

Uncertainty as a Best Practice: Beyond Compliance in Volume Measurement

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1. Introduction

Uncertainty analysis is intended to increase confidence in measurement results. Any measurable variable has an associated uncertainty. For example, the measurement of ambient temperature may be affected by different factors, such as the instrument used to take the measurement, nearby objects emitting heat, air circulation, and the person performing the measurement. All of these factors, together with any others that may be identified, can affect the true value of the room temperature. The purpose of estimating measurement uncertainty is to quantify the influence of the various disturbances that affect the final measurement result.

Looking more closely at the previous example, the instrument used to measure temperature is itself affected by other factors, such as the measurement method, instrument stability, resolution, error, and other related variables. These factors also contribute to the final uncertainty associated with the measurement.

This context helps illustrate the number of factors that can affect the variable being measured. It is important to clarify that the uncertainty contribution of each identified source is not the same; for example, instrument error may contribute more than the surrounding environment in which the measurement is performed.

Based on this context, this paper discusses how each influence quantity can affect volume, one of the most important variables in the Oil & Gas industry, and why it is important to estimate uncertainty from day to day and ticket by ticket, since these variations can be highly significant for different areas of an organization.

2. Definition of Uncertainty

To estimate measurement uncertainty and determine the contribution of each source of uncertainty, several guides and procedures are available, including the GUM (Guide to the Expression of Uncertainty in Measurement), which provides a mathematical framework for obtaining the result.

The GUM provides a step-by-step procedure for estimating uncertainty. This procedure begins by defining the variable to be measured and understanding the physical-mathematical model required to determine its value. For example, if the volume of a cylinder must be measured, it is necessary to recognize that the volume depends on the cylinder's height and diameter, which leads to the following mathematical model:

$$Volume = \pi * r^2 * h \quad (\text{Equation 1})$$

The GUM then establishes that the sources capable of disturbing the result must be identified. Continuing with the previous example, any source of uncertainty that creates doubt in the measurement of height must be determined, as well as any source that affects the measurement of the cylinder diameter. At this stage, the procedure relies heavily on the user's experience. Based on specific needs and practical knowledge, the user must determine which variables can affect the measurement.

After the sources are identified, the mathematical process begins. This process quantifies the sources, reduces them as needed for combination, evaluates their correlations, determines their contribution to the result, establishes the degree of reliability of the uncertainty estimate, and presents a report with the values obtained. Along with the measurement result, the report includes the absolute uncertainty, the relative uncertainty, and the contribution and sub-contribution of each source of uncertainty.

There are many other methods for estimating uncertainty, some more mathematically complex than others. One example is the Monte Carlo method, which uses repeated iterations and statistical analysis of the data to generate highly precise results. This method is widely used in industry, but its calculation is more complex and can be more demanding than the

GUM method, both manually and in software applications, since iterating each source of uncertainty can make the procedure lengthy and computationally intensive. In most cases, this method is used as an alternative or verification method to support the uncertainty results obtained through the GUM approach.

3. Uncertainty Calculations in the Hydrocarbons Industry

The American Petroleum Institute (API), which publishes many of the recommended practices for hydrocarbon measurement and management, states in MPMS Chapter 13.3, Measurement Uncertainty, that the GUM method for uncertainty estimation is valid and formally adopts its methodology.

In the hydrocarbons industry, precise measurements with low error have always been essential. In recent years, however, special importance has also been given to uncertainty estimation, together with the requirement to keep it within permissible limits. To illustrate its importance in crude oil production, consider that when a state, a country, or a company produces one million barrels per day with an uncertainty of 0.5%, the true crude oil volume could range from 997,500 to 1,002,500 barrels. At a WTI price of US\$80 per barrel, this represents US\$400,000 per day.

Throughout the hydrocarbons value chain there are several participants: producers, who are responsible for the exploration, extraction, treatment, and separation of hydrocarbons; transporters, who move the product from one point to another through pipelines, tank trucks, or other means; and refineries or petrochemical companies, which convert crude oil into other products for commercial distribution. For all of them, ensuring low uncertainty is critical because their economics depend directly on the measurement of volumes.

