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Enteric Methane Monitoring and Measurement Methodologies For Dairies and Feedlots

Measuring enteric methane expressions from dairy cows to provide practical solutions for carbon abatement regimes, carbon credit generation and for the verification of methane mitigation feed supplement efficacy.

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Executive Summary

Reducing methane emissions is central to the quest to avoid dangerous climate change. Some 155 countries have already signed up to the Global Methane Pledge, together representing more than 50% of global anthropogenic methane emissions. There is substantial evidence-based science supporting the level of CO_2 equivalent (CO2E) emissions contributed by dairy cows that has driven Governments around the world to demand the agricultural sector act to mitigate CO2E emissions. Farmers recognise this and have been pro-actively working on a wide range of measures to reduce their carbon footprint. They understand that they should instigate such measures whilst they have some degree of control over implementations. Equally, it can create genuine productivity enhancements, reduced costs and increased profit. Going "green" can have benefits for both the farm business and for society at large.

Of all possible carbon footprint reduction strategies on dairy and beef farms, contemporary science suggests that the greatest impact may be derived from feed supplements. They have been shown to improve rumination processes such that methane production is significantly reduced whilst providing measurable increases in milk production. However, historical claims have been somewhat anecdotal and lack supporting evidence. There are many competitors in this space, each offering different degrees of efficacy and permanency with limited scientific evidence. How does a farmer choose one and how do they verify the intended outcome. Direct and accurate monitoring is the only answer.

The challenge is to measure enteric methane in the dairy production environment in such a way that it is reliable, consistent and accurate, all without compromising normal dairy farming operations. Many papers have been written on this subject and almost all are highly speculative and are based on modelling. This is because there has not been a universally successful method to measure the breath of cows.

Until now.

This paper articulates the development of a reliable and accurate enteric methane monitoring and measurement process. This paper describes the methodology adopted to achieve the world's only genuine enteric methane meter. It is not concerned with validating the science behind methane reduction but proposes a commercially relevant mechanism for measuring enteric methane and verifying the feed supplement contribution to CO2E reduction and milk production on dairy farms. The focus for this paper is largely dairies, but also in-field and robotic feeders, loafing and Total Mixed Ration (TMR) Barns and where animals are housed near the dairy with purposely placed sheltered feeders.

One important factor to keep in mind relates to degrees of certainty and margins for error expected with agricultural monitoring. We are dealing with animals and a wide range of variables and can be averaging across hundreds of animals to produce the herd value. The purpose of these devices is to detect change, and the evidence suggests they do this very well when correctly installed.

Arcoflex has developed highly accurate, real time methane detection sensors, capable of reading as low as 50 ppm, with an accuracy of 5 ppm. Above 1500 ppm, we can achieve an accuracy of 20 ppm, up to at least

maximum of 3000 ppm. No other methane sensing device can capture and reading methane from the breath of animals as they respire and record all variations.

Development of these sensors only came about after substantial research into respiration chambers, in-field feeders, NDIR sensors, laser sensors, gas chromatographs and a small range of chemical methane sensor detectors. Most were found wanting in being able to work in real time in an agriculturally appropriate setting. Further, most sensors were not able to read accurately below 800 ppm, the zone which most relates to exhaled ruminant methane. Whilst a gas chromatograph can read very accurately, it is hyper-expensive and can only work from statically captured gas samples. This is not appropriate for real-time measurements.

All available technologies were reviewed. Of these, only chemical sensors offered any mechanism to provide a practical way to measure animal breath but the high accuracy of the gas chromatograph gave us a way to calibrate and validate our sensor accuracy and efficacy.

An important facet of measuring methane was where to place the sensor and how to do so. Arcoflex determined the most suitable location was just a few centimetres from the mouth of the animal, particularly when the animal was consuming feed. The availability of this location is unique to dairies and barns and the reason that dairies can provide such rich evidence for methane mitigation efficacy.

A significant role for Arcoflex is to develop individual farm baselines for methane emissions. These baselines are important for carbon credit creation, especially for VERRA and Gold Standard models. The other significant benefit to farmers, apart from policing supplement beneficial effects, is to provide genuine health issue detection and provide a way to manage overall emissions from a herd perspective.

1. What is Methane?

Methane (CH_4) belongs to a class of gases known as alkanes: single bond hydrocarbons [1]:

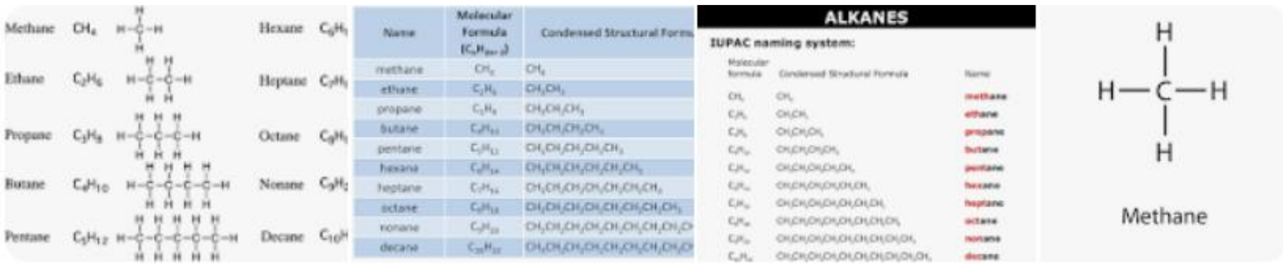

Figure 1 – Methane Chemistry

Alkanes are light, nonreactive but highly combustible gases, the lightest and simplest of which is methane. Methane's common name is natural gas and is used widely in homes and factories. Methane is lighter than air, disperses within seconds and is rated as one of the most destructive of our so-called greenhouse gases. Whilst methane has a shorter lifespan than CO_2, it decays into CO_2 and causes additional harm during its life as methane. This is because methane's hydrogen atoms absorb infrared light and vibrate, thus emitting heat. It is discussed in commercial and scientific circles in terms of its tonnes of CO_2 equivalence, hence the acronym CO2E. Agricultural methane is the result of natural biological processes taking place in the rumen of an animal. Globally, enteric fermentation is responsible for about 90% of all livestock derived CH_4 emissions, with cattle (77%) being the dominant source [30]. Dairies are considered a significant contributor overall. Ninety five percent of generated methane escapes out of the mouth of the animal with the balance in its manure [2].

Methane is combustible at concentrations above 5.5% (55,000 ppm) and most industrial detection systems are designed to detect 0.5% (5,000 ppm) and higher. In agriculture, we need to measure methane at concentrations below 1000 ppm (0.1%), even down to 100 ppm (0.01%). This is difficult as all the meters sold commercially that we have trialled, failed to read such low levels with any accuracy. Our trials included testing them against a gas chromatograph, operated by the independent laboratory, Ektimo [21].

2. The Source of Enteric Methane - Rumination

2.1 What are Ruminants?

Most ruminants have four stomachs and two-toed feet (Artiodactyla Ruminantia). They include giraffes, deer, cattle, buffaloes, antelopes, sheep and goats. Of these, cattle are the most prolific and hence the focus of intense scrutiny for an agrarian economy trying to reach net zero carbon emissions. Dairy cows come into focus because of the ease with which we can monitor methane and control supplement delivery for the suppression of enteric methane. Whilst pigs do produce methane, volumes are very low in comparison. Pigs, like horses, are not ruminants. They are monogastric herbivores [23].

2.2 Typical Breath Methane Concentrations

Most of the research papers reviewed (see bibliography) measure CH_4 yield in terms of g/kg of feed. This is considered inferior because to develop total CO2E requires the complete measurement of all feed intake, including monitoring the g/kg variances for differing feed types. How will this be possible on a regular dairy farm? The better and more modern approach is to measure the absolute methane concentration in parts per million (ppm). Now we only need to model animal size and respiration rate. Far easier than weighing all the cow eats! In consequence, our methodologies have evolved around direct exhaled breath measurements and a small amount of animal modelling, date for which is readily available for the herd.

Many studies show that methane levels in exhaled breath are directly proportional to methane produced in the rumen. Dutch researchers [7] have published typical breath concentrations of 300 ppm to 1500 ppm. Our own observations, shown in Figure 5, align with this. However, the natural breathing cycle (and consequential CH_4) is not constant and relates to health, age, weather and exertion.

2.3 Metrics for Expressing CO_2 Equivalents

This is an area with little scientific consensus. One of the more authoritative and oft cited papers by Dr Frank Mitloehner [8], writing for the CLEAR Centre, shows how difficult it can be to define comparable volumes. One challenge is to compare the metrics offered. For example, Mitloehner measures milk production in lbs/year but CO2E emissions in kg CO2E/kg of milk and then enteric CH_4 emissions as g/cow/day. He suggests that this number is 404. On a multiple of 28, this results in 4.13 tonnes per cow per year (404*365*28/1 million). The tables in reference [8] are credible but it is a challenge to convert to metrics for comparison. Our own research aligns well with Dr Mitloehner.

Dairy Australia – Australia's peak dairy research, development and extension agency - takes a different path [9]. Whilst the article is evasive on how their numbers were derived, it suggests that in 2023, the Australia dairy industry emitted 9.8 million tonnes of CO2E with enteric methane contributing 58% of this. On a dairy herd of 1.27 million beasts (see below) [10], this results in a number around 4.47 tonnes per cow, which is like Mitloehner's number.

