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Technical Paper

Methods of Determining and Verifying Fiscal Sampling System Uncertainty by Analysing 25 Years of Real Field Proving Data and Laboratory Tests Compared with International Acceptance Criteria

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ABSTRACT

As offshore production flow rates decline, oil-fields mature and water fractions climb, it becomes increasingly challenging to achieve a representative sample for use in fiscal, allocation, and custody transfer. It is therefore important that a sampling systems performance is evaluated on a regular basis so that any limitations are identified to mitigate the risks to measurement accuracy and uncertainty.

It is often difficult to conduct water injection certification tests of sampling systems due to the process conditions (varying water cut baseline, high pressure etc.) or the application (lack of space, access etc.). However each step in the "chain of uncertainty" of sampling should be analysed so that the overall uncertainty is both understood and determined to be within acceptable limits with respect to the transaction risks.

This paper examines these topics; the physical and theoretical methods of establishing systematic uncertainty, overall performance and the ongoing healthcare of sampling systems, whilst highlighting the acceptance criteria stated in the international automatic sampling standards for field and laboratory equipment.

The paper then examines more than 25 years of sampling system certification data from around the world with emphasis on the performance of different types of systems. The certification data highlights the systematic biases and uncertainty present in the common designs of sampling system, while demonstrating that CoJetix systems provide significantly less overall uncertainty than all other tested sampling designs. A real world site example is also included to further demonstrate the advantages of the CoJetix Sampling System.

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1 INTRODUCTION

Cameron Measurement has collected sampling system certification (proving by water injection) results over the last 25 years. This data set consists of validated test results from different types of sampling systems operating on various crude oils from across the world. This has provided a unique opportunity to review the performance of the different brands of sampling system as well as installation types. This test data has been reproduced to highlight the performance of various types of sampling system design available on the market both today and during the past 25 years.

The results presented in this paper are expressed as true relative errors in water fraction rather than the system typically presented as results in ISO 3171:1988 [2] which is only relative down to 1%, whereupon it becomes an absolute error. A negative error corresponds to an under reading of the amount of water that is predicted to be present in the oil, while a positive error is an over reading. The 95% confidence intervals are calculated using 1.96 standard deviations around the mean. These confidence intervals give a reasonable representation of the accuracy in any one single proving measurement and provide a reasonable indication of reproducibility of the results. The repeatability of the results would be expected to fall within the stated limits.

For the purposes of this analysis the sampling system installation types have been grouped into four different categories:

- Inline Sampling Systems with passive mixing
- Inline Sampling Systems with Jet mixing
- Fast Loop Sampling Systems
- CoJetix Sampling Systems

Any sampling system will have varying amounts of common and special cause variation. The problem with a sampling system is that there are multiple steps in taking a representative aliquot from a pipeline to the approved analyser. We call this the chain of uncertainty shown in Figure 1.

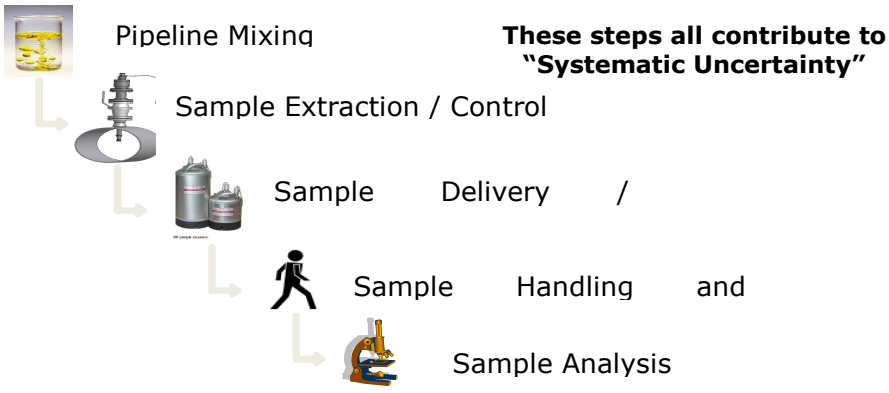

Figure 1 Chain of Uncertainty

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The sampling system certification proving test is a test that examines the uncertainty of the entire analysis sequence shown in Figure 1. This provides the ability to prove that the whole sampling system operation is within an acceptable uncertainty. The sampling system certification test provides the following:

- Proves the entire "grab to lab" sequence.
- Demonstrates that each batch has been sampled correctly, i.e., auditable reporting.

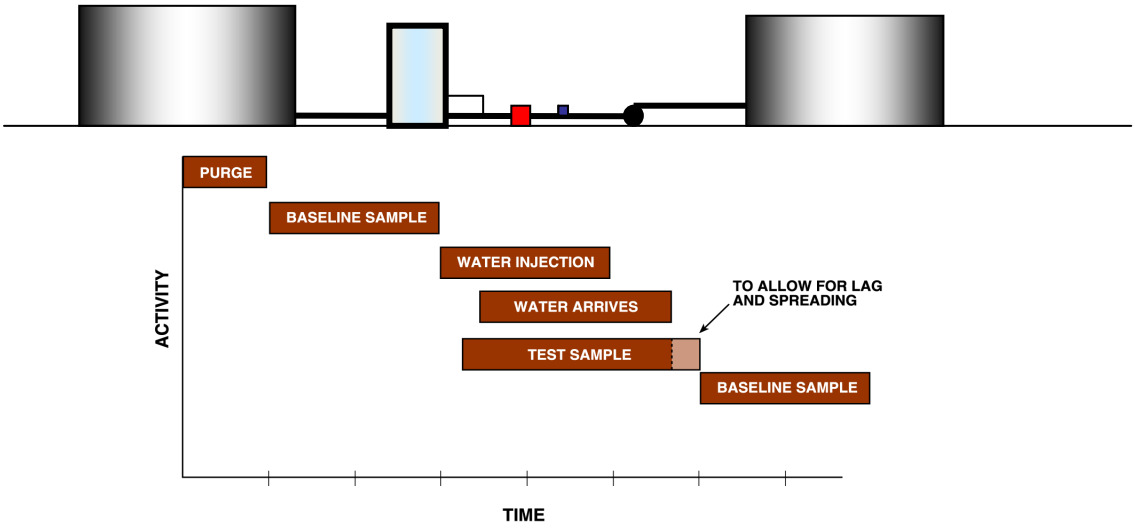


Figure 2 Sampling system proving test

It is normally required to test the sampling system under worst case process conditions:

