LNG ENERGY TRANSFER UNCERTAINTY- SENSITIVITY TO COMPOSITION AND TEMPERATURE CHANGES

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Abstract

Determining and reducing the measurement uncertainty of LNG energy transfer in custody transfer operations is considered extremely important and challenging for industry. The European Metrology Research Programme (EMRP) for Liquefied Natural Gas (LNG) project has been focusing on reducing the uncertainty in the evaluation of LNG energy transfers by improving existing measurement methods, validating new measurement methods and development of new traceable calibration systems. Part of this project was to produce realistic measurement uncertainty budgets and to determine the sensitivity of the overall LNG energy transfer uncertainty to changes in the composition and temperature of different LNG cargoes.

This paper provides details on development of an uncertainty budget, how correlation between uncertainty parameters was addressed, comparison with available literature and results from the sensitivity study.

1   DEVELOPMENT OF MODEL

An uncertainty model was produced using Microsoft Excel to determine the overall LNG energy transfer uncertainty. The LNG transferred energy can be calculated using the following formula [2]:

$$E = (V_{LNG} \cdot D_{LNG} \cdot GCV_{LNG}) - E_{Gas\ Disp} \pm E_{Gas\ to\ ER}$$

where:

- E_{LNG} is the overall LNG energy transfer
- V_{LNG} is the volume of LNG
- D_{LNG} is the density of the LNG
- GCV_{LNG} is the gross calorific value of the LNG
- $E_{gas\ disp}$ is the energy of the displaced gas, i.e. gas sent back to onshore tanks by the LNG carrier when loading and vice versa.
- $E_{gas\ to\ ER}$ is the energy of the gas consumed in the LNG carrier's engine room (+ve for LNG loading transfer and –ve for LNG unloading transfer)

Under some agreements the energy of the displaced gas ($E_{gas\ disp}$) and energy of gas consumed in the LNG carrier's engine room ($E_{gas\ to\ ER}$) can either be determined or a fixed value based on experience can be agreed between parties. For the purpose of this study the value of the displaced gas and energy of gas consumed in the engine room were not considered, partly due to lack of data and in many cases the uncertainty contribution from the displaced gas and gas consumed in the engine is considered negligible [1,2,3].

1.1   Component Uncertainty Budgets

The uncertainty of the LNG energy transferred is determined from the uncertainties of the:

- Calorific value (GCV_{LNG})
- Density (D_{LNG})
- Volume (V_{LNG})

The uncertainty of the gross calorific value is determined from the uncertainties of the:

- Composition
- Calorific value of the components

The uncertainty of the density is determined from the uncertainties of the:

- Composition
- Density calculation model
- Experimental data used to derive the density model
- Temperature

The uncertainty of the composition is determined from the uncertainties of the:

- Sampling and vaporisation process
- Gas chromatography equipment
- Calibration gas

The uncertainty of the volume has been assessed in a different task in the EMRP project [4] and used in this study.

Both the uncertainty of the calorific value and density depend on the uncertainty of the composition of the LNG, hence these uncertainties are correlated and are not independent. This means that the method for combining the uncertainty values must account for this mutual dependence. Uncorrelated uncertainties are combined by a root sum square method. This accounts for the unlikelihood that all the source uncertainties will be at their extreme values simultaneously and that to sum the input contributions directly would result in an overly pessimistic view of the overall uncertainty. However, correlated uncertainties are added by simple arithmetic addition to account for the mutual dependence on the same measurements.

It should be noted that some uncertainty values quoted from available references and in this paper are based on numerical examples from a specific data set. Therefore, the uncertainty values can change if the input parameters vary, such as the uncertainty of the equipment and composition. For

example, the uncertainty values provided by Enagas are numerical examples based on specific data.

2   LNG COMPOSITION UNCERTAINTY

The composition of the LNG is determined from sampling the LNG liquid flow, vaporising and analysing the gas using gas chromographic (GC) techniques. More details on LNG sampling are found in [5].

Conservative values were used to determine the uncertainty of the LNG composition. The uncertainty contributions considered were the:

- Chromatograph calibration
- Uncertainty in composition of calibration gas
- Sampling and vaporisation process

Selection of suitable calibration gases with a composition similar to the LNG being transferred and measured was acknowledged as potentially an important factor in minimising uncertainty [1]. In some cases, the variety of calibration gases maybe limited and operators will have to use what is available. For this reason conservative values of ±0.5% were used in this study for the calibration gas components uncertainty although reference [6] provided a value for the calibration gas uncertainty as ±0.1 % of the methane composition.

