Measurements and Modeling Thermophysical Properties of Lubricants

M. L. Huber
National Institute of Standards and Technology
Applied Chemicals and Materials Division
325 Broadway
Boulder, CO 80305 USA

Presentation for SAE E-34 Propulsion Lubricants Committee
Tuesday, September 24, 2019
Denver CO

- **History**
  - 2014 NAVAIR (Naval Air Systems Command) contacted NIST; interested in thermophysical property data for gas turbine engine oil MIL-PRF-23699 (used in most military aircraft and 95% of commercial aircraft)
    - Needed accurate properties to assist in their Modeling and Simulation programs
      - Properties of interest include: viscosity, specific heat, density, thermal conductivity, enthalpy
    - Used software GFSSP (General Fluid System Simulator Program) developed by NASA. Desired ability to incorporate fluid properties for MIL-PRF-23699 into this software.
  - NIST did not have anything available at that time.

- **History**
  - 2015 NIST and NAVAIR entered into an agreement for NIST to provide
    - Highly accurate thermophysical property measurements of 3 pure fluid base stock components (POE5, POE7, POE9).
    - Highly accurate thermophysical property measurements of a fully formulated lubricant meeting MIL-PRF-23699
    - Thermophysical property model within REFPROP software for a fully formulated lubricant.
    - A mini-course for up to 8 participants on the measurement and modeling of thermophysical properties
  - 2018 Work completed and Final report submitted to NAVAIR.

- 2019 Slightly sanitized version made available to the public at https://doi.org/10.6028/NIST.IR.8263

NISTIR 8263

Thermophysical Properties of Polyol Ester Lubricants

Thomas J. Bruno
Tara J. Fortin
Marcia L. Huber
Arno Laesecke
Eric W. Lemmon
Elisabeth Mansfield
Mark O. McLinden
Stephanie L. Outcalt
Richard A. Perkins
Kimberly N. Urness
Jason A. Widegren
Applied Chemicals and Materials Division
Material Measurement Laboratory

This publication is available free of charge from:
https://doi.org/10.6028/NIST.IR.8263

August 2019

U.S. Department of Commerce
Wilbur L. Ross, Jr., Secretary

National Institute of Standards and Technology
Walter Copan, NIST Director and Undersecretary of Commerce for Standards and Technology

- **Measurements Summary**
  - Completed measurements on 3 pure fluids (POE5, POE7, POE9) and the fully formulated lubricant MIL-PRF-23699
    - Thermal decomposition
    - Compressed liquid density (270 – 470 K, to 50 MPa, vib. tube, unc. <0.15%)
    - Ambient pressure density (278 – 343 K, vib. tube, unc. <0.18%)
    - Sound speed (283 – 423 K, up to 70 MPa, pulse-echo apparatus, unc. < 0.04%)
    - Ambient pressure sound speed (278 – 343 K, time of flight, unc. <0.2%
    - Ambient pressure C_p (208 – 503 K; DSC method, 2-3 % unc.)
    - Vapor pressure (gas saturation method, POE5 only)
    - Viscosity (275 – 450 K, up to 137 MPa, oscillating piston viscometer, unc. 5-10%)
    - Thermal conductivity (300 – 500 K, up to 69 MPa, transient hot wire apparatus, unc. 0.5%)
  - All the gory details in NISTIR 8263 https://doi.org/10.6028/NIST.IR.8263

- **Modeling Summary**
  - Use density, C_p, sound speed, p_{sat} data to develop an equation of state (EOS)
    - Can compute all thermodynamic properties from this equation
  - Use viscosity and thermal conductivity data to develop individual correlations for viscosity and thermal conductivity as functions of density and temperature
  - Initially tried to develop a “surrogate” fluid model for the lubricant
    - This had worked well in the past for complex fuels such as jet and rocket fuels, and diesel but did not work so well for the lubricant
  - Successfully developed a pseudo-pure fluid model for the lubricant
    - EOS coefficients and coefficients for viscosity and thermal conductivity correlations are in the NISTIR 8263
    - Much better way to disseminate results - REFPROP
      - “fluid” files are in the NISTIR 8263 or email us