Among the procedures carried out by companies across the hydrocarbons value chain, in both the liquid and natural gas sectors, is the preparation of daily or monthly balances. The purpose of this procedure is to identify losses or unaccounted-for volumes by balancing input volumes to the system, output volumes from the system, and inventory variations.

$$\text{Balance} = \text{Inlets} - \text{Outlets} - \Delta\text{Inventory} \quad (\text{Equation 2})$$

If this value is to be reported as a percentage, it is divided by the input volume, as shown in the following formula.

$$\% \text{Balance} = \frac{\text{Inlets} - \text{Outlets} - \Delta\text{Inventory}}{\text{Inlets}} \quad (\text{Equation 3})$$

All companies in the supply chain recognize that measurement uncertainty exists and that it should not be reported in the balance as a loss. As a result, part of any imbalance is often assumed to be attributable to measurement uncertainty. However, because it is not yet common industry practice to estimate uncertainty for each measurement report or ticket, it is not possible to determine with confidence what portion of the imbalance corresponds to uncertainty and what portion may be due to unidentified losses such as leaks, theft, evaporation, or other causes.

What is commonly done is that, because regulations often require measurement uncertainty to remain below 0.5%, companies assign that same value to the balance uncertainty. In other cases, because the uncertainty result is typically obtained when a measurement system is installed, some companies use that fixed value for each measurement system and combine it with the other uncertainties in the system to estimate the balance uncertainty.

4. Impact of Uncertainty Calculations

In practice, although the approaches described above can provide a reasonable approximation, measurement uncertainty may change from day to day due to variations in process conditions, instrument verification results, adjustments, and other operational factors. As a result, each measurement system may have a different uncertainty from one day to another and from one ticket to the next. Therefore, applying the same uncertainty value to all systems and all days may lead to uncertainty estimates that are either higher or lower than the actual values, which can mask unaccounted-for losses by incorrectly attributing them to measurement uncertainty.

To illustrate this point further, if measurement uncertainty is assumed to be 0.5% when the actual uncertainty is 0.2%, the 0.3% difference that is being attributed to the measurement systems may in fact be associated with losses that are not being investigated or corrected to reduce system imbalances.

These arguments show why companies should begin estimating uncertainty for each measurement ticket. The variation can be significant and should not be ignored. Having more reliable volume data can improve billing, nominations, royalty calculations, and balance results, which generally leads to better operational performance.

5. Evaluation of Real Industry Cases

The following examples present cases involving both static and dynamic measurement, for oil and gas applications, to highlight the magnitude and impact of uncertainty estimation when it is performed ticket by ticket.

5.1 Uncertainty in Static Measurement

In the case of static measurement for a crude oil tank with a maximum capacity of 150,000 barrels, the following table shows that when the tank level changes from 20% to 80% of capacity, the uncertainty can vary from 0.14% to 0.24%, representing 74 barrels in one case and 214 barrels in the other. Likewise, when the ambient temperature changes by 35 °F, this type of analysis shows that the uncertainty does not vary significantly. However, when the liquid temperature changes from 65 °F to 120 °F, the uncertainty for the same level can vary by 30 barrels. In addition, as shown in the last three entries in the table, if product quality changes, including both sediment and water content and API gravity, the resulting uncertainty, when the level is close to 50% of total capacity, can differ by 20 barrels.

