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CUSTODY TRANSFER:
UNCERTAINTY IN THE VOLUME OF LNG UNLOADED

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ABSTRACT

In LNG trading the determination of the volume of LNG transferred from ship's tanks to Receiving Terminal's tanks is essential to calculate the amount of energy, as LNG, involved in the Custody Transfer Process under CIF and DES LNG purchase and sale agreements. 'LNG Custody Transfer handbook', in force the Third Edition, usually is the reference Manual followed by the LNG industry to set how to proceed for the determination of the amount of energy transferred. Although the handbook explains in detail the instrumentation, devices, parameters to be measured, corrections to be made and also provides guidelines to guarantee a high quality measurement practice, and to achieve a good accuracy in the determination of the fundamental parameters involved in the calculation of the Energy transferred: Volume, LNG Density and Quality, there is a lack of information about the uncertainty associated to the measurement of the volume of LNG unloaded.

In this paper, Enagás presents the works carried out applying up-to-date metrological methodology, stated in the Guide to the Expression of Uncertainty in Measurement (GUM), and set out a general model for the estimation of the uncertainty associated to the volume of LNG unloaded in a Custody Transfer process. The model has also been implemented in a spreadsheet. Moreover, since the uncertainty of the volume depends strongly on the type of LNG carrier, forty cases with different sizes and designs of LNG carriers have been checked in order to establish a lower and upper limit for the uncertainty associated to the measurement of the volume of LNG unloaded. The sample may be considered representative of the LNG carriers that are sailing around the world.

From the results obtained the following conclusions may be drawn:

a) The uncertainty of the volume of LNG unloaded depends on the ship and the instrumentation fitted on it.
b) The uncertainty depends on whether the variables are correlated or not.
c) The older is the ship, the higher uncertainty shows.
d) The uncertainty depends strongly on the gauge tables error.
e) It may be set an upper uncertainty limit of 0.25% and a mean uncertainty value of 0.14%.

The results of this work will be discussed within the Working Group of the GIIGNL organization responsible for the updating of the *Custody Transfer* Manual, and with the suggestions of the members of the Group will be included in the next edition (Fourth) in order to improve the measurement of the volume of LNG unloaded and, hence, the amount of energy transferred.

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1. BACKGROUND

Liquefied Natural Gas (LNG) is natural gas that has been cooled down to the point that it condenses to a liquid for shipment and / or storage purposes. LNG is a liquid substance, mixture of light hydrocarbons with Methane as the main component and Nitrogen as inert. It is also made up of a little amount of Ethane, Propane, Butane and Pentane. Minor components concentrations vary with the source of the raw gas, the liquefaction pre-treatment and process and the storage conditions.

LNG may be classified taking into account several criteria: Density, Heat Value, Wobbe Index, Methane or Nitrogen amount, etc. Normally, its density is the most usual parameter used for classification. Thus, it is spoken of heavy, medium or light LNG. Table 1 presents three typical LNG qualities according to their density.

Composition (%)	**LNG Light**	**LNG Medium**	**LNG Heavy**
Methane	98.000	92.000	87.000
Ethane	1.400	6.000	9.500
Propane	0.400	1.000	2.500
Butane	0.100	0.000	0.500
Nitrogen	0.100	1.000	0.500
Properties	**LNG Light**	**LNG Medium**	**LNG Heavy**
GCV [kWh/m^3(n)]	11.290	11.650	12.340
Density [kg/m^3(n)]	427.742	445.694	464.831
Density Variation (%)	-	4.2	8.7

Table 1: Classification and properties of LNG by densities

LNG is normally stored in cryogenic double-walled ground tanks at very low temperature, - 160 ºC (- 260 ºF) and at pressure slightly above atmospheric pressure. Thus, LNG is stored very close to its boiling point. Furthermore, LNG is a cryogenic and inflammable substance.

LNG is sold in terms of energy content. Custody Transfer involves activities and measurements executed both on the ship and in the Receiving Terminal.

In the context of an LNG purchase and sale agreement, the invoicing of the energy transferred may be agreed as FOB (Free on Board), CIF (Cost Insurance & Freight) or DES (Delivery Ex Ship) sale. In the last two cases: CIF and DES, the determination of the energy transferred and billed will be made in the unloading port. Therefore, one of the most important tasks that any Receiving Terminals in Custody Transfer must accomplish is the determination, the more accurate the better, of the amount of energy transferred in form of LNG from ship's tanks to Terminal's tanks (see figure 1). *"LNG Custody Transfer handbook*", edited by GIIGNL organization (Groupe International des Importateurs de Gaz Natural Liquéfié), is the reference manual for the determination of the quantity transferred energy, as LNG, between LNG ships and LNG Terminals. Nowadays, the Third Edition is in force.

2. CLASSIFICATION OF LNG CARRIERS

LNG is transported around the world in ships (cryogenic sea vessels), from the Liquefaction Terminal to the Regasification Terminal, where it is transferred from ship to doubled-walled ground tanks and stored at fairly above atmospheric pressure. The reasons why the natural gas is cooled and transported by ship instead of by pipeline are long distances or physical features that make neither economical nor technical feasible to construct a natural gas pipeline, connecting the natural gas fields and the end users.

Design requirements of LNG carriers are established in the IGC code (International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk, 1975) and published by the International Maritime Organization (IMO). The IGC identifies five types of gas carriers:

independent tanks; membrane tanks; semi-membrane tanks; integral tanks and internal insulation tanks. The majority of vessels are either of Moss spherical tanks designs (independent tanks), or membrane tanks of either Technigaz (TGZ) or Gaztransport design (see figures 2 & 3). Membrane carriers are normally of two main types: the Mark III or GT No. 96 design, with a small number of the newer combined systems alternative.