- **REFPROP Model** **https://www.nist.gov/srd/refprop**
  - **REference Fluid Thermodynamic and Transport PROPerties (NIST23) sold by NIST Standard Reference Data**
    - Contains thermophysical properties of industrially important pure fluids (147 at present) and mixtures (up to 20 components)
  - **Easy-to-use computer program**
    - **Can provide tables or graphs of properties of fluids**
      - Thermodynamic properties (density, sound speed, heat capacity, enthalpy, entropy, boiling point, etc.)
      - Transport and other properties (viscosity and thermal conductivity, surface tension)
    - **Easy to add a new "fluid file" for the lubricant MILPRF23699**
      - Just place the MILPRF23699.FLD file (a plain text file) in a specific directory where all files of type .FLD reside, then run the program
  - **Source code (FORTRAN) included**
  - **Can Interface with common applications (Excel, MATLAB, LabView, Python, C/C++, etc.) through wrappers and DLL**
    - Info on wrappers here: https://github.com/usnistgov/REFPROP-wrappers

Results for MIL-PRF-23699

Developed a Helmholtz-form EOS
All thermodynamic properties come from the EOS

$$\frac{\alpha(\rho,T)}{RT} = \alpha(\delta,\tau) = \alpha^0(\delta,\tau) + \alpha^r(\delta,\tau) \qquad \delta = \rho/\rho_c \qquad \tau = T_c/T$$

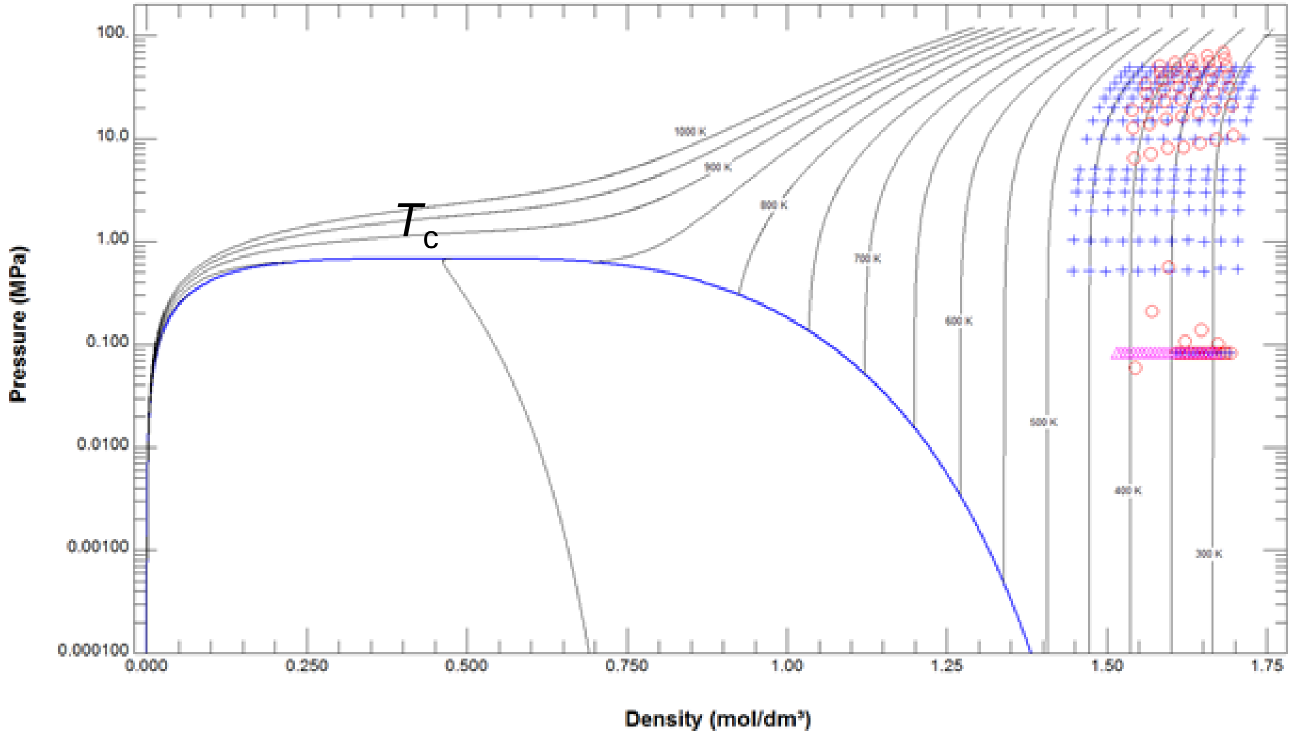
$$\alpha^0 = \frac{h_0^0 \tau}{RT_c} - \frac{s_0^0}{R} - 1 + \ln\frac{\delta\tau_0}{\delta_0\tau} - \frac{\tau}{R}\int_{\tau_0}^{\tau}\frac{c_p^0}{\tau^2}\mathrm{d}\tau + \frac{1}{R}\int_{\tau_0}^{\tau}\frac{c_p^0}{\tau}\mathrm{d}\tau$$

