# International Comparison CCQM-K118 Natural Gas. Introduction to the guidance note about the support of CMCs[†]

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[†]This document cancels and replaces document CCQM-GAWG CMC-06 B.

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# 1 Introduction

This document describes the way in which the support for Calibration and Measurement Capabilitys (CMCs) is established in the key comparison CCQM-K118 Natural Gas. CMC support is provided in the CCQM-K118 Guidance note. The CMCs mentioned in this document are provided for understanding of the CMCs given in the Guidance note. This document is of explanatory nature and is not to be used when reviewing CMCs.

In this key comparison two types of gas compositions have been used (see table 1). One mixture is a synthetic hydrogen-enriched natural gas with low calorific value to facilitate support to power-to-gas applications, which often involve blending hydrogen with natural gas [1, 2]. The other mixture is a synthetic natural gas with an LNG-type composition and high calorific value, a type of gas which has not been addressed before in CCQM Gas Analysis Working Group (CCQM-GAWG) key comparisons.

Table 1: Nominal compositions of the travelling standards used in the natural gas key comparisons since CCQM-K1, expressed in amount fractions ($\mathrm{cmol\,mol^{-1}}$) [3]

| | CCQM-K1 | | | CCQM-K16 | | CCQM-K23 | | | CCQM-K118 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | V | Ia | IIIa | IIa | IVa | LNG |
| Nitrogen | 4 | 7 | 14.4 | 12 | 1.2 | 4 | 14.4 | 7 | 12 | 0.12 |
| Carbon dioxide | 1 | 3 | 0.5 | 4 | 0.8 | 1 | 0.5 | 3 | 4 | 0.02 |
| Helium | | | | 0.5 | | | | | 0.5 | |
| Hydrogen | | | | | | | | | 3 | |
| Ethane | 3 | 9.4 | 3 | 0.75 | 11 | 3 | 3 | 9.4 | 0.75 | 10 |
| Propane | 1 | 3.4 | 0.5 | 0.3 | 4.5 | 1 | 0.5 | 3.4 | 0.3 | 2 |
| *iso*-Butane | | | | 0.2 | 0.1 | 0.2 | 0.1 | 0.8 | 0.2 | 0.15 |
| *n*-Butane | 0.2 | 1 | 0.1 | 0.2 | 0.1 | 0.2 | 0.1 | 1 | 0.2 | 0.15 |
| *iso*-Pentane | | | | 0.05 | 0.035 | | | | 0.05 | 0.02 |
| *n*-Pentane | | | | 0.05 | 0.035 | | | | 0.05 | 0.02 |
| *neo*-Pentane | | | | 0.05 | 0.05 | | | | 0.05 | |
| *n*-Hexane | | | | 0.05 | 0.02 | | | | 0.05 | |
| Methane | 90.8 | 76.2 | 81.5 | 81.85 | 82.16 | 90.6 | 81.4 | 75.4 | 78.85 | 87.52 |

The design, implementation and results of this key comparison have been described elsewhere [4].

# 2 Conventions

1. In this document, the same symbol ($u$) is used for standard uncertainty and relative standard uncertainty. The accompanying text, as well as table and figure captions clarify whether an absolute or relative standard uncertainty is meant.
2. In this document, the same symbol ($U$) is used for expanded uncertainty and relative expanded uncertainty. The accompanying text, as well as table and figure captions clarify whether an absolute or relative standard uncertainty is meant.
3. Unless stated otherwise, a coverage factor $k = 2$ is used.
4. The percentage sign (%) is reserved for relative uncertainties.

5. The amount fractions of the components in natural gas are usually expressed as a percentage, unit cmol mol$^{-1}$.

# 3 Support to CMCs

The support of CMC claims is described in more detail in the "GAWG strategy for comparisons and CMC claims" [5]. The results of this key comparison can be used to support CMC claims for the composition of natural gas in the following ranges (see table 2). CMCs outsite the listed ranges are not supported by the results of this key comparison without further evidence.

If an National Metrology Institute (NMI) participated only for one of the mixtures, then the respective columns in table 2 apply.

Table 2: Support to CMCs (cmol mol$^{-1}$) [4]

| Component | Both mixtures | | Low calorific mixture | | | High calorific mixture | | |
|---|---|---|---|---|---|---|---|---|
| | $x_{LB}$ | $x_{UB}$ | $x$ | $CMC_{LB}$ | $CMC_{UB}$ | $x$ | $CMC_{LB}$ | $CMC_{UB}$ |
| Nitrogen | 0.1 | 25 | 12 | 0.5 | 25 | 0.12 | 0.1 | 20 |
| Carbon dioxide | 0.02 | 20 | 4 | 0.5 | 20 | 0.02 | 0.02 | 10 |
| Hydrogen | 0.5 | 10 | 3 | 0.5 | 10 | | | |
| Helium | 0.05 | 2.5 | 0.5 | 0.05 | 2.5 | | | |
| Ethane | 0.2 | 25 | 0.75 | 0.2 | 20 | 10 | 0.5 | 25 |
| Propane | 0.05 | 12 | 0.3 | 0.05 | 10 | 2 | 0.1 | 12 |
| *iso*-Butane | 0.05 | 1.5 | 0.2 | 0.05 | 1.5 | 0.15 | 0.05 | 1.5 |
| *n*-Butane | 0.05 | 1.5 | 0.2 | 0.05 | 1.5 | 0.15 | 0.05 | 1.5 |
| *neo*-Pentane | 0.01 | 0.25 | 0.05 | 0.01 | 0.25 | | | |
| *iso*-Pentane | 0.01 | 0.25 | 0.05 | 0.01 | 0.25 | 0.02 | 0.01 | 0.25 |
| *n*-Pentane | 0.01 | 0.25 | 0.05 | 0.01 | 0.25 | 0.02 | 0.01 | 0.25 |
| *n*-Hexane | 0.01 | 0.25 | 0.05 | 0.01 | 0.25 | | | |
| Methane | 50 | 99.9 | 78.85 | 50 | 99.9 | 87.52 | 50 | 99.9 |

The support for submitting CMCs broadly follows the guidelines of the CCQM-GAWG of the Consultative Committee for Amount of Substance: Metrology in Chemistry and Biology (CCQM) [5]. Considering that there are two suites of travelling standards, there was a need to develop a specific interpretation, especially for those NMIs that participated

The support to CMCs is as follows. If a result is consistent, then the smallest standard uncertainty supported by the key comparison is

$$u_{CMC,j} = \sqrt{u_{lab,j}^2 + \tau^2} \tag{1}$$

and otherwise

$$u_{CMC,j} = \sqrt{u_{lab,j}^2 + d_j^2} \tag{2}$$

In the latter equation, $d_j$ denotes the difference of the degree of equivalence. Formula (2) follows from the CCQM-GAWG Strategy [5]. Given that these CMCs relate to multicomponent mixtures,

extrapolation beyond the intervals specified in table 2 is not permitted. The extrapolation scheme mentioned in [5] does not apply.

The consensus values for the low-calorific natural gas (type IVa) are shown in table 3. The value of $\tau$ was taken as the median of the posterior distribution. As this posterior is skewed (towards zero), there is choice between the mode (the maximum of the probability density function), the median, and the mean. As in the subsequent calculation the uncertainty about $\tau$ does not play a role (the Guide to the expression of Uncertainty in Measurement (GUM) suite does not consider the uncertainty of an uncertainty component [6–8]), a representative value is required. Generally, the median is for non-symmetric distributions considered to be the most representative value. The column $u(\tau)$ provides the standard deviation of the values of $\tau$ from the Markov Chain Monte Carlo method (MCMC), as an indication of the uncertainty about $\tau$.

Table 3: Consensus values hydrogen-enriched natural gas, expressed as amount fractions (cmol mol$^{-1}$, $\tau_{\text{rel}}$ in %)

| Component | $\mu$ | $u(\mu)$ | $\tau$ | $u(\tau)$ | $\tau_{\text{rel}}$ |
|---|---|---|---|---|---|
| Nitrogen | 11.98479 | 0.00558 | 0.00791 | 0.00742 | 0.066 |
| Carbon dioxide | 4.00436 | 0.00166 | 0.00240 | 0.00222 | 0.060 |
| Hydrogen | 3.00071 | 0.00291 | 0.00456 | 0.00347 | 0.152 |
| Helium | 0.50225 | 0.00039 | 0.00048 | 0.00048 | 0.095 |
| Ethane | 0.74501 | 0.00040 | 0.00056 | 0.00051 | 0.076 |
| Propane | 0.29849 | 0.00018 | 0.00030 | 0.00022 | 0.100 |
| iso-Butane | 0.19975 | 0.00008 | 0.00010 | 0.00010 | 0.050 |
| n-Butane | 0.19988 | 0.00011 | 0.00018 | 0.00012 | 0.089 |
| iso-Pentane | 0.04985 | 0.00006 | 0.00011 | 0.00006 | 0.226 |
| n-Pentane | 0.05017 | 0.00005 | 0.00009 | 0.00005 | 0.178 |
| neo-Pentane | 0.04934 | 0.00005 | 0.00008 | 0.00006 | 0.167 |
| n-Hexane | 0.04970 | 0.00006 | 0.00011 | 0.00007 | 0.218 |
| Methane | 78.88099 | 0.01311 | 0.01753 | 0.01741 | 0.022 |

The consensus values of the high-calorific natural gas (LNG) are given in table 4.

Table 4: Consensus values liquefied natural gas, expressed as amount fractions (cmol mol$^{-1}$, $\tau_{\text{rel}}$ in %)

| Component | $\mu$ | $u(\mu)$ | $\tau$ | $u(\tau)$ | $\tau_{\text{rel}}$ |
|---|---|---|---|---|---|
| Nitrogen | 0.12192 | 0.00036 | 0.00043 | 0.00046 | 0.349 |
| Carbon dioxide | 0.01989 | 0.00003 | 0.00006 | 0.00004 | 0.282 |
| Ethane | 10.00051 | 0.00263 | 0.00266 | 0.00305 | 0.027 |
| Propane | 1.99952 | 0.00073 | 0.00079 | 0.00103 | 0.040 |
| iso-Butane | 0.14915 | 0.00006 | 0.00006 | 0.00007 | 0.043 |
| n-Butane | 0.14859 | 0.00009 | 0.00010 | 0.00012 | 0.069 |
| iso-Pentane | 0.01990 | 0.00003 | 0.00003 | 0.00004 | 0.140 |
| n-Pentane | 0.02009 | 0.00002 | 0.00003 | 0.00002 | 0.154 |
| Methane | 87.53108 | 0.00894 | 0.01032 | 0.01099 | 0.012 |

To combine the performances shown for the low- and high-calorific natural gas, the following interpretation is used (see table 5). By 'pooled' it is meant that the variances from equations (1) and/or equations (2) for both types of natural gas are averaged, and that the resulting standard uncertainty

is used as the basis for supporting CMCs. The pooling is also applied if either (or both) of the submitted results have been flagged as discrepant. For methane, the performance for the low-calorific natural gas is considered relevant for hydrogen-enriched natural gas, and that for high-calorific natural gas for natural gas without hydrogen.

Table 5: Combination of the results in CCQM-K118 to support CMCs

| **Component** | **CMC support** |
|---|---|
| Nitrogen | Interpolation formula |
| Carbon dioxide | Interpolation formula |
| Helium | As for type IVa |
| Hydrogen | As for type IVa |
| Ethane | Pooled |
| Propane | Pooled |
| iso-Butane | Pooled |
| n-Butane | Pooled |
| iso-Pentane | Pooled |
| n-Pentane | Pooled |
| neo-Pentane | As for type IVa |
| n-Hexane | As for type IVa |
| Methane | Type IVa for hydrogen-enriched natural gas |
| Methane | LNG for natural gas without hydrogen |

As their amount fractions in the low- and high-calorific natural gas were vastly different, the CMCs computed for nitrogen and carbon dioxide are interpolated with the following model [9]

$$\lg u_{\mathrm{CMC}} = a_0 + a_1 \lg x \tag{3}$$

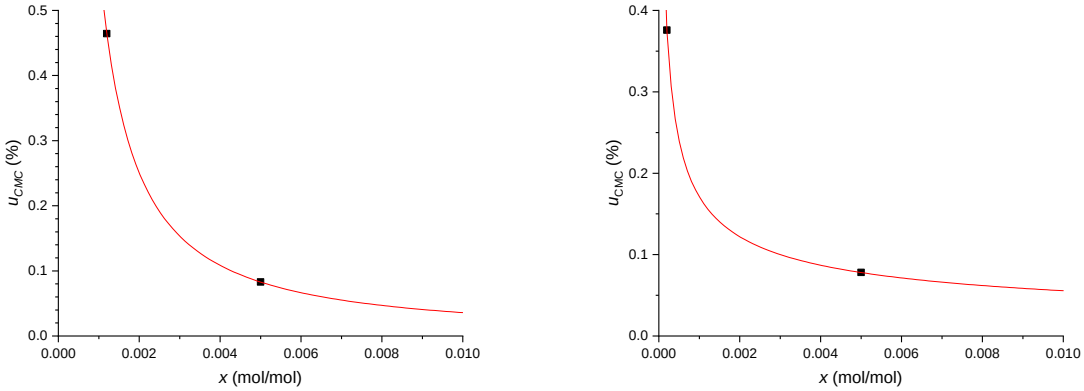
where $u_{\mathrm{CMC}}$ denotes the standard uncertainty and $x$ the amount fraction (both expressed in $\mathrm{mol\,mol^{-1}}$). The coefficients $a_0$ and $a_1$ are computed using the standard uncertainties as submitted by the participating NMI, where necessary combined with the difference of the degree of equivalence (see equations (1) and (2)).