Figure 1: Unloading arms at the jetty in an LNG Receiving Terminal connecting the ship's tanks and the ground's tanks during a Custody Transfer process

Figure 2: Membrane design LNG carrier

Figure 3: Moss sphere design LNG carrier

3. OBJECTIVE AND SCOPE

The present report is aimed to study the uncertainty of the volume of LNG unloaded from an LNG carrier to an LNG Receiving Terminal, with the following objectives:

- To describe the parameters and their contributions that have influence in the total uncertainty, such as: corrected level, volume from gauge tables and corrected volume.
- To develop a model, based on the above information, for calculating the uncertainty of the volume of LNG unloaded from a ship.
- To perform a case study with different types and sizes of LNG vessels representatives of the LNG shipping and trading, in order to find a lower and upper limit for the uncertainty of the volume of LNG unloaded.

To carry out the above mentioned tasks, a few of argued simplifications and hypotheses have been set without losing thoroughness in the work. These hypotheses are in concordance with GUM and simplify the calculations since the insignificant terms are ignored.

The results of the present work are applicable to all spherical LNG tanks, regardless of size. They are also applicable to the Membrane tanks GT No. 96 and TZ Mk III types, regardless of size. Roughly, the types of ship's tanks used in this study represent almost the 90% of the ships that arrive at Regasification Terminals worldwide. In terms of transported and delivered energy, the above percentage is similar or even though higher.

4. THE METROLOGY

The Metrology is defined by the International Bureau of Weights and Measures (BIPM) as "*the science of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology*".

Nowadays the Metrology is no longer regarded as a costly requirement, but rather as a strategic asset. Measurement gives manufacturers, producers, sellers, customers, etc. the assurance that the final product, service or good will meet stated requirements, provides reliable and easily comparable measures that help make a good product on the first time, and also to reach an agreement about the quality and quantity of good delivered or the service supplied.

According to the present metrological criteria, any measurement must be associated to its uncertainty. The uncertainty is a parameter, associated to the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand. The uncertainty may be also considered as a range that provides an idea about the quality of the measurement. Uncertainty allows comparing two measurements of the same parameter obtained with different methods, and also helps to improve the measurement process.

Therefore, at present it is no sufficient to give a value of the measured parameter, but it is also essential to add its associated uncertainty. *Exempli gratia:* measured value (y) ± uncertainty (U).

5. DEFINITIONS

For the purpose of this paper the following definitions apply:

Combined standard uncertainty $u_c(y)$: Standard uncertainty of the result of a measurement when that result is obtained from the values of a number of other quantities.

Corrected Level h: Liquid level at actual measurement conditions which is obtained by applying the appropriate corrections.

Corrected volume V: Volume contained in the tank at actual measurement conditions, obtained by applying the appropriate volume correction.

Correction: Increase or decrease of the measured variable, due to the differences between the operation and calibration conditions.

Correlation: Two quantitative variables are correlated when the values of one of them vary systematically with respect to the values of the other variable. If there are two variables, x_1 and x_2, they are correlated whether increases in x_1 imply increases in x_2, and vice versa. The correlation between two variables does not imply any causality relation.

Expanded uncertainty U(x): Quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand. It is obtained by multiplying the combined standard uncertainty by a coverage factor k (usually k=2).

Gauge tables: Numerical tables which relate the height of the liquid in a tank to the volume contained in that tank. These tables are made for each tank and are usually calibrated at -160 ºC.

Independence: Two random variables are statistically independent if their correlation coefficient is zero.

Level corrections c_i: Corrections applied to the measured level ($h_{measured}$) to take into account the actual conditions of the measurement.

Measured Level $h_{measured}$: Level value obtained directly from the level gauge (Float, Radar or Capacitance).

Sensitivity Coefficient: Parameter which describes how the output estimate "*y*" varies with changes in the values of the input estimates "x_1", "x_2",…,"x_N".

Standard uncertainty u(x): Uncertainty of the result of a measurement expressed as a standard deviation.

Uncertainty: Parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand.

Volume correction k: Correction applied to the volume from tables (V_{table}), to take into account the contraction of the tank due to the difference between the operation and calibration temperatures.

Volume from tables V_{table}: Tank volume read directly from the gauge tables that corresponds to the calibration temperature (usually -160 ºC).

6. THE LAW OF UNCERTAITY ACCORDING TO GUM

Before starting with the determination of the uncertainty of the LNG unloaded volume, it is essential to describe some principles of common use in the theory of uncertainty.

6.1. Combined standard uncertainty

In most cases, a measurand "*y*" can be determined from "N" other quantities through a functional relationship "*f*" as:

$$y = f(x_1, x_2, x_3, ..., x_N) \qquad \text{(Eq. 1)}$$

In these cases, the uncertainty of the variable "*y*" can be expressed as follows, if the variables "x_i" are independent:

$$u_c^2(y) = \sum_{i=1}^{N} \left[\frac{\partial f}{\partial x_i} \right]^2 u^2(x_i) \qquad \text{(Eq. 2)}$$

Where:

u_c (y)	Combined standard uncertainty of the variable "y"
$u(x_i)$	Standard uncertainty of the variable "x_i"

$\frac{\partial f}{\partial x_i} = c_{x_i}$ Sensitivity Coefficient

When the input quantities are not independent (are correlated), the appropriate expression is:

$$u_c^{\,2}(y) = \sum_{i=1}^{N} \left[\frac{\partial f}{\partial x_i} \right]^2 u^2(x_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} u(x_i, x_j) \qquad \text{(Eq. 3)}$$

Where the term u(x_i, x_j) is called covariance, and can be expressed as a function of the correlation coefficient:

$$u(x_i, x_j) = r(x_i, x_j) \cdot u(x_i) \cdot u(x_j) \qquad \text{(Eq. 4)}$$

Where:

u(x_i, x_j) Correlation Coefficient ranging between ±1

6.2. General concept of correlation

The correlation (r) is the relationship between two or several random variables within a distribution of two or more random variables.

- The correlation is positive or direct ($r>1$) when an increase in one variable produces also an increase in the other.
- The correlation is negative or inverse ($r<1$) when an increase in one variable produces a decrease in the other.
- The correlation is null ($r=0$) when a change in one variable does not imply an expected change in the other.