The fact that two distinct and politically diverse institutions come up with a similar number gives us cause to accept a number around 4.0 tonnes as appropriate. The CLEAR Centre's suggests [8] that enteric methane accounts for only 58% of the total CO2E that each cow is responsible for but does not go into detail regarding the other third tier contributors. What is important is to develop a common baseline for project accuracy and consistency. The moral of the story is that the same calculation model needs to be used on a before-and-after basis. It matters because it is important for the purposes of setting and achieving emissions reduction targets, alongside carbon credit programs, such as VERRA, Gold Standard, and the upcoming revision of the Australian Government's emissions mitigation policies (currently called the ACCU Scheme, administered by the Clean Energy Regulator for carbon credit generation). Participating partners in any trial need to agree on a calculation model. Our model is presented in Annex C.

2.4 The Biogenic Carbon Cycle

Methane production in the rumen waxes and wanes throughout the day. There is a well-known cycle and it relates to the eating and walking patterns of the cow. See Figure 2 below.

What is important to understand is that the cycle is consistent every day but you cannot measure the instantaneous level of methane and accept that as a base for calculations. The amount of methane delivered in each breath is different, shown in Figure 6 below.

Methane plays an important role in the planet's ecosphere. It breaks down into CO_2 over about 12 years through a process called hydroxyl oxidation, creating the CO_2 absorbed by plants and grasses, which animals then eat. Plants, animals and methane form a closed loop. Increased herd sizes will temporarily increase the amount of free CO_2 until the system stabilises. An increased herd will eat more grass, converting carbon to methane but also allowing more grass to grow from the increased CO_2. It follows then that if we can reduce the amount of CH_4, we can indirectly reduce total CO_2 in this closed loop.

The expectation is that total CO_2 levels might be reduced if the rumination process can be made more efficient, emitting less methane. It implies that if low-emission feed supplements work, the national cattle herd could be used to lower overall carbon emissions. This is where Arcoflex's role begins.

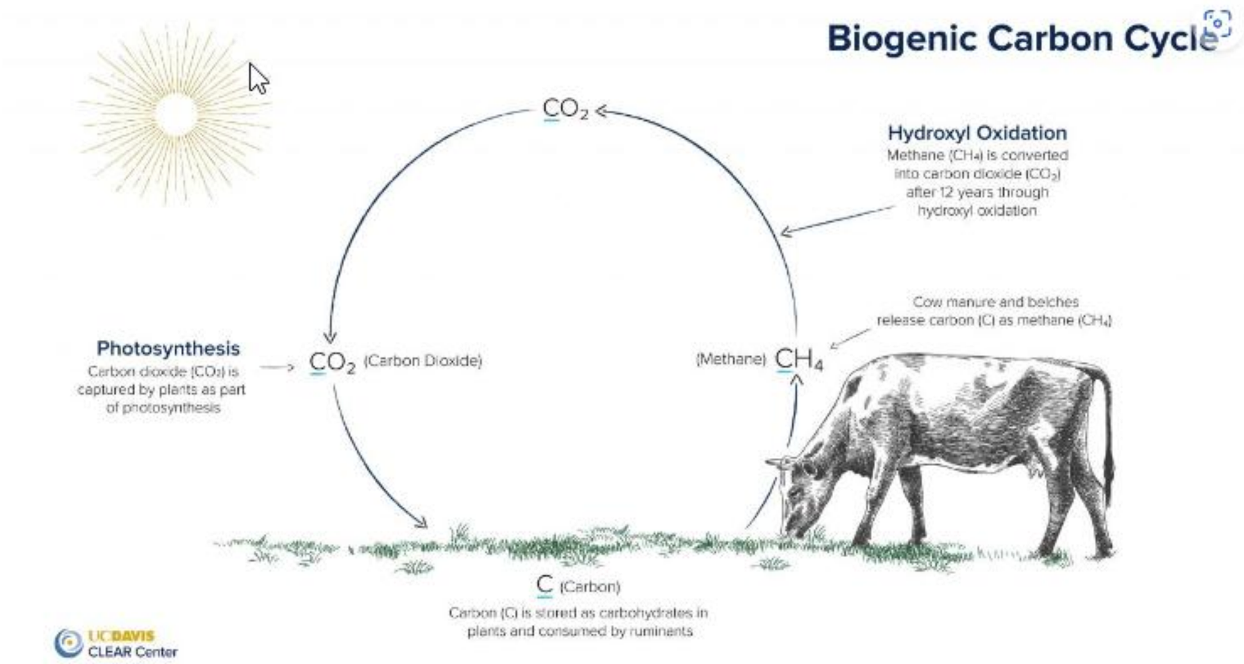

Figure 2 – The Biogenic Carbon Cycle

Our proposition is that if we measure methane at the same point in the cycle each day, we can make reasonable assumptions about total methane and thus assess genuine change. This is inherently possible with dairy cows where they eat, drink and take supplemented food at the same time, twice each day, within the lactation cycle.

3. The Dairy Herd vs the Beef Herd

The national Library of Medicine [24] published a paper discussing the evolution of dairy herds internationally. Global growth in milk production, lead chiefly in SE Asia and the USA, arises on the back of improved genetics, herd management and technology. Typically, using the USA as an example [25], dairy herds in many countries are less than one third their beef herd, but the higher metabolic rate and daily routine make dairy cows a more robust target for precise implementation of methane mitigation practices.

The controlled environments within which dairy cows are subject to makes the measurement of methane much more reliable compared with cattle in open pastures. Free ranging animals do not feed in a manner that allows the capture of rumen output easily but the science developed around dairy cows allows for broader extension. Dairy cows conveniently breathe at sheltered locations, twice a day, at the same time, making the dairy herd the perfect candidate to validate methane reduction. Some of the methodologies developed allow extension to feed lot or loafing barn animals and even sheep fed, through in-field feeders. Hence, the science developed can be extended to other animals and so further carbon reduction achieved.

According to the Meat and Livestock Association (MLA), Australian dairy cows are responsible for around 6 million tonnes of CO2E [10]. This number represents about 4-5 tonnes CO2E/cow per year and is consistent with our earlier research cited. This is visualised in Figure 3 below.

Figure 3 – Australian Dairy Production

4. Methanogenesis and Bio-Mechanics

To record methane effectively, we need to understand how it is produced. The rumen is the first of four chambers of the stomach in the adult cow as shown in a pictorial article courtesy a University of Minnesota website [11]). The article describes the relationship between volatile fatty acids (VFA), the eructation process (burping), milk production, grain vs grazing relevance and faeces output.

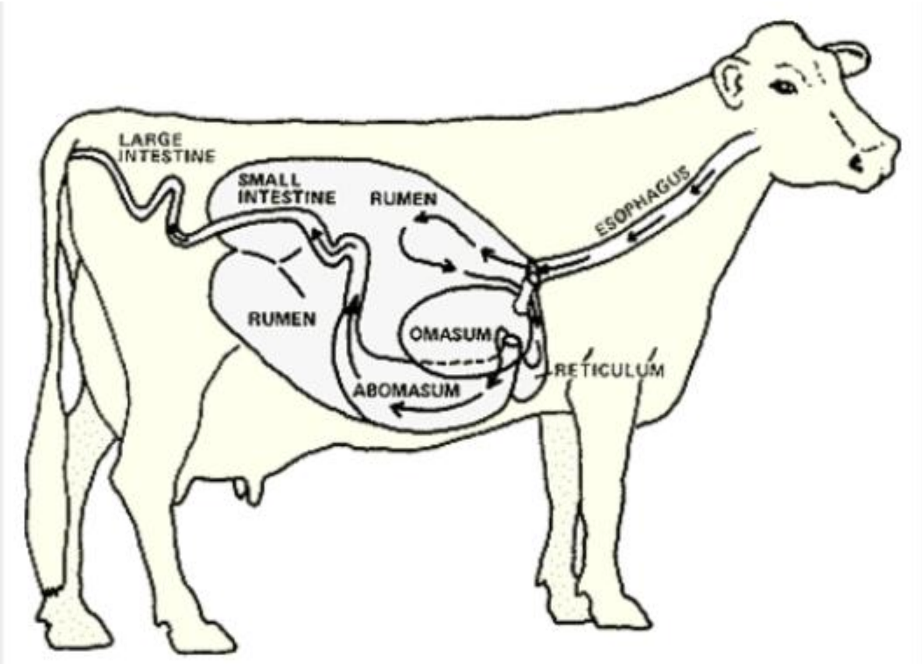

Figure 4 – Bovine Biology

It is important to understand that methane is not developed in the lungs and will not maintain a constant concentration. The rumen releases methane into lungs after a certain pressure builds up.

Microbes in the rumen ferment carbohydrates from grasses and other sources into Volatile Fatty Acids and gasses, mostly CO_2 and CH_4 [12]. Many factors affect the efficiency of this process, the amount of gas produced and the efficiency of food conversion. Gas produced is about 45 litres per hour. It builds up and then released in burps (eructation). The cow does not produce methane at the same rate throughout the day; it waxes and wanes in response to grazing and walking patterns. Because this daily pattern is consistent, it can be used to assess total methane if we can measure the breath at consistent times.

A healthy cow, breathing at roughly 30 breaths per minute (see Annex C), will eructate methane only once a minute or so [27]. It is not a constant level. All other breaths will usually have some methane concentration but typically, very much lower. Less healthy animals will throw more eructation breaths with a higher methane amplitude. Sick cows have a methane profile that is noticeably higher and often points to ketosis, worms or other digestive issues. Importantly, the type of grass grazed prior to milking and overall diet will affect methane output significantly. Our meters can detect pasture shifts from rye, lucerne, native, mixed and other grass types as shown in Figure 5. It shows as an immediate rise in methane and then a recovery to normal after 3-5 days. The vertical axis is in ppm (this is taken from real data).