$$\alpha^r(\delta,\tau) = \sum N_k \delta^{d_k}\tau^{t_k} + \sum N_k \delta^{d_k}\tau^{t_k}\exp\left(-\delta^{l_k}\right) + \sum N_k \delta^{d_k}\tau^{t_k}\exp\left(-\eta_k(\delta-\varepsilon_k)^2 - \beta_k(\tau-\gamma_k)^2\right)$$

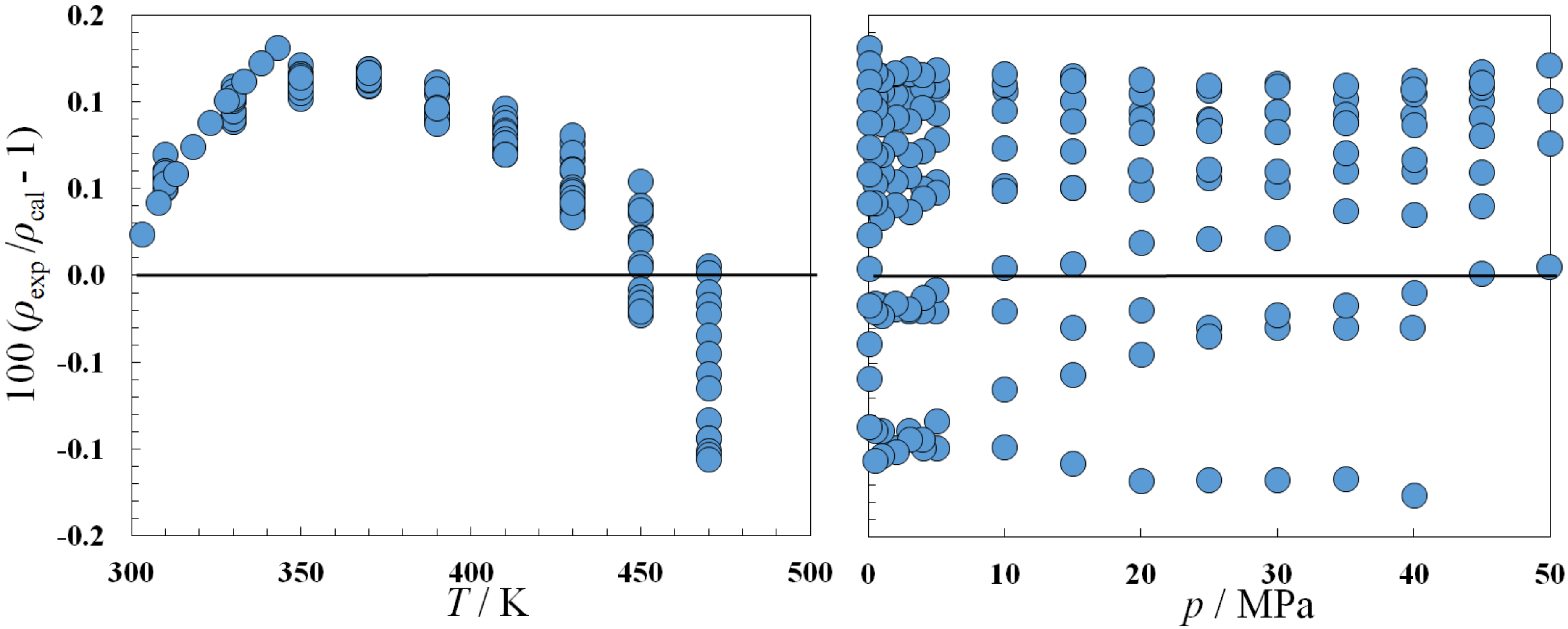
Uncertainties:
- density 0.2%
- sound speed 0.1%
- C_p 0.3%

