computational tools developed.
- Copies of all resulting publications.

Budget: $270,000 for 1/1/05 to 12/31/05 to cover staff salaries, equipment and travel.

Accomplishments and Results

LO_2 Measurements

- Density measurements completed. Achieved 0.028% precision in dielectric coefficient (κ) measurements and corresponding liquid density (ρ)
- Thermal conductivity (k) measurements completed to 0.24% precision
- Kinematic viscosity (ν) measurements complete with an error of < 1%

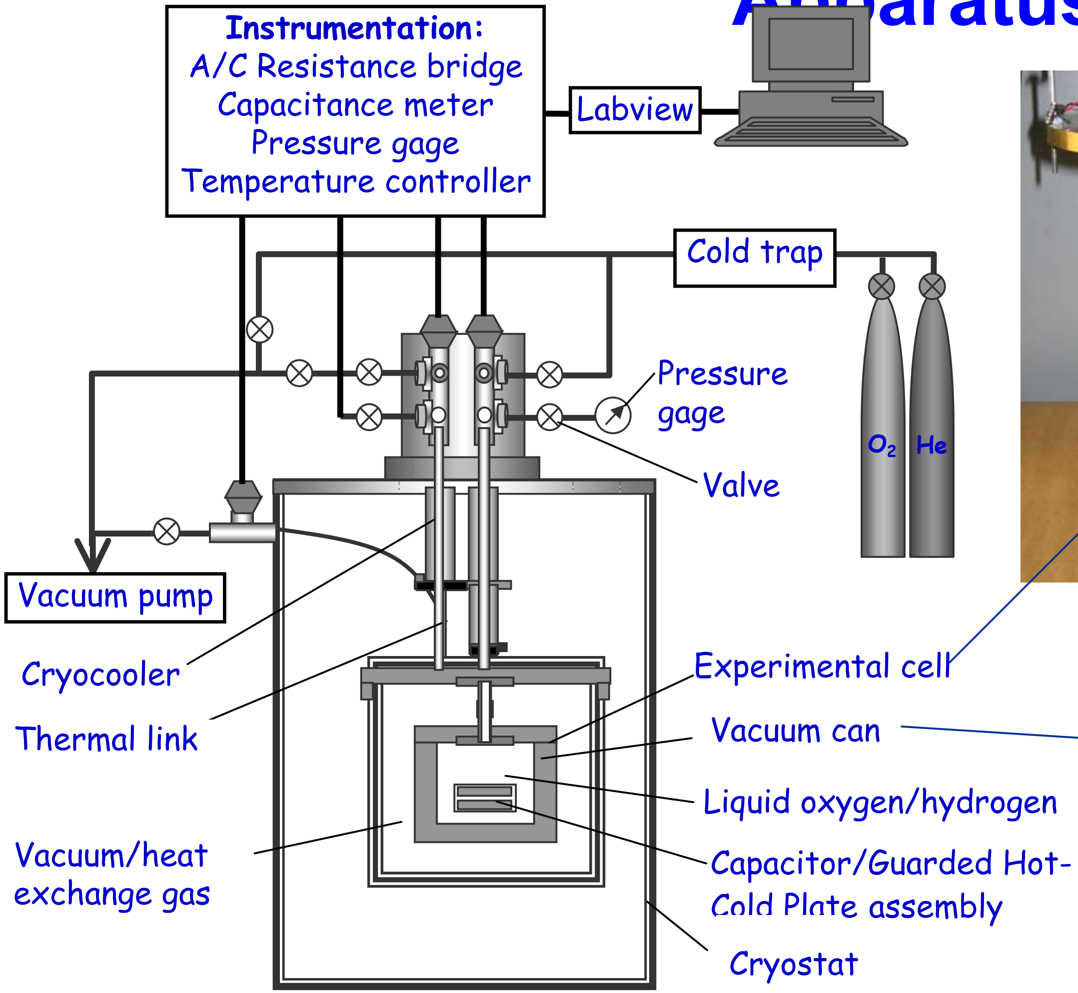
LH_2 Measurements

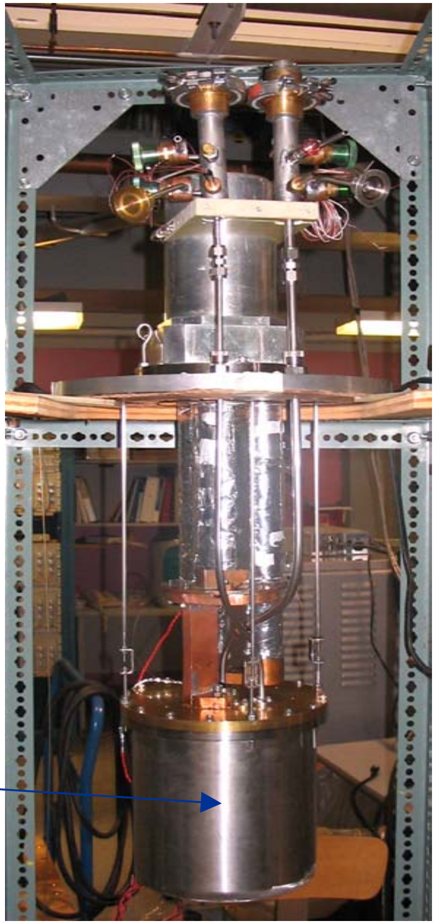
- Ortho-para H_2 converter apparatus completed and tested
- LH_2 density (ρ) measurements complete to 0.11% precision (He solubility in LH_2)
- Preliminary thermal conductivity (k) measurements
- Kinematic viscosity (ν) experiment currently being modified for LH_2 measurements