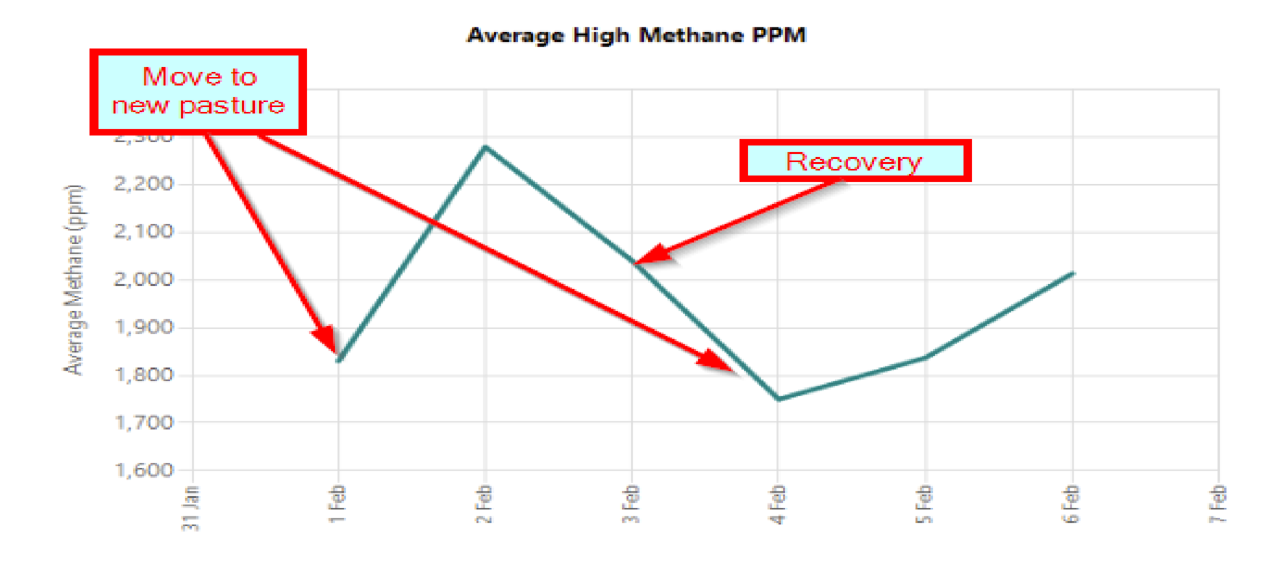

Figure 5 – Methane Pasture Cycles

What this shows is that there are natural variations to rumen health and consequential methane output. Other factors that show visibly in charts are health issues related to weather events and lactation cycles. When assessing feed supplement efficacy, all such natural variations must be considered. Weather has show to have as much impact on methane generation as pasture and feed type.

4.1 The Breathing Cycle

To measure methane from cow breath is no easy thing – high concentrations of methane are only present in about one in eight exhalations (Figure 5) and only briefly. From a monitoring point of view, methane is only present in sufficient concentrations at the mouth and for less than two seconds. Exhaled air from the lungs is mixed with this rumen output and diluted immediately upon leaving the mouth. Exhaled methane rises quickly and disappears within 4-5 seconds from entering the feed bin.

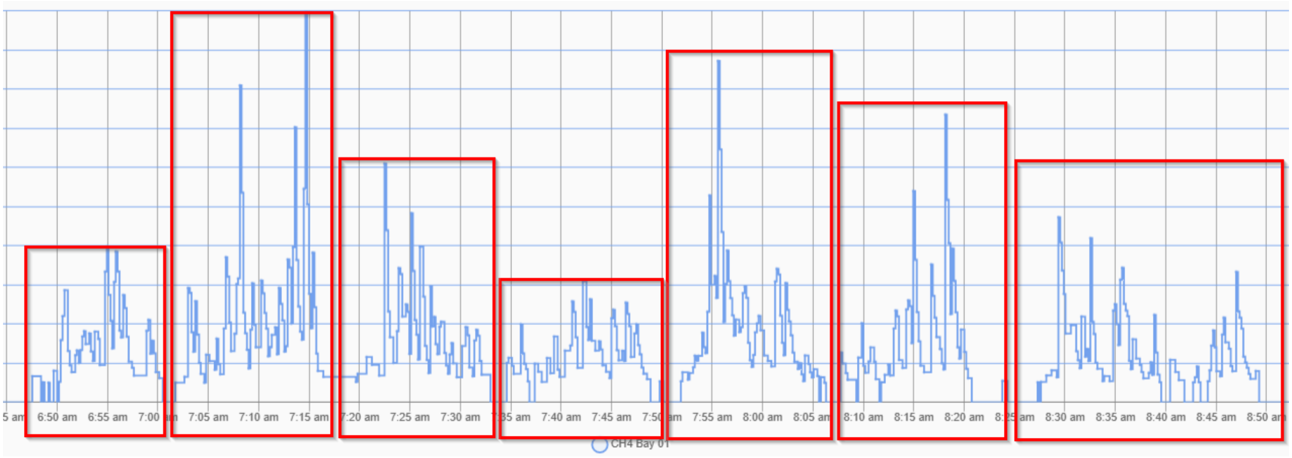

Figure 6 – Methane Output from Seven Cows

Figure 6 shows seven different animals entering one bay in a herringbone dairy over one milking session. The first thing to note is that detected methane varies in intensity. This diagram shows these animals being milked over a two-hour period; each animal being monitored for 12-15 minutes through its milking cycle. To obtain a methane reading, two things must coincide: the animal must breathe in the direction of the sensor and it must include an eructation pulse. This milking period is long enough to capture at least one eructation pulse. Again, Figure 6 shows this variation well. Some animals throw multiple high methane concentration pules and some only one. Often, the animal raises its head whilst chewing and so we miss that exhalation. Distracted animals show less. The sensors are housed inside cowls to capture methane long enough to read and placed within 10 cm of the cow's mouth. In Figure 7 you can see the cowl placed just above the feed cavity. As the cows reach in for feed, their mouth is the perfect distance from the cowl.

Figure 7 – Sensor Placement in Feeding Bays

The second thing to note is how quickly methane dissipates – it clears within seconds. This lack of persistence is important with proving that cross-contamination does not occur.

4.2 Seasonal and Pasture Variation

Whether we measure milk production or methane output, production of both varies naturally throughout the year, predominantly due to lactation, weather and pasture cycles (which affects feed digestibility). Figure 8 shows an example of milk production as it varies going into an Australian summer. The methane curve is similar. Hot days can dramatically reduce milk production, cold ones produce more.

Total Daily Milk Production From 2023-10-01 To 2024-01-09

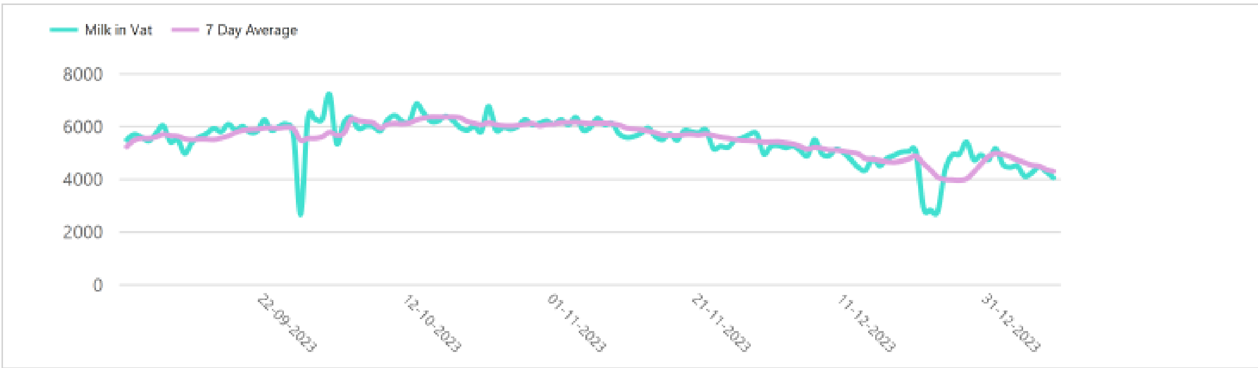

Figure 8 – Spring to Summer Variation of Milk Production

This annual cycle of variation will make supplement efficacy calculations very difficult. Consideration might be given to splitting a farm herd into a control group and treated group, separating them by using their ear tags at milking time. In that way, all animals will experience the same pasture and environmental factors but it is important to be able to identify and factor out natural variations. If not, we might reward or blame a supplement incorrectly for naturally varying events.

4.3 Effects of Animal Health on Methane Emissions

Our trial experience has shown that most low-emission supplements have very little detectable impact on sick animals, although anecdotally, sick animals seem to recover sooner when fed such low-emission supplements. When normal rumination processes are impacted (for example, worm infections), it is almost impossible to isolate out low-emission supplement effects. To accommodate this, we must have access to animal profile data from when the animal was healthy. To achieve that requires animal ID identification with each methane sample.

One side-effect of our methane monitoring observations was the ability to detect sickening animals well before collars or other measures. It arises from the direct effect on methane by rumen health, something we can detect immediately. Anecdotally, we also believe that recovery from sickness seems to happen fast when fed these supplemented diets. The obvious benefit would be to keep milk production higher by treating sickening animals sooner and being able to return them to the herd sooner. Formalising these observations will become the focus of future supplement trials.

The question arising from this is whether to isolate sick animals from any trial - from the point of view of assessing supplement efficacy, not for the purposes of assessing total farm methane loading. This does highlight the need for animal identification. Unseasonal rain or debilitating heat [28] will impact animal wellbeing and may contribute to good and bad carbon years. Perhaps two calculations should be produced: the impact on healthy animals and that of the total herd.

