

A3All data taken at the Pacific Northwest National Laboratory
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Composite spectrum for: Tributyl phosphate

- First Column: Position in wavenumber (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 cm^{-1} , Absolute Integrated Intensities, and Dipole Moment Derivatives of Methanol at 25°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: Tributyl phosphate, $\text{C}_{12}\text{H}_{27}\text{O}_4\text{P}$, [126-73-8]
- IUPAC name: Tributyl phosphate
- Synonyms: Butyl phosphate; TBP; N-Tributyl phosphate; Phosphoric acid tributyl ester
- Physical properties: FW = 266.31 g/mole; mp = -79°C ; bp = 289°C ; $\rho = 0.973\text{ g/cm}^3$
- Supplier and stated purity: MIR: Fluka, $\geq 99.0\%$ (Lot # 1251120), NIR: Aldrich, $\geq 99\%$ (Lot # MKBZ9243V)
- Temperature of sample: 26°C ($\pm 1^\circ\text{C}$)
- Individual samples were measured at the following path lengths: MIR: 5.2, 7.6, 15.0, 51.4, 96.3, 199, 497 and 1143 μm ; NIR: 101, 203, 507, 1018 and 3081 μm . Final data are a composite of these spectra.
- Sample cell window material is potassium bromide (KBr).
- Preparation: None.

NIR Instrument Parameters:

- Bruker Vertex 70, purged with UHP nitrogen
- Spectral range: 10,000 to $3,000\text{ cm}^{-1}$ (1.0 to 3.33 microns)
- IR source: Quartz tungsten bulb
- Beamsplitter: Broadband Potassium bromide (KBr)
- Detector: DLTGS at room temperature
- Aperture: 3 mm
- Folding limits: 15801 to 0 cm^{-1}

MIR Instrument Parameters:

- Tensor 27, purged with UHP nitrogen
- Spectral range: 7800 to 400 cm^{-1} (1.282 to 25 microns)
- NIR source: Silicon carbide glow bar
- Beamsplitter: Broadband Potassium bromide (KBr)
- Detector: DLTGS at room temperature
- Aperture: 3 mm
- Folding limits: 15802 to 0 cm^{-1}

NIR/MIR Instrument Parameters:

- Instrument resolution: 2.0 cm^{-1}
- Number of interferograms averaged per single channel spectrum: 128
- Apodization: Norton-Beer, Medium
- Phase correction: Mertz
- Scanner velocity: 10 kHz
- Interferogram zerofill: 4x
- Spectral interval after zerofilling: 0.4823 cm^{-1}

a)



b)



Figure 1: The Bruker Vertex 70 FTIR (a) and Tensor 27 FTIR (b).

Measured Refractive Index:

The refractive index for TBP 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 nm . The temperature was controlled to match that in the sample compartment of the FTIR using a heated circulating bath.

480 nm: $n = 1.426$	486 nm: $n = 1.4255$	546 nm: $n = 1.4233$
589 nm: $n = 1.4205$	644 nm: $n = 1.4191$	656 nm: $n = 1.4185$
1550 nm: $n = 1.405$		

The refractive index, n , vs. wavelength in microns, λ , 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 TBP, the results were

$$\begin{aligned} n(7800\text{ cm}^{-1}) &= 1.4069 \text{ at } 25\text{ }^{\circ}\text{C} \text{ for MIR data and} \\ n(10,000\text{ cm}^{-1}) &= 1.4103 \text{ at } 25\text{ }^{\circ}\text{C} \text{ for NIR and merged data.} \end{aligned}$$

Post Processing and Related Parameters:

For the MIR, a composite spectrum was created from 8 absorbance spectra (base-10) taken at 8 path lengths: 5.2, 7.6, 15.0, 51.4, 96.3, 199, 497 and 1143 micrometers (μm). For the NIR, a composite spectrum was created from 5 absorbance spectra (base-10) taken at 5 path lengths: 101, 203, 507, 1018 and 3081 μm . 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 KBr 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 ≥ 2.5 are given zero weight. For the MIR, four composite vectors were created and merged by hand.
 - a) The first k vector used the results from the 497 and 1143 μm cells. This k vector determined the final values for the range from 7800 to 4600 cm^{-1} .
 - b) The second k vector used the results from the 96, 199, 497 and 1143 μm cells. This k vector determined the final values for the range from 4600 to 3100 cm^{-1} and 2750 to 1550 cm^{-1} .
 - c) The third k vector used the results from the 5, 8 and 15 μm cells. This k vector determined the final values for the range from 3100 to 2750 cm^{-1} and 1550 to 700 cm^{-1} .
 - d) The fourth k vector used the results from the 51, 96 and 199 μm cells. This k vector determined the final values for the range from 700 to 400 cm^{-1} .
- 3) A frequency correction was applied to the resulting composite MIR k vector.
 - a) Frequency correction (already applied): $\tilde{\nu}(\text{corrected}) = [\tilde{\nu}(\text{instrument}) * .99975 + .003891]$ as determined by comparing measured atmospheric spectral lines (H_2O and CO_2) to values from the Northwest Infrared Spectral Library Database.
- 4) For the NIR, two composite vectors were created and merged by hand.
 - a) The first k vector used the results from the 3081 and 1018 μm cells. This k vector determined the final values for the range from 10000 to 7400 cm^{-1} .
 - b) The second k vector used the results from the 101 through 3081 μm cells. This k vector determined the final values for the range from 7400 to 400 cm^{-1} .
- 5) A frequency correction was applied to the resulting composite NIR k vector.
 - a) Frequency correction (already applied): $\tilde{\nu}(\text{corrected}) = [\tilde{\nu}(\text{instrument}) * 0.999869 + 0.0158818]$ as determined by comparing measured atmospheric spectral lines (H_2O and CO_2) to values from the Northwest Infrared Spectral Library Database.
- 6) Finally, the 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 to generate a final composite k vector across the entire spectral range. The NIR data were used exclusively above 3100 cm^{-1} , and only the MIR data were used below 3000 cm^{-1} . A weighted average, with the weight of the MIR vector increasing linearly from 0 to 100% between 3100 and 3000 cm^{-1} was used in the overlapping spectral region. The resulting composite k vector and the refractive index at 10,000 cm^{-1} were used to create the final n vector using the Kramers-Kronig relation, as per Bertie's program "LZZKTB."

Photograph of Sample Tributyl phosphate:



Figure 2: Tributyl phosphate in Fluka container for MIR measurements.



Figure 3: Tributyl phosphate in Aldrich container for NIR measurements.