Note on developing EOS

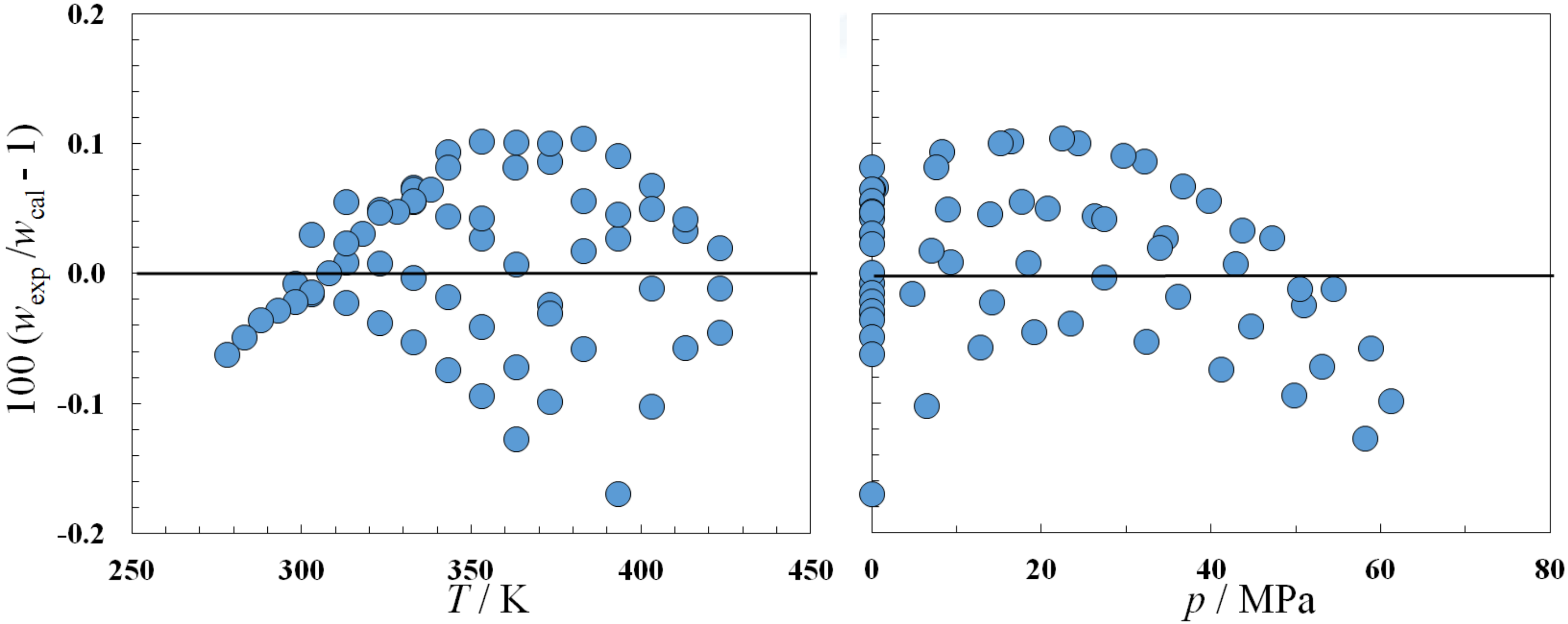
- Measurements, although seeming comprehensive, do not cover the entire fluid space
- Use a set of constraints during development to ensure appropriate behavior over entire fluid surface