5. Review of Ruminant Methane Measurement Technologies

There are several methodologies for measuring methane in ruminants, specifically dairy cows. A leading paper by Storm and Hellwig [1], explains them. Most involve the study of the rumination process and the source of methane production, not the practical implementation of such methods to common farming practices. Further, all these papers estimate methane with models, not actual measurements, because the ability to measure enteric methane from animal mouths did not exist. The following discussion is a summary of available technologies at the time of writing and is not intended to be exhaustive.

5.1 Respiration Chambers

Respiration chambers (or calorimeters) are very straight forward. A cow is placed in a confined chamber, fed and watered and the exhaled air examined.

Figure 9 shows a typical setup and several such units can be found at Ellinbank in Victoria, Australia [6]. These chambers are expensive and can only ***average*** the air travelling through the system. Air is sampled using gas chromatographs only periodically. Measuring CH_4 content in that air is also complicated by the need to continually mix with fresh air so as not to asphyxiate the animal. This renders the measuring of direct breathing output impossible. Respiration chambers are clearly not viable for widespread agricultural CH_4 monitoring.

Figure 9 – Respiration Chambers

Apart from the difficulty of making the cow enter and settle down, the respiration chamber process does not represent the usual daily walk-graze-milk cycle of the cow and the animal is now potentially under significant stress. These factors will distort the rumination process.

The conclusion is that respiration chambers are not practical for monitoring methane, mostly because of the variable dilution of the measured air. Further, there is no practical mounting point for the sensor, with the animal free to feed and munch in multiple places. The capacity to detect the very light methane contribution is almost impossible. We have already raised the fact that the mouth is the only place where there are sufficiently detectable concentrations of methane. Respiration chambers have never been successful for this purpose and these limitations explain why.

5.2 Sulphur Hexafluoride (SF_6) Tracers

This process is employed in several countries, including at Ellinbank Smart Farm in Victoria, Australia [6]. It is considered accurate but historically, highly variable. The cow is fitted with breathing tubes and made to swallow tracer sensors. The cow is then allowed to roam free and the sensors recovered later for analysis. This is time consuming, expensive and impossible to scale economically. This process is akin to respiration chambers in efficacy but is not commercially viable. It could be used to validate other techniques. One paper describes this process in detail [5]. Problematically, other variables as described for respiration chambers still apply. This method is shown in Figure 10 below. One of the biggest challenges, as discussed in their paper to this methodology is the extremely low rates of gas release (under 3mg/day) to achieve absorption metrics. How such low rates are measured and controlled presents credibility challenges.

5.3 *In Vitro* Gas Production

In vitro gas production technique [1] has been developed to evaluate factors influencing digestibility and fermentation kinetics from feeds and is carried out in a laboratory. Animal feed has natural rumen microbes added to promote fermentation with the methane produced recorded. It was initially favoured as a way of measuring supplement effects but could not prove that the fermentation processes developed imitated the rumen of a live animal. This may contribute to the science of methane production and feed supplement efficacy but it does assist with practical mass animal-based monitoring in a commercial setting.

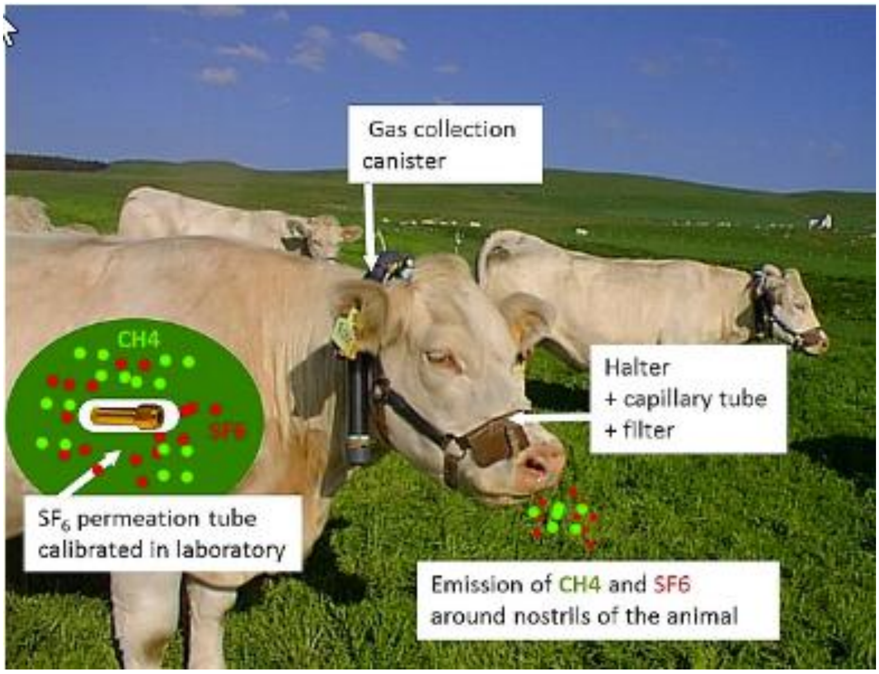

Figure 10 – SF6 Tracer Technology [4]

5.4 Building, Space and Area Measurement

There have been many attempts to analyse the air around herd activity using lasers and drones but this approach is hindered by the fact that laser technology is often difficult to calibrate and verify. Few references exist with evidence-based measurements. The problem is compounded by the fact that methane is colourless, odourless and lighter than air, dissipating completely within seconds. In sheds, the movement of animals, natural air flow and applied ventilation all dilute methane concentrations constantly. In the paddock it is extremely difficult to read methane at any distance. Feedlots and loafing barns potentially offer monitoring points of relevance and will be discussed later. Measuring methane in the broader airspace remains highly speculative. We know that methane rises in a barn and can collect in the roof space but it is diluting with every second passing. Identifying the specific animal source is impossible.

5.5 Electronic Sensors

Small, cost effective and accurate electronic sensors have only become commercially available in recent times. NDIR-based sensors first surfaced 10-15 years ago but are not practical for agricultural monitoring. Chemical sensors emerged around 2020 and are the sensor type to offer the opportunity to measure methane nearest its source – the mouth. No off-the-shelf sensors offer any practical way to measure the breath of an animal because all are designed for industrial gas detection. Agricultural implementations were not considered. The next section will explore all commonly used options to measure methane and how they might fit with monitoring dairy herds.

6. Methane Sensing Technologies

Sensors to measure methane (CH_4) have existed for many years but are mostly used in the scientific, mining and manufacturing sectors. The most common industrial purpose is gas leak detection, measuring the combustible ranges of 5,000 ppm to 25,000 ppm. By contrast, the agricultural implementation needs to measure as low as 50 ppm. Until 2020 there has not been a credible sensor for agricultural use. Figure 11 shows a summary of the four key technologies available.

Sensor	Speed of Reading	Cost (AUD)	Accuracy	Agricultural Implementation
Gas Chromatography	Very slow (15+ min)	80,000+	Very High	None
Laser Spectroscopy	Instant	4,000+	Poor	None
Nondispersive infrared sensors (NDIR)	Slow (20-30 sec)	3,000+	High	Poor
Arcoflex (Chemical – heated electrode) Sensors	Fast (2-3 sec)	500	Good	Excellent

Figure 11 – Comparative Sensor Costs

6.1 Gas Chromatography

Widely accepted as the most accurate gas analysis tool is the Gas Chromatograph. There are many types of internal detectors; the basic principle is that a sample of gas is captured and injected into the machine where it is analysed by flaming it. Depending on the specific process, the analysis will pick up a range of gases present, so the GC needs to be trained to prioritise the desired molecule. Costing upwards of AUD 80,000 each, the process takes 8 – 14 minutes for each statically captured sample. Consequently, it is not a viable contender for large scale commercial measurement, real time animal breath analysis.

Where the GC can be of value is to validate and calibrate mass produced sensors. The GC is unique in that it can accurately measure from as low as 10 ppm and up over 20,000 ppm. Arcoflex uses a NATA accredited lab to quality-assure each production batch with a GC using BOC reference gases [21]. Figure 12 shows Arcoflex working at Ektimo on sample sensor calibration run.

Figure 12 – Gas Chromatograph

6.2 Non-Dispersive Infrared Sensors (NDIR)

More commonly used for CO_2 and CO detection, NDIR spectroscopy sensors detect the decrease in transmitted infrared light which is in proportion to a gas concentration [22]. The technology can tune the frequency of the infrared light to specific molecules, thereby isolating interference from other gas contaminants. NDIR can also be used to detect multiple gases simultaneously.

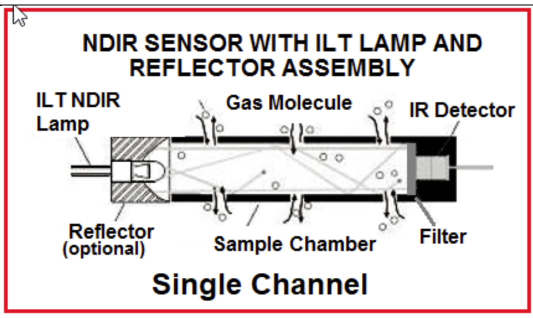

Figure 13 – NDIR Spectroscopy Gas Detection

Figure 14 – Gascard Guardian NH4 Sensor

This technology can be very accurate, above a minimum concentration (see below). Figures 13 and 14 show the internal structure and one very popular CH_4 sensor using this technology. When applied for the detection of methane, the chamber needs to be about 60 mm long with a wavelength of 1650 nm. At 1575 nm it can also detect CO_2. Properly tuned, it can detect CH_4 accurately, even in the presence of humidity, dust and CO_2; all contaminants found in animal breath. Edinburgh Sensors popularised this in the early 2000's by producing the Gascard Guardian NDIR CH_4 sensor. Widely used to measure methane, it was the sensor of choice for most white papers where methane measurement was required.