Other Hydrogen Experiments

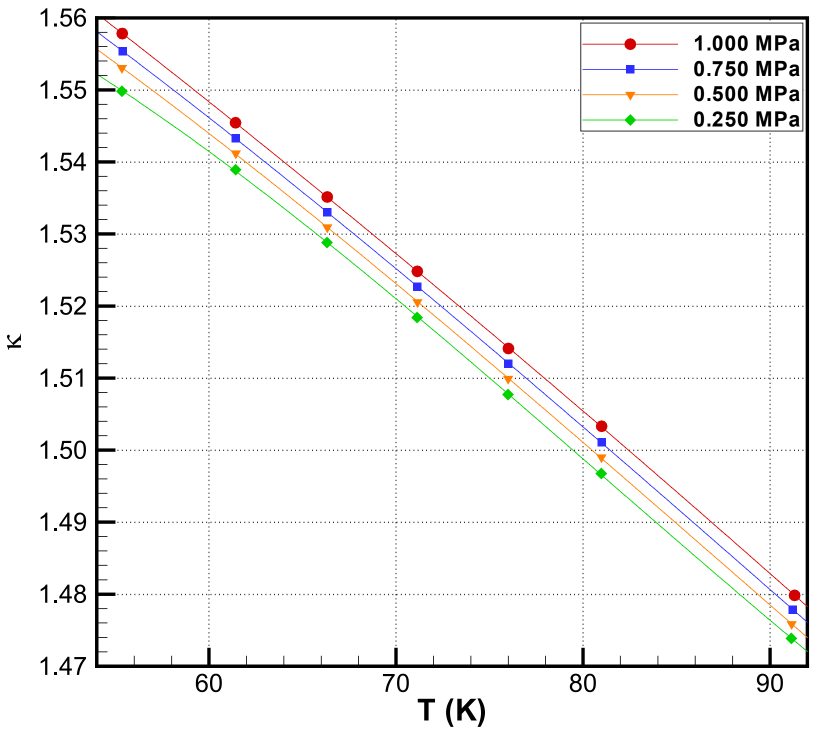
- Performed literature search on He solubility in LH_2 (PVT mass gauging)
- Prototype Acoustic Hydrogen Detector (AHD) developed

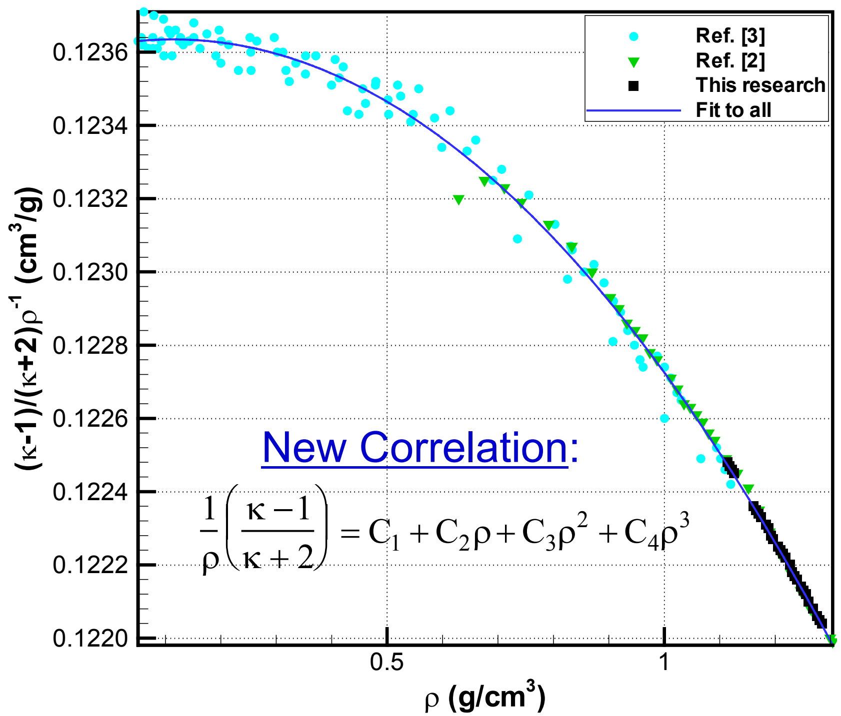
Thermal Conductivity/Density Measurement Apparatus

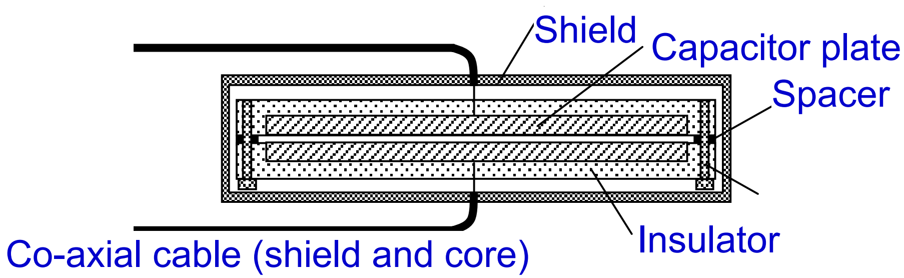




LO_2 Dielectric Coefficient (κ) /Density (ρ)



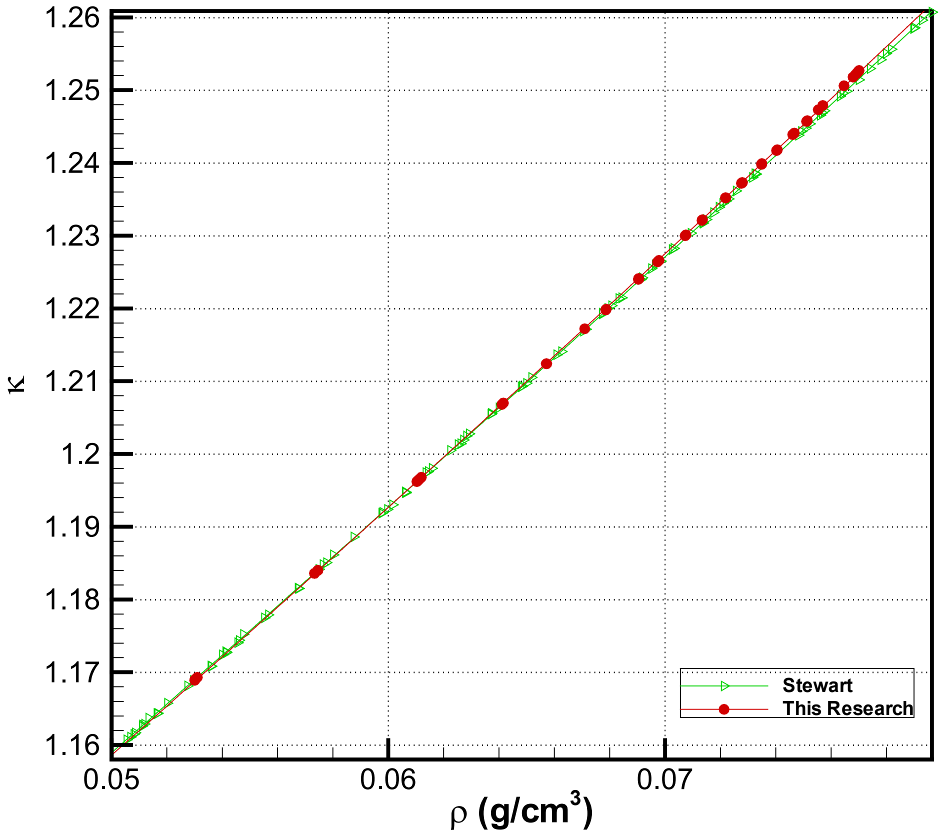




Predicts density of oxygen to better than:

- 0.005% for compressed liquid
- 0.08% for compressed gas
- 0.03% for saturated liquid (except near critical point)

p-H_2 Dielectric Coefficient (κ) Measurement



<u>Measurement Uncertainties</u>

|δP| < 0.001 MPa

|δT| < 0.001 K

|δκ| < 0.0003 (0.025%)

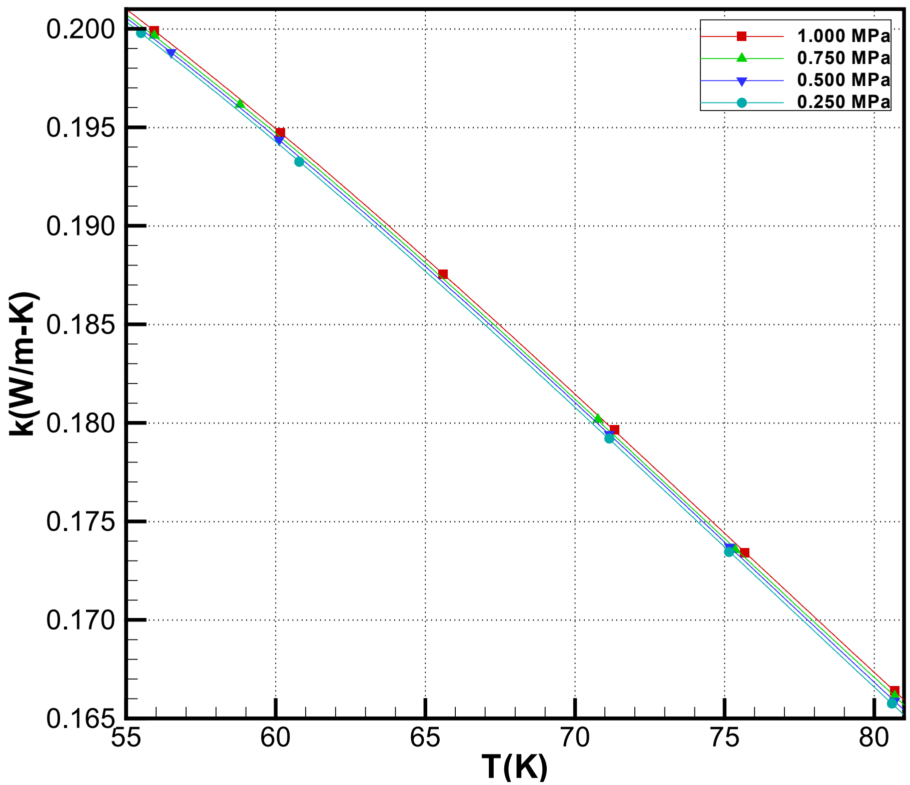
|δρ| < 0.11%

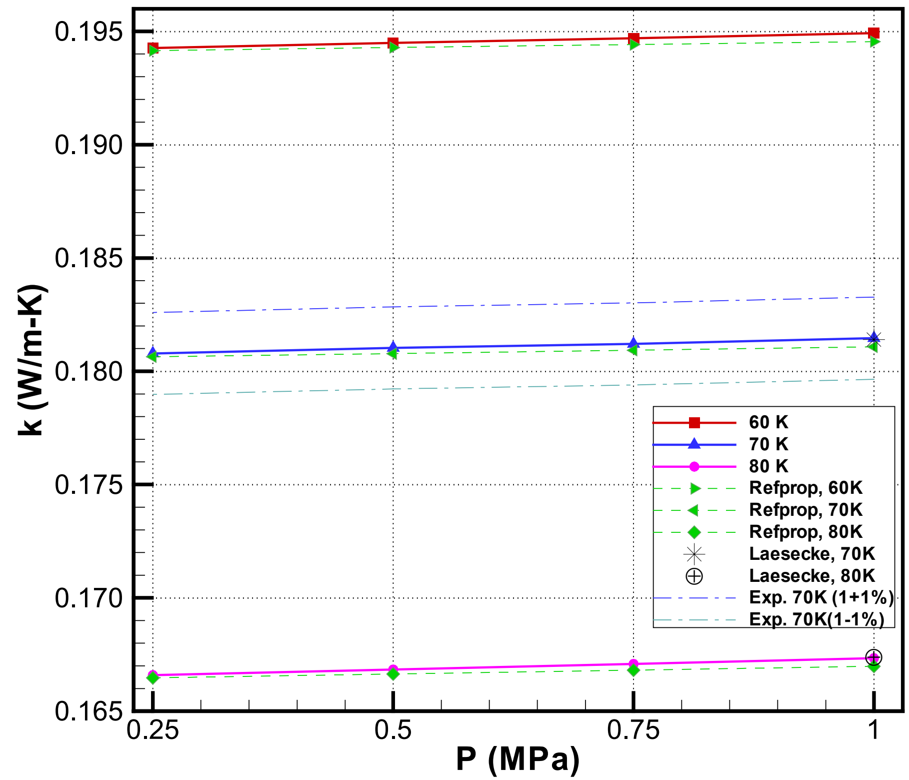
Stewart, J.W., J. Chem. Phy. 1964;40:3297.
T: 24-100 K, P: 0.2-24 MPa

This Research:
T: 14.8-30.6 K, P: 0.2-1 MPa

These results are still being analyzed in terms of Clausius-Mossatti relation vs density