Figure 1 shows the interpolation formula for nitrogen and carbon dioxide, computed from the standard uncertainties submitted by VSL. For nitrogen, the standard uncertainties used are 0.46 % and 0.08 % for nitrogen and 0.38 % and 0.08 % for carbon dioxide. The formula (3) is applied over the interval from 1000 $\mu\mathrm{mol\,mol^{-1}}$ (for nitrogen) and 200 $\mu\mathrm{mol\,mol^{-1}}$ (for carbon dioxide) to 0.5 $\mathrm{cmol\,mol^{-1}}$. Above this amount fraction, the relative standard uncertainty as computed from either equation (1) or (2) is used.

# 4 Results

## 4.1 Low-calorific natural gas

The results of this key comparison have been presented elsewhere [4].




(a) Nitrogen (b) Carbon dioxide

Figure 1: Extrapolation model for the CMCs for nitrogen and carbon dioxide for NMIs participating with both types natural gas. The relative standard uncertainty is plotted as a function of the amount fraction.

Table 6: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for nitrogen for natural gas type IVa (%).

| Lab | $u_{\text{lab}}$ | $u_{\text{CMC}}$ | $U_{\text{CMC}}$ |
|---|---|---|---|
| VSL | 0.05 | 0.08 | 0.17 |
| VNIIM | 0.13 | 0.39 | 0.79 |
| SMU | 0.14 | 0.16 | 0.31 |
| NIM | 0.10 | 0.12 | 0.25 |
| NPL | 0.07 | 0.10 | 0.20 |
| NMIA | 0.02 | 0.07 | 0.14 |
| BAM | 0.03 | 0.07 | 0.14 |
| GUM | 0.20 | 0.21 | 0.42 |
| CMI | 0.06 | 0.09 | 0.18 |
| NMISA | 0.33 | 0.33 | 0.66 |
| NMIJ | 0.24 | 0.25 | 0.50 |
| KRISS | 0.10 | 0.62 | 1.24 |
| UME | 0.10 | 0.12 | 0.24 |

The largest constistent subset (LCS) for the amount fraction nitrogen consists of the results of VSL, SMU, NPL, BAM, GUM, CMI, NMISA, NMIJ and UME. The consensus value is 11.9848 cmol mol$^{-1}$ with standard uncertainty 0.0056 cmol mol$^{-1}$. The excess standard deviation $\tau$ is 0.0079 cmol mol$^{-1}$ (0.07 % as relative standard uncertainty). The supported CMCs are shown in table 6. The degrees of equivalence computed from these data are shown in figure 2. The results of VNIIM and KRISS are not consistent with the key comparison reference value (KCRV).

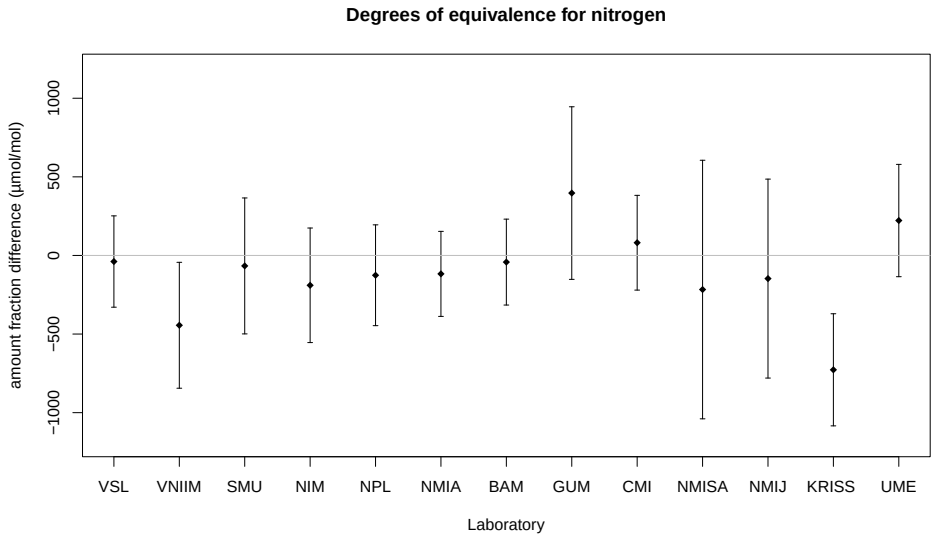
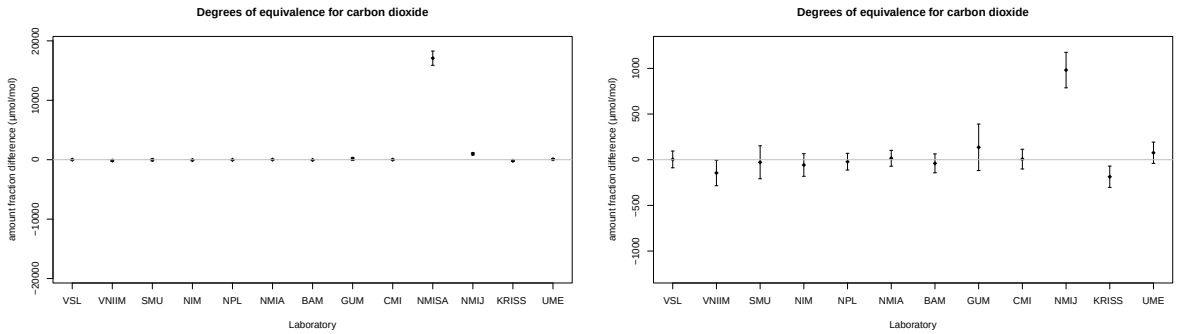



Figure 2: Degrees of equivalence for the amount fraction nitrogen (low-calorific natural gas) ($\mathrm{cmol\,mol^{-1}}$).

Table 7: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for carbon dioxide for natural gas type IVa (%).

| Lab | $u_{\mathrm{lab}}$ | $u_{\mathrm{CMC}}$ | $U_{\mathrm{CMC}}$ |
|---|---|---|---|
| VSL | 0.05 | 0.08 | 0.16 |
| VNIIM | 0.14 | 0.39 | 0.78 |
| SMU | 0.20 | 0.21 | 0.42 |
| NIM | 0.11 | 0.13 | 0.26 |
| NPL | 0.05 | 0.08 | 0.16 |
| NMIA | 0.04 | 0.07 | 0.14 |
| BAM | 0.08 | 0.10 | 0.19 |
| GUM | 0.30 | 0.30 | 0.61 |
| CMI | 0.09 | 0.10 | 0.21 |
| NMISA | 1.04 | 29.92 | 59.85 |
| NMIJ | 0.21 | 2.40 | 4.80 |
| KRISS | 0.10 | 0.48 | 0.96 |
| UME | 0.10 | 0.12 | 0.23 |

The LCS for the amount fraction carbon dioxide consists of the results of VSL, SMU, NIM, NPL, NMIA, BAM, GUM, CMI and UME. The consensus value is $4.0044\,\mathrm{cmol\,mol^{-1}}$ with standard uncertainty $0.0017\,\mathrm{cmol\,mol^{-1}}$. The excess standard deviation $\tau$ is $0.0024\,\mathrm{cmol\,mol^{-1}}$ (0.06 % as relative standard uncertainty). The supported CMCs are shown in table 7. The degrees of equivalence computed from these data are shown in figure 2. The results of VNIIM, NMISA, NMIJ and KRISS are not consistent with the KCRV.




(a) Complete dataset

(b) Without NMISA

Figure 3: Degrees of equivalence for the amount fraction carbon dioxide (low-calorific natural gas) ($\mathrm{cmol\,mol^{-1}}$).

Table 8: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for hydrogen for natural gas type IVa (%).

| Lab | $u_{\mathrm{lab}}$ | $u_{\mathrm{CMC}}$ | $U_{\mathrm{CMC}}$ |
|---|---|---|---|
| VSL | 0.07 | 0.17 | 0.34 |
| VNIIM | 0.22 | 0.27 | 0.53 |
| SMU | 0.53 | 0.55 | 1.11 |
| NIM | 0.12 | 0.20 | 0.39 |
| NPL | 0.25 | 0.29 | 0.59 |
| NMIA | 0.08 | 0.17 | 0.35 |
| BAM | 0.06 | 0.16 | 0.33 |
| GUM | 0.40 | 0.43 | 0.86 |
| CMI | 0.33 | 0.37 | 0.73 |
| NMISA | 2.10 | 2.11 | 4.22 |
| NMIJ | 0.23 | 2.94 | 5.88 |
| KRISS | 0.10 | 0.65 | 1.29 |
| UME | 0.07 | 0.17 | 0.33 |

The LCS for the amount fraction hydrogen consists of the results of VSL, VNIIM, SMU, NIM, NPL, BAM, GUM, CMI, NMISA and UME. The consensus value is $3.0007\,\mathrm{cmol\,mol^{-1}}$ with standard uncertainty $0.0029\,\mathrm{cmol\,mol^{-1}}$. The excess standard deviation $\tau$ is $0.0046\,\mathrm{cmol\,mol^{-1}}$ (0.15 % as relative standard uncertainty). The supported CMCs are shown in table 8. The degrees of equivalence computed from these data are shown in figure 4. The result of NMIJ is not consistent with the KCRV.

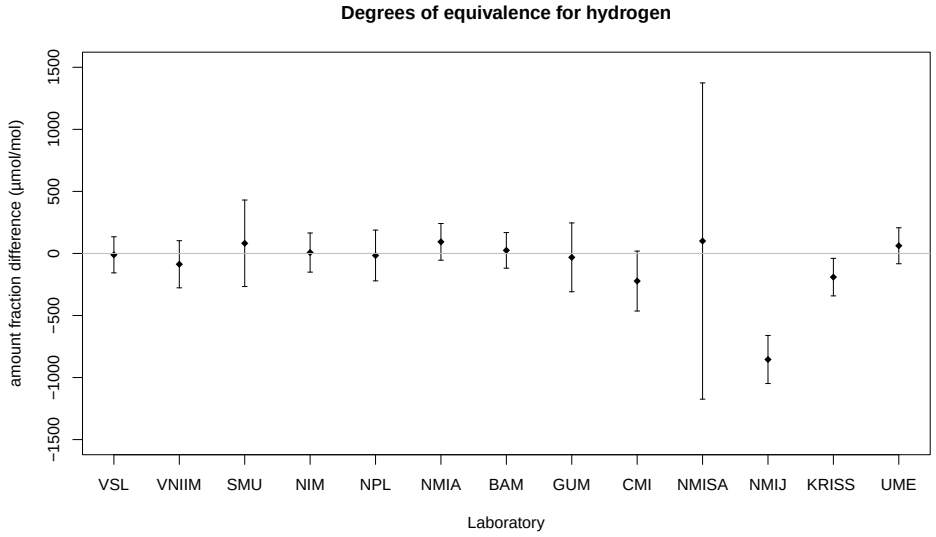



Figure 4: Degrees of equivalence for the amount fraction hydrogen (low-calorific natural gas) (cmol mol$^{-1}$).

Table 9: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for helium for natural gas type IVa (%).

| Lab | $u_{\text{lab}}$ | $u_{\text{CMC}}$ | $U_{\text{CMC}}$ |
|---|---|---|---|
| VSL | 0.10 | 0.14 | 0.28 |
| VNIIM | 0.25 | 0.27 | 0.53 |
| SMU | 0.54 | 0.55 | 1.09 |
| NIM | 0.14 | 0.17 | 0.34 |
| NPL | 0.25 | 0.27 | 0.53 |
| NMIA | 0.11 | 0.15 | 0.29 |
| BAM | 0.08 | 0.12 | 0.24 |
| GUM | 0.30 | 0.31 | 0.63 |
| CMI | 0.43 | 0.44 | 0.87 |
| NMISA | 2.78 | 2.78 | 5.55 |
| NMIJ | 0.16 | 1.27 | 2.54 |
| KRISS | 0.15 | 0.80 | 1.61 |
| UME | 0.14 | 1.24 | 2.47 |

The LCS for the amount fraction helium consists of the results of VSL, VNIIM, SMU, NIM, NPL, NMIA, BAM, GUM, CMI and NMISA. The consensus value is 0.5022 cmol mol$^{-1}$ with standard uncertainty 0.0004 cmol mol$^{-1}$. The excess standard deviation $\tau$ is 0.0005 cmol mol$^{-1}$ (0.10 % as relative standard uncertainty). The supported CMCs are shown in table 9. The degrees of equivalence computed from these data are shown in figure 5. The results of NMIJ, KRISS and UME are not consistent with the KCRV.

