

All data taken at the Pacific Northwest National Laboratory

FTS Operators: Tracy J. Baker

Data Analysis: Tracy J. Baker, Oliva M. Primera-Pedrozo and Russel G. Tonkyn

**Composite spectrum for: Tetraethylene glycol**

- First Column: Position in wavenumber ( $\text{cm}^{-1}$ )
- Second column: Real refractive index  $n(\tilde{\nu})$  (dispersion index)
- Third column: Imaginary refractive index,  $k(\tilde{\nu})$  (absorption index per unit length in centimeters)

Where the complex refractive index  $\hat{n} = n(\tilde{\nu}) + ik(\tilde{\nu})$

Following Bertie (in the references below) we define the absorbance as  $A = -\log_{10}(I/I_0)$  and the linear absorption coefficient  $K = A/d$ , where  $d$  is the path length. The connection between the imaginary refractive index and the absorbance coefficient arises from the following:  $2.303K = 4\pi\tilde{\nu}k$

See the following references for a detailed description of terms and units:

- 1) Bertie, J. E., Zhang, S. L., Eysel, H. H., Baluja, S., & Ahmed, M. K. (1993). Infrared Intensities of Liquids XI: Infrared Refractive Indices from 8000 to  $2\text{ cm}^{-1}$ , Absolute Integrated Intensities, and Dipole Moment Derivatives of Methanol at  $25^\circ\text{C}$ . *Appl. Spec.*, 47(8), 1100-1114 doi:10.1366/0003702934067973
- 2) Bertie, J. E., Zhang, S. L., & Keefe, C. D. (1995). Measurement and use of absolute infrared absorption intensities of neat liquids. *Vibrational Spectroscopy*, 8(2), 215-229. doi:10.1016/0924-2031(94)00038-i

**Sample:**

- Chemical name, formula and CAS number: Tetraethylene glycol,  $\text{C}_4\text{H}_{10}\text{O}_2$ , [112-60-7]
- IUPAC name: 2-[2-[2-(2-Hydroxyethoxy)ethoxy]ethoxy]ethanol
- Synonyms: Tetraglycol
- Physical properties: FW = 194.2 g/mole; mp =  $-9.4^\circ\text{C}$ ; bp =  $327^\circ\text{C}$ ; vp = 0.00005 Torr;  $\rho = 1.12\text{ g/cm}^3$
- Supplier and stated purity: Aldrich, 99% (Lot # STBJ5189)
- Temperature of sample:  $25^\circ\text{C}$  ( $\pm 1^\circ\text{C}$ )
- Individual samples were measured at the following path lengths: MIR: 5.75, 6.27, 6.56, 9.10, 9.58, 10.9, 15.0, 19.2, 23.8, 49.6, 99.5, 182 and 471 micrometers ( $\mu\text{m}$ ); NIR: 106, 205, 502, 989, 2076 and 4193  $\mu\text{m}$ . Final data are a composite of these spectra.
- Sample cell window material: MIR = Calcium fluoride ( $\text{CaF}_2$ ) except zinc selenide ( $\text{ZnSe}$ ) for the 5.75, 6.56, 9.10 and 10.9  $\mu\text{m}$  cells. NIR = Potassium chloride ( $\text{KCl}$ ) except potassium bromide ( $\text{KBr}$ ) for the 106 and 989  $\mu\text{m}$  cells.
- Preparation: None

**NIR Instrument Parameters:**

- Bruker Vertex 70, purged with UHP nitrogen
- Spectral range: 10,000 to  $400\text{ cm}^{-1}$  (1.0 to 25 microns)
- NIR source: Quartz tungsten bulb
- Beamsplitter: Broadband potassium bromide ( $\text{KBr}$ )
- Detector: DLTGS at room temperature
- Aperture: 3 mm
- Folding limits: 31597.6 to  $0\text{ cm}^{-1}$