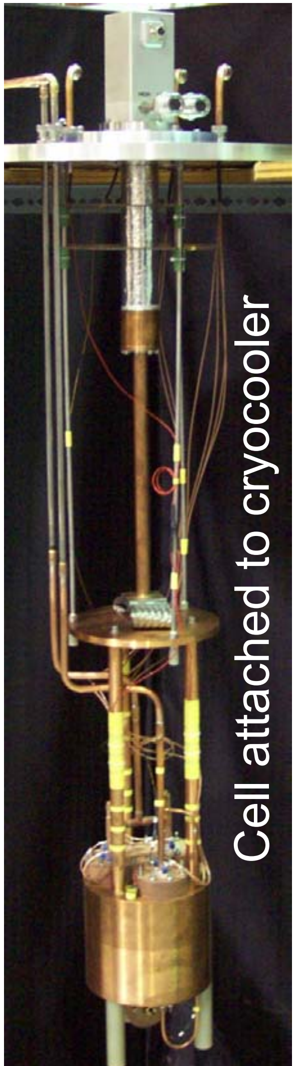
LO_2 Thermal Conductivity (k) Measurements

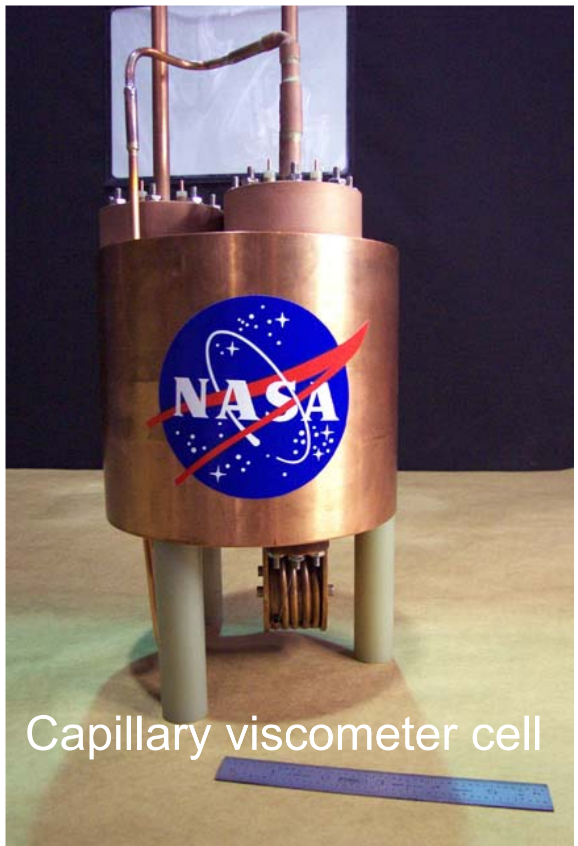


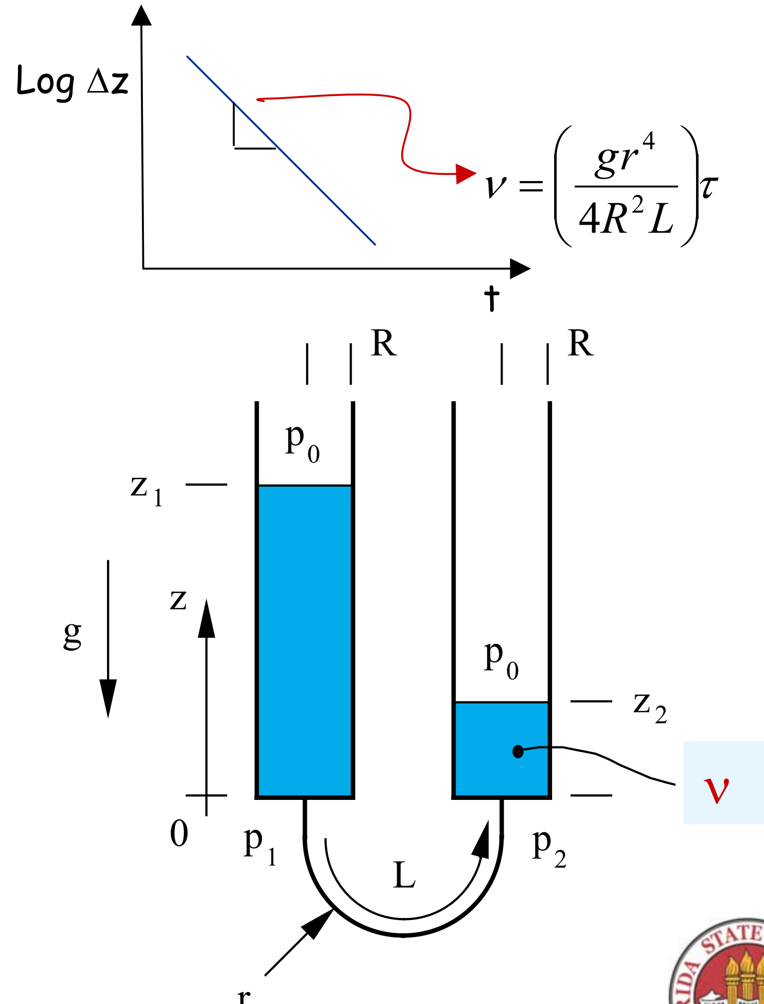


Measurement Uncertainties: $|\delta P| < 0.001$ MPa; $|\delta T| < 0.001$ K; → $|\delta k| < 0.0002$ W/m-K (0.24%)