- Lowest viscosity
- Lowest density
- Minimum pipeline velocity

Testing the sampling system under worst case conditions then provides confidence that the sampling system perform within the acceptance criteria inside its operating envelope.

1.1 Volume Balanced Test

The volume balance test injects a known volume of water (Q_{inj_water}) into a known volume of oil (Q_{wet_oil}) where the baseline of water fraction has been established and is stable ($W_{baseline}$). This then allows the calculation of the total water volume (Q_{total_water}) in the batch;

$$Q_{total\_water} = Q_{inj\_water} + Q_{wet\_oil} \times W_{baseline} \quad (1)$$

The total fraction of water expected (W_{tot}) can then be calculated through;

$$W_{tot} = \frac{Q_{total\_water}}{Q_{inj\_water} + Q_{wet\_oil}} \quad (2)$$

The lab analysis of the sample obtained via the sampler (W_{lab}) is then compared to that which was expected (W_{tot}) and the absolute (ΔW) and relative errors (δW) in the water fraction are then calculated through;

$$\Delta W = W_{lab} - W_{tot} \quad (3)$$

$$\delta W = \frac{\Delta W}{W_{tot}} \quad (4)$$

Two sequential tests are then normally conducted to check repeatability of the results;

The tolerance limits stipulated by the standards are typically taken to be;

±0.05% per 1% ISO (single test) [2]

±0.11% API (2 tests and based on metering volume and 1% water) [3]

1.2 ISO3171:1988 Annex A Calculations

The calculations for determining the mixing level within a pipeline are given by the ISO3171:1988 Annex A calculations, minor variants of these calculations are present in the both the standards of the IP [1] and API [3]. These calculations were developed during the late 1970s and early 1980s in a working group within the ISO and through researchers like Karabelas A. J. 1978 [7] and Sergev, A. 1984 [8].

The often quoted figure on the Annex A calculations is that of the C_1/C_2 ratio which provides an indication of the mixing within a horizontal pipe, where C_1/C_2 is the ratio of the water concentration in the top half of the pipe is compared with the concentration in the bottom half of the pipe.

The Annex A calculations however provide considerably more information than just the C_1/C_2 ratio, including the ratio of water settling rate to main pipeline velocity, which is typically used to determine mixing within vertical sampling conditions.

The Annex A calculations also estimate the Sauter mean diameter of the water droplets (d_{32}), which according to Paul et al [5] can then be used to estimate the maximum droplet diameter (d_{max}). Paul et al [5] give this relationship as

$$d_{max} = 1.8 d_{32} \tag{5}$$

This is not a definitive rule in that Pacek et al [6] found in their experimental tests that this relationship d_{max}/d_{32} varied from a low of 1.61 to a high of 2.21. As a result and given the importance of the maximum water droplet diameter we take the conservative relationship to be

$$d_{max} = 2 d_{32} \tag{6}$$

This maximum water droplet diameter can have a significant effect on accuracy of a sampling system and it's importance is explained in more detail within section 8.

2 INLINE SAMPLING SYSTEMS WITH PASSIVE MIXING (SUCH AS STATIC MIXERS)

An Inline Sampling System (shown in Figure 3), is generally the lowest cost option when pursuing automatic sampling technology. These are typically installed in pipelines that are considered to have either sufficient natural mixing or are combined with static mixers to increase the natural mixing to a level considered suitable for representative sampling.

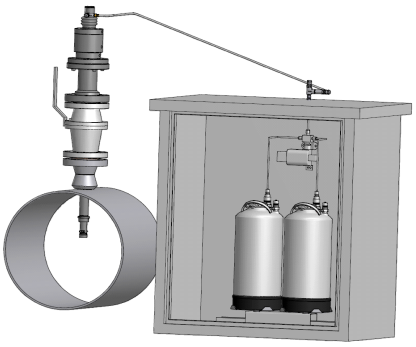


Figure 3 Typical Inline Sampling System (mixer not shown)

Figure 4 shows the historic water proving results for Inline Sampling Systems. It can be seen that this type of sampling system produces a mean error of about -0.1% relative water fraction. The scatter about this mean however is relatively large being about ±0.4% meaning any one system result can have a relatively large variation from this mean.