The combined standard uncertainty when the input quantities are correlated is calculated using the equation 3, where the correlation term is:

$$2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} u(x_i, x_j) \qquad \text{(Eq. 5)}$$

This term will contribute to increase or decrease the uncertainty according to its sign, which depends, in turn, on the sign of the derivatives and the covariance.

6.3. Elimination of a correlation

As described in the *Guide to the expression of uncertainty in measurement* the uncertainty should be “safe” of “conservative”, meaning that it must never err on the side of being too small. Taking into account this consideration, there are several ways to eliminate or simplify a correlation:

1) Disregard those terms of correlation that contribute to decrease the combined uncertainty. Therefore, the model can be simplified by eliminating the terms of correlation which fulfil the following condition:

$$2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} u(x_i, x_j) < 0 \qquad \text{(Eq. 6)}$$

2) If the sign and/or the degree of correlation are not exactly known, the maximum influence of the correlation can be evaluated by estimating the superior limit of the uncertainty of the measurand. In case of other correlations are not taking into account, the limit is calculated as follows:

$$u^2(y) \le \left(|u(x_1)| + |u(x_2)| \right)^2 + u^2(x_r) \qquad \text{(Eq. 7)}$$

Where:

x_1, x_2	Correlated variables
x_r	Other uncorrelated magnitudes

7. DETERMINATION OF THE ENERGY AND VOLUME OF LNG UNLOADED

According to *LNG Custody Transfer* handbook, the energy content of LNG unloaded is determined from:

$$E = \left(V_{LNG} \cdot D_{LNG} \cdot H_{LNG}\right) - E_{gas\ displaced} - E_{gas\ to\ ER} \qquad \text{(Eq. 8)}$$

Where:

E	the energy transferred from LNG carrier to the unloading facilities, in kWh.
V_{LNG}	the volume of LNG unloaded, in m^3
D_{LNG}	the density of LNG, in kg/m^3
H_{LNG}	the heat value of LNG, in kWh/kg
$E_{gas\ displaced}$	the energy of the displaced gas which is received by the LNG carrier when unloading, in replacement of the volume of LNG discharged, in kWh
$E_{gas\ to\ ER}$	if applicable, the energy of the gas consumed in the LNG carrier’s engine room during the unloading, in kWh

Therefore, the less uncertainty in the LNG unloaded volume the more accurate determination of the energy transferred. The standard method chosen for measuring the volume of LNG transferred is based on equipments fitted on LNG carriers, mainly the use of level gauges and calibration tables, relating the high of liquid to the volume content in the ship’s tank. Of course, depending on the ship’s characteristics, quality of LNG unloaded and operational conditions among other issues, corrections factors must be applied (see figure 4).

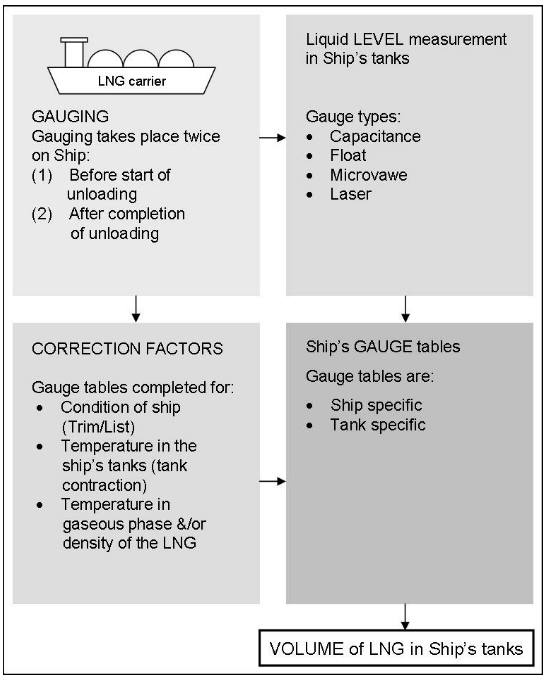

Figure 4: Schematic overview of the measurement process of the volume of LNG unloaded

The determination of the volume transferred requires two measurements, one before and another after unloading; so the result will be two LNG volumes. The difference between the larger and the smaller volume will represent the volume of liquid transferred. These volumes are obtained by adding the volume of each tank (as shown in figure 5):

$$V_{unloaded} = V_{initial} - V_{final} \qquad \text{(Eq. 9)}$$

Where:

$V_{initial}$ Initial volume, in m^3
V_{final} Final volume, in m^3
$V_{initial} = V_{1,initial} + V_{2,initial} + \ldots + V_{n,initial}$
$V_{final} = V_{1,final} + V_{2,final} + \ldots + V_{n,final}$
n Number of tanks, usually 4 or 5

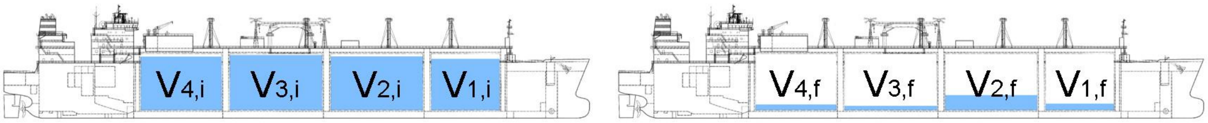

Figure 5: Before and after unloading

8. UNCERTAINTY OF THE LNG VOLUME IN A TANK

The procedure for measuring the level of LNG in ship's storage tanks is performed by using specific devices and numerical tables which relate the height of liquid in the tanks to the volume contained in the tanks under "*ideal*" conditions. As the process does not take place under "*ideal*" conditions, the operation also includes the measurement of certain other parameters for completing the measurement process with correction factors to reflect actual ("*non-ideal*") conditions. Normally, the corrections factors are automatically calculated using the computer system on the ship.

The LNG volume of each tank, both before and after unloading, is calculated with the following procedure (see figure 6).