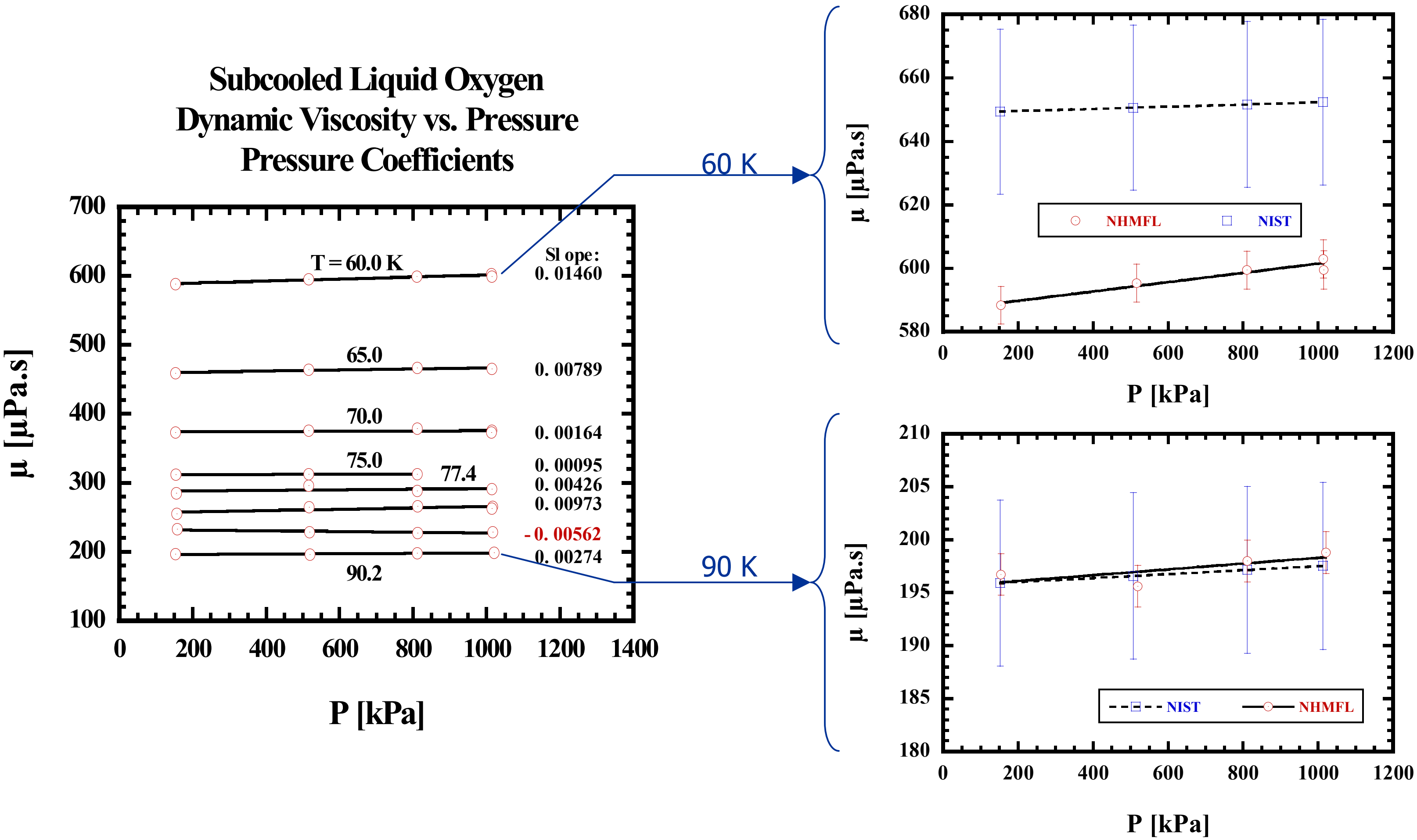
Viscosity Measurement Apparatus





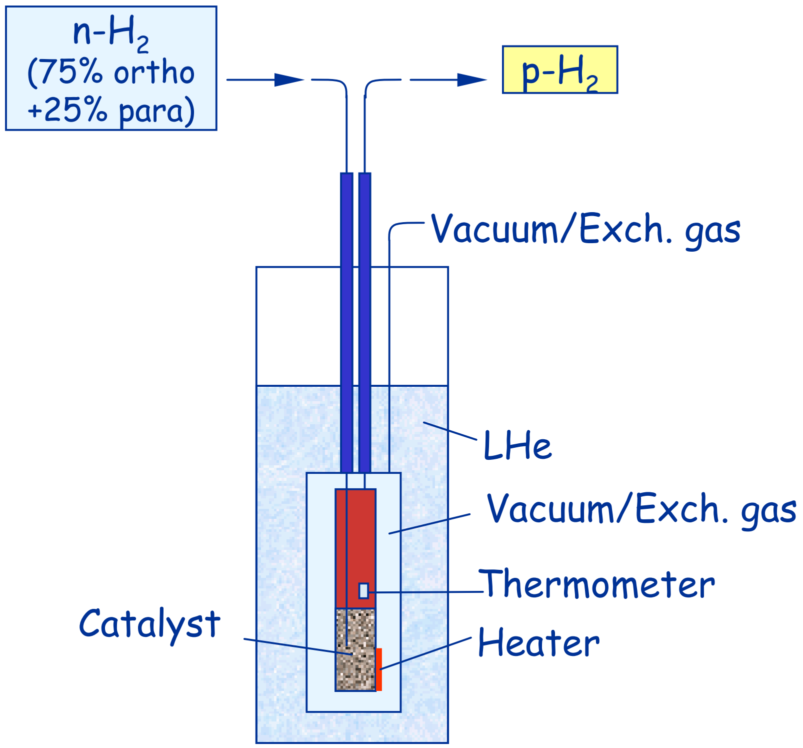


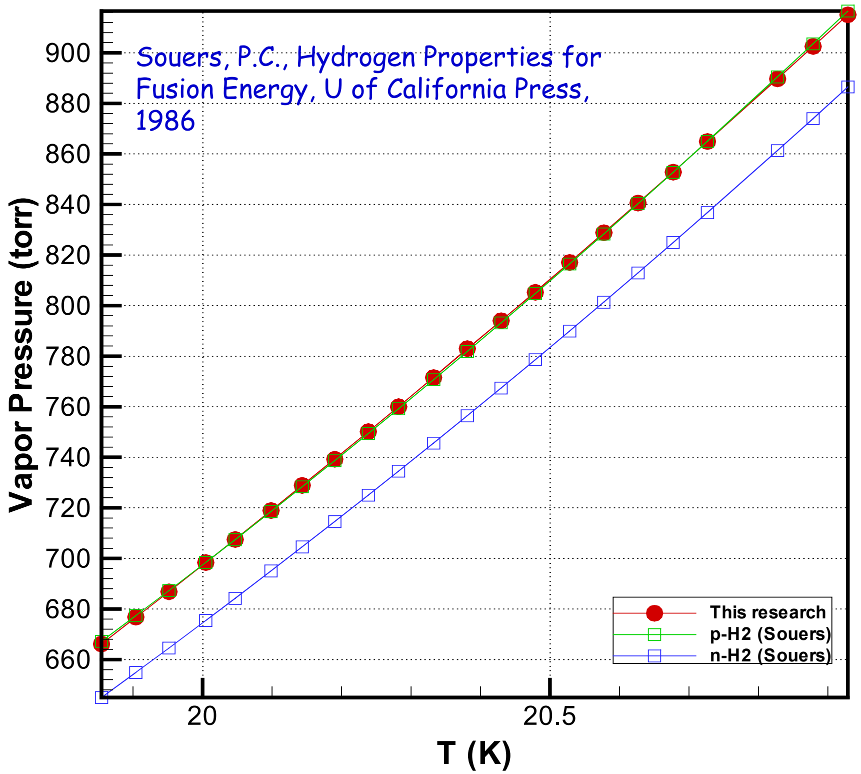
LO_2 Dynamic Viscosity (μ) Results



Comparison to NIST "REFPROP"