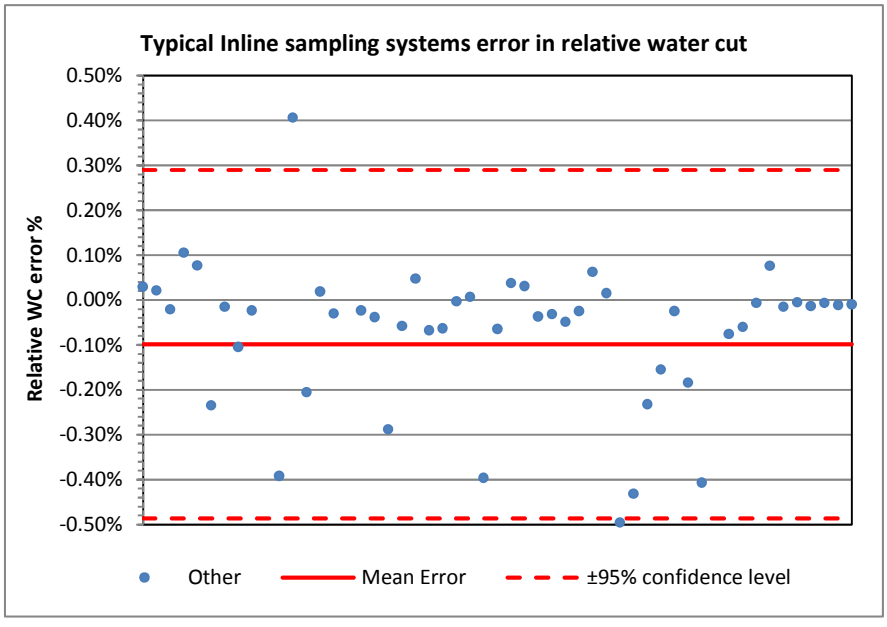


Figure 4 Inline Sampling System

3 FAST LOOP SAMPLING SYSTEMS

A Fast Loop or Bypass Sampling System (shown in Figure 5), typically incorporates a main line take off probe that provides a representative flowing stream to a Cell Sampler. A Fast Loop Sampling System is typically installed in pipelines that are considered to have either sufficient natural mixing or are combined with static mixers to increase the natural mixing to a level considered suitable for sampling.

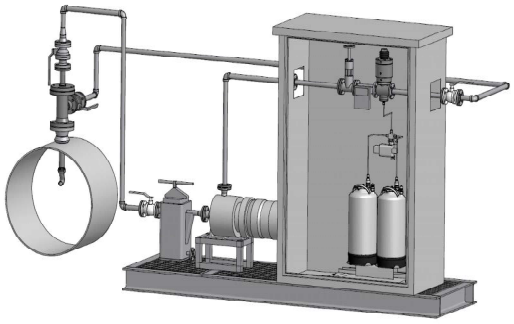


Figure 5 Typical Fast Loop Sampling System (mixer not shown)

When the Fast Loop Sampling System design is compared with the Inline Sampling System design the results show a marked increase in accuracy, as shown in Figure 6. It can be seen that the Fast Loop Sampling System design reduces the mean error to that of about -0.05% relative water fraction, while also significantly reducing the scatter in the individual results to that of about ±0.15%. This increase in accuracy and reduction in scatter clearly provides an improved confidence in the systems when compared with that of the typical Inline Sampling Systems shown in Figure 4.

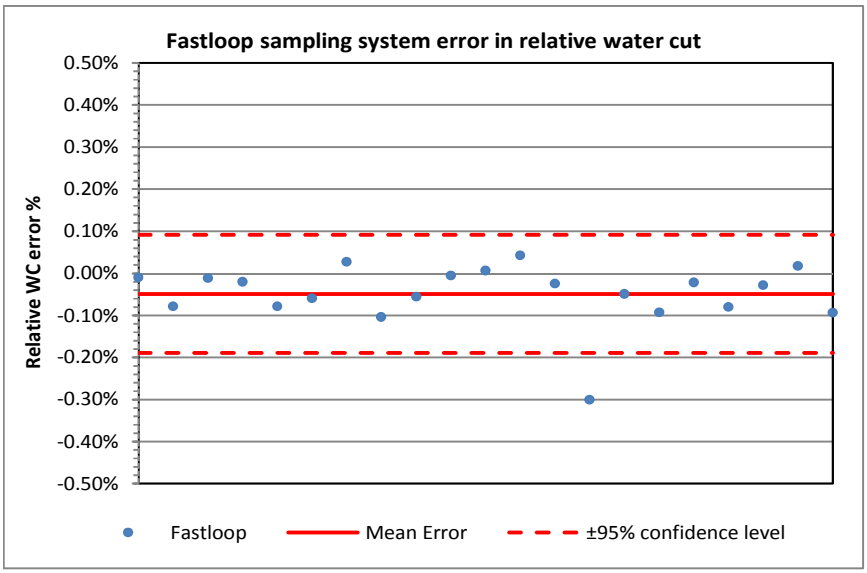


Figure 6 Fast Loop Sampling System

4 INLINE SAMPLING SYSTEM WITH JETMIX

Fast Loop Sampling Systems are typically installed in a pipeline where there is already sufficient natural mixing or a static mixer is suitable. These systems can be regarded as passive mixing systems. When a particular pipeline has poor natural mixing and a static mixer is not suitable the solution is to use an active mixing system like a JetMix system, which can be combined with an inline sample probe. Given the requirement for an active mixer the systems are typically used in more challenging situations, sometimes significantly more challenging (ie. lighter products), when compared with that of the passive mixing systems discussed earlier. Nevertheless as can be seen in Figure 7 the combination of an active mixer and Inline Sampling System significantly improves upon the results previously seen in the inline probe passive systems shown in Figure 4. In fact the results become comparable to that seen in the Fast Loop Sampling Systems results of Figure 6. The application of these JetMix Inline Sampling Systems demonstrates a marked increase in accuracy even in challenging conditions.