Until 2017, this sensor was the only reliable way to measure enteric methane but it has limitations:

- Air needs to be drawn into the sample chamber and filled before an accurate reading is possible. The unit provides a 6 mm tube for the purpose and it draws air through at 1 litre per minute, taking about 25 seconds to fill the chamber. Whilst this might be useful in a laboratory with a stable air volume mix, it is unlikely to be useful monitoring animal breath that rises and falls within 3-4 seconds. Consequently, it can only read averaged concentrations and is unable to assess peaks and troughs or assess methane pulse frequency. Most historical papers (see bibliography) rely on a modelled approach to computing methane so providing accurate direct measurement of methane became the principal driver for our methodology. Sampling tubes cannot work in a dairy.
- The 6 mm entry tube makes it difficult to position to capture quickly varying concentrations. Animal head movement prevents presenting the tiny opening to any reliable volume of breath.
- NDIR technology is only accurate above 1000 ppm. Between 800 ppm and 1000 ppm accuracy is marginal and we have been able to confirm this with a GC. It cannot detect anything below about 500 ppm and this is very limiting. The ranges we need to use are between 200 ppm and 500 ppm.
- NDIRs are moderately expensive – approximately $2000 when purchased at scale and no-one has yet devised a way to mount the inlet tubes to continually collect animal breath. Their use in Green Feed machines has not been historically successful.

In summary, NDIR sensors are not suitable for the direct analysis of enteric methane. At the time of writing, Chinese sensor makers are producing a range of NDIR CH_4 sensors that do not require the filling of an air chamber but they will still lack sensitivity below 1000 ppm. They have also not considered agricultural implementations. In other words, NDIR technology is unreliable for real time measurement of enteric CH4 with the appropriate accuracy and precision required for dairy cows in commercial settings.

6.3 Laser Spectroscopy with Tuneable Laser Diodes (TLD)

There are lasers produced for the gas industry designed to detect escaping plumes of gas but they are designed to read 10,000+ ppm from a steady flow and not from any distance. In a lab, they can be very accurate on a stable air mass sample but there is no scenario where a hand-held laser or drone-mounted laser can be used in the field or in a barn and effectively determine methane emissions. When considering normal air movement, convection currents, animal movement, weather and other factors, it is difficult to perceive how such devices might be used in agricultural scenarios. The units shown below cost between AUD 900 and AUD 3000 but are not manufactured in large numbers. They are not able to be used to detect agriculturally generated methane. To propose that drones might monitor a herd is fantasy.

Figure 15 – Laser Methane Measurers

6.4 Heated Electrode Sensors

The most common method for measuring alkanes is a small chamber holding heated electrodes coated with Tin Oxide (SnO_2). Air passing over the electrodes varies in conductivity with gas concentration and the resulting voltage change is measured. A typical handheld unit is shown below in Figure 16. The retail price for cheaper units starts at $700 but they do not have any data output capability and are deliberately tuned to 5000+ ppm. This renders them unfit to measure the low agriculturally generated values expected. Some models have a manually selectable low range (under 1000 ppm) but we have never been able to use them at concentrations below about 800 ppm. We took one commercial unit (see Figure 16) to Ektimo and could not use it effectively measure ppm levels below 1000 ppm. Further, it did not read as reliably as the Gascard Guardian units trialled at higher levels. The manufacturer was approached but declined to provide advice on our findings. The distributor refused to assist or comment.

Most hand-held units employ a heated electrode sensor. Whilst some models are suspected to use NDIR sensors they seldom disclose the internal sensor technology employed. However, the underlying heated electrode sensors are low in cost and available in large quantities, allowing the construction of cost-effective meters at scale.

Figure 16 – Typical Handheld Methane Sensor

7. The Arcoflex Methane Meter

The prior discussion shows that cost effective and accurate metering options at scale and for low methane concentrations are very limited. In response, Arcoflex has designed a sensor specifically tuned to the very low methane concentrations needed. This has been achieved using the heated electrode MQ-4 sensor from Winsen Electronic, China [13]. Winsen is a world leader in gas sensors and manufactures a wide range of sensors tuned to specific gases. Our challenge was to ensure that we could detect very low levels of methane with reasonable accuracy.

7.1 The MQ-4 Heated Electrode Sensor

As explained, Winsen Electronic is one of the more popular suppliers of heated electrode sensors for methane. When no methane is present, the MQ-4 sensor air gap has a very high natural resistance. As methane levels rise, that resistance falls instantly. Unlike NDIR sensors, there is no chamber to fill.

Figure 17 – Arcoflex Methane Sensor **ASCH401**

Air from the animal’s breath is passed directly over the heated electrode. The presence of specific gases increases the conductivity of the air gap, which is measured and compared with clean air resistance. Whilst the MQ-4 is an alkane detection sensor, its greatest sensitivity is to methane. However, cows do not exhale other alkanes and are not found in typical dairy scenarios. Winsen Electronic publishes a data sheet for gas calibration and detection purposes. Figure 18 demonstrates that sensor readings are very non-linear and this presents a challenge to meter designers. The lower two lines in the diagram on the left are of most

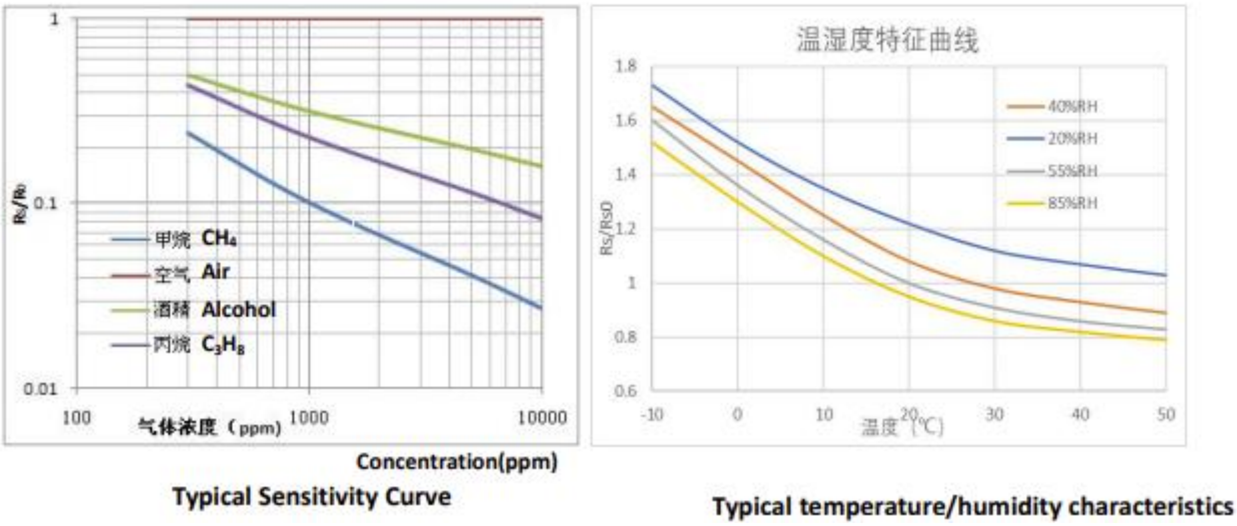

Figure 18 – MQ-4 Gas Calibration Curves

interest: propane (C_3H_8) and CH_4. Propane is a low-cost gas that can help us calibrate and validate sensors.

It is important to note is that the gas sensitivity curve is logarithmic, not linear. It is also reasonably low in general resolution, limiting overall accuracy. Software is required to convert voltages to parts per million (ppm). This chart also specifies the desired range over which the sensor must be tuned. Tuning for 5000+ ppm will not reliably detect 500 ppm and vice versa. Arcoflex tuned its sensor to be accurate in the range of 200 ppm to 1500 ppm and can detect as low as 50 ppm with reasonable certainty. Arcoflex confirmed the detection of 50 ppm using 100 ppm BOC reference gas and a gas chromatograph. One of the recent Ektimo-produced lab results comparing our finalised sensors with a gas chromatograph (GC) is presented in Figure 19. Formal evaluation statistics are available upon request.