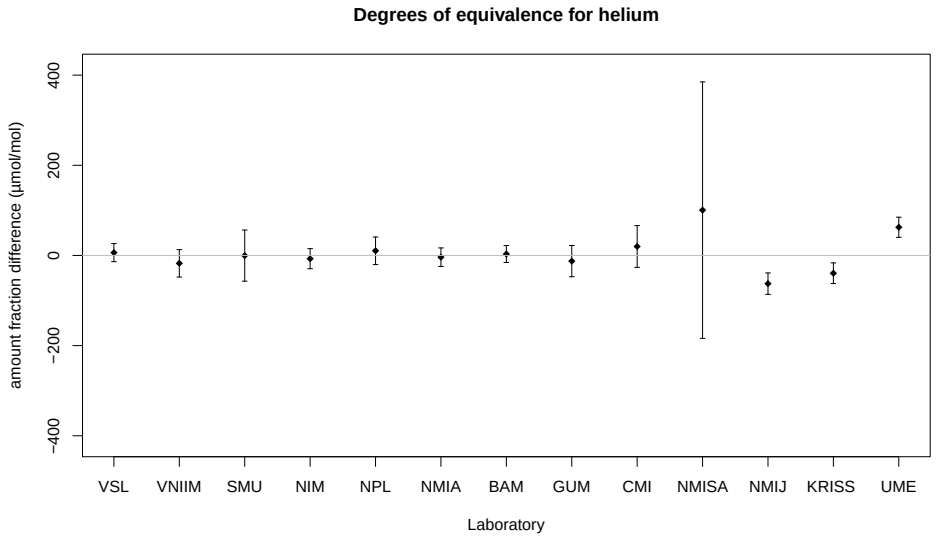



Figure 5: Degrees of equivalence for the amount fraction helium (low-calorific natural gas) (cmol mol$^{-1}$).

Table 10: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for ethane for natural gas type IVa (%).

| Lab | $u_{\text{lab}}$ | $u_{\text{CMC}}$ | $U_{\text{CMC}}$ |
|---|---|---|---|
| VSL | 0.10 | 0.13 | 0.25 |
| VNIIM | 0.27 | 0.28 | 0.56 |
| SMU | 0.14 | 0.16 | 0.32 |
| NIM | 0.13 | 0.15 | 0.30 |
| NPL | 0.10 | 0.13 | 0.25 |
| NMIA | 0.09 | 0.12 | 0.23 |
| BAM | 0.21 | 0.22 | 0.45 |
| GUM | 0.40 | 0.41 | 0.81 |
| CMI | 0.21 | 0.23 | 0.45 |
| NMISA | 1.26 | 1.27 | 2.53 |
| NMIJ | 0.04 | 0.09 | 0.17 |
| KRISS | 0.15 | 0.58 | 1.16 |
| UME | 0.09 | 0.12 | 0.24 |

The LCS for the amount fraction ethane consists of the results of VSL, VNIIM, SMU, NIM, NPL, NMIA, BAM, GUM, CMI, NMIJ and UME. The consensus value is 0.7450 cmol mol$^{-1}$ with standard uncertainty 0.0004 cmol mol$^{-1}$. The excess standard deviation $\tau$ is 0.0006 cmol mol$^{-1}$ (0.08 % as relative standard uncertainty). The supported CMCs are shown in table 10. The degrees of equivalence computed from these data are shown in figure 6. The result of KRISS is not consistent with the KCRV.

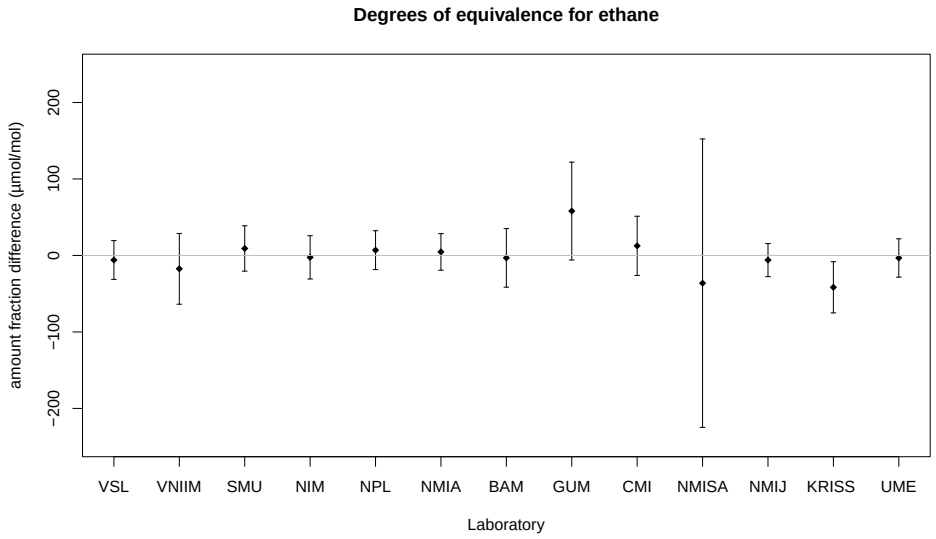



Figure 6: Degrees of equivalence for the amount fraction ethane (low-calorific natural gas) ($\mathrm{cmol\,mol^{-1}}$).

Table 11: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for propane for natural gas type IVa (%).

| Lab | $u_{\mathrm{lab}}$ | $u_{\mathrm{CMC}}$ | $U_{\mathrm{CMC}}$ |
|---|---|---|---|
| VSL | 0.15 | 0.18 | 0.36 |
| VNIIM | 0.27 | 0.29 | 0.57 |
| SMU | 0.25 | 0.27 | 0.54 |
| NIM | 0.14 | 0.17 | 0.34 |
| NPL | 0.08 | 0.13 | 0.25 |
| NMIA | 0.10 | 0.14 | 0.28 |
| BAM | 0.17 | 0.20 | 0.39 |
| GUM | 0.40 | 0.42 | 0.83 |
| CMI | 0.22 | 0.24 | 0.48 |
| NMISA | 1.20 | 1.20 | 2.41 |
| NMIJ | 0.04 | 0.11 | 0.22 |
| KRISS | 0.15 | 0.63 | 1.26 |
| UME | 0.10 | 0.14 | 0.28 |

The LCS for the amount fraction propane consists of the results of VSL, VNIIM, SMU, NIM, NPL, NMIA, BAM, GUM, CMI, NMISA, NMIJ and UME. The consensus value is $0.298\,49\,\mathrm{cmol\,mol^{-1}}$ with standard uncertainty $0.000\,18\,\mathrm{cmol\,mol^{-1}}$. The excess standard deviation $\tau$ is $0.000\,30\,\mathrm{cmol\,mol^{-1}}$ (0.10 % as relative standard uncertainty). The supported CMCs are shown in table 11. The degrees of equivalence computed from these data are shown in figure 7. The result of KRISS is not consistent with the KCRV.

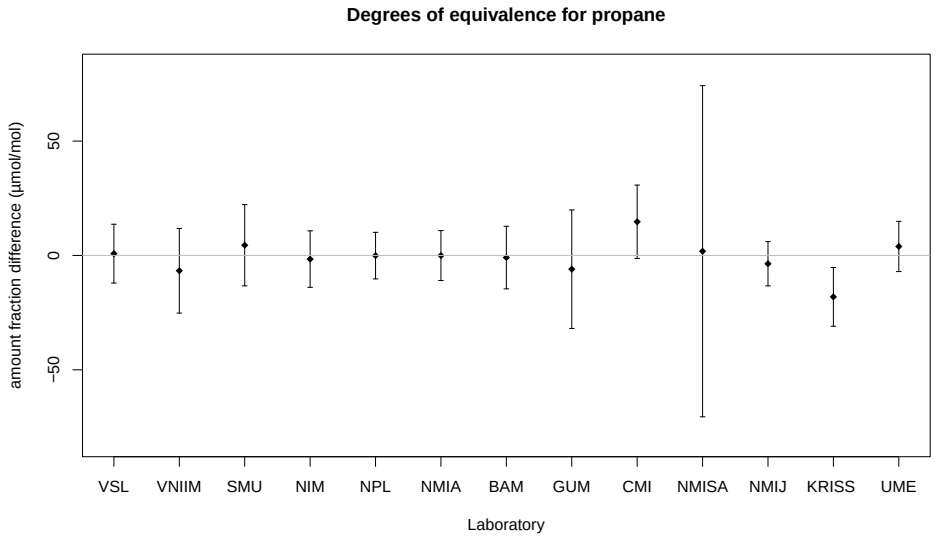



Figure 7: Degrees of equivalence for the amount fraction propane (low-calorific natural gas) ($\mathrm{cmol\,mol^{-1}}$).

Table 12: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for iso-butane for natural gas type IVa (%).

| Lab | $u_{\mathrm{lab}}$ | $u_{\mathrm{CMC}}$ | $U_{\mathrm{CMC}}$ |
|---|---|---|---|
| VSL | 0.05 | 0.07 | 0.14 |
| VNIIM | 0.38 | 0.38 | 0.76 |
| SMU | 0.28 | 0.28 | 0.56 |
| NIM | 0.13 | 0.13 | 0.27 |
| NPL | 0.18 | 0.18 | 0.36 |
| NMIA | 0.10 | 0.11 | 0.22 |
| BAM | 0.05 | 0.07 | 0.13 |
| GUM | 0.41 | 3.49 | 6.98 |
| CMI | 0.35 | 0.35 | 0.71 |
| NMIJ | 0.09 | 0.10 | 0.20 |
| KRISS | 0.15 | 0.47 | 0.94 |
| UME | 0.10 | 0.11 | 0.22 |

The LCS for the amount fraction iso-butane consists of the results of VSL, VNIIM, SMU, NIM, NPL, NMIA, BAM, CMI, NMISA and KRISS . The consensus value is $0.199\,75\,\mathrm{cmol\,mol^{-1}}$ with standard uncertainty $0.000\,08\,\mathrm{cmol\,mol^{-1}}$. The excess standard deviation $\tau$ is $0.000\,10\,\mathrm{cmol\,mol^{-1}}$ (0.05 % as relative standard uncertainty). The supported CMCs are shown in table 12. The degrees of equivalence computed from these data are shown in figure 8. The results of GUM and KRISS are not consistent with the KCRV.

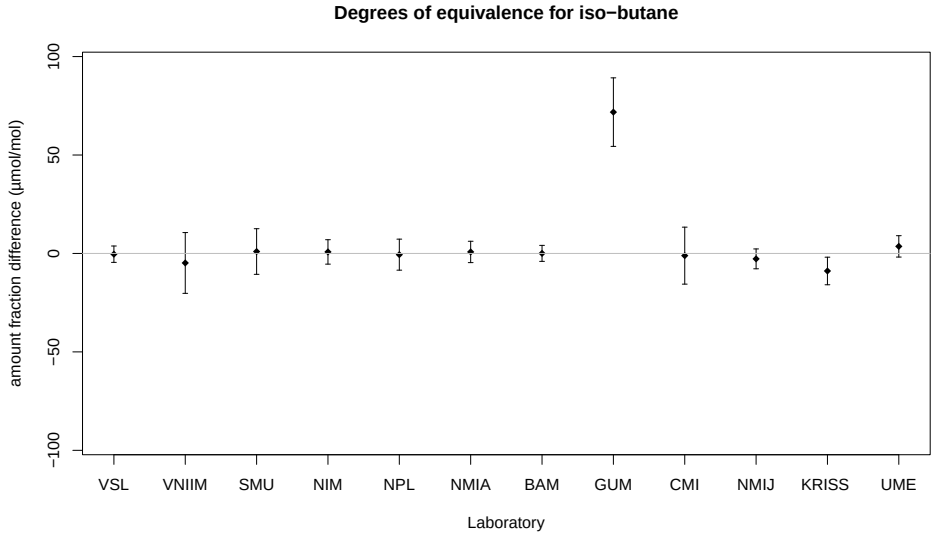



Figure 8: Degrees of equivalence for the amount fraction *iso*-butane (low-calorific natural gas) (cmol mol$^{-1}$).

Table 13: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for n-butane for natural gas type IVa (%).

| Lab | $u_{\text{lab}}$ | $u_{\text{CMC}}$ | $U_{\text{CMC}}$ |
|---|---|---|---|
| VSL | 0.05 | 0.10 | 0.20 |
| VNIIM | 0.40 | 0.41 | 0.82 |
| SMU | 0.27 | 0.29 | 0.58 |
| NIM | 0.13 | 0.15 | 0.31 |
| NPL | 0.17 | 0.20 | 0.39 |
| NMIA | 0.10 | 0.13 | 0.27 |
| BAM | 0.05 | 0.10 | 0.21 |
| GUM | 0.40 | 0.41 | 0.82 |
| CMI | 0.38 | 0.39 | 0.77 |
| NMISA | 1.17 | 1.17 | 2.34 |
| NMIJ | 0.09 | 0.40 | 0.80 |
| KRISS | 0.15 | 0.75 | 1.49 |
| UME | 0.10 | 0.13 | 0.27 |

The LCS for the amount fraction n-butane consists of the results of VSL, VNIIM, SMU, NIM, NPL, NMIA, BAM, GUM, CMI, NMISA and UME. The consensus value is 0.199 88 cmol mol$^{-1}$ with standard uncertainty 0.000 11 cmol mol$^{-1}$. The excess standard deviation $\tau$ is 0.000 18 cmol mol$^{-1}$ (0.09 % as relative standard uncertainty). The supported CMCs are shown in table 13. The degrees of equivalence computed from these data are shown in figure 9. The results of NMIJ and KRISS are not consistent with the KCRV.