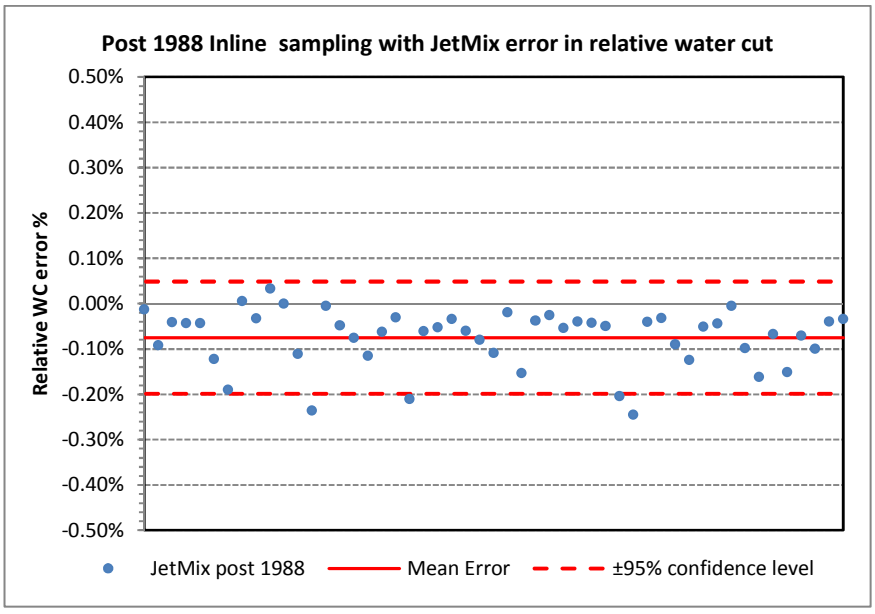
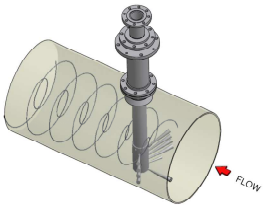


Figure 7 Inline Sampling System with JetMix (Post 1988)

5 COJETIX SAMPLING SYSTEMS (COMBINED FAST LOOP AND JETMIX)

The Jet mixer in combination with an inline sampler was the most accurate solution for challenging system conditions until circa 1995 when the CoJetix systems were developed. CoJetix Sampling Systems combine the principles of the Fast Loop within that of the JetMix system resulting in the name CoJetix.



JetMix Nozzle

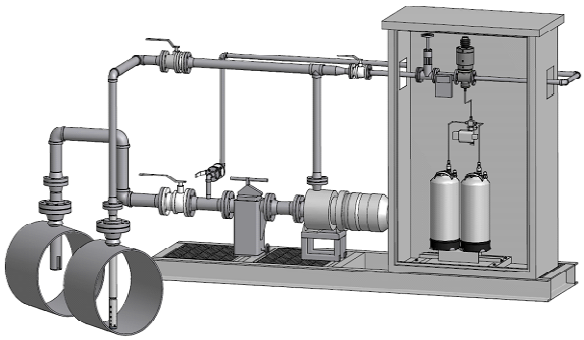


Figure 8 Typical CoJetix Sampling System

The results in Figure 9 show that the CoJetix Sampling System design is by far the most accurate of all types of Sampling System having a mean relative error of <-0.01% while the scatter in the results is down to less than ±0.1%. **This provides considerable assurance in the accuracy of the results when compared with all other sampling system types. Considering that the CoJetix Sampling System is applied in the most challenging environments it highlights just how accurate and precise these systems really are.**

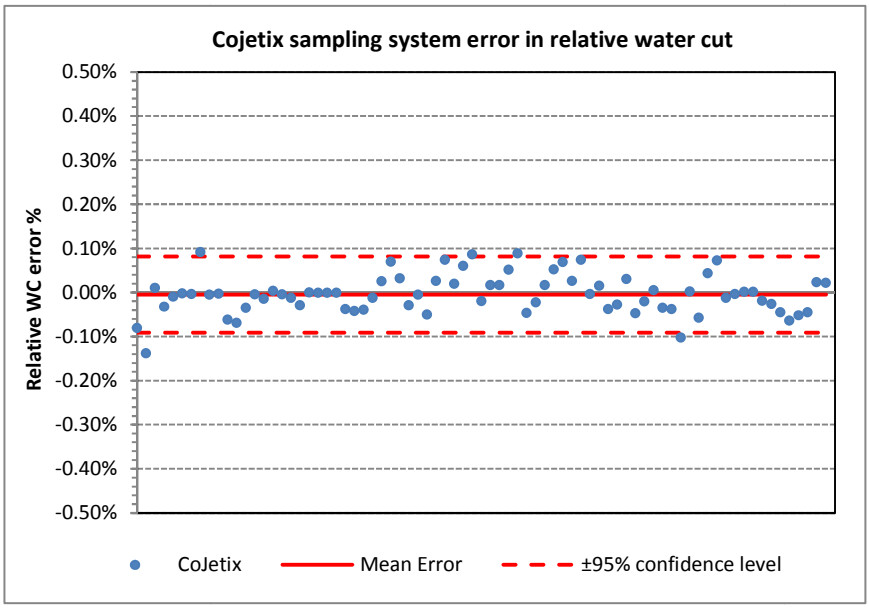


Figure 9 CoJetix Sampling System results

6 EARLY INLINE SAMPLING SYSTEMS AND JETMIX

The JetMix and Inline Sampling System combination was developed during the early 1980's, and during the early period these systems went through significant JetMix Nozzle development that culminated in the patented forward facing Nozzle design that is still used today.

The JetMix Nozzle development and subsequent improvement in both accuracy and reduced scatter of the systems is apparent when comparing the results after 1988 in Figure 7 with that of the results prior to 1988 shown in Figure 10.