Effective day	Product	Close Level (mm)	Free water level (mm)	Liquid Temperature (°F)	Ambient Temperature (°F)	Total observed volume (Bbl)	Gross Std volume (Bbl)	Total NSV (Bbl)	Liquid Mass (Kg)	Base density (API)	% BSW	Absolute expanded uncertainty	Relative expanded uncertainty (%)	Uncertainty calculation status	Uncertainty contributions
03/01/2023 02:00:00	CRUDO	3000		60	70	30624.36	30624.67	30622.69	4489806.17	21.9	0.333	73.958	0.242	Successful	Q
03/01/2023 03:00:00	CRUDO	14000		60	70	144209.19	144210.63	143730.41	21128235.29	21.9	0.333	213.814	0.149	Successful	Q
03/01/2023 04:00:00	CRUDO	8000		65	75	82257.17	82297.58	81824.19	12038079.7	21.9	0.333	130.40	0.159	Successful	Q
03/01/2023 05:00:00	CRUDO	8000		120	75	82257.17	80314.56	80047.12	11766860.78	21.9	0.333	159.604	0.199	Successful	Q
03/01/2023 06:00:00	CRUDO	8000		75	60	82257.17	81773.42	81501.11	11980586.99	21.9	0.333	131.306	0.161	Successful	Q
03/01/2023 07:00:00	CRUDO	8000		75	95	82257.17	81778.32	81506	11981305.71	21.9	0.333	131.313	0.161	Successful	Q
03/02/2023 02:00:00	CRUDO	8000		75	75	82257.17	81775.67	80958.93	11980946.35	21.9	0.999	137.511	0.17	Successful	Q
03/02/2023 03:00:00	CRUDO	8000		75	75	82257.17	81775.67	81503.56	11980946.35	21.9	0.333	131.31	0.161	Successful	Q
03/03/2023 02:00:00	CRUDO	8000		75	75	82257.17	81657.4	81385.48	10753000.21	39.17	0.333	156.009	0.192	Successful	Q

Figure 1 – Volume calculation and uncertainty estimation for atmospheric tanks

The trends described above can also be seen in the following graph, which shows the variation in relative uncertainty for the nine tickets presented in the table.

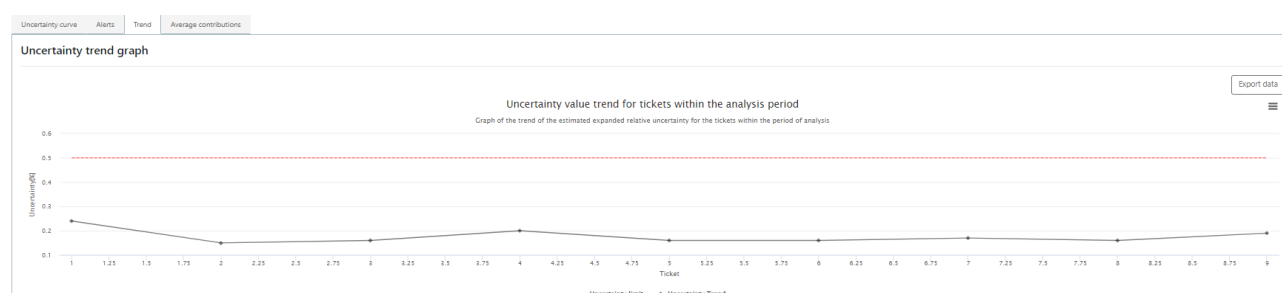


Figure 2 – Uncertainty trend over time

As anticipated, the following table also includes a variation in the error of the liquid temperature transmitter from 0.2 °F to 0.9 °F, together with a change in level from 3,000 mm to 14,000 mm. Under these conditions, the absolute uncertainty can vary from 84 barrels to 303 barrels. This is a significant difference in barrel volume and can materially affect balance results.

03/04/2023 02:00:00	CRUDO	8000		75	75	82257.17	81775.87	81503.56	11980846.35	21.9	0.333	135.284	0.166	Successful	Q _L
03/05/2023 02:00:00	CRUDO	14000		120	75	144209.19	140454.29	139051.15	19529681.57	29.31	0.999	303.711	0.218	Successful	Q _L
03/05/2023 03:00:00	CRUDO	3000		120	75	30524.36	29526.97	29529	4168572.3	29.31	0.999	84.164	0.285	Successful	Q _L
03/05/2023 04:00:00	CRUDO	14000		120	75	144209.19	140454.29	139051.15	19529681.57	29.31	0.999	310.224	0.223	Successful	Q _L
03/05/2023 05:00:00	CRUDO	14000		120	75	144209.19	140454.29	139051.15	19529681.57	29.31	0.999	317.842	0.229	Successful	Q _L

Figure 3 – Variation of uncertainty sources in atmospheric tanks II

5.2 Uncertainty in Dynamic Measurement

In the case of dynamic measurement, the same effect can be observed. Variations in process variables such as pulses, pressure, temperature, and density cause the expanded uncertainty to vary from 0.2% to 0.3%, which, for a batch measured by a meter of approximately 25,000 barrels, can represent a difference of 75 barrels. If that meter is part of a station with four arms, each with similar uncertainty and each measuring the same batch volume, the total station throughput would be 100,000 barrels. Combining the uncertainty of each measurement yields an expanded uncertainty of 0.15% for the station, which corresponds to an expanded absolute uncertainty of 150 barrels per batch.