The uncertainty contribution from the sampling and vaporisation process has been incorporated into the composition uncertainty rather than as a separate contribution in the uncertainty of the gross calorific value (GCV) and density. It was noted that the GIIGNL Handbook only considered the uncertainty of sampling and vaporisation in the calorific value and not in the density calculation [2].

The uncertainty generally accepted for the sampling and vaporisation process by industry for custody transfer is ±0.30 % (k=2). Although well designed sampling and vaporisation systems, in which there is no partial vaporisation before the vaporiser unit, have been assessed to have uncertainty values as low as ±0.2 % (k=2) in the composition of the methane [7]. The value of ±0.30 % (k=2) has been considered to represent the uncertainty in composition from the sampling and vaporisation process.

The uncertainty in the measurement of methane composition in the LNG was estimated by reference [6] to be ±0.11% (k=2). However, in the present study a conservative value for the CG calibration uncertainty of ±0.2% was used.

Table 1 is taken from the uncertainty calculation spreadsheet which shows the expanded relative uncertainty (k=2) for each component as an example of LNG composition.

The combined uncertainty in each component is the "root sum square" combination of the chromatograph calibration uncertainty, calibration

gas uncertainty and the sampling uncertainty. For comparison the uncertainty values for each component from reference [8] are presented in Table 2.

2.1   Determining Repeatability

It was noted when reviewing existing uncertainty budgets that methods for calculating the repeatability can widely vary, which can result in a wide variation of values. For determining the repeatability in the GC analysis, usually the data from the GC is assessed to ensure large fluctuations in the data are removed from the overall determination of the LNG composition as described in [7]. After the removal of composition data that is out-with set criteria there tends to exist a large data set (greater than 30 points) to determine the average composition due to continuous or intermittent sampling during the transfer of the LNG. The uncertainty in any one data point can usually be considered to be much larger than the average value of a large data set.

Provided there is large data set of greater than 30 points, which provides a statistically meaningful data set, then the uncertainty in the mean composition value can be calculated as:

$$\text{Standard uncertainty in mean value } (U_{mean}) = \frac{\text{Standard deviation}}{\sqrt{(\text{sample population}, n)}}$$

Increasing the number of data points from the analysis that are inside the set criteria will reduce the uncertainty in the mean value for each of the LNG components.

2.2   LNG Composition Uncertainty Contribution to the Density and GCV Uncertainty

The effect of composition uncertainty on the overall uncertainty of the LNG, gross calorific value (GCV) and density may be evaluated in several ways. The method used for this study was to vary the proportions of individual components to determine the effects each has on the overall mixture GCV and density of a specific LNG example. Table 3 shows the values of the incremental changes in the composition and effect on the density and GCV values. The shaded cells show the composition of the component that has been changed. In the last column the composition of all components were varied at the same time. The value of the incremental changes was determined from the uncertainty of the components as given below:

$$\text{Incremental change } = \%_{component} + \left(\frac{\%_{component}.U_{component}}{100} \right)$$

2

Where:

- %component is the percentage of the component in LNG,
- Ucomponent is the expanded uncertainty of the LNG component.

The maximum difference in the calculated density and calorific value was used as the uncertainty contribution as this provided the most conservative values. It can be seen that the uncertainty in LNG composition has a more significant contribution to the uncertainty of the density than for the gross calorific value. Alternative approaches can be applied to the model including using half the difference and the maximum difference from the median value.

For comparison the values of composition uncertainty from available references [2, 3, 8 & 9] are given in the full report of this work [17]

3 DENSITY UNCERTAINTY

The LNG industry currently uses the revised Klosek-McKinley model for calculating LNG density as described in the GIIGNL [2]. This model was reviewed in another part of the EMRP project and is described in detail in reference [10].

Table 4 shows the uncertainty budget for the LNG density. The divisor (k) is used to convert the expanded uncertainty (U) with k values given in the table (approximately 95% coverage) to the standard uncertainty (u) with k=1. The product of the standard uncertainty (u) and the sensitivity (c) determines the contribution to the uncertainty of the LNG density. In this example all the sensitivity values are equal to one as the components uncertainties are in the same units as density, e.g. the temperature uncertainty of 0.2°C has been converted into a density uncertainty. The total uncertainty is determined from a quadratic summation (root mean square) of all the contributions and expressed as the expanded uncertainty (U) with k=2.