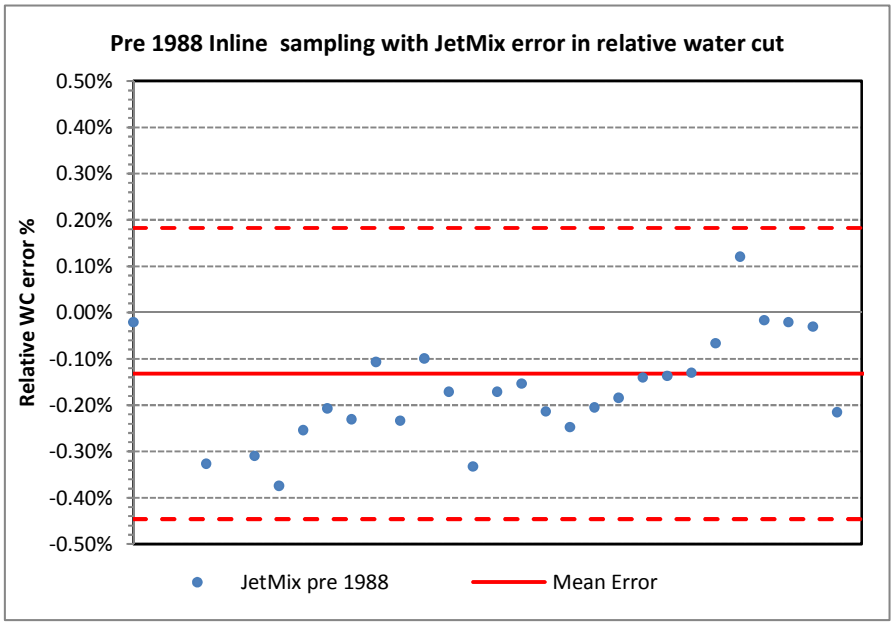


Figure 10 Inline Sampling System with JetMix (Pre 1988)

7 EVOLUTION OF SAMPLING / MIXING SYSTEM PERFORMANCE

The engineering development that led to higher accuracies that are now obtained with the CoJetix Sampling System is clearly highlighted when the results of the Inline Sampling System with JetMix prior to 1988 (Figure 10), Inline Sampling System with JetMix after 1988 (Figure 7) and CoJetix (Figure 9) are combined onto a single plot as shown in Figure 11. The CoJetix Sampling Systems results are clearly contained within a much narrower 95% confidence interval while also averaging closer to the desired 0% relative error. **These results show that the most accurate measurement of water fraction is obtained through the use of a CoJetix Sampling System even if the ISO 3171:1988 Annex A mixing calculations [2] determine that there is sufficient mixing using an Inline Sampling System.**

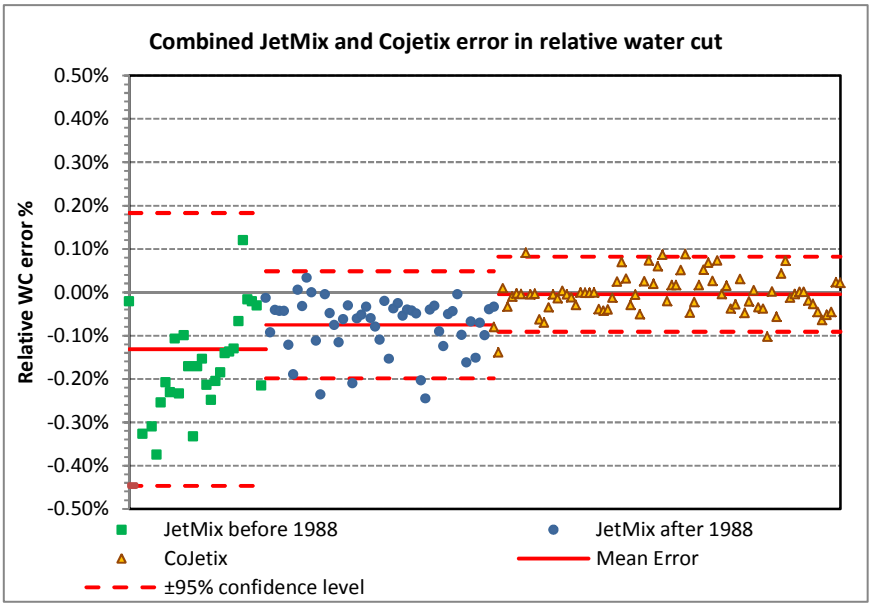


Figure 11 Combined chart showing the accuracy improvement of the JetMix and CoJetix Sampling System

8 EFFECTS OF SAMPLE TAKE-OFF DESIGN

In principle the quality of the water dispersion within the oil is a function of the turbulence induced by piping elements or a mixing device. If the extraction mechanism is capable of taking an entire slice of the cross sectional area of the pipe then no mixing would be necessary when the relative velocities of the water and oil phases are sufficiently close. This argument suggests that the larger the size of the opening to the extractor the less sensitive it will be to dispersion quality.

Additional pipeline mixing is only relevant to fluids that are not already homogenous. The position of the take-off in a well-mixed line or in a homogenous fluid is not important and need only ensure that the extractor is not subject to wall effects.

Many designers insist that to be in accordance with the ISO 3171:1988 [2], the sample take-off must be 0.1D below the true centre line in a horizontal pipe. However installing the take-off 0.1D below the centre line will only improve the sample accuracy when the pipeline is poorly mixed, and if the pipeline is poorly mixed, it is unsuited to fiscal sampling.