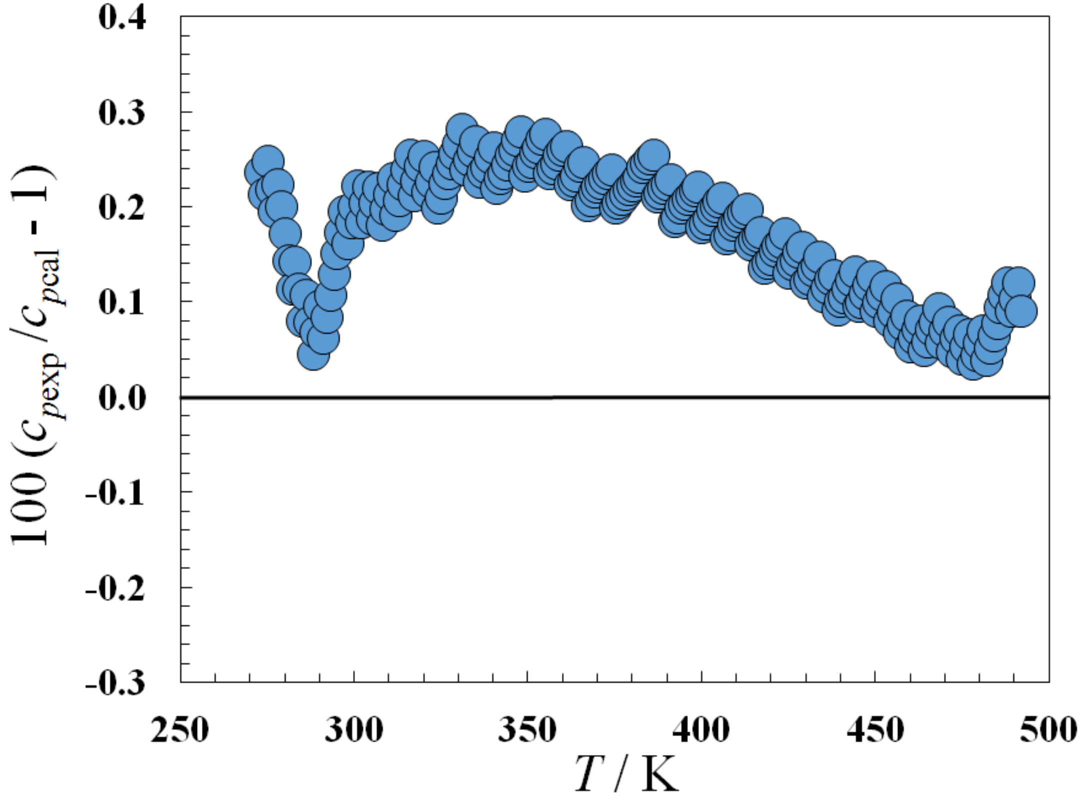
Results for MIL-PRF-23699: density



Results for MIL-PRF-23699: speed of sound

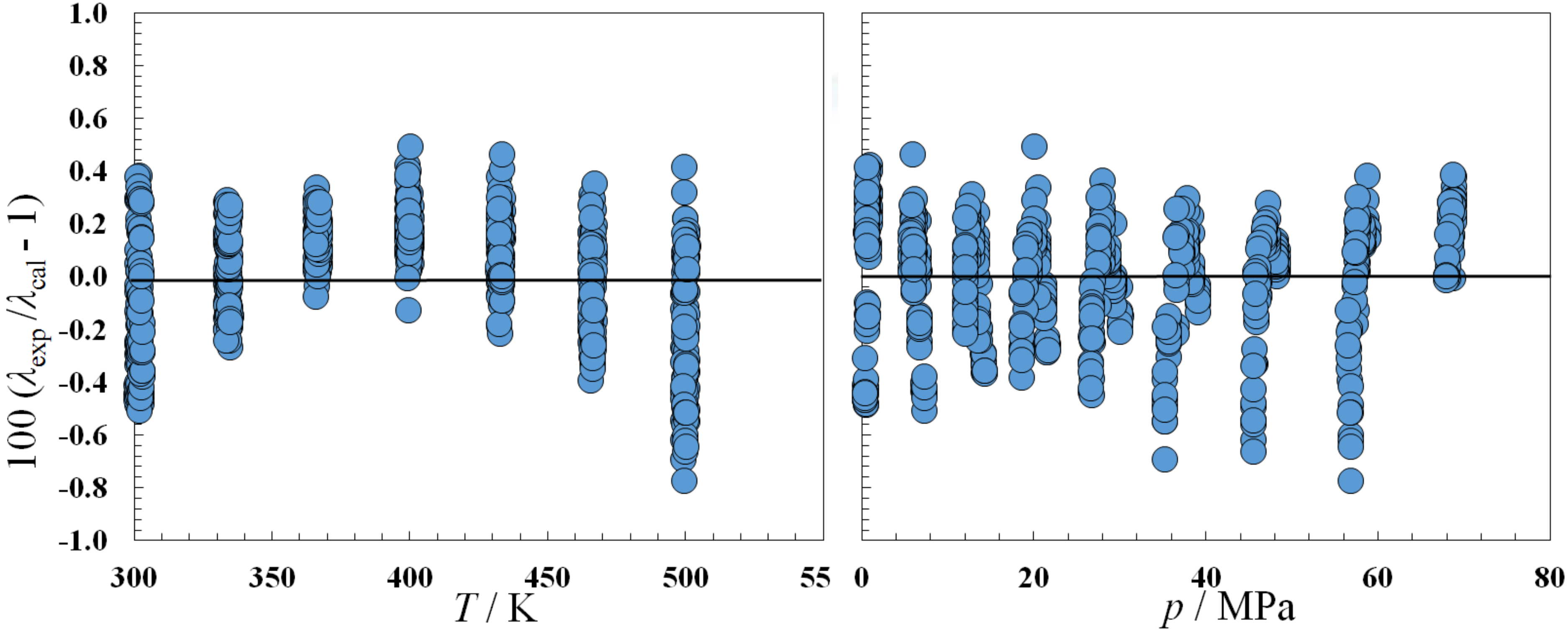


Results for MIL-PRF-23699: heat capacity



All measurements at ambient pressure (0.083 MPa)