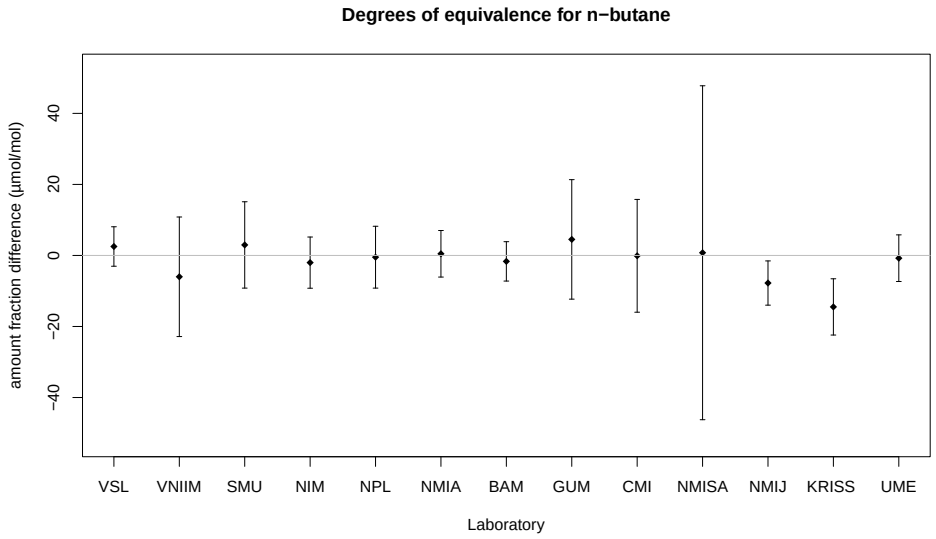



Figure 9: Degrees of equivalence for the amount fraction *n*-butane (low-calorific natural gas) (cmol mol$^{-1}$).

Table 14: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for iso-pentane for natural gas type IVa (%).

| Lab | $u_{\text{lab}}$ | $u_{\text{CMC}}$ | $U_{\text{CMC}}$ |
|---|---|---|---|
| VSL | 0.12 | 0.26 | 0.52 |
| VNIIM | 0.50 | 0.55 | 1.10 |
| SMU | 0.43 | 0.49 | 0.98 |
| NIM | 0.20 | 0.30 | 0.60 |
| NPL | 0.20 | 0.30 | 0.60 |
| NMIA | 0.14 | 0.26 | 0.53 |
| BAM | 0.13 | 0.26 | 0.52 |
| GUM | 0.50 | 0.55 | 1.10 |
| CMI | 0.30 | 0.38 | 0.75 |
| NMIJ | 0.05 | 0.97 | 1.93 |
| KRISS | 1.49 | 1.51 | 3.02 |
| UME | 0.14 | 0.27 | 0.53 |

The LCS for the amount fraction iso-pentane consists of the results of VSL, VNIIM, SMU, NIM, NPL, NMIA, BAM, GUM, CMI, NMIJ and KRISS . The consensus value is 0.049 85 cmol mol$^{-1}$ with standard uncertainty 0.000 06 cmol mol$^{-1}$. The excess standard deviation $\tau$ is 0.000 11 cmol mol$^{-1}$ (0.23 % as relative standard uncertainty). The supported CMCs are shown in table 14. The degrees of equivalence computed from these data are shown in figure 10. The result of NMIJ is not consistent with the KCRV.

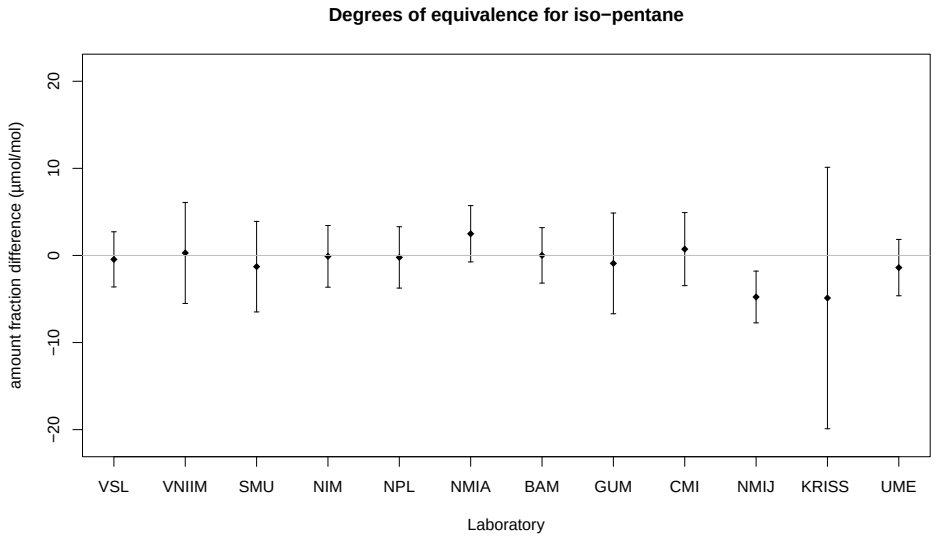



Figure 10: Degrees of equivalence for the amount fraction *iso*-pentane (low-calorific natural gas) (cmol mol$^{-1}$).

Table 15: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for n-pentane for natural gas type IVa (%).

| Lab | $u_{\text{lab}}$ | $u_{\text{CMC}}$ | $U_{\text{CMC}}$ |
|---|---|---|---|
| VSL | 0.10 | 0.20 | 0.41 |
| VNIIM | 0.40 | 0.44 | 0.87 |
| SMU | 0.37 | 0.41 | 0.82 |
| NIM | 0.15 | 0.23 | 0.47 |
| NPL | 0.20 | 0.27 | 0.54 |
| NMIA | 0.16 | 0.24 | 0.48 |
| BAM | 0.22 | 0.28 | 0.56 |
| GUM | 0.30 | 0.35 | 0.69 |
| CMI | 0.30 | 0.35 | 0.70 |
| NMISA | 1.17 | 1.18 | 2.36 |
| NMIJ | 0.05 | 0.19 | 0.37 |
| KRISS | 1.26 | 1.27 | 2.54 |
| UME | 0.18 | 0.25 | 0.51 |

The LCS for the amount fraction n-pentane consists of the results of VSL, VNIIM, SMU, NIM, NPL, NMIA, BAM, GUM, CMI, NMISA, NMIJ and UME. The consensus value is 0.050 17 cmol mol$^{-1}$ with standard uncertainty 0.000 05 cmol mol$^{-1}$. The excess standard deviation $\tau$ is 0.000 09 cmol mol$^{-1}$ (0.18 % as relative standard uncertainty). The supported CMCs are shown in table 15. The degrees of equivalence computed from these data are shown in figure 11. The result of GUM is not consistent with the KCRV.

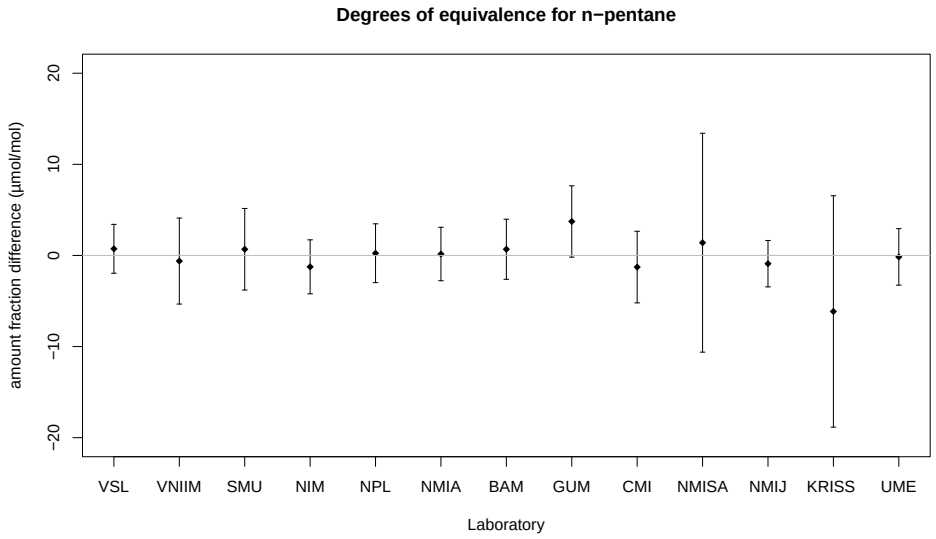



Figure 11: Degrees of equivalence for the amount fraction *n*-pentane (low-calorific natural gas) (cmol mol$^{-1}$).

Table 16: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for neo-pentane for natural gas type IVa (%).

| Lab | $u_{\text{lab}}$ | $u_{\text{CMC}}$ | $U_{\text{CMC}}$ |
|---|---|---|---|
| VSL | 0.10 | 0.19 | 0.39 |
| VNIIM | 0.30 | 0.35 | 0.69 |
| SMU | 0.50 | 0.53 | 1.06 |
| NIM | 0.16 | 0.23 | 0.47 |
| NPL | 0.25 | 0.30 | 0.60 |
| NMIA | 0.16 | 0.23 | 0.47 |
| BAM | 0.12 | 0.21 | 0.41 |
| GUM | 1.00 | 1.01 | 2.03 |
| CMI | 0.50 | 0.53 | 1.06 |
| NMIJ | 0.13 | 0.21 | 0.43 |
| KRISS | 1.00 | 1.01 | 2.03 |
| UME | 0.14 | 0.62 | 1.24 |

The LCS for the amount fraction neo-pentane consists of the results of VSL, VNIIM, SMU, NIM, NPL, NMIA, BAM, GUM, CMI and NMISA. The consensus value is 0.049 34 cmol mol$^{-1}$ with standard uncertainty 0.000 05 cmol mol$^{-1}$. The excess standard deviation $\tau$ is 0.000 08 cmol mol$^{-1}$ (0.17 % as relative standard uncertainty). The supported CMCs are shown in table 16. The degrees of equivalence computed from these data are shown in figure 12. All results are consistent with the KCRV.

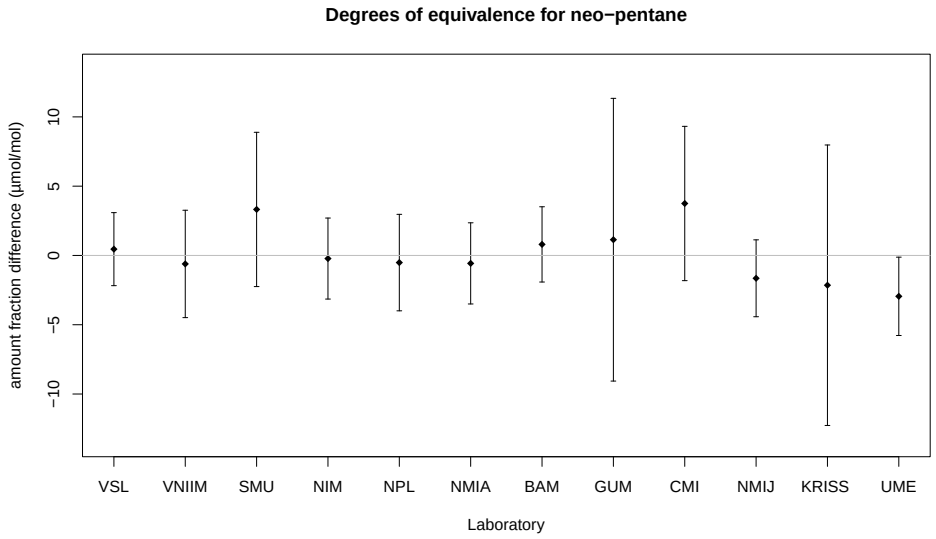



Figure 12: Degrees of equivalence for the amount fraction *neo*-pentane (low-calorific natural gas) (cmol mol$^{-1}$).

Table 17: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for n-hexane for natural gas type IVa (%).

| Lab | $u_{\text{lab}}$ | $u_{\text{CMC}}$ | $U_{\text{CMC}}$ |
|---|---|---|---|
| VSL | 0.10 | 0.24 | 0.48 |
| VNIIM | 0.60 | 0.64 | 1.28 |
| SMU | 0.38 | 0.44 | 0.88 |
| NIM | 0.13 | 0.25 | 0.51 |
| NPL | 0.20 | 0.30 | 0.59 |
| NMIA | 0.81 | 0.84 | 1.67 |
| BAM | 0.16 | 0.27 | 0.54 |
| GUM | 0.30 | 0.37 | 0.74 |
| CMI | 0.30 | 0.37 | 0.74 |
| NMISA | 1.17 | 1.19 | 2.38 |
| NMIJ | 0.05 | 0.66 | 1.32 |
| KRISS | 1.00 | 1.02 | 2.04 |
| UME | 0.22 | 0.31 | 0.62 |

The LCS for the amount fraction n-hexane consists of the results of VSL, VNIIM, SMU, NIM, NPL, NMIA, BAM, GUM, CMI, NMISA and UME. The consensus value is 0.049 70 cmol mol$^{-1}$ with standard uncertainty 0.000 06 cmol mol$^{-1}$. The excess standard deviation $\tau$ is 0.000 11 cmol mol$^{-1}$ (0.22 % as relative standard uncertainty). The supported CMCs are shown in table 17. The degrees of equivalence computed from these data are shown in figure 13. The result of UME is not consistent with the KCRV.