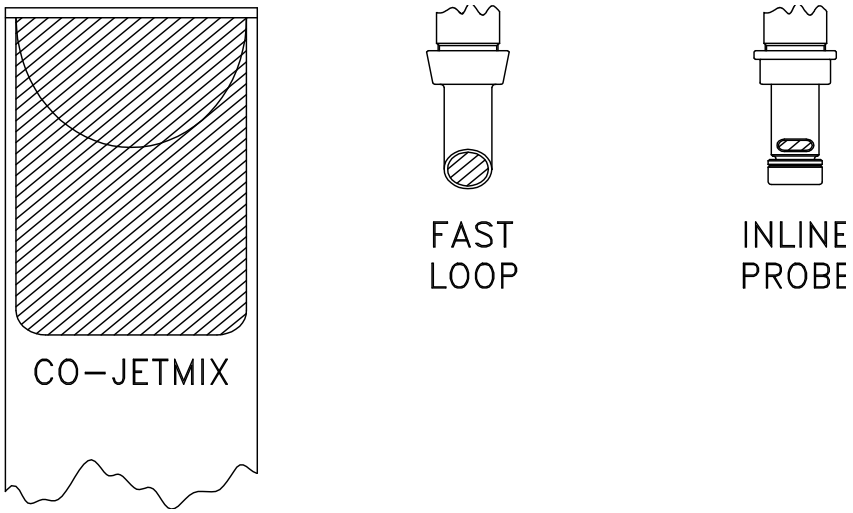


Figure 12 Designs for the sampling system take-off

The diameter of the water droplets in the crude oil can also influence the effectiveness of sampling systems. This happens when the droplet are large in relation to the sampler opening, in that the largest diameter water droplets can then be preferentially directed around the sampler opening rather than into it. As a result the IP [1] recommends that the maximum water droplet diameter should be less than $1/10^{th}$ the diameter of the sampler opening. This frequently ignored sampling requirement predominately affects inline probes due to their significantly smaller opening (5mm to 8mm) when compared to the much larger CoJetix, see Figure 12. It should be noted that the CoJetix take off is dependent on the flow through the nozzle and so the scale does vary considerably.

Unlike inline sample probes the requirement of $1/10^{th}$ the diameter of the sampler opening is commonly met by the CoJetix when sufficient mixing is predicted by ISO 3171:1998 [2]. This larger opening is one of the key reasons why the CoJetix Sampling Systems perform so well when compared to in-line systems.

It should also be understood that this limit on water droplet diameter applies is not limited to grab samplers in that it applies to any analysis equipment that needs to obtain a representative sample of the process fluid. This is particularly true of online water in oil meters that either use a fast loop or flow through insertion design.

9 EFFECT OF PROCESS CONDITIONS ON PROVING RESULTS

9.1 Effect of Line Size on Relative Errors

We can now look at the effect of process conditions on all sampling systems types as well as CoJetix results in particular.

Plotting the line size against the relative water fraction error for all sampling systems produces the results shown in Figure 13.

The best fit linear trend line indicates that in general systems tend to under read water fraction but there may be a slight trend to under read more in smaller line sizes.

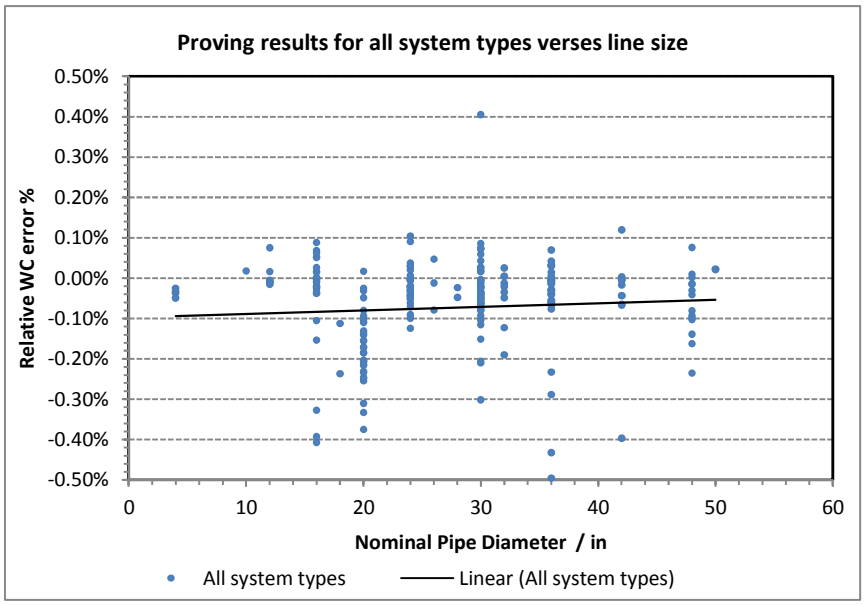


Figure 13 Effect of nominal line size on relative error in water fraction results.

Plotting the line size against the relative water fraction error for just CoJetix Sampling Systems produces the results shown in Figure 14. Contrary to the results shown in Figure 13 the best fit linear line indicates that their maybe a slight trend to over read at smaller line sizes while under reading at the larger line sizes.

The historic higher results for the smallest 16" line size are predominately from a single site configuration so it is therefore difficult to determine conclusively if this apparent over reading is indeed real. However, under reading for the very large line sizes 48"+ can be easily explained due to the greater expected difficulty in mixing the larger pipes.

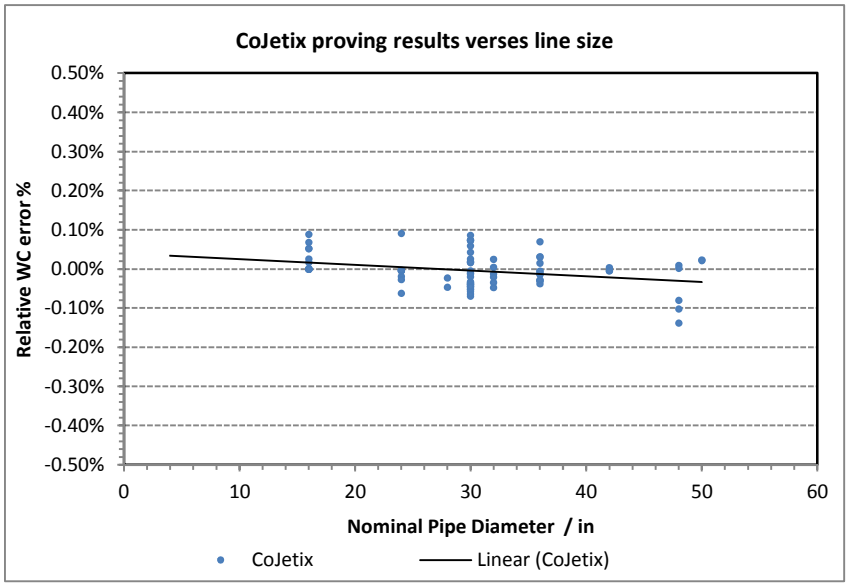


Figure 14 Effect of nominal line size on relative error in water fraction in CoJetix Sampling System results