Batch Number	Effective day	Effective End day	Product	Pulses	Meter factor	K Factor	Pressure (psig)	Close Temperature (°F)	Base density (API)	Indicated Volume (bbl)	Gross Std volume (bbl)	Total NSV (bbl)	Liquid Mass (kg)	Absolute expanded uncertainty	Relative expanded uncertainty (%)	Uncertainty calculation status	Uncertainty contributions
			Select 													Successful 	
4181	08/01/2022 00:00:00	08/02/2022 00:00:00	CRUDO	27424440	1.0017	1000	30	146.4	17	27424.44	26572.19	26572.19	8864.208	76.72 (bbl)	0.289	Successful	Q _L
4182	08/02/2022 00:00:00	08/03/2022 00:00:00	CRUDO	27424440	1.0017	1000	5	146.4	17.2	27424.44	26567.76	26567.76	8853.626	76.75 (bbl)	0.29	Successful	Q _L
4183	08/03/2022 00:00:00	08/04/2022 00:00:00	CRUDO	27424440	1.0017	1000	70	146.4	17.2	27424.44	26575.84	26575.84	8853.626	76.61 (bbl)	0.259	Successful	Q _L
4184	08/04/2022 00:00:00	08/05/2022 00:00:00	CRUDO	27424440	1.0017	1000	30	80	20.9	27424.44	27258.21	27258.21	8862.283	62.66 (bbl)	0.23	Successful	Q _L
4185	08/05/2022 00:00:00	08/06/2022 00:00:00	CRUDO	27424440	1.0017	1000	30	160	16.5	27424.44	25457.39	25457.39	8852.694	63.65 (bbl)	0.317	Successful	Q _L
4186	08/06/2022 00:00:00	08/07/2022 00:00:00	CRUDO	27424440	1.0017	1000	30	146.4	12.6	27424.44	25628.02	25628.02	9155.673	73.425 (bbl)	0.234	Successful	Q _L
4187	08/07/2022 00:00:00	08/08/2022 00:00:00	CRUDO	27424440	1.0017	1000	30	146.4	21.7	27424.44	26515.36	26515.36	8877.551	78.141 (bbl)	0.295	Successful	Q _L
4188	08/08/2022 00:00:00	08/09/2022 00:00:00	CRUDO	34734000	1.0017	1000	30	146.4	17.2	34724	23954.4	23954.4	7981.824	69.142 (bbl)	0.289	Successful	Q _L
4189	08/09/2022 00:00:00	08/10/2022 00:00:00	CRUDO	30134000	1.0017	1000	30	146.4	17.2	30124	29186.31	29186.31	9725.144	84.345 (bbl)	0.239	Successful	Q _L
4190	08/10/2022 00:00:00	08/11/2022 00:00:00	CRUDO	27424440	1.0017	1000	30	146.4	17.2	27424.44	26570.79	26570.79	8853.626	76.696 (bbl)	0.289	Successful	Q _L
4191	08/11/2022 00:00:00	08/12/2022 00:00:00	CRUDO	27424440	1.0017	1000	30	146.4	17.2	27424.44	26570.79	26570.79	8853.626	77.529 (bbl)	0.282	Successful	Q _L
4192	08/12/2022 00:00:00	08/13/2022 00:00:00	CRUDO	27424440	1.0017	1000	30	146.4	17.2	27424.44	26570.79	26570.79	8853.626	76.696 (bbl)	0.239	Successful	Q _L
4193	08/13/2022 00:00:00	08/14/2022 00:00:00	CRUDO	30134000	1.0017	1000	30	146.4	17.2	30124	29186.31	29186.31	9725.144	84.345 (bbl)	0.289	Successful	Q _L

Figure 4 – Volume settlement and uncertainty estimation for dynamic measurement

The expanded uncertainty for the station in the previous example was calculated assuming that each arm had an uncertainty of 0.3%. If the same exercise is performed assuming an expanded uncertainty of 0.5% for each arm, the combined expanded uncertainty for the station becomes 0.25%. For a total station measurement of 100,000 barrels, this corresponds to an expanded absolute uncertainty of 250 barrels.