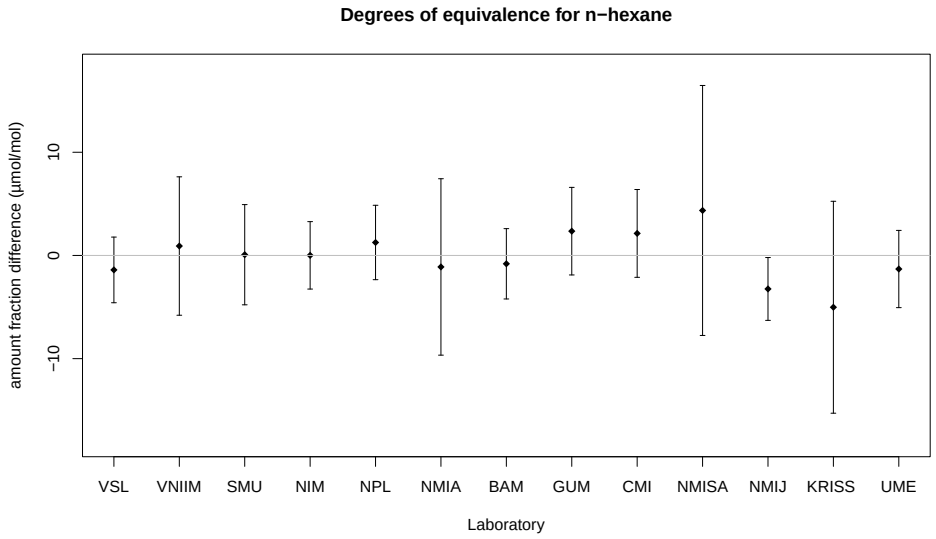



Figure 13: Degrees of equivalence for the amount fraction *n*-hexane (low-calorific natural gas) ($\mathrm{cmol\,mol^{-1}}$).

Table 18: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for methane for natural gas type IVa (%).

| Lab | $u_{\mathrm{lab}}$ | $u_{\mathrm{CMC}}$ | $U_{\mathrm{CMC}}$ |
|---|---|---|---|
| VSL | 0.05 | 0.19 | 0.38 |
| VNIIM | 0.03 | 0.03 | 0.07 |
| SMU | 0.08 | 0.08 | 0.16 |
| NIM | 0.02 | 0.03 | 0.06 |
| NPL | 0.02 | 0.03 | 0.06 |
| NMIA | 0.03 | 0.04 | 0.08 |
| BAM | 0.01 | 0.02 | 0.05 |
| GUM | 0.05 | 0.05 | 0.11 |
| CMI | 0.02 | 0.03 | 0.06 |
| NMISA | 1.03 | 1.03 | 2.06 |
| NMIJ | 0.21 | 0.21 | 0.42 |
| KRISS | 0.05 | 0.15 | 0.30 |
| UME | 0.10 | 0.10 | 0.20 |

The LCS for the amount fraction methane consists of the results of VNIIM, SMU, NPL, NMIA, BAM, GUM, CMI, NMISA, NMIJ and UME. The consensus value is $78.881\,\mathrm{cmol\,mol^{-1}}$ with standard uncertainty $0.013\,\mathrm{cmol\,mol^{-1}}$. The excess standard deviation $\tau$ is $0.018\,\mathrm{cmol\,mol^{-1}}$ (0.02 % as relative standard uncertainty). The supported CMCs are shown in table 18. The degrees of equivalence computed from these data are shown in figure 14. The results of VSL and KRISS are not consistent with the KCRV.

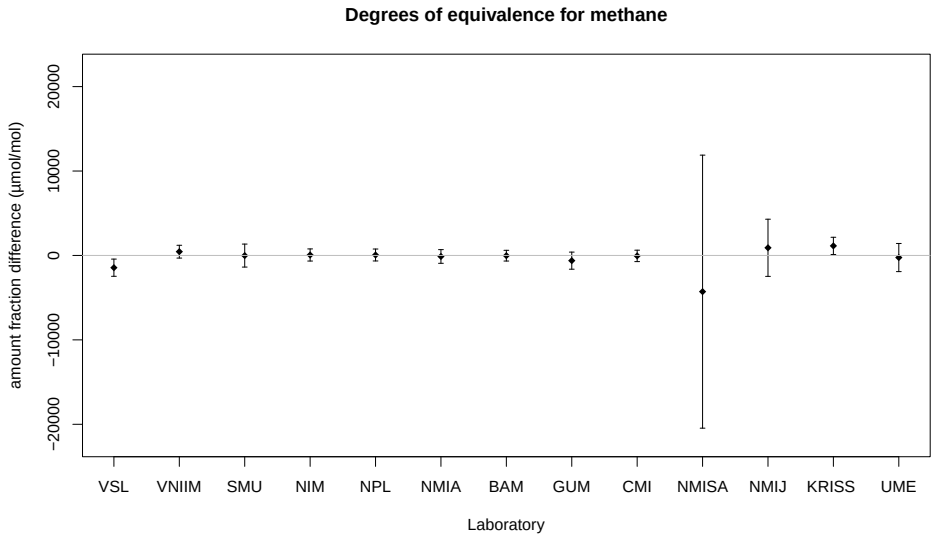



Figure 14: Degrees of equivalence for the amount fraction methane (low-calorific natural gas) (cmol mol$^{-1}$).

## 4.2 High-calorific natural gas

Table 19: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for nitrogen for natural gas type LNG (%).

| Lab | $u_{\text{lab}}$ | $u_{\text{CMC}}$ | $U_{\text{CMC}}$ |
|---|---|---|---|
| VSL | 0.31 | 0.47 | 0.93 |
| VNIIM | 0.33 | 0.48 | 0.97 |
| NIM | 0.25 | 2.48 | 4.96 |
| NPL | 0.25 | 0.43 | 0.86 |
| NMIA | 0.25 | 0.43 | 0.86 |
| BAM | 0.30 | 0.46 | 0.92 |
| GUM | 0.20 | 0.41 | 0.82 |
| CMI | 0.38 | 1.91 | 3.83 |
| NMISA | 3.67 | 3.69 | 7.38 |
| BFKH | 0.21 | 0.41 | 0.82 |
| NMIJ | 0.21 | 0.41 | 0.81 |
| UME | 0.08 | 0.36 | 0.72 |

The LCS for the amount fraction nitrogen consists of the results of VSL, NPL, NMIA, BAM, NMISA and BFKH. The consensus value is 0.121 92 cmol mol$^{-1}$ with standard uncertainty 0.000 36 cmol mol$^{-1}$. The excess standard deviation $\tau$ is 0.000 43 cmol mol$^{-1}$ (0.35 % as relative standard uncertainty). The supported CMCs are shown in table 19. The degrees of equivalence computed from these data are shown in figure 15. NIM and CMI report results that are not consistent with the KCRV.

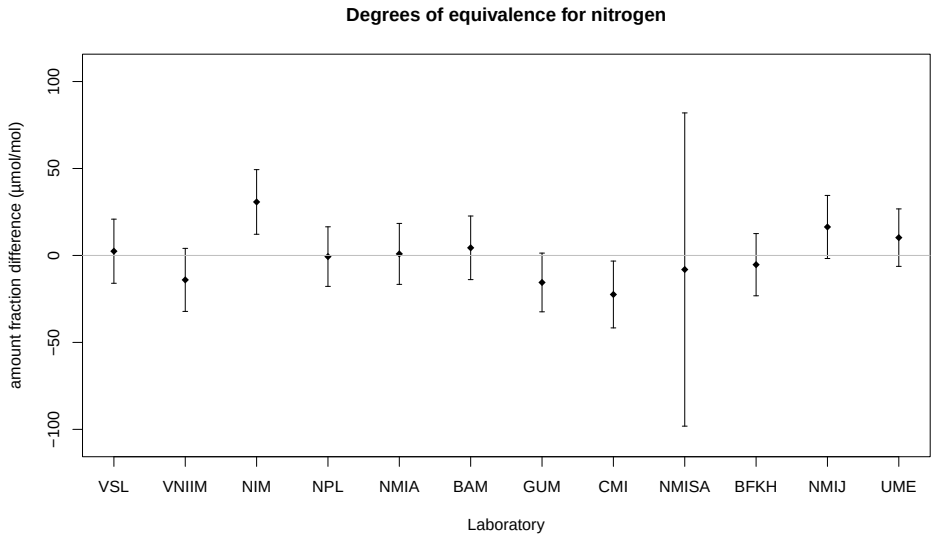



Figure 15: Degrees of equivalence for the amount fraction nitrogen (high-calorific natural gas) (cmol mol$^{-1}$).

Table 20: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for carbon dioxide for natural gas type LNG (%).

| Lab | $u_{\text{lab}}$ | $u_{\text{CMC}}$ | $U_{\text{CMC}}$ |
|---|---|---|---|
| VSL | 0.25 | 0.38 | 0.75 |
| VNIIM | 0.38 | 0.47 | 0.95 |
| NIM | 0.25 | 0.38 | 0.76 |
| NPL | 1.00 | 1.04 | 2.08 |
| NMIA | 0.76 | 0.81 | 1.62 |
| BAM | 0.16 | 0.32 | 0.65 |
| GUM | 0.10 | 0.30 | 0.60 |
| CMI | 0.50 | 0.57 | 1.15 |
| NMISA | 3.59 | 3.60 | 7.20 |
| BFKH | 0.51 | 0.58 | 1.16 |
| NMIJ | 0.11 | 0.30 | 0.60 |
| UME | 0.30 | 0.41 | 0.82 |

The LCS for the amount fraction carbon dioxide consists of the results of VSL, VNIIM, NPL, NMIA, BAM, GUM, CMI, NMISA, BFKH and UME. The consensus value is 0.019 89 cmol mol$^{-1}$ with standard uncertainty 0.000 03 cmol mol$^{-1}$. The excess standard deviation $\tau$ is 0.000 06 cmol mol$^{-1}$ (0.28 % as relative standard uncertainty). The supported CMCs are shown in table 20. The degrees of equivalence computed from these data are shown in figure 15. All results are consistent with the KCRV.

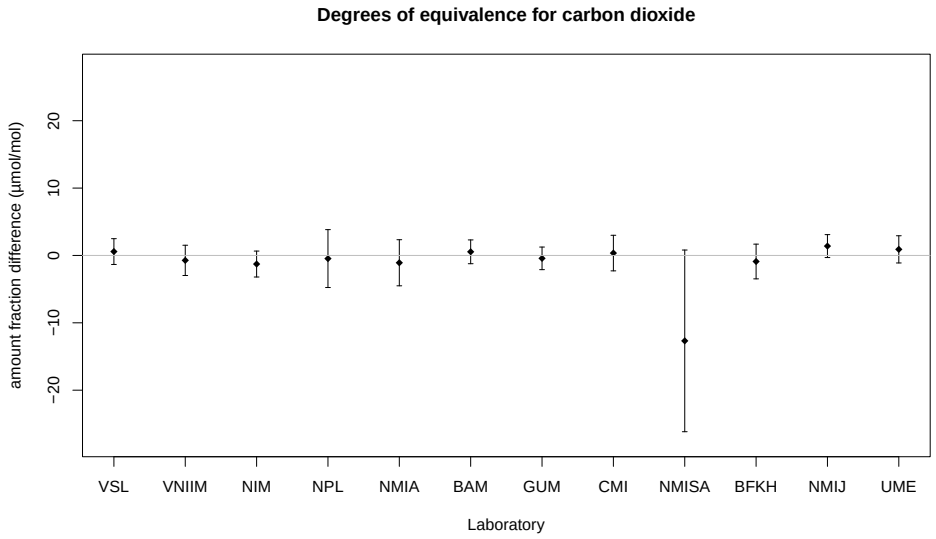



Figure 16: Degrees of equivalence for the amount fraction carbon dioxide (high-calorific natural gas) ($\mathrm{cmol\,mol^{-1}}$).

Table 21: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for ethane for natural gas type LNG (%).

| Lab | $u_{\mathrm{lab}}$ | $u_{\mathrm{CMC}}$ | $U_{\mathrm{CMC}}$ |
|---|---|---|---|
| VSL | 0.05 | 0.06 | 0.11 |
| VNIIM | 0.25 | 0.25 | 0.50 |
| NIM | 0.12 | 0.12 | 0.24 |
| NPL | 0.10 | 0.10 | 0.21 |
| NMIA | 0.03 | 0.04 | 0.08 |
| BAM | 0.07 | 0.07 | 0.15 |
| GUM | 0.40 | 0.40 | 0.80 |
| CMI | 0.10 | 0.40 | 0.80 |
| NMISA | 1.15 | 1.15 | 2.30 |
| BFKH | 0.06 | 0.07 | 0.14 |
| NMIJ | 0.07 | 0.07 | 0.15 |
| UME | 0.04 | 0.05 | 0.10 |

The LCS for the amount fraction ethane consists of the results of VSL, VNIIM, NIM, NPL, NMIA, BAM, GUM, NMISA, BFKH, NMIJ and UME. The consensus value is $10.000\,51\,\mathrm{cmol\,mol^{-1}}$ with standard uncertainty $0.002\,63\,\mathrm{cmol\,mol^{-1}}$. The excess standard deviation $\tau$ is $0.002\,66\,\mathrm{cmol\,mol^{-1}}$ (0.03 % as relative standard uncertainty). The supported CMCs are shown in table 21. The degrees of equivalence computed from these data are shown in figure 17. CMI reports a result that is not consistent with the KCRV.

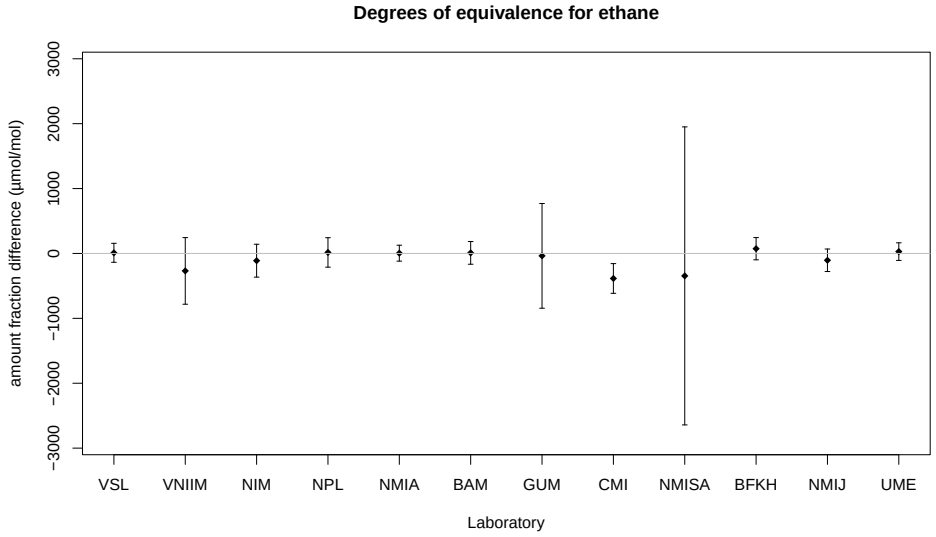



Figure 17: Degrees of equivalence for the amount fraction ethane (high-calorific natural gas) (cmol mol$^{-1}$).