9.2 Effect of Total Water Fraction on Relative Errors

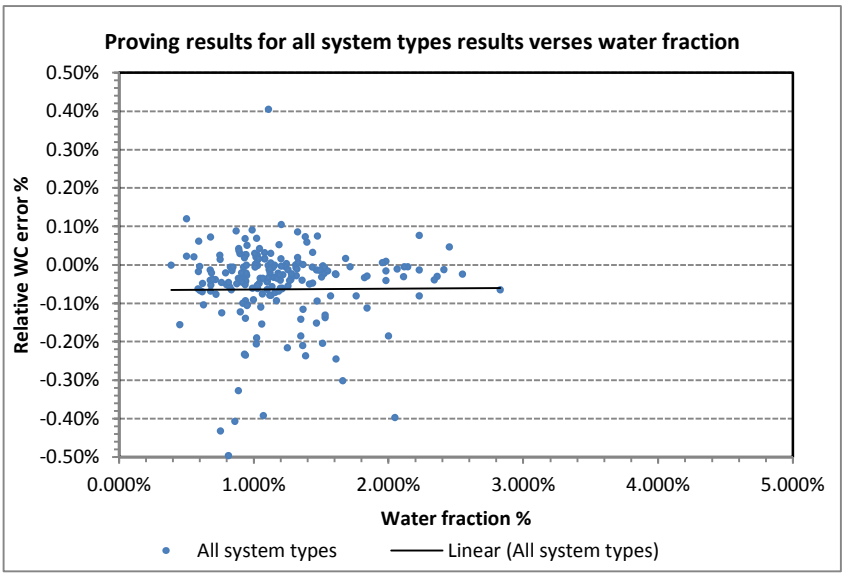


Figure 15 Effect of total water fraction on relative error in water fraction results.

The water proving results verses the total fractions for all system types is shown in Figure 15. The best fit trend line shows that the typical under reading of water is unaffected through the range of water fractions typically tested during a water injection proving test, (0.5%- 2.5% WC). Figure 16 demonstrates that the CoJetix Sampling System does not suffer from the same negative bias.

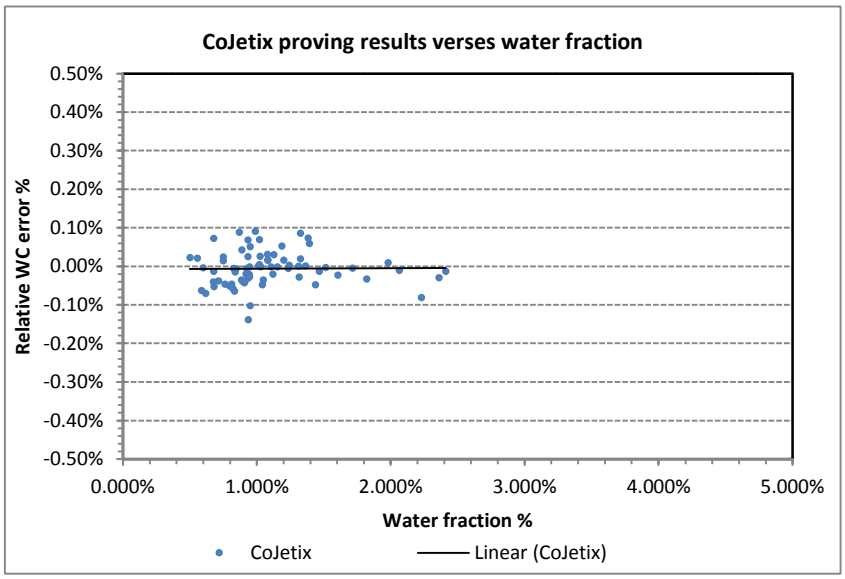


Figure 16 Effect of total water fraction on relative error in water fraction results for CoJetix systems.

9.3 Effect of Density on Relative Errors

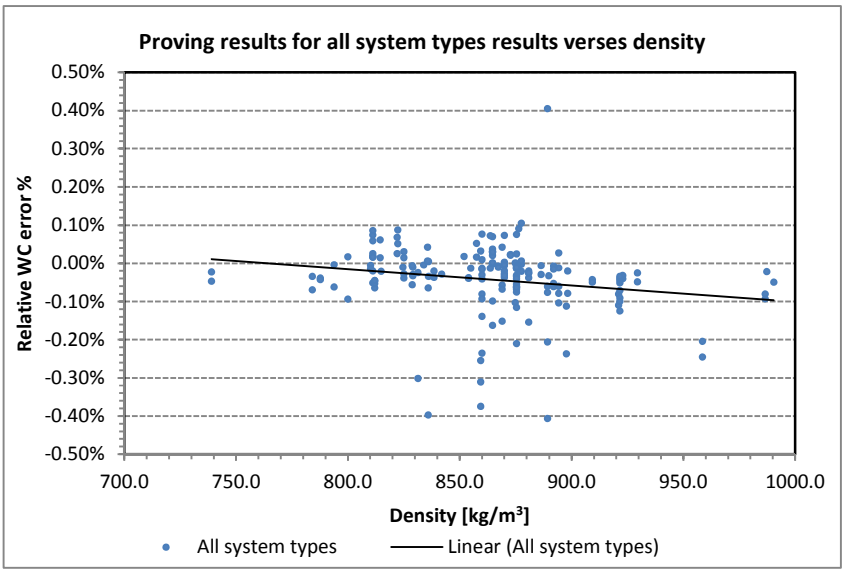


Figure 17 Effect of oil density on relative error in water fraction results.