Correlation of uncertainty contributions:

- The molecular masses of the components are assumed to be 100 % correlated as they are calculated from the same values of atomic masses – this was considered negligible.
- Mole fractions of the components are assumed to be 100 % correlated due to the use of the same analysis equipment and normalisation procedure. This is accounted for by taking the maximum difference in the density value as the composition uncertainty contribution as described in section 2.2.
- Correction factors K_1 and K_2 and the molar volume of the components are assumed to be 100 % correlated as they depend on the LNG molecular mass – this was not considered and assumed to be accounted for by taking the maximum difference in the density value as described in section 2.2.
- Correction factors K_1 and K_2 and the molar volume of the components are also correlated as they depend on the LNG temperature – this effect was evaluated separately in section 3.2.

Values of the uncertainty of the density from available references are:

- ±0.21 % (k=1)   [2]
- ±0.16 % (k=2)   [3]
- ±0.23 % (assumed k=3) [9]
- ±0.35 % (k=2)   [8]

The uncertainty of the LNG density was determined in this study as ±0.20 % (k=2), which compares well with the references. The uncertainty contributions to the density uncertainty from the available references are given in the full report of this work [17]

3.1 Density Model Uncertainty Contribution

The uncertainty commonly quoted for the revised Klosek-McKinley model is ±0.1% [2, 3]. A comprehensive study to assess the LNG density models [9] quoted that the revised Klosek-McKinley model can predict the density to within ±0.1% based on evaluation using experimental data with an uncertainty of ±0.1%. The uncertainty evaluation by reference [9] incorporated the uncertainty from using the model and the experimental data. This conservative approach was adopted in this uncertainty budget. Reference [9] determined the experimental uncertainty taking a conservative approach using three standard deviations. Using the industry-standard approach of two standard deviations reduces the uncertainty to ±0.06%, this was the value used in this model.

It was noted that the GIIGNL only considers uncertainty of the model used (±0.1%) and does not include the uncertainty contribution from the sampling and vaporisation in the composition uncertainty.

3.2 Temperature Uncertainty Contribution

The revised Klosek-McKinley model requires only the LNG composition and temperature for calculation of LNG density.

The correlation through temperature was addressed by varying the temperature by a set amount (e.g. 0.2°C) and the effect this has on the volume correction value, V_c, (V_c incorporates correction factors K_1 and K_2) and the molar volumes of the components was calculated. The density difference was calculated when varying the temperature on one component and this difference was used as the uncertainty contribution for each molar volume.

Values are presented in Table 5 with both the correlated and uncorrelated uncertainty components.

The uncorrelated uncertainty was determined from quadratic summation (root mean square) of all the contributions (u.c) to give ±0.094% (k=2).

The correlated uncertainty contributions (u.c) are added by simple arithmetic addition to account for the mutual dependence on the same measurements. In this model the correlated uncertainties are assumed to be 100% (i.e. fully) correlated. The correlated uncertainty was determined as ±0.100% (k=2).

Comparison of the correlated and uncorrelated uncertainties shows insignificant difference using this uncertainty method.

Table 6 shows the uncertainty budget for the density using temperature sensitivity values determined by calculating the effect of a small change in temperature (e.g. 0.5 °C) on the density (i.e., $\partial\rho/\partial T = \Delta\rho/(T_+ - T_-)$). Comparing the different methods for determining the density uncertainty in Table 4 with that in Table 6 gives an insignificant difference in the density uncertainty of ±0.014%.

The uncertainty of the temperature value has been quoted by various sources as:
- ± 0.25°C (k=2) [3]
- ± 0.5°C (k=1) [2]
- ± 0.1 K (assumed k=3) [9]
- ± 0.17°C (k=2) [8]
- ± 0.2°C (k=2) [11]
- ± 0.3°C (k=2) [12]

The tolerance for temperature measurement equipment quoted by ISO 10976 is ± 0.2 °C [11]. However, a more conservative value of ± 0.5°C (i.e. sum of ±0.2 and ±0.3 in Table 4) was used in these models.