Table 22: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for propane for natural gas type LNG (%).

| Lab | $u_{\text{lab}}$ | $u_{\text{CMC}}$ | $U_{\text{CMC}}$ |
|---|---|---|---|
| VSL | 0.06 | 0.07 | 0.14 |
| VNIIM | 0.28 | 0.28 | 0.56 |
| NIM | 0.13 | 0.13 | 0.26 |
| NPL | 0.07 | 0.08 | 0.17 |
| NMIA | 0.08 | 0.09 | 0.18 |
| BAM | 0.06 | 0.07 | 0.14 |
| GUM | 0.20 | 0.69 | 1.37 |
| CMI | 0.14 | 0.39 | 0.78 |
| NMISA | 1.12 | 1.12 | 2.25 |
| BFKH | 0.05 | 0.06 | 0.13 |
| NMIJ | 0.07 | 0.80 | 1.59 |
| UME | 0.05 | 0.06 | 0.13 |

The LCS for the amount fraction propane consists of the results of VSL, VNIIM, NIM, NPL, NMIA, BAM, CMI, NMISA, BFKH and UME. The consensus value is 1.999 52 cmol mol$^{-1}$ with standard uncertainty 0.000 73 cmol mol$^{-1}$. The excess standard deviation $\tau$ is 0.000 79 cmol mol$^{-1}$ (0.04 % as relative standard uncertainty). The supported CMCs are shown in table 22. The degrees of equivalence computed from these data are shown in figure 18. GUM, CMI and NMIJ report results that are not consistent with the KCRV.

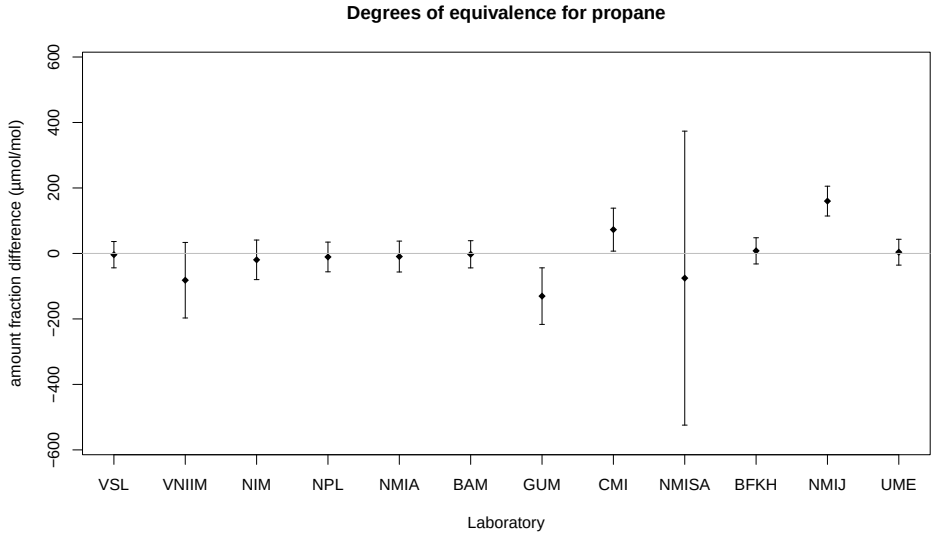



Figure 18: Degrees of equivalence for the amount fraction propane (high-calorific natural gas) (cmol mol$^{-1}$).

Table 23: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for iso-butane for natural gas type LNG (%).

| Lab | $u_{\text{lab}}$ | $u_{\text{CMC}}$ | $U_{\text{CMC}}$ |
|---|---|---|---|
| VSL | 0.05 | 0.07 | 0.13 |
| VNIIM | 0.34 | 0.34 | 0.68 |
| NIM | 0.12 | 0.13 | 0.26 |
| NPL | 0.18 | 0.18 | 0.36 |
| NMIA | 0.20 | 0.21 | 0.41 |
| BAM | 0.06 | 0.07 | 0.14 |
| GUM | 0.40 | 0.40 | 0.81 |
| CMI | 0.33 | 0.34 | 0.67 |
| BFKH | 0.17 | 0.17 | 0.35 |
| NMIJ | 0.08 | 0.10 | 0.19 |
| UME | 0.07 | 0.08 | 0.16 |

The LCS for the amount fraction iso-butane consists of the results of VSL, VNIIM, NIM, NPL, NMIA, BAM, GUM, CMI, NMISA, BFKH and NMIJ. The consensus value is 0.149 15 cmol mol$^{-1}$ with standard uncertainty 0.000 06 cmol mol$^{-1}$. The excess standard deviation $\tau$ is 0.000 06 cmol mol$^{-1}$ (0.04 % as relative standard uncertainty). The supported CMCs are shown in table 23. The degrees of equivalence computed from these data are shown in figure 19. All results are consistent with the KCRV.

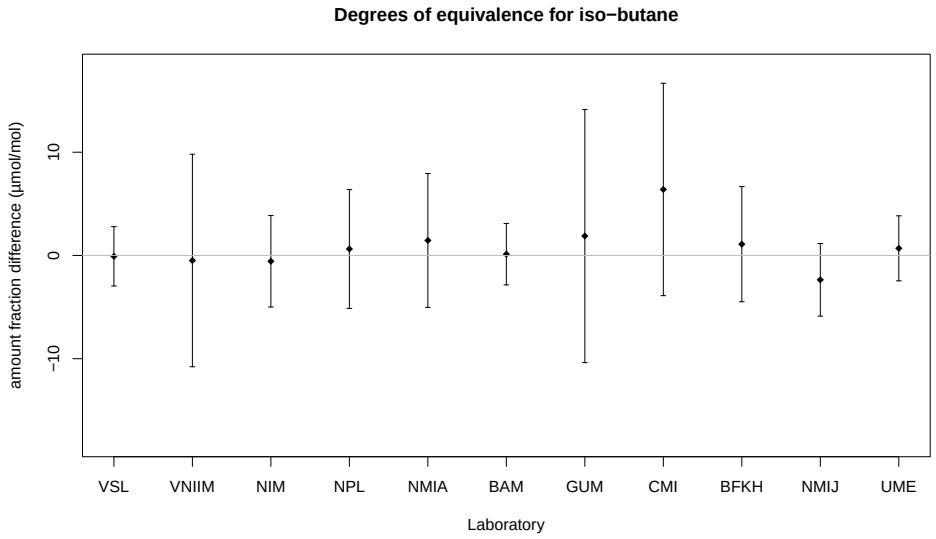



Figure 19: Degrees of equivalence for the amount fraction *iso*-butane (high-calorific natural gas) ($\mathrm{cmol\,mol^{-1}}$).

Table 24: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for n-butane for natural gas type LNG (%).

| Lab | $u_{\mathrm{lab}}$ | $u_{\mathrm{CMC}}$ | $U_{\mathrm{CMC}}$ |
|---|---|---|---|
| VSL | 0.05 | 0.09 | 0.17 |
| VNIIM | 0.51 | 0.51 | 1.02 |
| NIM | 0.13 | 0.15 | 0.30 |
| NPL | 0.18 | 0.19 | 0.38 |
| NMIA | 0.20 | 0.21 | 0.43 |
| BAM | 0.06 | 0.09 | 0.18 |
| GUM | 0.41 | 0.41 | 0.82 |
| CMI | 0.34 | 0.34 | 0.69 |
| NMISA | 1.17 | 2.79 | 5.57 |
| BFKH | 0.13 | 0.15 | 0.30 |
| NMIJ | 0.11 | 0.13 | 0.25 |
| UME | 0.07 | 0.10 | 0.19 |

The LCS for the amount fraction n-butane consists of the results of VSL, VNIIM, NIM, NPL, NMIA, GUM, CMI, NMISA, BFKH and UME. The consensus value is $0.148\,59\,\mathrm{cmol\,mol^{-1}}$ with standard uncertainty $0.000\,09\,\mathrm{cmol\,mol^{-1}}$. The excess standard deviation $\tau$ is $0.000\,10\,\mathrm{cmol\,mol^{-1}}$ (0.07 % as relative standard uncertainty). The supported CMCs are shown in table 24. The degrees of equivalence computed from these data are shown in figure 20. NMISA reports a result that is not consistent with the KCRV.

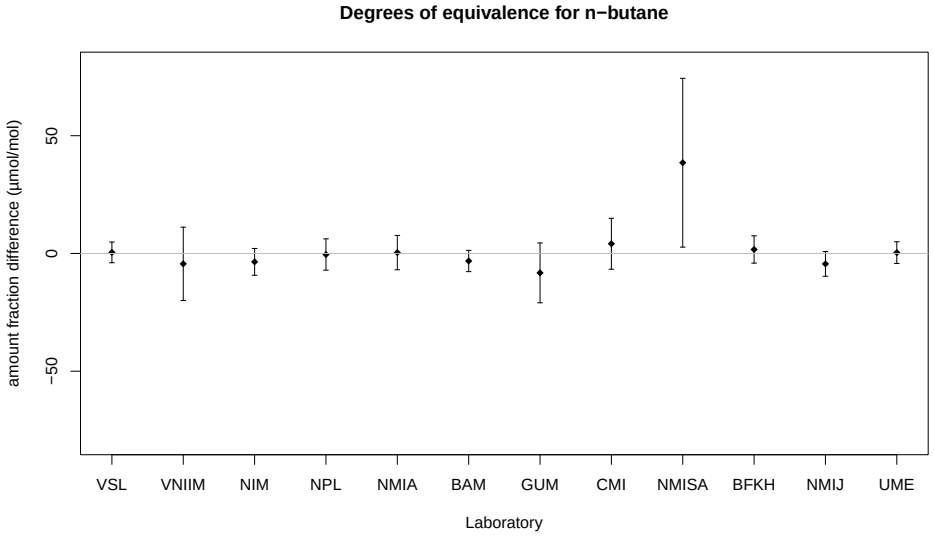



Figure 20: Degrees of equivalence for the amount fraction *n*-butane (high-calorific natural gas) (cmol mol$^{-1}$).

Table 25: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for iso-pentane for natural gas type LNG (%).

| Lab | $u_{\text{lab}}$ | $u_{\text{CMC}}$ | $U_{\text{CMC}}$ |
|---|---|---|---|
| VSL | 0.20 | 0.24 | 0.49 |
| VNIIM | 0.48 | 0.50 | 0.99 |
| NIM | 0.18 | 0.23 | 0.45 |
| NPL | 0.20 | 0.24 | 0.49 |
| NMIA | 0.20 | 0.98 | 1.97 |
| BAM | 0.09 | 0.17 | 0.33 |
| GUM | 0.51 | 1.90 | 3.80 |
| CMI | 0.25 | 1.45 | 2.91 |
| NMISA | 1.43 | 1.44 | 2.88 |
| BFKH | 0.25 | 1.04 | 2.08 |
| NMIJ | 0.13 | 1.82 | 3.63 |
| UME | 0.15 | 2.47 | 4.95 |

The LCS for the amount fraction iso-pentane consists of the results of VSL, VNIIM, NIM, NPL, BAM and NMISA. The consensus value is 0.019 90 cmol mol$^{-1}$ with standard uncertainty 0.000 03 cmol mol$^{-1}$. The excess standard deviation $\tau$ is 0.000 03 cmol mol$^{-1}$ (0.14 % as relative standard uncertainty). The supported CMCs are shown in table 25. The degrees of equivalence computed from these data are shown in figure 21. NMIA, GUM, CMI, BFKH, NMIJ and UME report results that are not consistent with the KCRV.

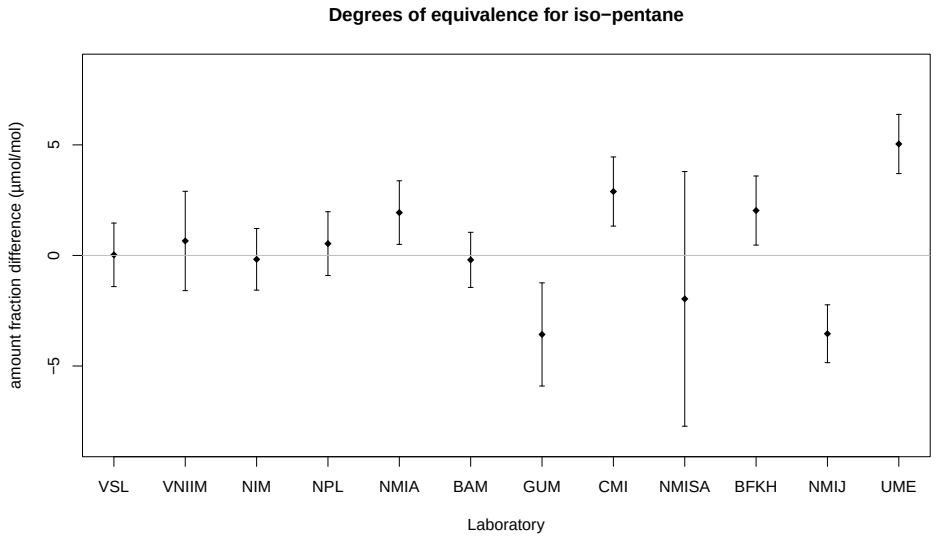



Figure 21: Degrees of equivalence for the amount fraction *iso*-pentane (high-calorific natural gas) (cmol mol$^{-1}$).