There are several complexities that must be considered:

- The sensor manufacturing process is not precise. The degree of Tin Oxide (SnO_2) coating affects the measured voltage levels and so a load resistor matching the sensor's native resistance must be provided. Every sensor requires separate calibration - there is little commonality. Arcoflex does this in collaboration with manufacturer. Arcoflex specifies the desired manufactured load resistance and Winsen Electronic adjusts their construction process accordingly. This assists greatly with sensor consistency. Arcoflex has written software that causes continual self-calibration.
- The conversion is logarithmic but with three distinct gradients: one for below 1000 ppm, one to 5000 ppm and then another for above that. Variation of measured values is greatest below 1000 ppm so our calculation code must detect and apply the correct gradient, retaining sensitivity in the lowest range yet detecting and then adjusting for higher ranges.
- We ignore values over 5000 ppm. It is almost impossible for a cow to generate over 5000 ppm so we are comfortable with this limitation. It allows us to better tune for accuracy where we need it.
- The manufacturer advises that they cannot guarantee sensor sensitivity below 200 ppm. With the underlying sensor being low in cost, we test each unit and discard those that cannot achieve that low level of accuracy. In this way we have been able to devise a configuration that reliably measures down to 50 ppm, well beyond manufacturer expectations. As explained, this has been confirmed with gas chromatography. Laboratory testing procedures are presented in Annex D.
- The sensor must be fully heated if it is to report correctly. The manufacturer provides advice on how and when to use the sensors and when to conduct calibration tests. Arcoflex causes the sensor to heat continuously to allow for instantaneous readings at any time of day. We have no certainty of when an animal might approach a sensor so always-on is our only option.
- Calculation accuracy relies on knowing the supply voltage to the sensor. Arcoflex has provided an adjustable power source, accurate to +/-0.01V (0.2%).
- The derived voltage from the sensor is based on a ratio comparison with the clean air value. Every sensor is different so each one is measured independently by Arcoflex. It is the clean-air ratio that is important. To accommodate this, Arcoflex automatically recalibrates clean air resistance twice daily for every sensor until it falls outside the manufacturer's specified range. This compensates automatically for age drift. As of December 2024, sensors have lasted for almost three years without loss of sensitivity or detectable drift. This is good news for sensor maintenance purposes.
- The manufacturer has defined the expected sensor voltage range in clean air that constitutes correct operation. Arcoflex can therefore detect when a sensor should be considered defective and replaced. This is part of our standard maintenance regime.
- We have determined issues that relate to dairy design, especially for robotic or in-field feeders, the placement in TMR barns and for use with hydraulic lift herringbones. We have proven that in the absence of moving air, methane rises as it dissipates. Sensor placement is important for accurate measurement. Hydraulic lift feed bays presented us with explicit challenges.

The following table shows some of our earlier testing results at the Ektimo lab.

		Time	Reference gas concentration	Methane sensor result range		GC Result (ppm)	Methane sensor result (ppm)				
				Minimum	Maximum		Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5
First batch of sensors	Test 1 *	11:20	1000 ppm	700	1000	920	757	504	426	1824	1012
	Test 2	11:36		850	900	955	910	902	514	853	860
	Test 3	11:43		600	900	947	1041	489	700	984	926
	Test 4	11:54		700	1000	996	1041	522	680	975	935
First batch of sensors	Test 1	12:54	100 ppm	130	150	85	153	152	157	130	129
	Test 2	13:05		116	140	88	136	131	142	120	116
	Test 3	13:16		120	148	84	139	133	148	125	120
Second batch of sensors	Test 1	12:16	1000 ppm	700	900	955	809	842	829	913	738
	Test 2	12:29		900	1000	950	987	866	997	1061	913
	Test 3	12:41		930	1090	901	1156	998	1161	997	927

* Insufficient warm up time allowed

Figure 19 – Sensor to GC Calibration Comparison Table

It should be noted that we are attempting to compare air trapped in a small container with air expelled from an animal's mouth. The purpose of the lab test is to use a relatively stable air mass (the container was not airtight) to assess how well the Arcoflex sensor matched the GC. What these tests did show was a reasonable degree of accuracy with a high degree of confidence. Our sensors will never reach the accuracy of a GC but the agricultural nature of data collection implies that it is not necessary. The aim has been to achieve statistically relevant values.

7.2 Sensor Circuitry

Confirming earlier discussion, when no methane is present, the air gap in the MQ-4 sensor has a very high natural resistance (Figure 17). As methane levels rise, the heated air gap of the MQ-4 sensor develops increasing conductivity. This manifests as a non-linear reducing voltage drop across the load resistor (R_L). The choice of load resistor is crucial to sensor sensitivity and must match the natural internal sensor resistance. The manufacturer sorts sensors into three broad batches so that users can apply appropriate load resistors with which to produce the required conversion curves.

The manufacturer provides the charts (Fig. 15) which define these three sensitivity ranges. Although the lines look similar, they are not because they are logarithmic. The margin for error does rise below 200 ppm but can be accommodated. This is our range of interest. The Arcoflex implementation is based on the following electrical characteristics:

- A very accurate 5V supply (+/- 0.01V).
- MQ-4 sensors with a load resistance matched for 10kΩ.
- Clean air voltage measurements in the valid range of 0.3V to 0.9V.
- Two conversion options: one for below 1000 ppm and one up to 5000 ppm.
- Above 5000 ppm we simply assume 'too high'. If such readings are detected the animal is in extreme distress and must be isolated quickly. Such high readings should be rare.
- As shown in Annex D and with charts above, our sensor maintains a high degree of accuracy from 50 ppm to 1500 ppm – the range of most relevance. Readings up to and over the range of 3000 ppm indicate sick animals that should be isolated. At that level, feed supplements have little effect so the recording accuracy is not as relevant.
- As stated in several places, the important measuring range for compassion is 400 ppm to 1500 ppm. If methane levels are to halve then this is accuracy to 200 ppm is essential.
- Arcoflex has achieved these low levels of detection and proven it in an independent laboratory.

A significant feature of our design is a reliable and constantly-heating circuit so that the sensors are always sufficiently sensitive. If the heater circuit fails, readings are invalid. Arcoflex monitors this and automated alerts are triggered when heater failure or power loss occurs.

7.3 Sensor Sensitivity

One challenge for a commercial methane meter designer is to understand the desired end-user range of interest. Arcoflex is mostly interested from 100 ppm to 1500 ppm and has optimised circuitry accordingly. This makes comparisons with handheld testing instruments a challenge because such instruments cannot switch ranges automatically, making it difficult to determine accuracy or reading relevance. As Arcoflex has decided to restrict its interest to the very low ranges of measurement, handheld meters cannot assist.


Figure 20 – Sensors in the Field and Sensors Under Construction

This is why gas chromatographs were used to verify our results. See Annex D.

Another challenge was to ensure that sensors did not lose sensitivity in the field. The main worry, with the sensor only millimetres from the animal’s mouth, was clogging from saliva and dust. To monitor this, all sensors are assessed daily against their peers and their 14-day average. Any sensor displaying loss of sensitivity is identified for replacement. Any sensor that cannot retain the manufacturer’s recommended operating voltage is also replaced. Arcoflex monitors both metrics.

Farmers are given a brush with which to give the sensors a pre-emptive clean, otherwise, six monthly brushes are recommended. In three years of operation, this has so far been adequate.

7.4 Sensor and Cowl Placement

One of important lessons learned in 2024 was how animal trapped breath mattered. The initial design had us bolt the cowl tightly to the back of the feed bay. What concerned us was that when the animal breathed into the cowl there was back pressure (the cowl was “full”) and most additional breath flowed out and around the cowl. We tried a range of aerodynamic options such as slots in the cowl housing, but we found that by lifting the cowl just 5m off the back of the feed bay (using washers and nuts) allowed more air to flow into the cowl for longer. This potentially overcame encrusting (saliva coating) and infill due to molasses feeds. We monitored this specific change over several days.

Lifting the cowl just this little amount led to better outcomes, increased sensor life and better detection of eructation pulses. This is now our standard installation configuration.

7.5 Sensor Construction and Age

Arcoflex relies on the manufacturing quality of Winsen Electronic but challenges arise from the sensor manufacturing process. The layering depth of Tin Oxide (SnO_2) on sensor electrodes cannot be made consistently. This means that every sensor will measure differently. Fortunately, regardless of the coating depth, resulting electrical characteristics are completely predictable. The implication though is that each sensor must be calibrated individually. A further complexity is ensuring constant heater current provision and knowing when to cancel readings from a break in the heater current supply.

Desensitisation with age was discussed earlier. Arcoflex accommodates this with its daily autonomous recalibration. This recalibration compensates for sensor degradation by using the manufacturer's charts for ppm conversions. The life of the sensor is rated at 10 years but they have not yet been used continuously anywhere for that duration so exact life expectancy is conjecture. Our sensors have been operating now for over 36 months and not yet shown any signs of losing sensitivity. Our plan is to suggest a six-monthly regimen of giving the sensors a light brush but paying close attention to the daily sensor sensitivity report.

7.6 Ambience Factors

Another challenge for the commercial methane meter designer is to consider the need to compensate for dust, smoke, temperature and humidity. Operating variations in temperature and humidity impose their own non-linear impact, as show in Figure 18. The common dairy environment in Tasmania, Australia would be 10°C – 25°C at an RH of 55% but in Queensland Australia this is more likely to be 25-30°C and 70% RH. This might imply that a morning milking in Tasmania might have higher sensitivity compared with afternoons in Queensland or that we might see a summer to winter variation. Should there be different profiles for Queensland dairies compared with Tasmania? Whilst we can discount smoke and dust, the cow's breath is warm and humid and is consistent. Because we are measuring breath at the point of escape from the mouth, we are in fact measuring at a consistent temperature and humidity and do not need to compensate. This is another reason for needing instantaneous readings. Concentration decays quickly.

7.7 Long Term Sensor Stability

Winsen Electronics provides detailed advice on how to care for and manage the sensor. None of the more corrosive items discussed are found routinely in dairies but the sensor does degrade with age. The manufacturer suggests a 7% reduction in sensitivity after about 6 years (see Figure 21), but then is stable for another 4 years. Our daily recalibration in clean air will compensate but a replacement cycle should be considered as part of a monitoring maintenance program. This chart shows very good stability with age.