For the teams responsible for daily or monthly balances, being able to determine whether the absolute uncertainty associated with a station is 150 barrels or 250 barrels is very important. As noted previously, part of the imbalance is often justified by measurement uncertainty, but the difference between 150 and 250 barrels directly affects the balance result.

5.3 Uncertainty in Pressurized Tanks

Measurement in pressurized tanks follows a similar pattern: changes in process variables can cause the uncertainty to vary from 0.9% to 2.0%.

Effective day	Product	Close Level (mm)	Vapor Temperature (°F)	Liquid Temperature (°F)	Tank Pressure (PSI)	Atmospheric Pressure (°F)	Base density (API)	Vapor Density	Total observed volume (Bbl)	Gross Std volume (Bbl)	Total NSV (Bbl)	Liquid NSV (Bbl)	Liquid Mass (Kg)	Vapor Mass (Kg)	Total Mass (Kg)	Absolute expanded uncertainty (bbl)	Relative expanded uncertainty (%)
	Select 																
03/01/2023 02:00:00	GLP	3002	100	80	144	14.7	149.2032	6557.2	911.87	1009.55	1009.55	880.78	1679.035	245.488	1924.52	55.996	1.93
03/01/2023 03:00:00	GLP	9002	100	80	144	14.7	149.2032	6557.2	3605.57	3682.14	3682.14	3675.8	7007.233	13.968	7021.22	52.98	0.945
03/01/2023 04:00:00	GLP	6002	100	80	144	14.7	149.2032	6557.2	2532.84	2507.22	2507.22	2446.47	4663.743	115.807	4779.55	54.275	1.229
03/01/2023 05:00:00	GLP	6002	100	120	144	14.7	149.2032	6557.2	2532.84	2309.4	2309.4	2248.66	4236.645	115.807	4402.45	53.893	1.263
03/01/2023 06:00:00	GLP	6002	140	80	144	14.7	149.2032	7272.2	2532.84	2501.35	2501.35	2446.47	4663.743	104.623	4768.37	47.259	1.117
03/01/2023 07:00:00	GLP	6002	100	80	220	14.7	149.2032	4517.7	2532.84	2546.22	2546.22	2446.47	4663.743	186.348	4850.09	68.802	1.222
03/01/2023 08:00:00	GLP	6002	100	80	120	14.7	149.2032	7950.3	2532.84	2496.75	2496.75	2446.47	4663.743	95.844	4759.59	50.846	1.245
03/03/2023 02:00:00	GLP	6002	100	80	144	14.7	147.5326	6354.9	2532.84	2510.01	2510.01	2447.74	4654.094	119.419	4813.51	56.47	1.261
03/03/2023 03:00:00	GLP	6002	100	80	144	14.7	151.747	6835.1	2532.84	2503.04	2503.04	2444.19	4617.552	111.187	4728.74	51.538	1.187
03/03/2023 04:00:00	GLP	3002	100	80	144	14.7	147.5326	3878.2	911.87	1013.23	1013.23	881.23	1689.962	253.144	1943.11	58.267	1.955
03/03/2023 05:00:00	GLP	3002	100	80	144	14.7	147.5326	6354.9	911.87	1013.23	1013.23	881.23	1689.962	253.144	1943.11	59.541	2.008
03/03/2023 06:00:00	GLP	9002	100	80	144	14.7	147.5326	5987.5	3605.57	3688.22	3688.22	3677.7	7052.835	14.422	7067.26	60.951	1.074

Figure 5 – Volume calculation and uncertainty estimation for pressurized tanks

To determine which sources of uncertainty most affect the measurement, the contribution and sub-contribution analysis described in the GUM methodology can be used. This analysis identifies the influence quantities that contribute most strongly to the uncertainty result. In turn, for influence quantities such as pressure or temperature, it is possible to determine which sub-contributions have the greatest effect, such as repeatability, resolution, error, and stability.