Table 26: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for n-pentane for natural gas type LNG (%).

| Lab | $u_{\text{lab}}$ | $u_{\text{CMC}}$ | $U_{\text{CMC}}$ |
|---|---|---|---|
| VSL | 0.20 | 0.25 | 0.50 |
| VNIIM | 0.35 | 0.38 | 0.76 |
| NIM | 0.16 | 0.22 | 0.45 |
| NPL | 0.20 | 0.25 | 0.50 |
| NMIA | 0.25 | 0.29 | 0.58 |
| BAM | 0.10 | 0.18 | 0.37 |
| GUM | 0.30 | 0.34 | 0.67 |
| CMI | 0.25 | 1.02 | 2.03 |
| NMISA | 0.99 | 1.01 | 2.01 |
| BFKH | 0.25 | 0.29 | 0.58 |
| NMIJ | 0.18 | 0.23 | 0.47 |
| UME | 0.15 | 1.18 | 2.37 |

The LCS for the amount fraction n-pentane consists of the results of VSL, VNIIM, NIM, NPL, NMIA, BAM, GUM, NMISA and BFKH. The consensus value is 0.020 09 cmol mol$^{-1}$ with standard uncertainty 0.000 02 cmol mol$^{-1}$. The excess standard deviation $\tau$ is 0.000 03 cmol mol$^{-1}$ (0.15 % as relative standard uncertainty). The supported CMCs are shown in table 26. The degrees of equivalence computed from these data are shown in figure 22. CMI and UME report results that are not consistent with the KCRV.

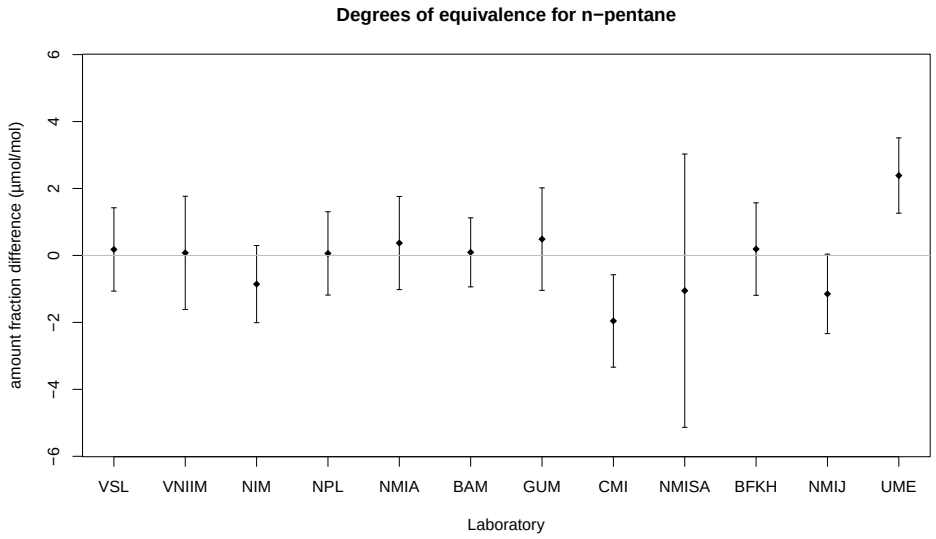



Figure 22: Degrees of equivalence for the amount fraction *n*-pentane (high-calorific natural gas) ($\mathrm{cmol\,mol^{-1}}$).

Table 27: Results and key comparison reference values for methane (high-calorific natural gas) ($\mathrm{cmol\,mol^{-1}}$).

| Lab | Mixture | $y_{\mathrm{lab}}$ | $U(y_{\mathrm{lab}})$ | $k_{\mathrm{lab}}$ | $y_{\mathrm{KCRV}}$ | $U(y_{\mathrm{KCRV}})$ | $u(y_{\mathrm{KCRV}})$ | $k_{\mathrm{KCRV}}$ |
|---|---|---|---|---|---|---|---|---|
| VSL | D322696 | 87.505 | 0.088 | 2.0 | 87.526 | 0.025 | 0.012 | 2.0 |
| VNIIM | D322705 | 87.561 | 0.050 | 2.0 | 87.529 | 0.021 | 0.010 | 2.0 |
| NIM | D322700 | 87.534 | 0.030 | 2.0 | 87.540 | 0.021 | 0.011 | 2.0 |
| NPL | D322741 | 87.534 | 0.035 | 2.0 | 87.530 | 0.021 | 0.011 | 2.0 |
| NMIA | D322718 | 87.521 | 0.050 | 2.0 | 87.539 | 0.019 | 0.010 | 2.0 |
| BAM | D322734 | 87.518 | 0.015 | 2.0 | 87.517 | 0.020 | 0.010 | 2.0 |
| GUM | D322699 | 87.519 | 0.088 | 2.0 | 87.516 | 0.025 | 0.012 | 2.0 |
| CMI | D322707 | 87.555 | 0.027 | 2.0 | 87.537 | 0.020 | 0.010 | 2.0 |
| NMISA | D322742 | 87.119 | 1.625 | 2.0 | 87.533 | 0.024 | 0.012 | 2.0 |
| BFKH | D322726 | 87.515 | 0.028 | 2.0 | 87.531 | 0.022 | 0.011 | 2.0 |
| NMIJ | D322736 | 87.162 | 0.273 | 2.0 | 87.525 | 0.025 | 0.012 | 2.0 |
| UME | D322701 | 87.519 | 0.064 | 2.0 | 87.529 | 0.019 | 0.010 | 2.0 |

Table 28: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for methane for natural gas type LNG (%).

| Lab | $u_{\text{lab}}$ | $u_{\text{CMC}}$ | $U_{\text{CMC}}$ |
|---|---|---|---|
| VSL | 0.05 | 0.05 | 0.10 |
| VNIIM | 0.03 | 0.03 | 0.06 |
| NIM | 0.02 | 0.02 | 0.04 |
| NPL | 0.02 | 0.02 | 0.05 |
| NMIA | 0.03 | 0.03 | 0.06 |
| BAM | 0.01 | 0.01 | 0.03 |
| GUM | 0.05 | 0.05 | 0.10 |
| CMI | 0.02 | 0.02 | 0.04 |
| NMISA | 0.93 | 0.93 | 1.87 |
| BFKH | 0.02 | 0.02 | 0.04 |
| NMIJ | 0.16 | 0.45 | 0.89 |
| UME | 0.04 | 0.04 | 0.08 |

The LCS for the amount fraction methane consists of the results of VSL, VNIIM, NPL, NMIA, BAM, GUM, CMI, NMISA, BFKH, NMIJ and UME. The consensus value is 87.5311 cmol mol$^{-1}$ with standard uncertainty 0.0089 cmol mol$^{-1}$. The excess standard deviation $\tau$ is 0.0103 cmol mol$^{-1}$ (0.01 % as relative standard uncertainty). The supported CMCs are shown in table 28. The degrees of equivalence computed from these data are shown in figure 23. NMIJ reports a result that is not consistent with the KCRV.

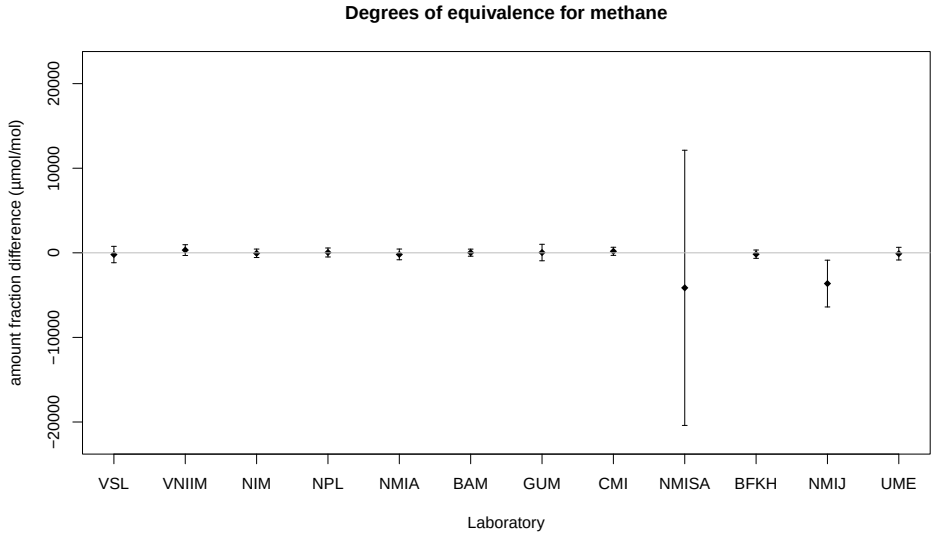



Figure 23: Degrees of equivalence for the amount fraction methane (high-calorific natural gas) (cmol mol$^{-1}$).

# 5 Supported capabilities

## 5.1 Nitrogen

Table 29: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for nitrogen (%). Lower and upper bounds given in cmol mol$^{-1}$.

| Lab | $x_{LB}$ | $x_{UB}$ | $a_0$ | $a_1$ | $U_{CMC}$ |
|---|---|---|---|---|---|
| VSL | 0.10 | 25 | -5.865 | -0.209 | 0.17 |
| VNIIM | 0.10 | 25 | -2.743 | 0.853 | 0.79 |
| SMU | 0.50 | 25 | | | 0.31 |
| NIM | 0.10 | 25 | -7.744 | -1.102 | 0.25 |
| NPL | 0.10 | 25 | -5.348 | -0.021 | 0.20 |
| NMIA | 0.10 | 25 | -6.096 | -0.276 | 0.14 |
| BAM | 0.10 | 25 | -6.130 | -0.298 | 0.14 |
| GUM | 0.10 | 25 | -3.750 | 0.534 | 0.42 |
| CMI | 0.10 | 25 | -7.993 | -1.148 | 0.18 |
| NMISA | 0.10 | 25 | -6.361 | -0.687 | 0.66 |
| BFKH | 0.10 | 20 | | | 0.82 |
| NMIJ | 0.10 | 25 | -3.394 | 0.657 | 0.50 |
| KRISS | 0.50 | 25 | | | 1.24 |
| UME | 0.10 | 25 | -4.690 | 0.231 | 0.24 |

For laboratories for which the cells in the columns $a_0$ and $a_1$ in table 29 are populated, the interpolation formula [9]

$$\lg u_{CMC} = a_0 + a_1 \lg x \tag{4}$$

applies, where $x$ denotes the amount fraction nitrogen and $u_{CMC}$ the supported absolute standard uncertainty (both expressed in mol mol$^{-1}$). The relative expanded uncertainty $U_{CMC} = ku_{CMC}/x$ is calculated as

$$U_{CMC} = \frac{k}{x} \cdot 10^{a_0 + a_1 \lg x}$$

where $x$ denotes the amount fraction in mol mol$^{-1}$ and $k$ the coverage factor. The interpolation formula applies up to an amount fraction of 0.5 cmol mol$^{-1}$. For $x \geq 0.5$ cmol mol$^{-1}$, the relative expanded uncertainty in the column $U_{CMC}$ applies.

As an example, consider the data of NIM. At $x = 0.5$ cmol mol$^{-1}$, their CMC is

$$U_{CMC} = \frac{2}{0.005} \cdot 10^{-7.7438 - 1.1016 \lg 0.005} = 0.25\,\%$$

For an amount fraction of 20 cmol mol$^{-1}$, $U_{CMC} = 0.25$ % (see also table 29).

For all other cases, the relative expanded uncertainty in the column $U_{CMC}$ applies.

## 5.2 Carbon dioxide

Table 30: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for carbon dioxide (%). Lower and upper bounds given in cmol mol$^{-1}$.

| Lab | $x_{LB}$ | $x_{UB}$ | $a_0$ | $a_1$ | $U_{CMC}$ |
|---|---|---|---|---|---|
| VSL | 0.02 | 20 | -4.233 | 0.511 | 0.16 |
| VNIIM | 0.02 | 20 | -2.549 | 0.939 | 0.78 |
| SMU | 0.50 | 20 | | | 0.42 |
| NIM | 0.02 | 20 | -3.665 | 0.663 | 0.26 |
| NPL | 0.02 | 20 | -4.959 | 0.195 | 0.16 |
| NMIA | 0.02 | 20 | -4.896 | 0.242 | 0.14 |
| BAM | 0.02 | 20 | -3.868 | 0.627 | 0.19 |
| GUM | 0.02 | 20 | -2.507 | 1.004 | 0.61 |
| CMI | 0.02 | 20 | -4.193 | 0.472 | 0.21 |
| NMISA | 0.02 | 20 | 0.990 | 1.658 | 59.85 |
| BFKH | 0.02 | 10 | | | 1.16 |
| NMIJ | 0.02 | 20 | -0.136 | 1.645 | 4.80 |
| KRISS | 0.50 | 20 | | | 0.96 |
| UME | 0.02 | 20 | -3.838 | 0.607 | 0.23 |

For laboratories for which the cells in the columns $a_0$ and $a_1$ in table 30 are populated, the interpolation formula [9]

$$3 \lg u_{CMC} = a_0 + a_1 \lg x \tag{5}$$

applies, where $x$ denotes the amount fraction carbon dioxide and $u_{CMC}$ the supported absolute standard uncertainty (both expressed in mol mol$^{-1}$). The relative expanded uncertainty $U_{CMC} = k u_{CMC}/x$ is calculated as

$$U_{CMC} = \frac{k}{x} \cdot 10^{a_0 + a_1 \lg x}$$

where $x$ denotes the amount fraction in mol mol$^{-1}$ and $k$ the coverage factor. The interpolation formula applies up to an amount fraction of 4 cmol mol$^{-1}$. For $x \geq 4$ cmol mol$^{-1}$, the relative expanded uncertainty in the column $U_{CMC}$ applies.