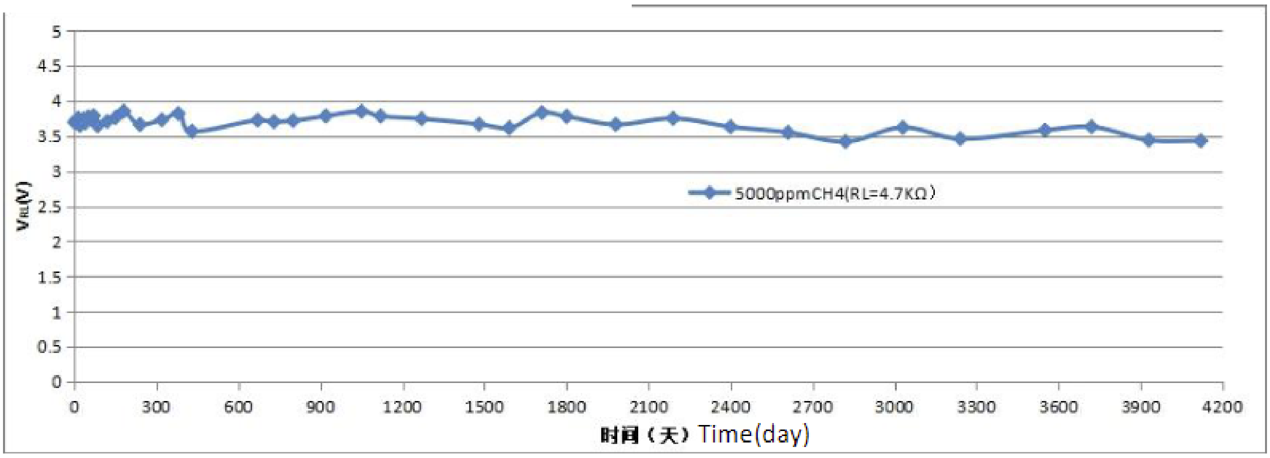

Figure 21 - Sensor Degradation with Age

7.8 Sensor Response Time

An important attribute when using a sensor is how fast the sensor can respond to gas presence and then detect any residual persistence once the gas source is removed. Figure 18, sourced from Winsen Electronic, demonstrates this. It suggests that 3 seconds is the longest time it should take to register a new value and that CH_4 dissipates within 8 seconds. In practice we find that it only takes about half this time for both. As mentioned above, NDIR sensors need much more time with a stable gas concentration to read accurately. A normal cow breathing pattern will not provide that.

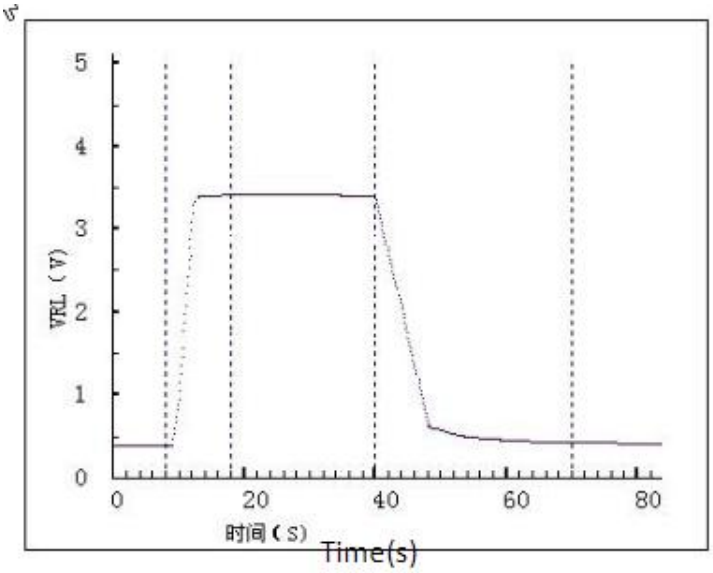

Figure 22 - Sensor Responsiveness

As we need only 1-2 seconds for the sensor to register gas present, we have provided a cowl to temporarily trap the breath for the sensor to read. The downside is that it can take twice as long to disperse but the return to fully clean air will still usually occur within 10 seconds. Our goal is to capture just one significant breath over the 9-15 minutes of milking time and resolve methane levels quickly. Figure 23 represents a different collection of animals considered to be very healthy. It demonstrates how quickly methane dissipates, proving there is no cross-contamination.

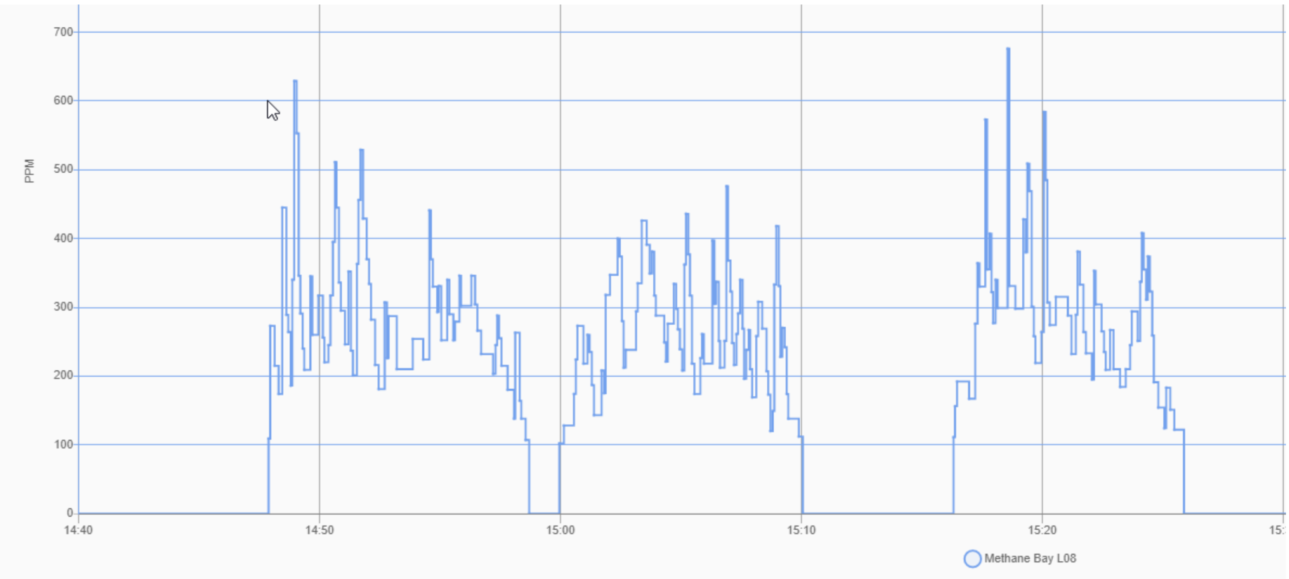

Figure 23. Sensor Replay for three Animals

Arcoflex sensors read methane levels 2-3 times per second, reporting the highest reading found over eight seconds. Whilst the cow is feeding on supplied pellets, it is breathing directly into our sensor. We can easily detect animal changeover, when a bay has been excluded and how the cow behaves in the stall. Every reading is coded with the animal's NLIS ID so that we can profile the herd or specific animals.

7.9 Methane Sensor Calibration

Arcoflex has developed a two-stage manufacturing process. All sensors undergo local test verification and calibration, rejecting all sensors that exhibit inadequate properties. A sample from each batch is taken to a commercial NATA accredited laboratory [6] for independent calibration assessment. Some of tooling used for pre-calibration is shown in Figure 24.

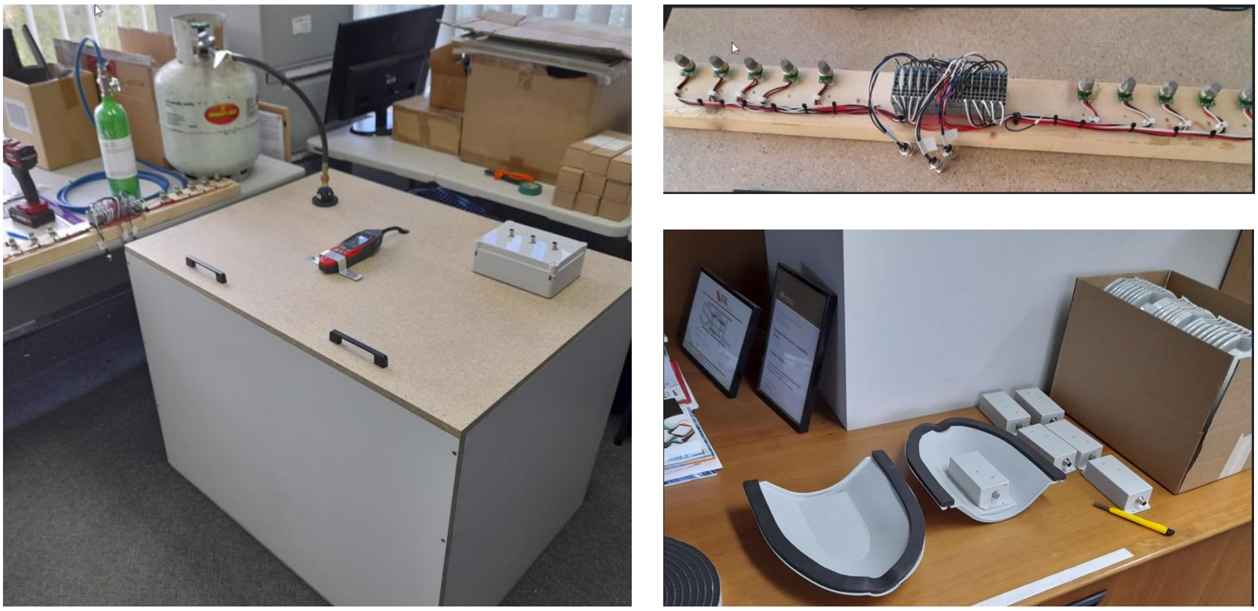

Figure 24 - Calibration Fume Cupboard and Test Rig

- A locally designed fume cupboard is used to house multiple sensors in a stable concentration for a few minutes. A group of these sensors will be put through this process so that they can be used as a calibration baseline for the others (using their clean-air ratio).
- A handheld meter (or a Gascard Guardian) is used to validate our calibration and isolate sensors that do not fit appropriate specifications. Unfortunately, these devices can only be used at higher concentrations for methane (greater than 1000 ppm). Confirmation of the low range still requires the use of a gas chromatograph and reference gases. This is being carried out at Ektimo labs.
- Certified BOC reference gas (0.1% methane) is used to confirm manufacturer curves for each batch of sensors. A chart of measured levels will be recorded and compared to the data sheet.
- The process will cull sensors that do not meet minimum sensitivity requirements. Propane can be used for this stage because it is much cheaper than bottled methane and exhibits lower sensitivity with the MQ-4. Unacceptable sensors are destroyed before the final lab testing step.
- Any sensors found to exhibit very high accuracy will be kept aside as reference candidates to speed up future calibrations. It will help identify unwanted manufacturer variances prior to lab testing.