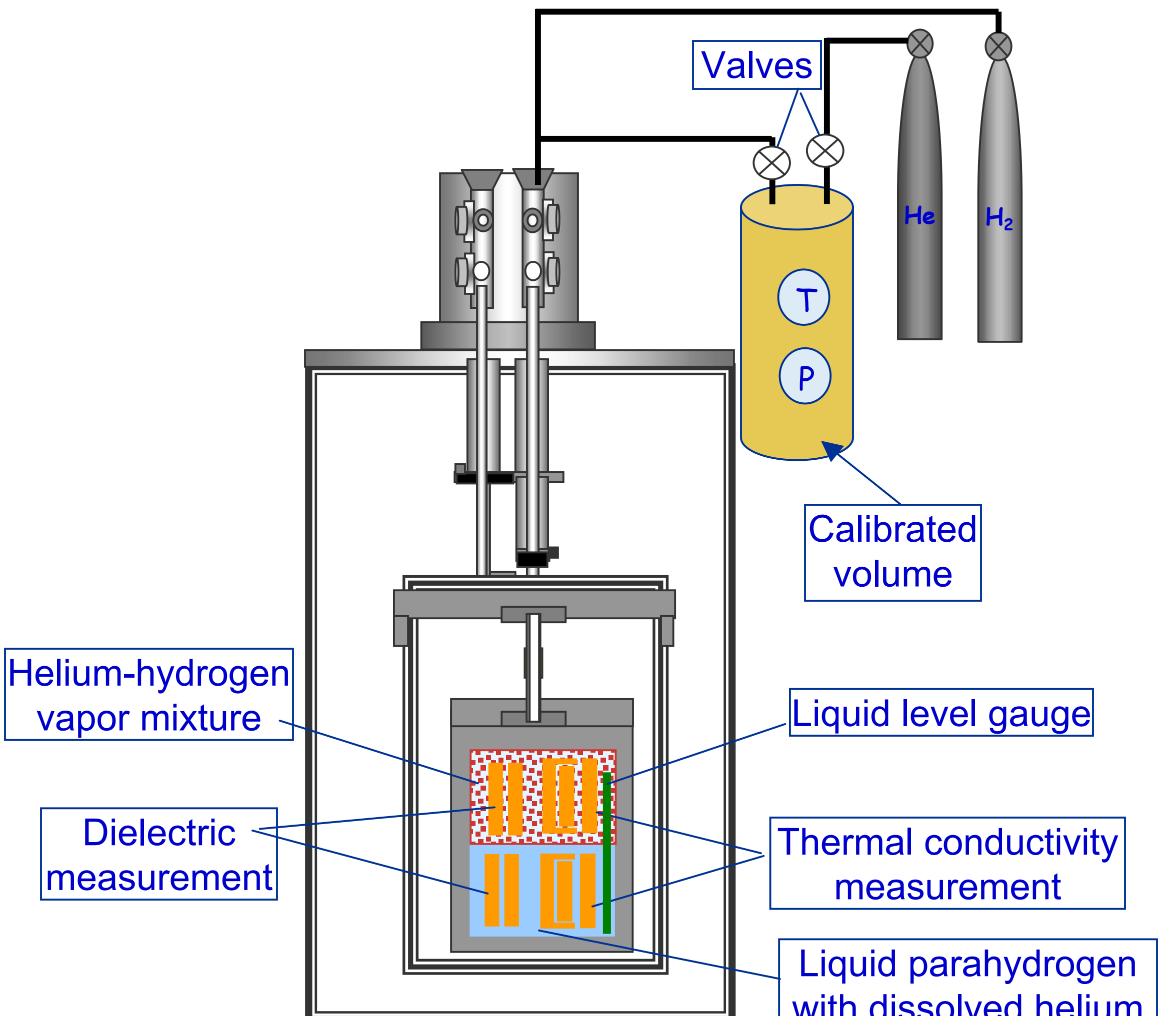
Ortho/Para Conversion of H_2





- Uses hydrous ferric oxide ($Fe(OH)_3$) catalyst
- Ortho/para ratio determined based on ~3% difference in vapor pressures of p-H_2 and n-H_2 (75% ortho + 25% para)