For all other cases, the relative expanded uncertainty in the column $U_{CMC}$ applies.

## 5.3 Hydrogen

Table 31: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for hydrogen (%). Lower and upper bounds given in cmol mol$^{-1}$.

| Lab | $x_{LB}$ | $x_{UB}$ | $U_{CMC}$ |
|---|---|---|---|
| VSL | 0.5 | 10 | 0.34 |
| VNIIM | 0.5 | 10 | 0.53 |
| SMU | 0.5 | 10 | 1.11 |
| NIM | 0.5 | 10 | 0.39 |
| NPL | 0.5 | 10 | 0.59 |
| NMIA | 0.5 | 10 | 0.35 |
| BAM | 0.5 | 10 | 0.33 |
| GUM | 0.5 | 10 | 0.86 |
| CMI | 0.5 | 10 | 0.73 |
| NMISA | 0.5 | 10 | 4.22 |
| NMIJ | 0.5 | 10 | 5.88 |
| KRISS | 0.5 | 10 | 1.29 |
| UME | 0.5 | 10 | 0.33 |

## 5.4 Helium

Table 32: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for helium (%). Lower and upper bounds given in cmol mol$^{-1}$.

| Lab | $x_{LB}$ | $x_{UB}$ | $U_{CMC}$ |
|---|---|---|---|
| VSL | 0.05 | 2.5 | 0.28 |
| VNIIM | 0.05 | 2.5 | 0.53 |
| SMU | 0.05 | 2.5 | 1.09 |
| NIM | 0.05 | 2.5 | 0.34 |
| NPL | 0.05 | 2.5 | 0.53 |
| NMIA | 0.05 | 2.5 | 0.29 |
| BAM | 0.05 | 2.5 | 0.24 |
| GUM | 0.05 | 2.5 | 0.63 |
| CMI | 0.05 | 2.5 | 0.87 |
| NMISA | 0.05 | 2.5 | 5.55 |
| NMIJ | 0.05 | 2.5 | 2.54 |
| KRISS | 0.05 | 2.5 | 1.61 |
| UME | 0.05 | 2.5 | 2.47 |

## 5.5 Ethane

Table 33: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for ethane (%). Lower and upper bounds given in cmol mol$^{-1}$.

| Lab | $x_{LB}$ | $x_{UB}$ | $U_{CMC}$ |
|---|---|---|---|
| VSL | 0.2 | 25 | 0.19 |
| VNIIM | 0.2 | 25 | 0.53 |
| SMU | 0.2 | 20 | 0.32 |
| NIM | 0.2 | 25 | 0.27 |
| NPL | 0.2 | 25 | 0.23 |
| NMIA | 0.2 | 25 | 0.17 |
| BAM | 0.2 | 25 | 0.33 |
| GUM | 0.2 | 25 | 0.81 |
| CMI | 0.2 | 25 | 0.65 |
| NMISA | 0.2 | 25 | 2.42 |
| BFKH | 0.5 | 25 | 0.14 |
| NMIJ | 0.2 | 25 | 0.16 |
| KRISS | 0.2 | 20 | 1.16 |
| UME | 0.2 | 25 | 0.18 |

## 5.6 Propane

Table 34: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for propane (%). Lower and upper bounds given in cmol mol$^{-1}$.

| Lab | $x_{LB}$ | $x_{UB}$ | $U_{CMC}$ |
|---|---|---|---|
| VSL | 0.05 | 12 | 0.27 |
| VNIIM | 0.05 | 12 | 0.57 |
| SMU | 0.05 | 10 | 0.54 |
| NIM | 0.05 | 12 | 0.30 |
| NPL | 0.05 | 12 | 0.21 |
| NMIA | 0.05 | 12 | 0.24 |
| BAM | 0.05 | 12 | 0.30 |
| GUM | 0.05 | 12 | 1.13 |
| CMI | 0.05 | 12 | 0.64 |
| NMISA | 0.05 | 12 | 2.33 |
| BFKH | 0.10 | 12 | 0.13 |
| NMIJ | 0.05 | 12 | 1.14 |
| KRISS | 0.05 | 10 | 1.26 |
| UME | 0.05 | 12 | 0.22 |

## 5.7 iso-Butane

Table 35: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for iso-butane (%). Lower and upper bounds given in cmol mol$^{-1}$.

| Lab | $x_{LB}$ | $x_{UB}$ | $U_{CMC}$ |
|---|---|---|---|
| VSL | 0.05 | 1.5 | 0.14 |
| VNIIM | 0.05 | 1.5 | 0.72 |
| SMU | 0.05 | 1.5 | 0.56 |
| NIM | 0.05 | 1.5 | 0.27 |
| NPL | 0.05 | 1.5 | 0.36 |
| NMIA | 0.05 | 1.5 | 0.33 |
| BAM | 0.05 | 1.5 | 0.14 |
| GUM | 0.05 | 1.5 | 4.97 |
| CMI | 0.05 | 1.5 | 0.69 |
| BFKH | 0.05 | 1.5 | 0.35 |
| NMIJ | 0.05 | 1.5 | 0.20 |
| KRISS | 0.05 | 1.5 | 0.94 |
| UME | 0.05 | 1.5 | 0.19 |

## 5.8 n-Butane

Table 36: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for n-butane (%). Lower and upper bounds given in cmol mol$^{-1}$.

| Lab | $x_{LB}$ | $x_{UB}$ | $U_{CMC}$ |
|---|---|---|---|
| VSL | 0.05 | 1.5 | 0.19 |
| VNIIM | 0.05 | 1.5 | 0.93 |
| SMU | 0.05 | 1.5 | 0.58 |
| NIM | 0.05 | 1.5 | 0.30 |
| NPL | 0.05 | 1.5 | 0.38 |
| NMIA | 0.05 | 1.5 | 0.36 |
| BAM | 0.05 | 1.5 | 0.19 |
| GUM | 0.05 | 1.5 | 0.82 |
| CMI | 0.05 | 1.5 | 0.73 |
| NMISA | 0.05 | 1.5 | 4.27 |
| BFKH | 0.05 | 1.5 | 0.30 |
| NMIJ | 0.05 | 1.5 | 0.59 |
| KRISS | 0.05 | 1.5 | 1.49 |
| UME | 0.05 | 1.5 | 0.23 |

## 5.9 iso-Pentane

Table 37: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for iso-pentane (%). Lower and upper bounds given in cmol mol$^{-1}$.

| Lab | $x_{LB}$ | $x_{UB}$ | $U_{CMC}$ |
|---|---|---|---|
| VSL | 0.01 | 0.25 | 0.50 |
| VNIIM | 0.01 | 0.25 | 1.05 |
| SMU | 0.01 | 0.25 | 0.98 |
| NIM | 0.01 | 0.25 | 0.53 |
| NPL | 0.01 | 0.25 | 0.55 |
| NMIA | 0.01 | 0.25 | 1.44 |
| BAM | 0.01 | 0.25 | 0.44 |
| GUM | 0.01 | 0.25 | 2.79 |
| CMI | 0.01 | 0.25 | 2.12 |
| NMISA | 0.01 | 0.25 | 2.88 |
| BFKH | 0.01 | 0.25 | 2.08 |
| NMIJ | 0.01 | 0.25 | 2.91 |
| KRISS | 0.01 | 0.25 | 3.02 |
| UME | 0.01 | 0.25 | 3.52 |

## 5.10 n-Pentane

Table 38: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for n-pentane (%). Lower and upper bounds given in cmol mol$^{-1}$.

| Lab | $x_{LB}$ | $x_{UB}$ | $U_{CMC}$ |
|---|---|---|---|
| VSL | 0.01 | 0.25 | 0.46 |
| VNIIM | 0.01 | 0.25 | 0.82 |
| SMU | 0.01 | 0.25 | 0.82 |
| NIM | 0.01 | 0.25 | 0.46 |
| NPL | 0.01 | 0.25 | 0.52 |
| NMIA | 0.01 | 0.25 | 0.53 |
| BAM | 0.01 | 0.25 | 0.48 |
| GUM | 0.01 | 0.25 | 0.68 |
| CMI | 0.01 | 0.25 | 1.52 |
| NMISA | 0.01 | 0.25 | 2.19 |
| BFKH | 0.01 | 0.25 | 0.58 |
| NMIJ | 0.01 | 0.25 | 0.42 |
| KRISS | 0.01 | 0.25 | 2.54 |
| UME | 0.01 | 0.25 | 1.71 |

## 5.11 neo-Pentane

Table 39: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for neo-pentane (%). Lower and upper bounds given in cmol mol$^{-1}$.

| Lab | $x_{LB}$ | $x_{UB}$ | $U_{CMC}$ |
|---|---|---|---|
| VSL | 0.01 | 0.25 | 0.39 |
| VNIIM | 0.01 | 0.25 | 0.69 |
| SMU | 0.01 | 0.25 | 1.06 |
| NIM | 0.01 | 0.25 | 0.47 |
| NPL | 0.01 | 0.25 | 0.60 |
| NMIA | 0.01 | 0.25 | 0.47 |
| BAM | 0.01 | 0.25 | 0.41 |
| GUM | 0.01 | 0.25 | 2.03 |
| CMI | 0.01 | 0.25 | 1.06 |
| NMIJ | 0.01 | 0.25 | 0.43 |
| KRISS | 0.01 | 0.25 | 2.03 |
| UME | 0.01 | 0.25 | 1.24 |

## 5.12 n-Hexane

Table 40: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for n-hexane (%). Lower and upper bounds given in cmol mol$^{-1}$.

| Lab | $x_{LB}$ | $x_{UB}$ | $U_{CMC}$ |
|---|---|---|---|
| VSL | 0.01 | 0.25 | 0.48 |
| VNIIM | 0.01 | 0.25 | 1.28 |
| SMU | 0.01 | 0.25 | 0.88 |
| NIM | 0.01 | 0.25 | 0.51 |
| NPL | 0.01 | 0.25 | 0.59 |
| NMIA | 0.01 | 0.25 | 1.67 |
| BAM | 0.01 | 0.25 | 0.54 |
| GUM | 0.01 | 0.25 | 0.74 |
| CMI | 0.01 | 0.25 | 0.74 |
| NMISA | 0.01 | 0.25 | 2.38 |
| NMIJ | 0.01 | 0.25 | 1.32 |
| KRISS | 0.01 | 0.25 | 2.04 |
| UME | 0.01 | 0.25 | 0.62 |

### 5.13 Methane (natural gas)

Table 41: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for methane (%). Lower and upper bounds given in cmol mol$^{-1}$.

| Lab | $x_{LB}$ | $x_{UB}$ | $U_{CMC}$ |
|---|---|---|---|
| VSL | 50 | 100 | 0.10 |
| VNIIM | 50 | 100 | 0.06 |
| NIM | 50 | 100 | 0.04 |
| NPL | 50 | 100 | 0.05 |
| NMIA | 50 | 100 | 0.06 |
| BAM | 50 | 100 | 0.03 |
| GUM | 50 | 100 | 0.10 |
| CMI | 50 | 100 | 0.04 |
| NMISA | 50 | 100 | 1.87 |
| BFKH | 50 | 100 | 0.04 |
| NMIJ | 50 | 100 | 0.89 |
| UME | 50 | 100 | 0.08 |

### 5.14 Methane (hydrogen-enriched natural gas)

Table 42: Reported standard uncertainty, supported minimum standard uncertainty and CMC, expressed as relative uncertainties, for methane (%). Lower and upper bounds given in cmol mol$^{-1}$.

| Lab | $x_{LB}$ | $x_{UB}$ | $U_{CMC}$ |
|---|---|---|---|
| VSL | 50 | 100 | 0.38 |
| VNIIM | 50 | 100 | 0.07 |
| SMU | 50 | 100 | 0.16 |
| NIM | 50 | 100 | 0.06 |
| NPL | 50 | 100 | 0.06 |
| NMIA | 50 | 100 | 0.08 |
| BAM | 50 | 100 | 0.05 |
| GUM | 50 | 100 | 0.11 |
| CMI | 50 | 100 | 0.06 |
| NMISA | 50 | 100 | 2.06 |
| NMIJ | 50 | 100 | 0.42 |
| KRISS | 50 | 100 | 0.30 |
| UME | 50 | 100 | 0.20 |

## A List of symbols

### A.1 Symbols

- $a_0$ intercept
- $a_1$ slope
- $U$ expanded uncertainty
- $u$ standard uncertainty
- $x$ amount fraction

### A.2 Subscripts

| | |
|---|---|
| CMC | calibration and measurement capability |
| LB | lower bound (of the amount fraction interval) |
| UB | upper bound (of the amount fraction interval) |

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