Results for MIL-PRF-23699: thermal conductivity

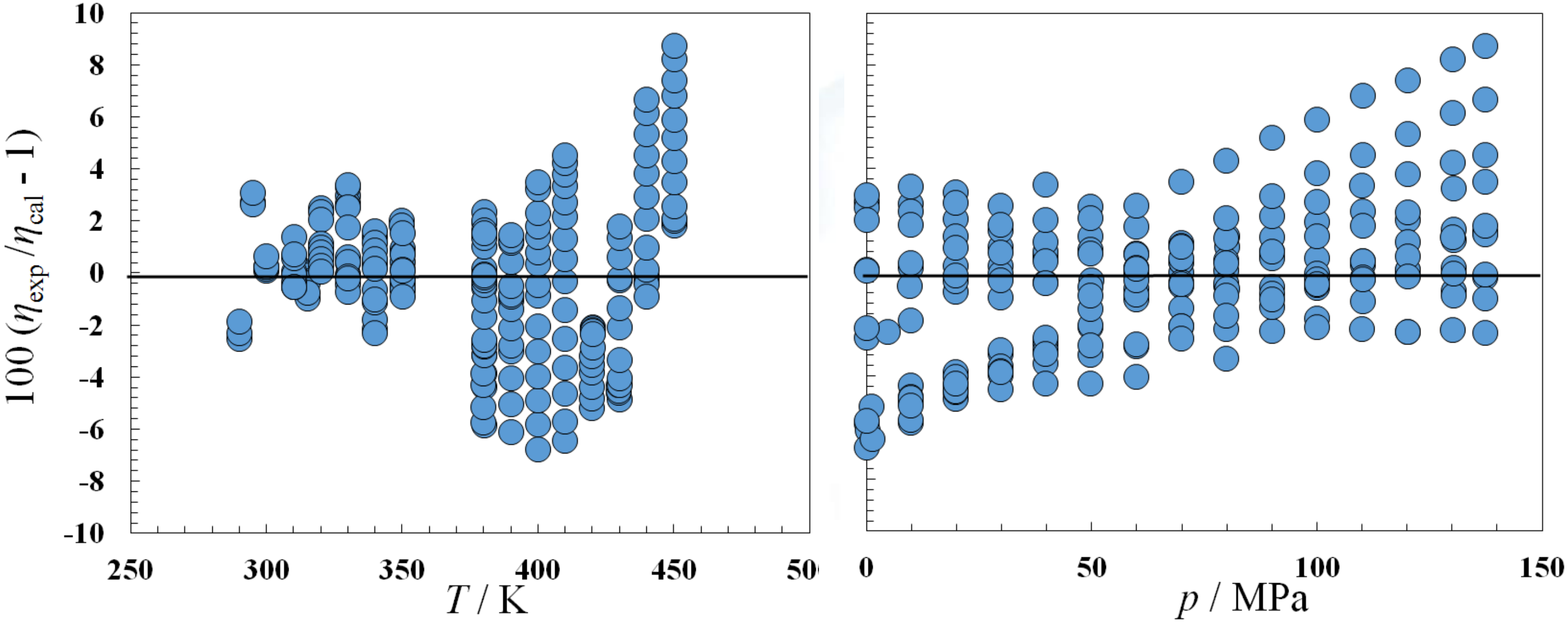


$$\lambda(T_r, \rho_r) = \lambda^0(T_r) + \Delta\lambda^{res}(T_r, \rho_r) + \lambda^{crit}(T_r, \rho_r),$$

$$\lambda^0(T_r) = \sum_{k=0}^{n} \alpha_k T_r^k \qquad \Delta\lambda^{res}(T, \rho) = \sum_{l=1}^{3} (\beta_{1,l} + \beta_{2,l}(T/T_c))(\rho/\rho_c)^l$$

$\lambda^{crit}(T_r, \rho_r)$ found with generalized method f(T_c, ρ_c, p_c, MW, ω)