The effect of density on all system types is shown in Figure 17. The general trend of Figure 17 is contrary to what is expected in the calculations of ISO3171:1988 Annex A [2], in that lower viscosity oils are generally expected to be a harder medium in which to adequately create a homogeneous dispersion of water.

Figure 18 shows the historic results for only the CoJetix Sampling Systems where the trend is reversed when compared with Figure 17, and in fact trending in the direction predicted by that of the IS03171 Annex A calculations [2]. The difference between Figure 17 and Figure 18 can be explained through the likelihood that the ISO3171 Annex A calculations will predict that sufficient mixing is present in systems that have denser oils and so frequently suggesting that only a passive mixing system is required for denser oils.

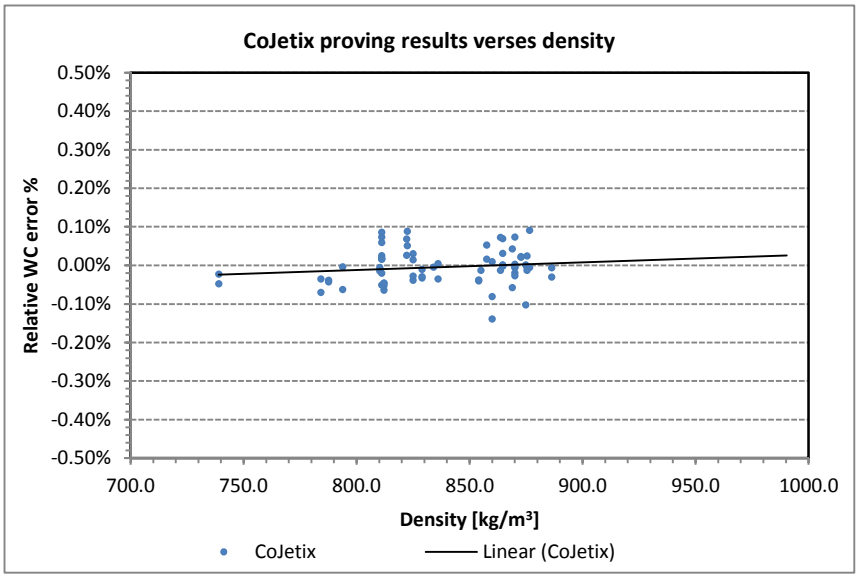


Figure 18 Effect of oil density on relative error in water fraction results in CoJetix results.

As has been previously stated, the CoJetix Sampling System design produces better results than any passive mixing system and therefore this is likely another demonstration of the improved accuracy of the CoJetix Sampling System especially in adverse conditions.

10 A REAL CASE STUDY – THE PROOF IS IN THE PUDDING

So how does historic sampling system proving test data relate to day to day performance?

A good example to illustrate this is a 42" marine unloading facility in North America. This had an Inline Sampling System fitted with a static mixer. The sampling system was operating satisfactorily and had been certified to the API acceptance criteria with a -0.13% deviation. However, to meet environmental regulations the sampler had to be relocated further away from the waterline. Rather than simply move the existing sampler it was decided to install a CoJetix Sampling System and then run both systems together to monitor individual performance. The new CoJetix Sampling System was installed and subsequently certified to the API acceptance criteria with a -0.02% deviation. Both sampling systems were independently operated for 3 months on exactly the same crude oils from around the world.

Figure 19 shows the comparison of the two sampling systems with the CoJetix Sampling System detecting an additional 21,088 bbls of water over the 3 month period and the data collected using an approved third party laboratory.

Study by Company X for a three month period	CoJetix® compared to original Inline Sampling System
Volume Of Oil (bbls) passed by sampler	25,418,379
Additional water recovered compared to original sampler (bbls)	21,088 (0.083%)
Additional water recovered compared to original sampler (@ $100/bbl)	$2,108,800 (in 3 months)

Figure 19 Field study In Line Sampling System with static mixer compared to CoJetix Sampling System

11 CONCLUSION

The analysis of the real field proving data has provided the ability to determine how various system types have performed over a period of more than 25 years. The data clearly show that the CoJetix design has both the highest overall system accuracy and narrowest distribution of results, despite the fact this system design is usually installed in the most challenging of process conditions.

The data indicates that passively mixed Inline Sampling Systems, although complying with International Sampling Standards, perform relatively poorly when compared to the CoJetix Sampling System design, even though these passively mixed Inline Sampling Systems are typically only used in conditions that the ISO3171:1988 Annex A C_1/C_2 calculations show as not requiring additional mixing. This could be at least partially due to the often overlooked condition that the maximum water droplet size should be small when compared with the diameter of the sample opening.

Over the narrow range of water fraction utilized in the historic water proving results the overall water fraction can be seen to have little effect on the accuracy of samplers, in addition the line size appears to have only a very limited effect on accuracy of the overall system accuracy. The effect of density again points to the improved accuracy of the CoJetix Sampling System even when used in the more challenging situations of lighter density oils.

Figure 20 An example of a CoJetix sampling system

12 NOTATION

d_{32}	Sauter mean diameter of the water droplets.
d_{max}	Estimated maximum water droplet diameter
C_1/C_2	ISO3171:1988 Ratio of the concentration of water in top verses bottom of the pipeline.
Q_{inj_water}	Volume of injected water
Q_{total_water}	Total volume water including injected water
Q_{wet_oil}	Volume of wet oil this includes baseline water
$W_{baseline}$	Fraction of water in the wet oil
W_{lab}	Total water fraction measured in lab from the grab sample of the batch.
W_{tot}	Total water fraction expected to be in the batch
ΔW	Absolute error in water fraction
δW	Relative error in water fraction

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