In the case of pressurized tanks, the following image shows the influence quantities that contribute most to the uncertainty result. In this example, gas pressure contributes 88.63% of the total uncertainty, gas temperature contributes 6.64%, and gas density contributes 3.66%. Likewise, the following graph shows the sub-contributions associated with gas pressure.

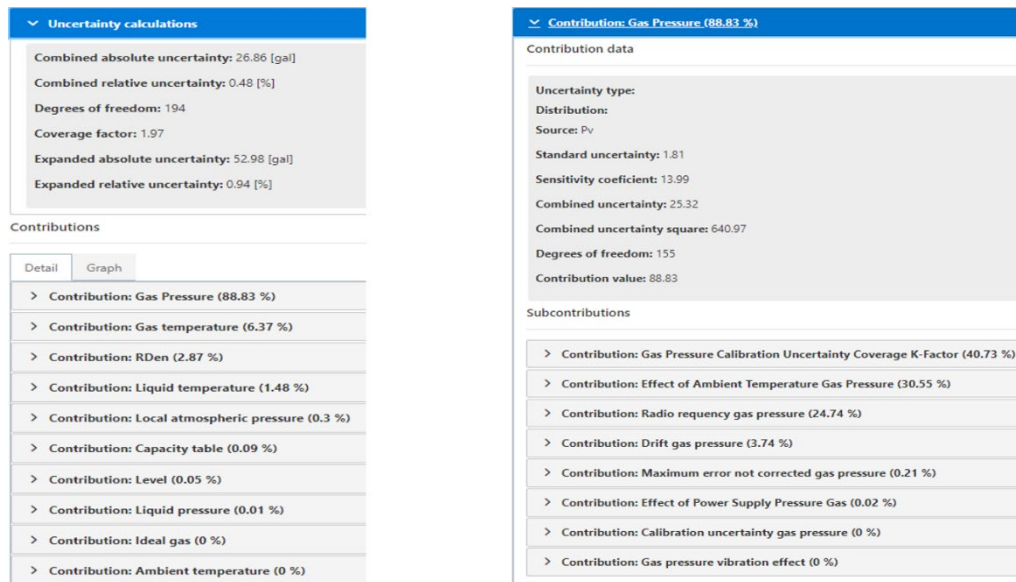


Figure 6 – Graph of contributions and sub-contributions

As shown in the case of pressurized tanks, pressure is a very important variable and one of the main factors affecting both the measurand and the uncertainty result. Because gas is a compressible product, it is highly sensitive to pressure changes.

5.4 Uncertainty in Natural Gas Measurement

The same type of analysis can also be applied to natural gas measurement. Once again, the importance of pressure measurement becomes evident, and variations in daily measurement data highlight their impact on daily uncertainty results.

The graph below shows uncertainty results for various operating conditions in natural gas measurement. In this case, as in the previous examples, the largest variations occur when adjustments are made to transmitter error. When the uncertainty data for the pressure transmitter obtained from the laboratory are changed, or when the transmitter error itself increases, the uncertainty changes from approximately 4% to 8% and even 11%. Process variables also have an important effect: when operating pressure changes from 561 psi to 700 psi, the expanded uncertainty changes from 4.1% to 5.1%. Similarly, although to a lesser degree, a temperature change of approximately 35 °F can increase the expanded uncertainty from 3.6% to 4.5%.