It can be concluded that the uncertainty in the density is ±0.20 % (k=2) for this specific example. This uncertainty model is applicable for other cargoes with different compositions and temperatures. The sensitivity study in Section 7 determines the density uncertainty for 461 different LNG cargoes.

4   GROSS CALORIFIC VALUE UNCERTAINTY

The calorific value of the LNG was determined on a mass basis using ISO 6976 [13] at standard conditions 15°C and 1.01325 bara. Superior calorific values were used in compliance with reference [2].

Values of the uncertainty of the calorific value from available references are:
- ±0.30% (k=1) [2]

- ±0.15% (k=2) [3] (NB this uncertainty value is for the product of the density times the calorific value to account for correlation)
- ±0.35% (assumed k=3) [9]
- ±0.08% (k=2) [14]

The uncertainty contributions to the calorific value uncertainty from the available references are given in the full report [17].

Within the uncertainty model developed in this study the uncertainty contributions towards the LNG calorific value were the composition and calorific values from the LNG components. The contribution from the calorific values of the components was taken from ISO 6976 [13] as the uncertainty of the calorific value of methane since this is the major component. The uncertainty of the calorific value of methane is quoted as ±0.06 MJ/kg (at 95% confidence level).

Correlation of the molecular masses of the LNG components (as these are determined from the same values of atomic masses) was not included as this was considered to be insignificant compared to other uncertainty contributions.

Correlation of the mole fractions for the LNG components from using the same analysis equipment and normalisation procedure was considered to be accounted for in the composition uncertainty. This was done by taking a conservative approach to determine the uncertainty by taking the maximum difference in the calculated GCV values (see section 2.2).

Table 7 shows the uncertainty budget for the calorific value of LNG. In this table the uncertainty in LNG composition is taken from the analysis presented in section 2.2 and Table 3. As shown in Table 3, the uncertainty in LNG composition has much less significant contribution to the uncertainty of calorific value than for density.

It can be concluded that the uncertainty of the calorific value is 0.11% (k=2) for this specific example. The sensitivity study in section 5 shows the uncertainty results from 461 LNG cargoes.

5   VOLUME UNCERTAINTY

The volume uncertainty contribution has been reviewed and determined as part of a separate study within the EMRP project in reference [4]. Values from the EMRP study and from other references are presented in Table 8.

The most conservative value of ±0.53% (from the EMRP study) has been used to determine the overall uncertainty of the energy transfer of LNG. The GIIGNL value of 0.094 is calculated from five tanks as ±(0.21/√5) assuming that all contributions are independent and are not correlated. This is

4

highly unlikely in practice and therefore the uncertainty value determined for the volume of one tank of ±0.21 % (k=1) is more representative.

6 UNCERTAINTY IN TOTAL ENERGY TRANSFER

The uncertainty contributions from the density, gross calorific value and volume have a degree of correlation towards the total LNG energy uncertainty. The density and calorific value both have a dependence on the composition of the LNG. The volume of the LNG has a dependence on the LNG temperature (which is also required for density calculation), composition and density. The uncertainty contribution from the density, calorific value and volume were first treated as completely uncorrelated and then 100% correlated to obtain extreme uncertainty values. These uncertainties are presented in Table 9.

The uncertainty contributions from the displaced gas and gas consumed by the engine can be considered in the determination of the overall energy transferred uncertainty. However, in this study these were considered negligible and not necessary for the sensitivity study due to their small values.

From Table 9 it can be seen that the uncorrelated uncertainty in LNG energy transferred is ±0.26% while the 100% correlated uncertainty is ±0.44 %. The level of correlation is difficult to determine and usually is assumed to be 50%. In this report a conservative approach was taken by using 80% correlation. Figure 1 shows the effect of selecting different degrees of correlation on the value of the uncertainty.

Table 10 shows the LNG energy uncertainty budget using 80% correlation. The correlated uncertainty contribution from the calorific value, density and volume was determined by taking 80% of the product of the standard uncertainty and sensitivity coefficient (u.c). The sum of the (u.c) values was taken as the overall correlated uncertainty contribution to the LNG energy. The uncorrelated uncertainty contribution from the calorific value, density and volume was determined by taking 20% of the product of the standard uncertainty and sensitivity coefficient (u.c). The root mean square of the (u.c) values was then taken as the overall uncorrelated uncertainty contribution to the LNG energy.