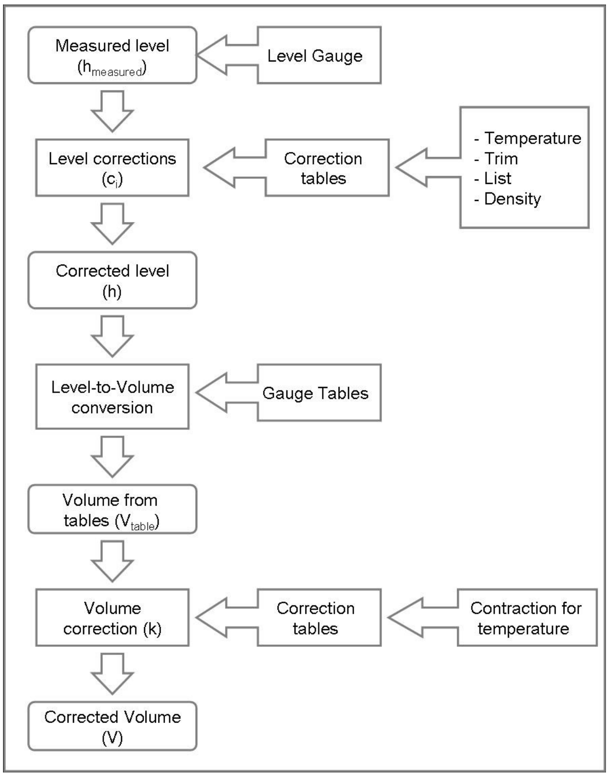

Figure 6: Procedure for calculating the volume in a tank

1) The liquid level in the tank is measured using the level gauge ($h_{measured}$).
2) The corrected level (h) is calculated as the algebraic sum of the measured level and the appropriate corrections (which can be positive or negative).
    a. Temperature
    b. Density
    c. Trim
    d. List

3) The corrected level is transformed into the tank volume (V_{table}) using the gauge tables.
4) Finally, the volume read from tables is corrected according to the contraction of the tank due to the temperature, obtaining the corrected volume (V), which is the actual volume contained in the tank.

8.1. Calculation of the volume in a tank

The equations employed to calculate the volume contained in a tank are described as follows:

Calculation of the corrected level

$$h = h_{measured} + c_T + c_\rho + c_{trim} + c_{list} \tag{Eq. 10}$$

Where:

h	Corrected level, in mm
$h_{measured}$	Measured level, in mm
c_T	Level correction for temperature, in mm
$c\rho$	Level correction for density (only in float gauge), in mm
c_{trim}	Level correction for trim, in mm
c_{list}	Level correction for list, in mm

Calculation of the volume from tables

$$V_{table} = V_1 + \frac{V_2 - V_1}{h_2 - h_1}\left(h - h_1\right) \tag{Eq. 11}$$

Where:

V_{table}	Volume read from the gauge tables and obtained from the corrected level "h", in m^3
h	Corrected liquid height, in mm
h_1, h_2	Liquid levels read in the gauge table among which is the value h, in mm
V_1	Volume of LNG read from the gauge table and corresponding to the level h_1, in m^3
V_2	Volume of LNG read from the gauge table and corresponding to the level h_2, in m^3

Calculation of the corrected volume

$$V = k \cdot V_{table} \tag{Eq. 12}$$

Where:

V	Corrected volume, in m^3
k	Correction factor due to the contraction/expansion of the tank

8.2. Hypotheses and simplifications

The following hypotheses and simplifications have been done in the development of the uncertainty expressions:

Initial hypotheses

1) In the calculation of the uncertainty of the corrected level u(h), all variables are considered as independent. Hence, the correlations are not taken into account since their contribution is insignificant. This hypothesis is based on the experience and the knowledge of the measurement system.
2) The uncertainty of the corrected volume u(V) has been developed taking into account the correlations. However, their degree of correlation is not known so the maximum uncertainty has been evaluated, by assuming that the variables are directly correlated, $r = 1$.
3) The expression for calculating the uncertainty of the volume from tables has been developed for the two main types of tanks (membrane and spherical).

Simplifications to obtain the final expression

1) The insignificant terms have been simplified to obtain the final expressions of the uncertainties of the corrected level u(h) and the corrected volume u(V).
These simplifications have been done by means of sensitivity studies based on different scenarios. The extreme cases have been studied, using the maximum permissible and observed values for the sources of uncertainty and the other variables involved.

2) Regarding the final expression of the uncertainty of the volume from tables $u(V_{table})$: The results can be applied to all tanks with spherical geometry, regardless of their size. In case of Membrane tanks, the Sensitivity Coefficient depends on the tank shape (tank model), so it has been obtained an empirical coefficient by studying the models GT No 96 and TZ Mk III, which are the most common in LNG carriers.

8.3. Uncertainty formula

Uncertainty of the corrected level

Depending on whether the temperature correction is significant or insignificant, two equations may be used.

The uncertainty of the corrected level when the uncertainty of the temperature correction is insignificant is applying:

$$u_c(h) = u(h_{measured}) \qquad \text{(Eq. 13)}$$

The uncertainty of the corrected level when the uncertainty of the temperature correction is significant is applying:

$$u_c(h) = \sqrt{u^2(h_{measured}) + w^2(\alpha) \cdot c_T^2} \qquad \text{(Eq. 14)}$$

Where:

$u_c(h)$	Combined standard uncertainty of the corrected level, in mm
$u(h_{measured})$	Uncertainty of the measured level, in mm
$w(\alpha)$	Relative uncertainty of the expansion factor
c_T	Level correction for temperature, in mm

Uncertainty of the volume from tables

For spherical tanks:

$$u_c(V_{table}) = \sqrt{\pi^2 \cdot (2 \cdot h \cdot r - h^2)^2 \cdot u^2(h) + u^2(\text{tank table})} \qquad \text{(Eq. 15)}$$

For membrane tanks:

$$u_c(V_{table}) = \sqrt{\left(\frac{V_{\text{tank}}}{41.2}\right)^2 \cdot u^2(h) + u^2(\text{tank table})} \qquad \text{(Eq. 16)}$$