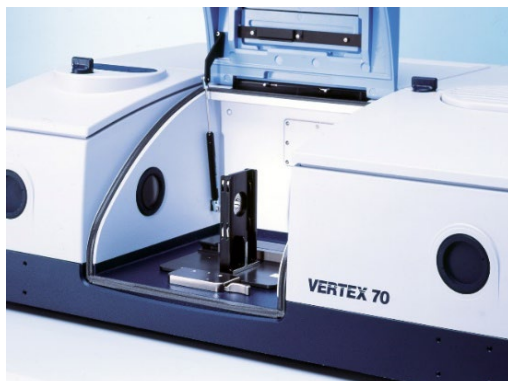
**MIR Instrument Parameters:**

- Tensor II with sample stage rotated 6 degrees, purged with UHP nitrogen
- Spectral range: 7,800 to  $400\text{ cm}^{-1}$  (1.282 to 25 microns)
- IR source: Silicon carbide glow bar
- Beamsplitter: Potassium bromide ( $\text{KBr}$ )
- Detector: DTGS at room temperature
- Aperture: 3 mm
- Folding limits: 11664.14 to  $0\text{ cm}^{-1}$

### NIR/MIR Instrument Parameters:

- Instrument resolution:  $2.0\text{ cm}^{-1}$
- Number of interferograms averaged per single channel spectrum: 128
- Apodization: Norton-Beer, Medium
- Phase correction: Mertz
- Scanner velocity: 10 kHz; 7.5 kHz (MIR)
- Interferogram zerofill: 4x
- Spectral interval after zerofilling:  $0.4822\text{ cm}^{-1}$

a)



b)



Figure 1: The Bruker Vertex 70 FTIR (a) and Tensor II (b).

### Measured Refractive Index:

The refractive index for 2-Methylcyclohexanol was measured at  $25\text{ }^{\circ}\text{C}$  using an Atago model DR-M2/1550 Abbe refractometer. Notch filters were employed in front of a white light source to make measurements at multiple wavelengths. An infrared viewer from Atago was used to detect signal at  $1550\text{ nm}$ . The temperature was controlled to match that in the sample compartment of the FTIR using a heated circulating bath.

480 nm:	$n = 1.4633$	486 nm:	$n = 1.4629$	546 nm:	$n = 1.4592$
589 nm:	$n = 1.4572$	644 nm:	$n = 1.4554$	656 nm:	$n = 1.4551$
1550 nm:	$n = 1.4389$				

The refractive index,  $n$ , vs. wavelength in microns,  $\lambda$ , was fit to an equation similar to that of Sellmeier:

$$n(\lambda) = \{a + b/(\lambda^2 - c)\}^{1/2}$$

The resulting best-fit equation was used to find the refractive index at the highest energy data points in our experimental spectra. For 2-Methylcyclohexanol the results were

$$\begin{aligned} n(7,800\text{ cm}^{-1}) &= 1.4412 \text{ at } 25\text{ }^{\circ}\text{C} \text{ for MIR data and} \\ n(10,000\text{ cm}^{-1}) &= 1.4452 \text{ at } 25\text{ }^{\circ}\text{C} \text{ for NIR and merged data.} \end{aligned}$$

### Post Processing and Related Parameters:

For the MIR, a composite spectrum was created from 15 absorbance spectra (base-10) taken at 15 path lengths: 5.75, 6.27, 6.56, 9.10, 9.58, 10.9, 15.0, 19.2, 23.8, 49.6, 99.5, 182 and 471 micrometers ( $\mu\text{m}$ ). These data were collected with the sample stage rotated by  $6^\circ$  to minimize artifacts resulting from back-reflection into spectrometer (see Johnson et al., *Appl. Spectrosc.*, 76(5) 620-624, 2021). For the NIR, a composite spectrum was created from 5 absorbance spectra (base-10) taken at 5 path lengths: 106, 205, 502, 989, 2076 and 4193  $\mu\text{m}$ . At each path length several spectra were measured and the results averaged for better signal to noise. The measured cell lengths were adjusted using Beer's law plots in which the NIR and MIR data were analyzed independently.