The uncorrelated (±0.05%) and correlated (±0.35%) expanded uncertainty contributions were combined by the root mean square method to provide an overall LNG energy uncertainty of ±0.36% (k=2).

Values of the uncertainty of the total energy transfer from available references are:

- ±0.76% (k=2) [2]
- ±0.34 % (k=2) [3]
- ±0.46 % (k value not provided) – uncertainty value for unloading from a single tank [9]

Reference [2] and [9] assumed no correlation between the density, volume and calorific value and combined the overall uncertainties in quadrature. Reference [3] took account of correlation.

From comparison with these references the overall uncertainty of the total energy transfer in this study of ±0.36 % (k=2) agrees with reference [3] despite using a different approach. However, it must be noted that this is applicable to the specific example given in this study and dependant on the uncertainty contributions taken from available literature for volume, density and calorific value. A complete independent calculation of uncertainty in energy transfer requires significant effort which was beyond the scope of this study.

7 SENSITIVITY STUDY

The main purpose of this study is to evaluate the sensitivity of the overall LNG energy transfer uncertainty to changes in the composition and temperature of different LNG cargoes. Composition and temperature data from a significant number of LNG cargoes over a period of time has been collected to conduct this study as described below.

7.1 Data for Sensitivity Study

Enagas provided an extensive set of composition and temperature data for 461 cargoes. The data were used as the input data for uncertainty model for the energy transfer of LNG. The temperature of the cargoes ranged from -162.32^{o}C to -156.64^{o}C.

Table 11 shows the composition range of the components of the LNG from these cargoes.

7.2 Results from Sensitivity Study

The 80% correlation model was used for the sensitivity study. The results from the sensitivity study showed that the uncertainty of the energy transfer of LNG varied from ±0.35% to ±0.36% with an average value of ±0.36%. Only 26 of the cargoes produced an uncertainty of ±0.35%, while 435 produced an uncertainty of ±0.36%.

Table 12 shows the range of percentage uncertainty values from the composition, density and calorific value.

8 CONCLUSIONS

A model was developed to determine the uncertainty in the LNG energy transfer and this was used to assess the sensitivity to changes in composition and temperature.

The results show that the uncertainty in density, calorific value and overall LNG energy transfer are not significantly sensitive to the changes in

temperature or composition within the typical range seen in LNG cargoes. The values should cover all types of tanks as conservative values were used.

The model was used to assess the uncertainty from 461 LNG cargoes and determined the range in uncertainty values as:

- Uncertainty in density between ±0.19% and ±0.20%
- Uncertainty in gross calorific value between ±0.11% and ±0.12%
- Uncertainty in total energy transfer between ±0.35% and ±0.36%.

It is important to note that uncertainty results presented in this study were dependant on the uncertainty contributions taken from available literature and current industry experience for the volume uncertainty and the elements contributing to the density and calorific value uncertainties. A complete independent calculation of uncertainty in energy transfer requires significant effort which was beyond the scope of this study.

The uncertainty of the different parameters involved in the global uncertainty of the LNG energy transferred ideally should be calculated for each cargo and equipment used. Therefore, it can be difficult to determine an uncertainty range or upper limit because the values depend on the quality of the measurement at each terminal.

9   RECOMMENDATIONS

The use of Monte Carlo simulation may have been beneficial to apply a range of values for the input parameters (e.g. composition, temperature etc) to determine the range and distribution of variations in the overall energy transfer value. One of the advantages of this method is the availability of the output distribution and to determine if the output is skewed.

Due to the variation in methods and values for the uncertainty in overall energy transfer, guidelines for producing a realistic uncertainty budget would be beneficial. It was noted that many companies produce in-house uncertainty budgets rather than rely on the GIIGNL values [2].

It is recommended to produce an additional uncertainty budget table for the energy transferred using the source input parameters from the density, calorific value and volume. This includes LNG temperature, composition, ship list and trim measurements, start and end liquid level measurements, start and end tank volume measurements, density model etc. The sensitivity coefficients determined would account for correlation. This model would eliminate the need to assume the percentage correlation dependence for the density, calorific value and volume.