Where:

$u_c(V_{table})$	Uncertainty of the volume from tables, in m^3
r	Radius of the tank, in m
u(tank table)	Uncertainty of the gauge tables, as appears in the calibration certificates
V_{tank}	Tank capacity, in m^3

Uncertainty of the corrected volume

Final expression of the uncertainty of the volume contained in a spherical tank:

$$u_c(V) = \sqrt{k^2 \cdot u^2(V_{table})} \qquad \text{(Eq. 17)}$$

Where:

$u_c(V)$	Uncertainty of the corrected volume, in m^3
k	Correction factor due to the contraction/expansion of the tank

In case of membrane tanks, the corrected volume is the volume read just directly from tables since there is no contraction of the tank wall.

$$u_c(V) = u_c(V_{table}) = \sqrt{\left(\frac{V_{\text{tank}}}{41.2}\right)^2 \cdot u^2(h) + u^2(\text{tank table})} \qquad \text{(Eq. 18)}$$

9. UNCERTAINTY OF THE VOLUME UNLOADED

The present section develops the uncertainty of the whole volume of the LNG unloaded from an LNG carrier $u(V_{\text{unloaded}})$.

9.1. Calculation of the unloaded volume

The volume unloaded from an LNG carrier is calculated as the difference between the volumes before and after unloading. These volumes are obtained by adding the volume of each tank.

$$V_{\text{unloaded}} = V_{initial} - V_{final} = \sum_{j=1}^{n} V_{j,initial} - \sum_{j=1}^{n} V_{j,final} \qquad \text{(Eq. 19)}$$

9.2. Hypotheses

The expressions of uncertainty have been developed under two hypotheses:

1) The tanks volumes are uncorrelated
This is a general hypothesis usually applied, as a first approximation, in the calculation of uncertainties in any field. Nevertheless, if there is any knowledge or suspicion that some variables are correlated, the second hypothesis must be applied.

2) The tanks volumes are correlated
Equation 3 is used whether the correlation can be calculated. Otherwise, own estimations should be produced based on the experience and the knowledge of the process.
In this case the volumes of each tank both before and after unloading ($V_{1,\text{initial}},\ldots,V_{n,\text{initial}}$, $V_{1,\text{final}},\ldots,V_{n,\text{final}}$) are correlated due to the following factors:
    - Normally all gauges used in the volume determination: level, temperature probes and clinometers are of the same trademark and model. Therefore, we ought to assume that they are calibrated with the same procedure and standard.
    - Concerning the gauge tables and corrections tables, although the tables are developed specifically for each tank, we ought to assume that they have been generated using the same procedure (ISO), with the same gauges and under identical conditions.

As a result of the above mentioned, a maximum direct correlation (r = 1) between each pair of volumes is considered. The sign of the corresponding correlation terms depends on the sign of the sensitivity coefficients (see table 2).

Correlated volumes	Vj,initial, Vk,initial	Vj,final, Vk,final	Vj,initial, Vk,final
Correlation sign	Positive	Positive	Negative

Table 2: Correlation sign for each pair of correlated volumes

In order to avoid underestimating the uncertainty, only the positive correlation terms are taken into account in the expressions of uncertainty.

9.3. Uncertainty formulas

The final expression for calculating the uncertainty of the unloaded volume is developed for each hypothesis described above section:

1) Volumes are independent

Equation 2 (uncorrelated variables) is directly applied to the unloaded volume expression (equation 19):

$$u_c^2(\mathrm{V}_{\mathrm{unloaded}}) = \sum_{j=1}^{n} u_c^2(V_{j,initial}) + \sum_{j=1}^{n} u_c^2(V_{j,final}) \qquad \text{(Eq. 20)}$$

$$u_c(\mathrm{V}_{\mathrm{unloaded}}) = \left[\sum_{j=1}^{n} u_c^2(V_{j,initial}) + \sum_{j=1}^{n} u_c^2(V_{j,final})\right]^{1/2} \qquad \text{(Eq. 21)}$$

Where:

$u_c(V_{unloaded})$	Uncertainty of the volume unloaded from the ship, in m^3
$u_c(V_{j,initial})$	Uncertainty of the initial volume (before unloading) in tank “j”, in m^3
$u_c(V_{j,final})$	Uncertainty of the final volume (after unloading) in tank “j”, in m^3

2) Volumes are correlated

The uncertainties of the initial and final volumes are calculated taking into account a correlation coefficient r = 1, between the volumes of the tanks:

$$u_c(\mathrm{V}_{\mathrm{initial}}) = \sum_{j=1}^{n} u_c(V_{j,initial}) \qquad \text{(Eq. 22)}$$

$$u_c(\mathrm{V}_{\mathrm{final}}) = \sum_{j=1}^{n} u_c(V_{j,final}) \qquad \text{(Eq. 23)}$$

Where:

$u_c(V_{initial})$	Uncertainty of the initial volume in the LNG carrier (before unloading), in m^3
$u_c(V_{final})$	Uncertainty of the final volume in the LNG carrier (after unloading), in m^3

The uncertainty of the unloaded volume is calculated without taking into account the correlation between the initial and final volumes of each tank (since the correlation term is negative):

$$u_c^2(\mathrm{V}_{\mathrm{unloaded}}) = u_c^2(V_{initial}) + u_c^2(V_{final}) = \left[\sum_{j=1}^{n} u_c(V_{j,initial})\right]^2 + \left[\sum_{j=1}^{n} u_c(V_{j,final})\right]^2 \qquad \text{(Eq. 24)}$$

$$u_c(\mathrm{V}_{\mathrm{unloaded}}) = \left\{\left[\sum_{j=1}^{n} u_c(V_{j,initial})\right]^2 + \left[\sum_{j=1}^{n} u_c(V_{j,final})\right]^2\right\}^{1/2} \qquad \text{(Eq. 25)}$$

9.4. Uncertainty model

Figures 7 & 8 summarize the expressions employed to calculate de uncertainty of the LNG unloaded volume depending on the type of tank and the assumptions.