- 1) The imaginary part of the refractive index, or  $k$  vector, was determined for each absorbance file as per Bertie's program "RNJ46A" (see reference above). This takes into account the reflective losses due to the  $\text{BaF}_2$ ,  $\text{ZnSe}$  and/or  $\text{Qz}$  windows.
- 2) A composite  $k$  vector is created via a classical, weighted, linear, least squares fit using the output files of program "RNJ46A": Intercept=0, slope is fitted, individual absorbance values weighted by  $T^2$  (transmission squared), all absorbance values  $\geq 2.5$  are given zero weight. For the MIR  $\text{CaF}_2$  data, five composite vectors were created and merged by hand.
  - a) The first  $k$  vector used the results from the 182 and 471  $\mu\text{m}$  cells. This  $k$  vector determined the final values for the range from 7800 to 3700  $\text{cm}^{-1}$ .
  - b) The second  $k$  vector used the results from the 15.0 and 19.2  $\mu\text{m}$  cells. This  $k$  vector determined the final values for the range from 3700 to 2980  $\text{cm}^{-1}$  and 1500 to 1150  $\text{cm}^{-1}$ .
  - c) The third  $k$  vector used the results from the 6.27, 9.58 and 15.0  $\mu\text{m}$  cell. This  $k$  vector determined the final values for the range from 2980 to 2770  $\text{cm}^{-1}$ .
  - d) The fourth  $k$  vector used the results from the 182 and 471  $\mu\text{m}$  cells. This  $k$  vector determined the final values for the range from 1800 to 1500  $\text{cm}^{-1}$ .
  - e) The fifth  $k$  vector used the results from the 6.27 and 9.58  $\mu\text{m}$  cells. This  $k$  vector determined the final values for the range from 1150 to 1000  $\text{cm}^{-1}$ .
- 3) For the MIR  $\text{ZnSe}$  data, one composite vector was created and merged by hand.
  - a) The first  $k$  vector used the results from the 6.56 and 9.10  $\mu\text{m}$  cells. This  $k$  vector determined the final values for the range from 7800 to 400  $\text{cm}^{-1}$ .
- 4) A frequency correction was applied to the resulting  $\text{ZnSe}$  and  $\text{BaF}_2$  composite MIR  $k$  vectors.
  - a) Frequency correction (already applied):  $\tilde{\nu}(\text{corrected}) = [\tilde{\nu}(\text{instrument}) * 0.99988 + 0.025]$  as determined by comparing measured atmospheric spectral lines ( $\text{H}_2\text{O}$  and  $\text{CO}_2$ ) to values from the Northwest Infrared Spectral Library Database.
- 5) The MIR composite  $\text{CaF}_2$   $k$  vector and the MIR composite  $\text{ZnSe}$   $k$  vector were merged around 1400  $\text{cm}^{-1}$ .
- 6) For the NIR, four composite vectors were created and merged by hand.
  - a) The first  $k$  vector used the results from the 502 through 4193  $\mu\text{m}$  cells. This  $k$  vector determined the final values for the range from 10,000 to 6000  $\text{cm}^{-1}$ .
  - b) The second  $k$  vector used the results from the 205 through 4193  $\mu\text{m}$  cells. This  $k$  vector determined the final values for the range from 6000 to 400  $\text{cm}^{-1}$ .
- 7) The resulting composite NIR  $k$  vector and the refractive index at 10,000  $\text{cm}^{-1}$  were used to create the real or  $n$  vector using the Kramers-Kronig relation, as per Bertie's program "LZZKTB."
  - a) Frequency correction (already applied):  $\tilde{\nu}(\text{corrected}) = [\tilde{\nu}(\text{instrument}) * 0.99998 - 0.0005]$  as determined by comparing measured atmospheric spectral lines ( $\text{H}_2\text{O}$  and  $\text{CO}_2$ ) to values from the Northwest Infrared Spectral Library Database.
- 8) The composite MIR data were mapped onto the NIR x-axis using an interpolation routine, i.e. the Make Compatible command in OPUS 5.5. Then the composite MIR and NIR  $k$  vectors were merged around 3600  $\text{cm}^{-1}$  to generate a final composite  $k$  vector across the entire spectral range. Absorption increases for  $\text{ZnSe}$  at wavenumbers below 550  $\text{cm}^{-1}$  resulting in increased noise; thus the data were truncated at 500  $\text{cm}^{-1}$ . The resulting composite  $k$  vector and the refractive index at 10,000  $\text{cm}^{-1}$  were used to create the final  $n$  vector using the Kramers-Kronig relation, as per Bertie's program "LZZKTB."

### Photograph of Sample Tetraethylene glycol:



Figure 2: Tetraethylene glycol in Aldrich container for MIR and NIR measurements.