Effective day	Effective End day	Flow time	Product	Pulses	Static pressure	Temperature	Relative density	Heating Value	Raw Volume	Standard Volume	Energy	Absolute expanded uncertainty	Relative expanded uncertainty (%)	Uncertainty calculation status
			Select 											Successful 
06/12/2022 00:00:00	06/13/2022 00:00:00	24:00:00	GAS	421112076	564.82	115.2	0.747	1209.439	974.796472222222	38.293	46.459	13.034.293	4.574	Successful
06/13/2022 00:00:00	06/14/2022 00:00:00	23:59:58.8	GAS	422478241	560.53	150.96	0.7491	1212.3204	977.958891203703	35.094	42.678	9.430.999	3.644	Successful
06/14/2022 00:00:00	06/15/2022 00:00:00	24:00:00	GAS	421104120	563.92	115.64	0.753	1217.627	974.778055555555	38.261	46.734	12.992.841	4.563	Successful
06/15/2022 00:00:00	06/16/2022 00:00:00	24:00:00	GAS	421484125	563.37	114.39	0.753	1217.627	975.680844907407	38.396	46.954	24.179.692	8.462	Successful
06/16/2022 00:00:00	06/17/2022 00:00:00	24:00:00	GAS	425079558	561.74	115.72	0.753	1217.627	983.980458333334	38.444	46.958	13.037.616	4.547	Successful
06/17/2022 00:00:00	06/18/2022 00:00:00	24:00:00	GAS	425079558	561.74	130	0.753	1217.627	983.980458333333	37.145	45.37	11.374.025	4.123	Successful
06/18/2022 00:00:00	06/19/2022 00:00:00	24:00:00	GAS	425079558	700	115.72	0.753	1217.627	983.980458333334	48.919	59.752	16.514.006	5.176	Successful
06/19/2022 00:00:00	06/20/2022 00:00:00	24:00:00	GAS	305026590	561.74	115.72	0.753	1217.627	706.080087942963	27.538	33.697	9.355.656	4.548	Successful
06/20/2022 00:00:00	06/21/2022 00:00:00	24:00:00	GAS	425079558	561.74	115.72	0.753	1217.627	983.980458333333	38.446	46.959	13.063.666	4.564	Successful
06/21/2022 00:00:00	06/22/2022 00:00:00	23:59:58.2	GAS	425079558	561.74	115.72	0.7519	1216.1234	983.980458333334	38.431	46.984	13.110.031	4.575	Successful
06/22/2022 00:00:00	06/23/2022 00:00:00	24:00:00	GAS	425079558	561.74	115.72	0.75	1213.431	983.980458333333	38.406	46.749	33.638.754	11.748	Successful
06/23/2022 00:00:00	06/24/2022 00:00:00	24:00:00	GAS	425079558	561.74	115.72	0.75	1213.431	983.980458333334	38.406	46.749	13.084.529	4.573	Successful
06/24/2022 00:00:00	06/25/2022 00:00:00	24:00:00	GAS	425079558	561.74	115.72	0.75	1213.431	983.980458333334	37.783	45.991	12.620.887	4.535	Successful
06/25/2022 00:00:00	06/26/2022 00:00:00	24:00:00	GAS	425079558	561.74	115.72	0.75	1213.431	983.980458333333	38.234	46.528	12.951.157	4.562	Successful
06/26/2022 00:00:00	06/27/2022 00:00:00	24:00:00	GAS	425079558	561.74	115.72	0.75	1213.431	983.980458333333	38.406	46.75	13.013.717	4.545	Successful

Figure 7 – Volume settlement and uncertainty estimation for natural gas

6 Conclusions

The cases reviewed in this document show that uncertainty varies from ticket to ticket and that treating it as a fixed value for measurement systems is not appropriate. They also highlight that, although part of a system imbalance may be caused by measurement uncertainty, assuming a constant balance uncertainty over time can either mask losses that are not being identified or, conversely, lead to the reporting of losses that are actually associated with uncertainty.

The hydrocarbon production, transportation, and processing segments base the profitability of their businesses on the volumes they produce, move, and refine. Ensuring that the flow computer records the most accurate possible volume has a direct impact on companies' financial results. For this reason, the industry has always placed strong emphasis on good measurement practices: periodic loop checks are performed on transmitters, primary elements are calibrated at defined intervals, suitable equipment is selected, and investment is made in sound measurement principles, training, procedures, inspections, and audits to ensure that accounted volumes are as accurate as possible. However, the industry should not overlook barrels or cubic feet that remain unaccounted for by simply attributing them to measurement uncertainty.