Uncorrelated volumes

$$u_c(V_{\text{unloaded}}) = \left[\sum_{j=1}^{n} u_c^2(V_{j,initial}) + \sum_{j=1}^{n} u_c^2(V_{j,final})\right]^{1/2}$$

Membrane

c_T insignificant

$$u_c(V_{\text{unloaded}}) = \left\{ \begin{array}{l} \sum_{j=1}^{n}\left[\left(\frac{V_j}{41{,}2}\right)^2 \cdot u^2(h_{\substack{measured\\ j,initial}}) + w^2(\text{tables})\cdot V_{j,initial}^2\right] + \\ + \sum_{j=1}^{n}\left[\left(\frac{V_j}{41{,}2}\right)^2 \cdot u^2(h_{\substack{measured\\ j,final}}) + w^2(\text{tables})\cdot V_{j,final}^2\right] \end{array} \right\}^{1/2} \tag*{(Eq.26)}$$

c_T significant

$$u_c(V_{\text{unloaded}}) = \left\{ \begin{array}{l} \sum_{j=1}^{n}\left[\left(\frac{V_j}{41{,}2}\right)^2 \cdot \left(u^2(h_{\substack{measured\\ j,initial}}) + w^2(\alpha)\cdot c_{T,j,initial}^2\right) + w^2(\text{tables})\cdot V_{j,initial}^2\right] + \\ + \sum_{j=1}^{n}\left[\left(\frac{V_j}{41{,}2}\right)^2 \cdot \left(u^2(h_{\substack{measured\\ j,final}}) + w^2(\alpha)\cdot c_{T,j,final}^2\right) + w^2(\text{tables})\cdot V_{j,final}^2\right] \end{array} \right\}^{1/2} \tag*{(Eq.27)}$$

Spherical

c_T insignificant

$$u_c(V_{\text{unloaded}}) = \left\{ \begin{array}{l} \sum_{j=1}^{n} k^2 \cdot \left[\pi^2 \cdot (2 \cdot h_{\substack{measured\\ j,initial}} \cdot r - h_{\substack{measured\\ j,initial}}^2)^2 \cdot u^2(h_{\substack{measured\\ j,initial}}) + w^2(\text{tables})\cdot V_{j,initial}^2\right] + \\ + \sum_{j=1}^{n} k^2 \cdot \left[\pi^2 \cdot (2 \cdot h_{\substack{measured\\ j,final}} \cdot r - h_{\substack{measured\\ j,final}}^2)^2 \cdot u^2(h_{\substack{measured\\ j,final}}) + w^2(\text{tables})\cdot V_{j,final}^2\right] \end{array} \right\}^{1/2} \tag*{(Eq.28)}$$

c_T significant

$$u_c(V_{\text{unloaded}}) = \left\{ \begin{array}{l} \sum_{j=1}^{n} k^2 \cdot \left[\pi^2 \cdot (2 \cdot h_{\substack{measured\\ j,initial}} \cdot r - h_{\substack{measured\\ j,initial}}^2)^2 \cdot \left(u^2(h_{\substack{measured\\ j,initial}}) + w^2(\alpha)\cdot c_{T,j,initial}^2\right) + w^2(\text{tables})\cdot V_{j,initial}^2\right] + \\ + \sum_{j=1}^{n} k^2 \cdot \left[\pi^2 \cdot (2 \cdot h_{\substack{measured\\ j,final}} \cdot r - h_{\substack{measured\\ j,final}}^2)^2 \cdot \left(u^2(h_{\substack{measured\\ j,final}}) + w^2(\alpha)\cdot c_{T,j,final}^2\right) + w^2(\text{tables})\cdot V_{j,final}^2\right] \end{array} \right\}^{1/2} \tag*{(Eq.29)}$$

Figure 7: Uncertainty of the volume of LNG unloaded (uncorrelated volumes case)

Correlated volumes

$$u_c(V_{\text{unloaded}}) = \left\{\left[\sum_{j=1}^{n} u_c(V_{j,initial})\right]^2 + \left[\sum_{j=1}^{n} u_c(V_{j,final})\right]^2\right\}^{1/2}$$

Membrane

c_T insignificant

$$u_c(V_{\text{unloaded}}) = \left\{ \begin{array}{l} \left[\sum_{j=1}^{n}\sqrt{\left(\frac{V_j}{41{,}2}\right)^2 \cdot u^2(h_{\substack{measured\\ j,initial}}) + w^2(\text{tables})\cdot V_{j,initial}^2}\right]^2 + \\ + \left[\sum_{j=1}^{n}\sqrt{\left(\frac{V_j}{41{,}2}\right)^2 \cdot u^2(h_{\substack{measured\\ j,final}}) + w^2(\text{tables})\cdot V_{j,final}^2}\right]^2 \end{array} \right\}^{1/2} \tag*{(Eq.30)}$$

c_T significant

$$u_c(V_{\text{unloaded}}) = \left\{ \begin{array}{l} \left[\sum_{j=1}^{n}\sqrt{\left(\frac{V_j}{41{,}2}\right)^2 \cdot \left(u^2(h_{\substack{measured\\ j,initial}}) + w^2(\alpha)\cdot c_{T,j,initial}^2\right) + w^2(\text{tables})\cdot V_{j,initial}^2}\right]^2 + \\ + \left[\sum_{j=1}^{n}\sqrt{\left(\frac{V_j}{41{,}2}\right)^2 \cdot \left(u^2(h_{\substack{measured\\ j,final}}) + w^2(\alpha)\cdot c_{T,j,final}^2\right) + w^2(\text{tables})\cdot V_{j,final}^2}\right]^2 \end{array} \right\}^{1/2} \tag*{(Eq.31)}$$