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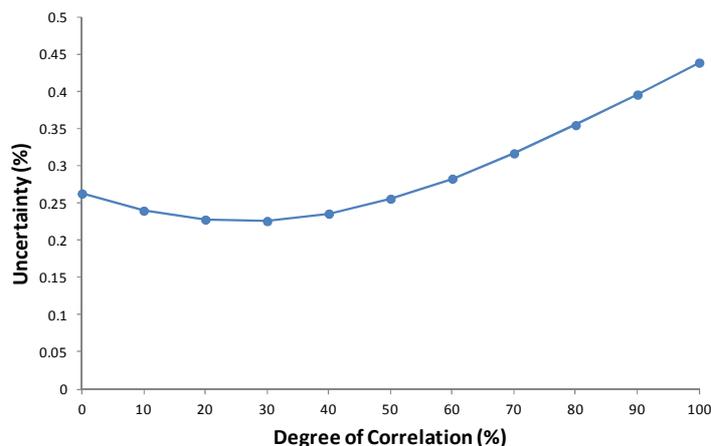**Figure 1 –** Effect of degree of correlation on the uncertainty

Table 1 Uncertainty of the LNG composition

Chromatograph Calibration Uncertainty (%)	0.2

Gas Component	%mol	Calibration Gas Uncertainty (%)	Sampling uncertainty (%)	Combined Uncertainty (% mol/mol)
Methane	90.072	0.5	0.3	0.616
Nitrogen	0.192	0.5	0.3	0.616
Ethane	6.381	0.5	0.3	0.616
Propane	2.301	0.5	0.3	0.616
i-Butane	0.415	0.5	0.3	0.616
n-Butane	0.623	0.5	0.3	0.616
i-Pentane	0.014	0.5	0.3	0.616
n-Pentane	0.002	0.5	0.3	0.616
Hexane	0.000	0.5	0.3	0.616

Table 2 Expanded Uncertainty of the LNG Components from Reference [8] (Values include reference gas mixture uncertainty, GC calibration uncertainty, analysis uncertainty and sampling uncertainty)

Component	Expanded Uncertainty (% mol/mol) (k=2)
Methane	± 0.46
Ethane	± 0.41
Propane	± 0.18
i-Butane	± 0.059
n-Butane	± 0.13
i-Pentane	± 0.0045
n-Pentane	± 0.0024
Hexane	± 0.0015
Nitrogen	± 0.028

Table 3 - Effect of varying the composition on the GCV and density values (The shaded cells highlight that the composition has been modified)

	Composition	Methane	Nitrogen	Ethane	Propane	i-Butane	n-Butane	i-Pentane	n-Pentane	Hexane	All
Methane	90.072	90.627	90.072	90.072	90.072	90.072	90.072	90.072	90.072	90.072	90.627
Nitrogen	0.192	0.192	0.193	0.192	0.192	0.192	0.192	0.192	0.192	0.192	0.193
Ethane	6.381	6.381	6.381	6.420	6.381	6.381	6.381	6.381	6.381	6.381	6.420
Propane	2.301	2.301	2.301	2.301	2.315	2.301	2.301	2.301	2.301	2.301	2.315
i-Butane	0.415	0.415	0.415	0.415	0.415	0.418	0.415	0.415	0.415	0.415	0.418
n-Butane	0.623	0.623	0.623	0.623	0.623	0.623	0.627	0.623	0.623	0.623	0.627
i-Pentane	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014
n-Pentane	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Hexane	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Δ Density	0.000	0.018	-0.003	-0.102	-0.067	-0.017	-0.026	-0.001	0.000	0.000	-0.197
Density	458.479	458.461	458.482	458.580	458.545	458.496	458.505	458.480	458.479	458.479	458.676
CV	54.522	54.527	54.521	54.520	54.521	54.522	54.522	54.522	54.522	54.522	54.522
Δ CV	0.000	-0.005	0.001	0.002	0.001	0.000	0.001	0.000	0.000	0.000	0.000

	Max Difference	Absolute Uncertainty	Relative Uncertainty
Density	0.214883	0.214883	0.046869
Calorific Value	0.006845	0.006845	0.012554