Results for MIL-PRF-23699: viscosity



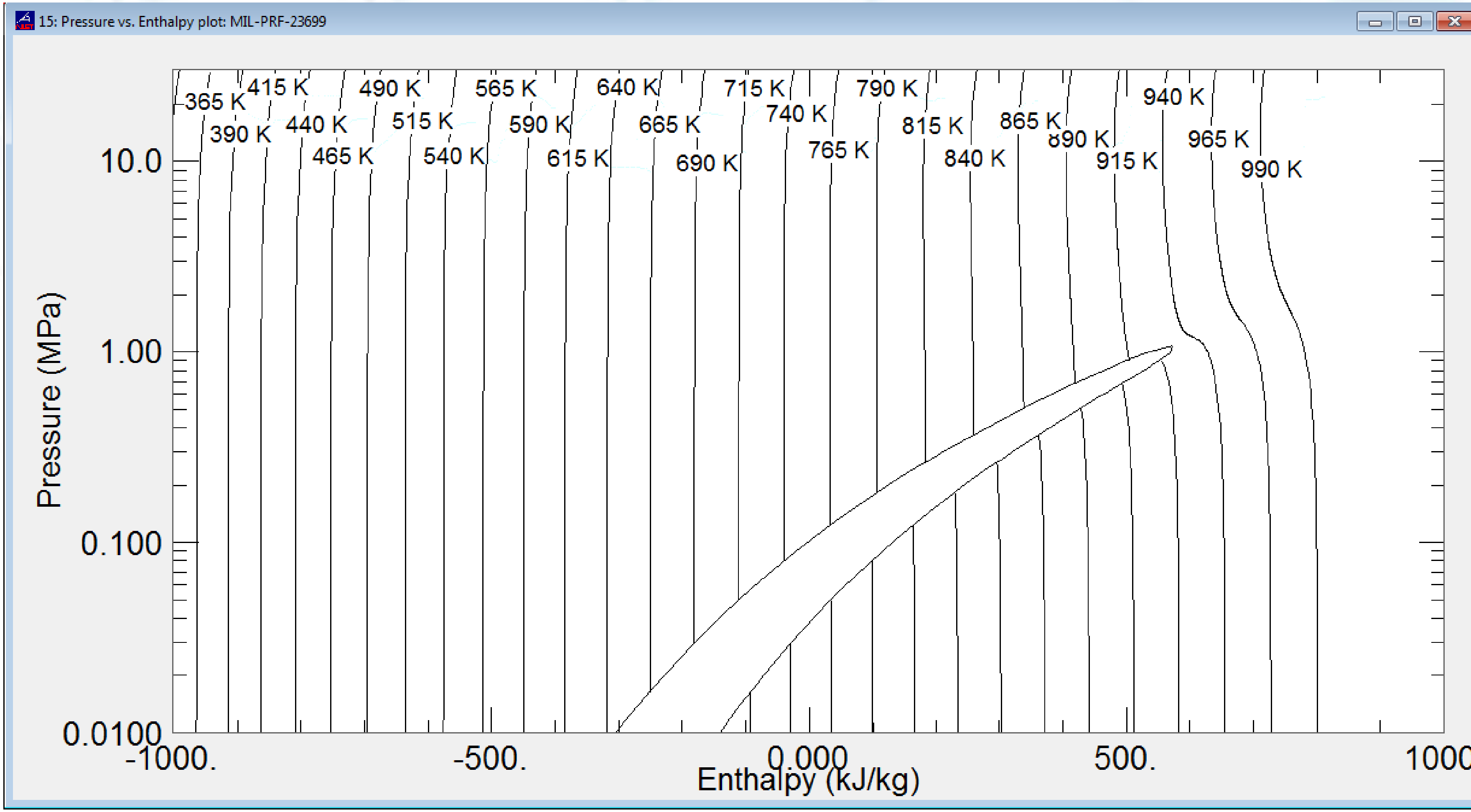
$$\eta(\rho_r, T_r) = \eta_0(T_r) + \Delta\eta(\rho_r, T_r) + \Delta\eta_c(\rho_r, T_r)$$

$\eta_0(T_r)$ found from method of Chung *et al.* (1988)

$$\Delta\eta(\rho_r, T_r) = (a_1\Gamma + a_2\Gamma^2 + a_3\Gamma^3 + a_4\Gamma^{11})\sqrt{T_r}\rho_r^{2/3} \quad \Gamma = \rho_r^{3.36}/T_r,$$