Vapor-Liquid Equilibria in Para-H_2-He System

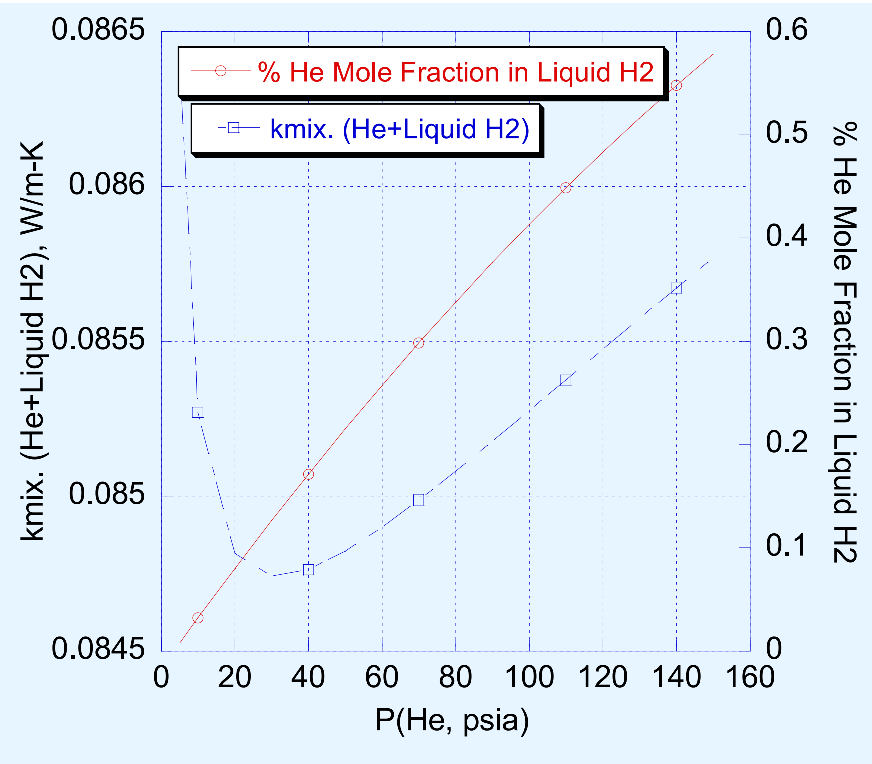


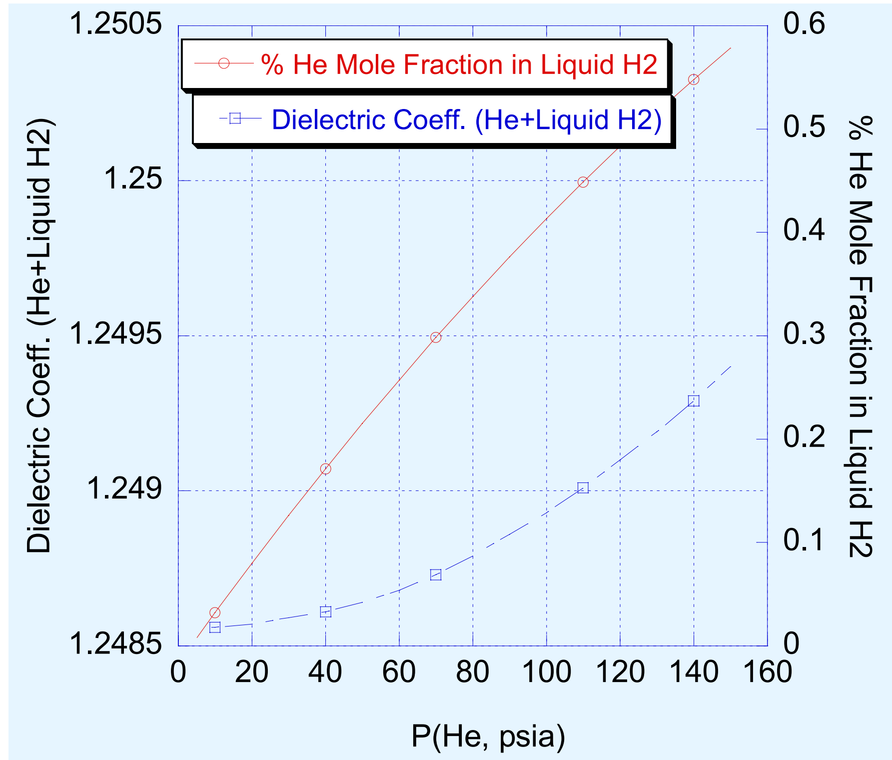
- Vital for the accuracy of PVT mass gauging technique.
- Data does not exist below 20.4 K
- Dielectric coefficient and thermal conductivity measurements both in liquid and vapor…
- Precise measurement of helium gas amount in the experiment
- Combined with appropriate mixing rules give the amount of helium dissolved

Helium Solubility Case Study:

Resolution of the current apparatus: κ to +/-0.0002; k to +/-0.0002 W/m-K

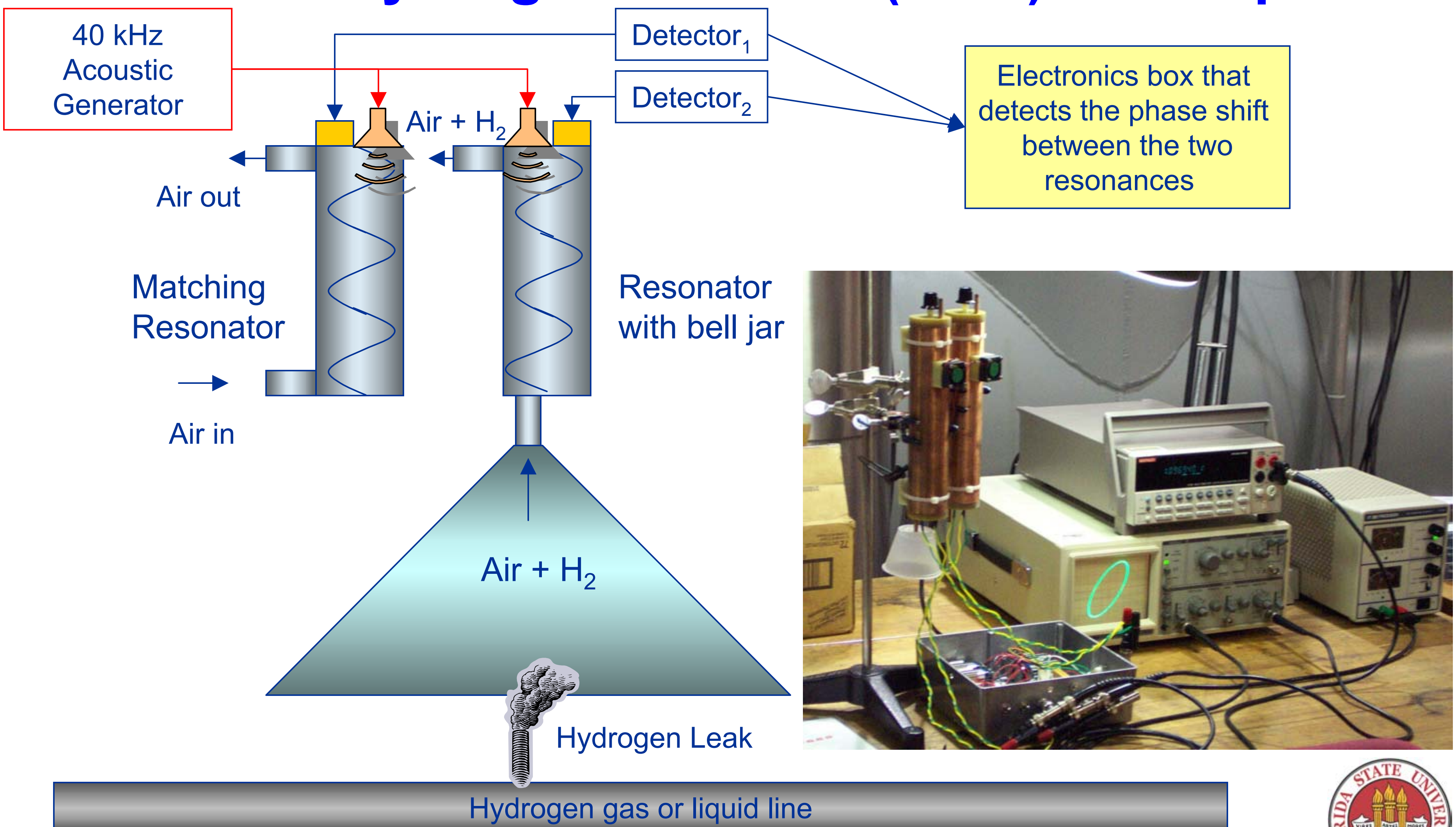
This resolution should be sufficient to determine the He in LH_2