Spherical

c_T insignificant

$$u_c(V_{\text{unloaded}}) = \left\{ \begin{array}{l} \left[\sum_{j=1}^{n} k \cdot \sqrt{\pi^2 \cdot (2 \cdot h_{\substack{measured\\ j,initial}} \cdot r - h_{\substack{measured\\ j,initial}}^2)^2 \cdot u^2(h_{\substack{measured\\ j,initial}}) + w^2(\text{tables})\cdot V_{j,initial}^2}\right]^2 + \\ + \left[\sum_{j=1}^{n} k \cdot \sqrt{\pi^2 \cdot (2 \cdot h_{\substack{measured\\ j,final}} \cdot r - h_{\substack{measured\\ j,final}}^2)^2 \cdot u^2(h_{\substack{measured\\ j,final}}) + w^2(\text{tables})\cdot V_{j,final}^2}\right]^2 \end{array} \right\}^{1/2} \tag*{(Eq.32)}$$

c_T significant

$$u_c(V_{\text{unloaded}}) = \left\{ \begin{array}{l} \left[\sum_{j=1}^{n} k \cdot \sqrt{\pi^2 \cdot (2 \cdot h_{\substack{measured\\ j,initial}} \cdot r - h_{\substack{measured\\ j,initial}}^2)^2 \cdot \left(u^2(h_{\substack{measured\\ j,initial}}) + w^2(\alpha)\cdot c_{T,j,initial}^2\right) + w^2(\text{tables})\cdot V_{j,initial}^2}\right]^2 + \\ + \left[\sum_{j=1}^{n} k \cdot \sqrt{\pi^2 \cdot (2 \cdot h_{\substack{measured\\ j,final}} \cdot r - h_{\substack{measured\\ j,final}}^2)^2 \cdot \left(u^2(h_{\substack{measured\\ j,final}}) + w^2(\alpha)\cdot c_{T,j,final}^2\right) + w^2(\text{tables})\cdot V_{j,final}^2}\right]^2 \end{array} \right\}^{1/2} \tag*{(Eq.33)}$$

Figure 8: Uncertainty of the volume of LNG unloaded (correlated volumes case)

10. RESULTS

The uncertainty model developed has been also implemented in a spreadsheet to make easier the calculation of the uncertainty. Moreover, forty cases with different sizes and designs of LNG carriers have been checked in order to establish a lower and upper limit for the uncertainty associated to the measurement of the LNG unloaded volume. The sample may be considered representative of the LNG carriers that sail around the world.

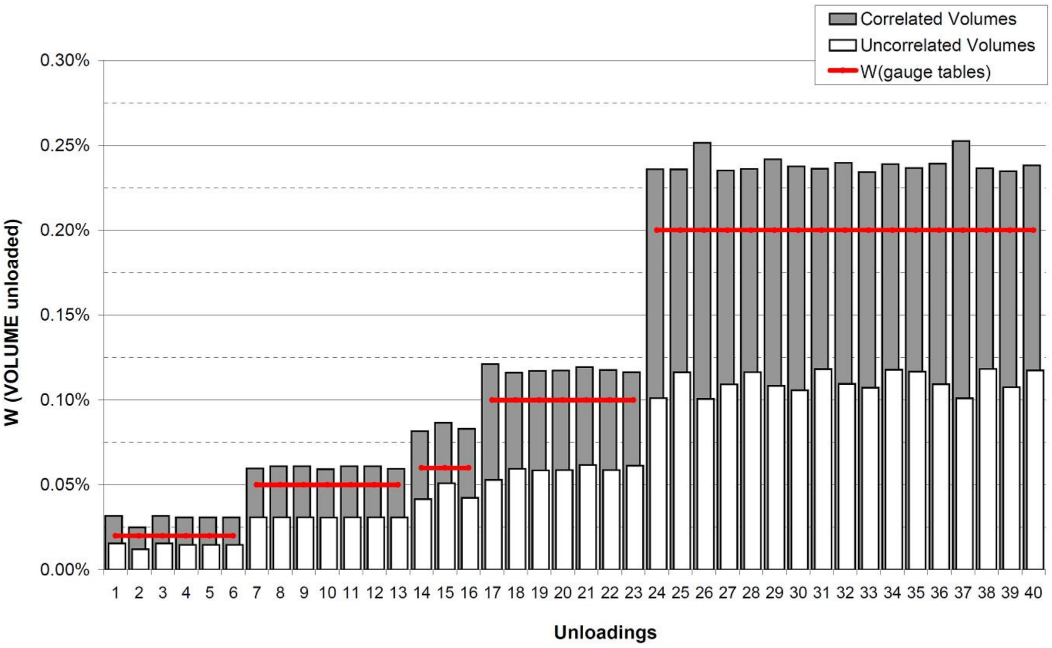

Figure 9: Uncertainty depending on the uncertainty model (correlated or uncorrelated volume)