7

Table 4 - Uncertainty budget for the LNG density

Rank	Source	Units	Value	Uncert. U	U*%	Distribution	Divisor k	Stand. Unc u	Sens. (∂f/∂xi) c	Product u.c	Square (u.c)²
5	Composition	kg/m^3	458.479	0.215	0.047	Rectangular	1.732	0.124	1	0.124	1.54E-02
2	Revised Klosek-McKinley Method	kg/m^3	458.479	0.458	0.100	Rectangular	1.732	0.265	1	0.265	7.01E-02
4	Exp data to derive K-M Model	kg/m^3	458.479	0.275	0.060	Normal	2.000	0.138	1	0.138	1.89E-02
3	Temperature (±0.2 ºC)	kg/m^3	458.479	0.320	0.070	Rectangular	1.732	0.185	1	0.185	3.41E-02
1	Temp - Field experience (additional ±0.3 ºC)	kg/m^3	458.479	0.480	0.105	Rectangular	1.732	0.277	1	0.277	7.68E-02
	Combined uncertainty	kg/m^3	458.479	0.928	0.202	Normal	2	0.464	1	0.464	2.15E-01

Table 5 - Uncertainty budget for the temperature contribution to LNG density (values determined for $\Delta t = 0.2$ ºC)

Rank	Source	Units	Value	Uncertainty U	U*%	Distribution	Divisor k	Stand. Unc u	Sensitivity (∂f/∂xi) c	Product u.c	Uncorrel. Square (u.c)²
1	Methane molar volume	kg/m^3	458.479	0.272	0.059	Rectangular	1.732	0.157	-1.362	-0.214	4.59E-02
5	Nitrogen molar volume	kg/m^3	458.479	0.003	0.001	Rectangular	1.732	0.002	-0.013	0.000	4.18E-10
3	Ethane molar volume	kg/m^3	458.479	0.012	0.003	Rectangular	1.732	0.007	-0.062	0.000	1.98E-07
4	Propane molar volume	kg/m^3	458.479	0.005	0.001	Rectangular	1.732	0.003	-0.024	0.000	4.54E-09
7	i-Butane molar volume	kg/m^3	458.479	0.001	0.000	Rectangular	1.732	0.001	-0.005	0.000	7.32E-12
6	n-Butane molar volume	kg/m^3	458.479	0.001	0.000	Rectangular	1.732	0.001	-0.007	0.000	3.05E-11
8	i-Pentane molar volume	kg/m^3	458.479	0.000	0.000	Rectangular	1.732	0.000	0.000	0.000	1.30E-17
9	n-Pentane molar volume	kg/m^3	458.479	0.000	0.000	Rectangular	1.732	0.000	0.000	0.000	4.76E-21
10	Hexane molar volume	kg/m^3	458.479	0.000	0.000	Rectangular	1.732	0.000	0.000	0.000	0.00E+00
2	Volume correlation (Vc)	kg/m^3	458.479	0.018	0.004	Rectangular	1.732	0.010	-1.38	-0.014	2.04E-04
	Combined correl. uncertainty	kg/m^3	458.479	-0.458	-0.100	Normal	2.000	-0.229	1	-0.229	
	Combined uncorrel. uncertainty	kg/m^3	458.479	0.429	0.094	Normal	2	0.215	1	0.215	4.61E-02

Table 6 - Uncertainty budget for the LNG density using temperature sensitivity method

Rank	Source	Units	Value	Uncertainty U	U*%	Distribution	Divisor k	Stand. Unc u	Sensitivity (∂f/∂xi) c	Product u.c	Square (u.c)²
5	Composition	kg/m^3	458.479	0.215	0.047	Rectangular	1.732	0.124	1	0.124	1.54E-02
1	Klosek-McKinley Method	kg/m^3	458.479	0.458	0.100	Rectangular	1.732	0.265	1	0.265	7.01E-02
4	Exp data to derive K-M Model	kg/m^3	458.479	0.275	0.060	Normal	2.000	0.138	1	0.138	1.89E-02
3	Temperature	ºC	-160.000	0.2	-0.125	Rectangular	1.732	0.115	-1.3709	-0.158	2.51E-02
2	Temp - field experience	ºC	-160.000	0.3	-0.188	Rectangular	1.732	0.173	-1.3709	-0.237	5.64E-02
	Combined uncertainty	kg/m^3	458.479	0.862	0.188	Normal	2	0.431	1	0.431	1.86E-01