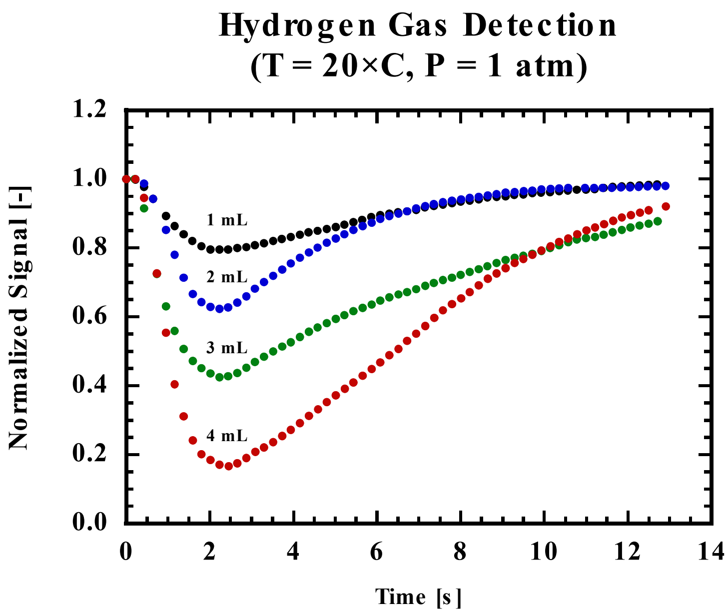


Change in the thermal conductivity and dielectric coefficient as a function of pressure (n-H_2, T=15.50 K, 10<P_{he}<150 psi)

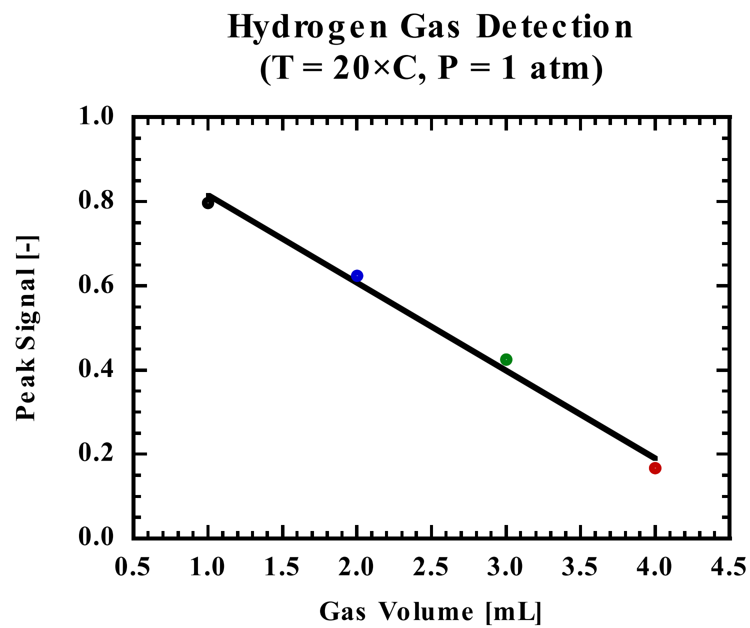
Acoustic Hydrogen Detector (AHD) Development



Acoustic Hydrogen Detector (Test Results)



Response of the AHD to a small quantity of H_2 gas being injected under the collection cone.



Peak signal from the AHD versus H_2 gas injected. Note that the range of sensitivity can be adjusted by collecting the H_2 in the detector

Future Plans (2006)

1. Complete the measurements of the transport properties of LH_2 as originally proposed. Compare results to database codes (REFPROP). Publish results in the literature.
2. Develop capability to measure He solubility in LH_2 using both dielectric constant measurements and thermal conductivity measurements. Compare to PVT measurement of gas injected.
3. Complete development of the Acoustic Hydrogen Detector. Quantify performance for varying leak rates.
4. Seek additional funding to support transport property experiments

Publication & Presentations

- “Thermal Conductivity Measurements of Subcooled Oxygen below 80 K” T. Kucukomeroglu, D. Celik and S.W.Van Sciver. **Advances in Cryogenic Engineering**, ed. by Waynert, J., et. al, Vol. 49, pp. 1123-1129, 2003.
- “Dielectric Coefficient and Density of Subcooled Liquid Oxygen”, Celik, D., Van Sciver, S.W., **Cryogenics** Vol. 45, 356-361 (2005)
- “Thermal Conductivity of Subcooled Liquid Oxygen”, D. Celik and S.W. Van Sciver, **Cryogenics** Vol. 45, 620-625 (2005)
- "Pressurized Rankine Viscometer for Kinematic Viscosity Measurements from 0.1 to 1.0 MPa of Liquefied Gases,” D. K Hilton and S. W. Van Sciver, APS Division of Fluid Dynamics 57th Annual Meeting, 21-23 Nov. 2004, Seattle, WA
- “Ortho and Para Hydrogen Concentration Determination Based on Vapor Pressure”, S.R. Lydzinski, D. Celik, A. Hemmati and S.W. Van Sciver, **Advances in Cryogenic Engineering**, Vol 51A (to be published)
- “High Precision Transport Properties Measurements of Liquid Propellants”, D. Celik, D.K. Hilton and S.W. Van Sciver, 2005 Space Cryogenics Workshop, Colorado Springs, CO, August 24-26, 2005.