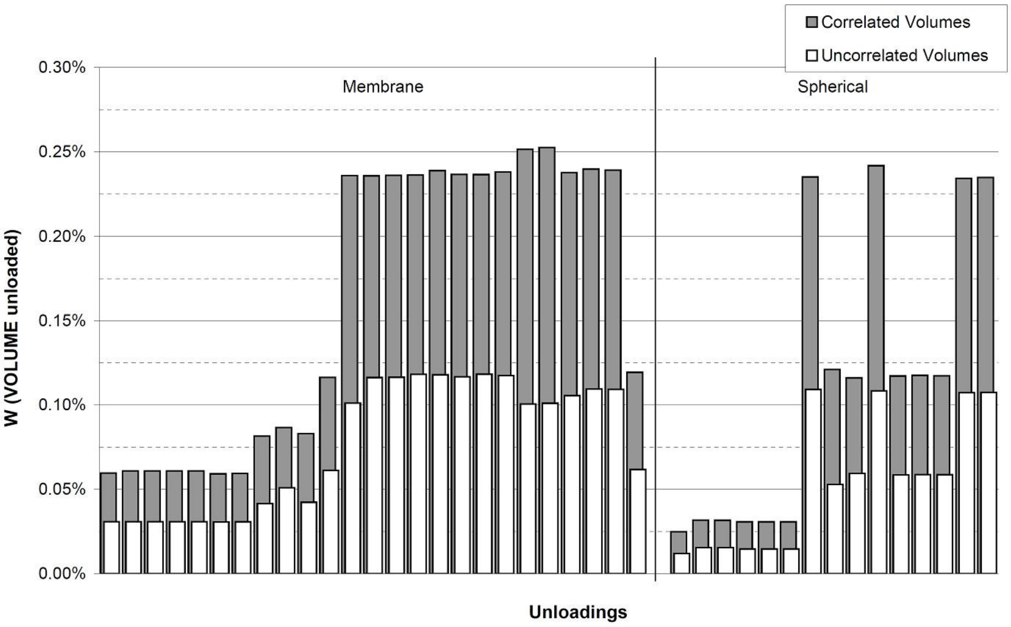

Figure 10: Uncertainty in function of the type of tank

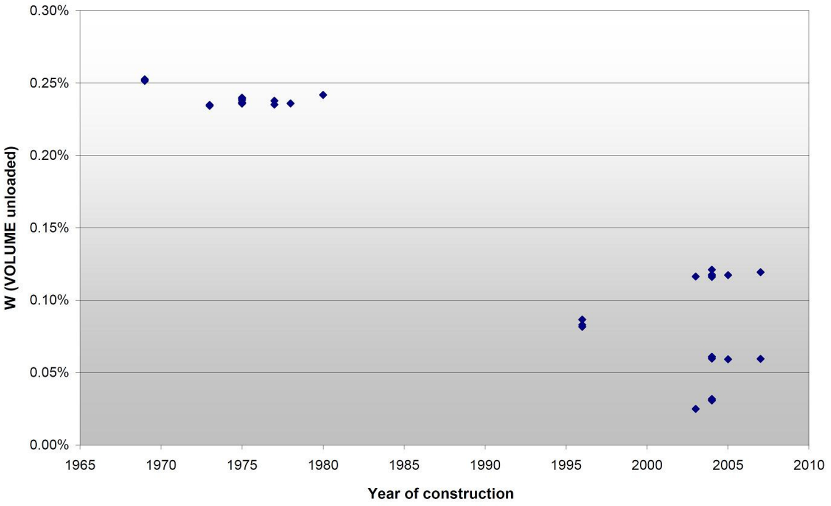

Figure 11: Uncertainty in function of the year of construction

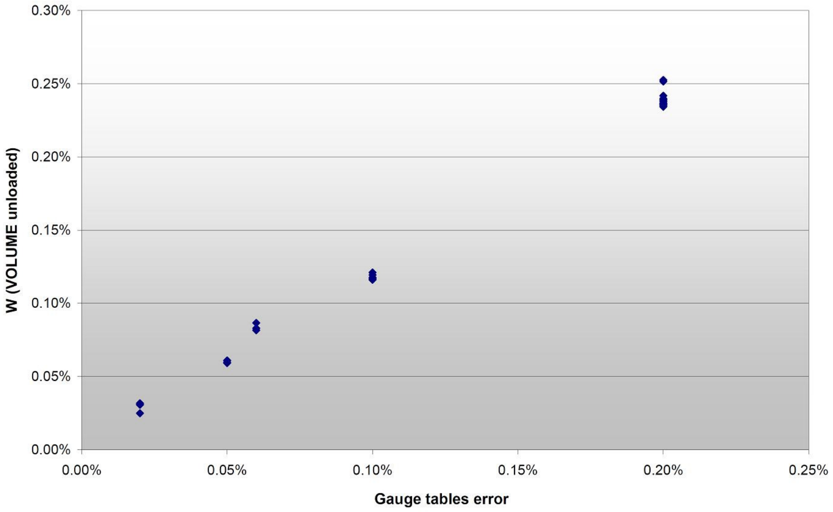

Figure 12: Uncertainty in function of the gauge tables error

11. CONCLUSIONS

A model for the calculation of the uncertainty of the volume of LNG unloaded during a process of LNG Custody Transfer has been developed following the instructions of the GUM. The model presents the formulas for calculating the uncertainty in two cases: whether the variables are correlated or not.

Furthermore, the model has been implemented in a spreadsheet and forty cases with different sizes and designs of LNG carriers have been checked in order to find out how ranges the uncertainty associated to the volume of LNG unloaded. The results of the present work are applicable to all spherical LNG tanks and also Membrane tanks GT No 96 and TZ Mk III types, regardless of size. The types of ships tanks used in this study represent 90% of the ships that arrive at any LNG Regasification Terminals. In terms of transported energy, the above percentage is similar or even though higher.

From the results obtained the following conclusions may be drawn:

a) The uncertainty of the volume of LNG unloaded depends on the ship and the instrumentation fitted on it.
b) The uncertainty depends on whether the variables are correlated or not (see figure 10).
c) Following the principle given in the GUM "*be conservative*" and from the experience obtained during the development of this work, our opinion is that uncertainty must be calculated taken into account that the tanks volumes are correlated.

d) The uncertainty hardly depends on the type of ship's tanks: spherical or prismatic (see figure 11).
e) The older is the ship, the higher uncertainty shows (see figure 12).
f) The uncertainty depends strongly on the gauge tables error (see figure 13).

The hypotheses and simplifications assumed in this study are in concordance with the guidelines provided by the GUM and emerge from the experience and the sensitivity studies carried out by Enagás. They have allowed eliminating the terms whose contribution to the uncertainty are insignificant.

Nevertheless, a deeper work must be carried out in order to study in detail the terms neglected in this paper, whose objective was to develop a simply, easy-to-apply model of uncertainty. Likewise, the study should be carried out to all type of LNG carriers.

The results of this work will be discussed within the Working Group of the GIIGNL organization, responsible for the updating and upgrading of the *Custody Transfer* Manual, and with the suggestions of the members of the Group will be included in the next edition (Fourth), in order to improve the measurement of the volume of LNG unloaded and, hence, the amount of energy transferred.

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