$\Delta\eta_c(\rho_r, T_r)$ set to zero

Results for MIL-PRF-23699: PH chart generated by REFPROP



Results for MIL-PRF-23699: tables generated by REFPROP

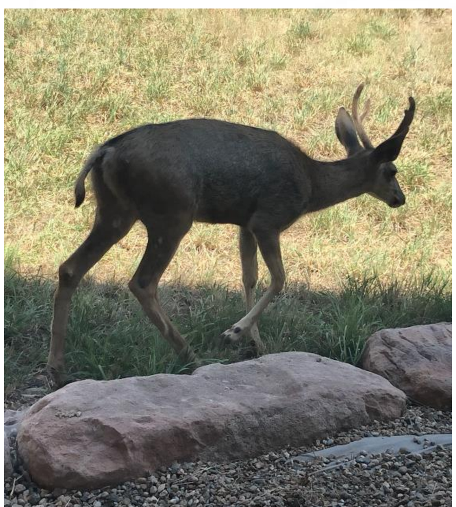
16: MIL-PRF-23699: Specified state points

	Temperature (K)	Pressure (MPa)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Cp (kJ/kg-K)	Sound Speed (m/s)	Therm. Cond. (W/m-K)	Viscosity (mPa-s)
1	315.02	79.941	1018.8	-998.87	-2.0982	1.8429	1618.9	0.16236	75.570
2	315.02	69.898	1014.2	-1006.8	-2.0920	1.8417	1585.8	0.16033	66.052
3	315.01	59.865	1009.4	-1014.7	-2.0856	1.8407	1551.5	0.15824	57.548
4	315.00	49.827	1004.4	-1022.6	-2.0791	1.8399	1515.7	0.15606	49.937
5	315.01	39.787	999.12	-1030.5	-2.0722	1.8394	1478.2	0.15378	43.113
6	315.01	29.759	993.56	-1038.3	-2.0651	1.8391	1438.9	0.15140	37.079
7	315.02	19.733	987.66	-1046.1	-2.0577	1.8393	1397.6	0.14889	31.726
8	300.01	0.051000	986.76	-1088.6	-2.1311	1.8010	1358.2	0.14580	44.160
9	300.02	9.7320	992.84	-1081.1	-2.1388	1.8001	1401.4	0.14832	52.491
10	300.03	19.737	998.75	-1073.3	-2.1464	1.7998	1443.6	0.15078	62.320
11	300.04	29.740	1004.3	-1065.5	-2.1537	1.7998	1483.6	0.15312	73.505
12	300.04	39.759	1009.6	-1057.7	-2.1608	1.8002	1521.7	0.15535	86.240
13	310.09	0.030000	978.77	-1070.3	-2.0711	1.8279	1324.9	0.14429	28.114
14	310.08	9.7170	985.13	-1062.9	-2.0790	1.8267	1369.3	0.14694	33.178
15	310.08	19.721	991.28	-1055.1	-2.0866	1.8262	1412.4	0.14952	39.115
16	310.07	29.725	997.07	-1047.4	-2.0940	1.8260	1453.3	0.15196	45.881
17	310.07	39.748	1002.5	-1039.5	-2.1011	1.8263	1492.2	0.15430	53.533
18	310.08	49.776	1007.7	-1031.7	-2.1079	1.8269	1529.3	0.15653	62.136
19	310.07	59.807	1012.7	-1023.8	-2.1146	1.8277	1564.9	0.15867	71.862
20	310.08	69.868	1017.4	-1015.9	-2.1210	1.8288	1599.1	0.16073	82.712
21	310.08	79.917	1021.9	-1008.0	-2.1272	1.8300	1632.0	0.16271	94.839
22	290.04	0.064000	994.74	-1106.4	-2.1915	1.7750	1392.0	0.14725	72.968
23	290.05	4.7480	997.61	-1102.8	-2.1953	1.7747	1412.7	0.14843	79.603

Conclusions

- We developed, based on our experimental measurements, models for the thermophysical properties of MIL-PRF-23699 (and 3 pure POE's)
  - including *p*, density, *T*, heat capacity, sound speed, vapor pressure, enthalpy, entropy, viscosity, thermal conductivity
- Models implemented in easy-to-use computer program REFPROP
- Details and REFPROP-compatible files in freely available publication https://doi.org/10.6028/NIST.IR.8263

Questions?




DEPARTMENT OF COMMERCE
BOULDER LABORATORIES
325 BROADWAY
NTIA
NIST