Table 7 - Uncertainty budget for the Gross Calorific Value

Rank	Source	Units	Value	Uncert. U	U*%	Distribution	Divisor k	Stand. Unc u	Sens. (∂f/∂xi) c	Product u.c	Square (u.c)²
2	Composition	MJ/kg	54.522	0.007	0.013	Rectangular	1.732	0.004	1	0.004	1.56E-05
1	CV value of components	MJ/kg	54.522	0.060	0.110	Normal	2.000	0.030	1	0.030	9.00E-04
	Combined uncertainty	MJ/kg	54.522	0.061	0.111	Normal	2	0.030	1	0.030	9.16E-04

Table 8 - Reference values for the volume uncertainty

Tank Type	Gauge Level Type	U* (%)	k	Ref
Membrane	Radar	0.53	2	4
Moss	Float	0.38	2	4
Spherical	Radar	0.31	2	3
Membrane	Float	0.30	2	3
Membrane	Capacitance	0.30	2	3
Membrane	Radar	0.14	2	15
Membrane	-	0.09	1	2
Prismatic	-	0.12*	-	9
Membrane	-	0.16*	-	9
Spherical	-	0.04*	-	9
-	Capacitance, float, radar	0.30	2	12

*Value for a single tank - assumed to be same for all tanks

Table 9 - Uncertainty budget for Total LNG Energy for Uncorrelated and 100% Correlated Uncertainties

Estimate of Uncertainty in Total Energy

Source	Units	Value	Uncertainty U	U*%	Distribution	Divisor k	Stand. Unc u	Sensitivity $(\partial f/\partial x_i)$ c	Product u.c	Uncorrel. Square $(u.c)^2$
Calorific Value	MJ/kg	54.522	0.061	0.111	Normal	2.000	0.030	55950004	1693000	2.87E+12
Density	Kg/m³	458	0.928	0.202	Normal	2.000	0.464	6653559	3087440	9.53E+12
Volume	m³	122034	646.780	0.53	Normal	2.000	76.408	24997.262	1909980	3.65E+12
Combined correlated uncertainty	MJ	3050515810	13380840	0.439	Normal	2	6690420	1	6690420	
Combined uncorrel. uncertainty	MJ	3050515810	8011631	0.263	Normal	2	4005816	1	4005816	1.60E+13

Table 10 - Uncertainty budget for Total LNG Energy for 80% Correlated Uncertainties

Estimate of Uncertainty in Total Energy

Source	Units	Value	Uncertainty U	U*%	Distribution	Divisor k	Stand. Unc u	Sensitivity $(\partial f/\partial x_i)$ c	Product u.c	Uncorrel. Square $(u.c)^2$	% correlation	Correl. (u.c)	Uncorrel. $(u.c)^2$
Calorific Value	MJ/kg	54.522	0.061	0.111	Normal	2.000	0.030	55950004	1693000	2.87E+12	80	1.35E+06	1.1465E+11
Density	Kg/m³	458	0.928	0.202	Normal	2.000	0.464	6653559	3087440	9.53E+12	80	2.47E+06	3.8129E+11
Volume	m³	122034	646.780	0.53	Normal	2.000	76.408	24997.262	1909980	3.65E+12	80	1.53E+06	1.4592E+11
Uncertainty of correlated components	MJ	3050515810	10704672	0.351	Normal	2	5352336.198	1	-	-	-	5.35E+06	-
Uncertainty of uncorrel. Components	MJ	3050515810	1602326	0.053	Normal	2	801163.1057	1	-	-	-	801163.1	6.42E+11
Combined correlated and uncorrel. uncertainty	MJ	3050515810	10823930	0.355									

Table 11 - Composition range of the components from 461 LNG cargoes

Composition	Lowest value (%)	Highest value (%)
Methane	79.154	97.717
Ethane	2.128	15.41
Propane	0.048	4.678
i-Butane	0	0.633
n-Butane	0	0.724
i-Pentane	0	0.062
n-Pentane	0	0.045
Hexane	0	0.023
Nitrogen	0.002	1.082
Carbon dioxide	0	0

Table 12 - Range of uncertainty values from the composition, density and calorific value from the 461 LNG cargoes (k=2)

Uncertainty	Lowest value	Highest value
Composition uncertainty contribution to density (%)	± 0.046	± 0.074
Uncertainty in density (%)	± 0.188	± 0.204
Composition uncertainty contribution to calorific value (%)	± 0.003	± 0.026
Uncertainty in calorific value (%)	± 0.108	± 0.116