Once this local testing process is completed, sample batches are taken to Ektimo in Mitcham [6] for formal testing with gas chromatography. See Annex D for some examples.

8. Methane Capture Methodology - Dairies

The University of Wageningen has substantial research on where and how to record animal methane concentrations [16]. We have based our cowl and placement on similar principles. One of the key findings of this Wageningen paper is that regardless of placement, there is a linear correlation to actual densities. In summary, we have been able to validate our measurements in parallel with Wageningen research.

8.1 Sensor and Cowl Placement

The only valid location for measuring methane from an animal is near its mouth. The challenge was to place the sensor close enough to capture breath yet not get coated with saliva or otherwise contaminated. Initial placement of meters in the feeding stalls caused the animals significant stress. Once in place they could not be moved and it took time for the animals to settle down and ignore the cowls. For sensor placement, materials chosen needed to very neutral in appearance and smell. Monitoring a subset of the herd was ruled out because every cow must be presented with the same feeding experience and same environmental layout. Arcoflex has concluded that a discrete sensor, at the place of feeding for every animal, is required. See Figure 25. Once the cow ignores the sensor, genuine readings will be captured. The methodology offers the possibility of similar systems for TMR barns, robot milkers and in-field feeders.

Even so, cows look up, sniff around and do not always exhale downward. This is why specific single readings are not used. There needs to be a pattern of readings to make sure we capture the eructation pulses. Even one is enough because standard biology can be reliably used to model the rest. Methane data must be collected in real time and stored for permanent recall for aggregation calculations and auditing purposes. Based on several of the white papers cited, we needed to find a practical way to capture and compare methane emissions from animal breath with the following characteristics:

- Capture needs to take place at the same time each day.
- Capture needs to take place at the same part of the feeding cycle.
- Capture needs to take place sheltered from other animals and local air movement.
- Capture needs to accommodate the animal’s natural breathing/eating process.
- Capture needs to be associated with an RFID or other unique number.
- The animal must not be under any duress or stress and in good health.
- Sensors must be calibrated to the expected normal range for ruminant breath.

Fortunately, all standard dairy configurations offer suitable monitoring options.

Cows are nervous and intemperate by nature. Several unsuccessful configurations were trialled before finding that placing our sensor just above where the cows munch on their dry feed supplement was ideal. The position of the sensor is critical: too close to the mouth and it becomes clogged with saliva and husk, too far back and sensitivity is lost. We discovered the best position where methane lingers just long enough

Figure 25. The Arcoflex Methane Capture Methodlogy

for our sensors to gain a valid reading yet dissipates within a few seconds, ready for the next cow or next breath is from 60 – 100 mm. In this way, we have managed to accurately capture CH_4, breath-by-breath.

A refinement developed in 2024 was to space the cowl 5mm of the feed-bay walls and dispense with the padding. Our original model had them fixed down hard but this later revision allowed for better breath capture. The greater flow gave us more and longer readings. We believe that this is because an enclosed space would pressurise slightly with each new breath, thus losing the latter half of each breath. This refinement did not change reading accuracy but gave us greater flow over the sensor. In other words, greater resilience to clogging and longer durations to analyse the gasses.

It takes 2-3 days for a herd to accept new devices but they do learn to ignore them. This is one reason every bay must be fitted with a sensor. An unusual bay will be resisted, causing trouble for milking staff. It was important to ensure that the animals behave and respire naturally, to gain consistent and valid readings. Distracted animals look up and around and do not breath into the sensor cowls. This has been learned by hard experience. Failed feed drops will also contribute to failed readings, causing the cows to become angry, furtive and distracted. They would often then try to eat their neighbour's feed.

8.2 Methane Capture Methodologies

The University of Wageningen has done substantial research on where and how to record animal methane concentrations [16]. We have based our cowl and placement on similar principles. One of the key findings of this Wageningen paper is that regardless of the placement, there is a linear correlation with actual densities. The Wageningen research is not, unfortunately, based on credible sensors.

8.3 Baseline Calculations

Before dietary changes or feed interventions are introduced, it is important to establish current methane and milk production levels. This is done by assessing animals over at least an eight-week period, bearing in mind the natural seasonal variations as discussed earlier. These are specified in VERRA standards [31]. The most important calculations include herd average, number of high methane animals, average CO2E, animal age, stage of pregnancy and basic animal health. An example of standard Arcoflex animal profiling is presented in Annex A. Arcoflex has been profiling this data for over three years.

8.4 Natural Modifiers to the Methane Cycle

Methane production follows a natural daily cycle, based on when the animal presents itself to the dairy for milking. However, there are a significant range of factors, all affecting the rumen and hence, the methane cycle. The following external factors need to be closely monitored when considering baselines and trials. All these impacts have been strongly visible in all trials to date:

- **Pasture changes** – the simple change of grass type can alter methane levels up to 40% in most animals. The farmer must constantly advise of pasture usage throughout a trial. The effect on the rumen is usually transitory but it will be important to avoid such changes at critical monitoring points in any trial or baseline calculations. Any such effects have been shown to last up to a week.
- **Animal health** – this is vital to understanding rumen efficiency. An animal with worms or other digestive ailments will exhibit higher methane output. Crucially, this is an important indicator for farm staff. Early detection of health problems preserves milk capacity and reduces contagion risk.
- **Pregnancy Cycle** – this is important as every animal is different and should be assessed against the herd average. Pregnancy cycle matters when assessing feed conversion ratios.
- **Feed Supplements** – Perhaps the most contentious modifier. Feed supplements are designed to achieve an impact so the date of commencement, dosage and manner of delivery are important to record and assess. Some supplements exhibit persistence and some do not.
- **Time of Year** – grass grows in cycles and has a seasonal impact on methane output. With any trial, time-of-year influences on pasture are relevant. This is a critical variable that must be considered.
- **Weather Events** – excessive rain or hot waves [28] have a measurable impact on daily readings. This is why the shorter the trial duration, the riskier the assessment becomes. We track the Heat Stress Index as an indicator to milk production efficiency and methane output.

8.5 On Farm Methane Sensor Calibration

Once sensors have been installed, it is important to continually assess sensor accuracy and operation. To achieve this, Arcoflex has developed an extensive but fully automated on-site calibration process. Briefly, it involves twice daily clean-air assessments and voltage level adjustments. Along with daily exception reporting, all sensors are assessed and adjustment for sensitivity. The full process is explained in Annex B.

Once in place, methane delivery was found to be of a very consistent pattern. Figure 26 shows the methane peaks for a one-hour period. Cow changeover is very clear every 11 minutes. From this, we are certain that there is no residual methane carry-over from animal to animal as it dissipates within seconds. This process will be linked with an animal identifier so that specific animals can be profiled:

- If an animal refuses to enter a specific bay, the readings go to zero. The animal count will be adjusted to compensate. This can only happen in rotaries and needs to be accommodated.
- If a sensor gets clogged or malfunctions, it can be discounted from the methane total yet still have the cow contribute to supplement and milk totals. Such sensors are identified in the sensor sensitivity report which is processed daily across all sites. Farmers are required to manage this.

The methane recording system accumulates every possible value for each cow but mostly, we are looking for the largest peak in the 11–14-minute cycle. These are used to develop herd averages for baseline comparison. Issues such as deliberate platform stoppages or delays will not have any effect on the outcome. Average values cannot and must not be used (see below). The peak identifies the highest concentration found in the rumen for that 12-minute cycle, thereby allowing for accurate biological modelling. With RFID tagged data we can isolate specific animals for genetic or phenomic research. A farmer may wish to retire poor performing animal sooner and so improve his overall herd carbon profile.

A short note about averages. Usage of time-based averaging or geometric means to analyse methane data would be mathematically incorrect. We can only capture breath when the cow chooses to breathe into the sensor. Distracted or stressed animals offer less breath opportunities. Cows concentrate on their feed and each one is fed a different quantity of rations. This means that we might see deliberately less breathing directed at the sensor and this cannot be mistaken for lower methane. Remember too that the rumen does not inject methane into every breath. Only one or two breaths per minute contain the eructation pulse of methane. This is why averaging of any kind cannot be applied.

8.6 Comparison Metrics for Carbon Audits

Once methane is measured, how do we find a number to use in baseline data for each site? Raw methane values are not helpful because each animal behaves differently at each milking session. Instead, we need to compute herd averages. All animals are inspected and averaged to accommodate health, environment, feed and other variable factors. Further, there are the seasonal and weather-related variables to consider.

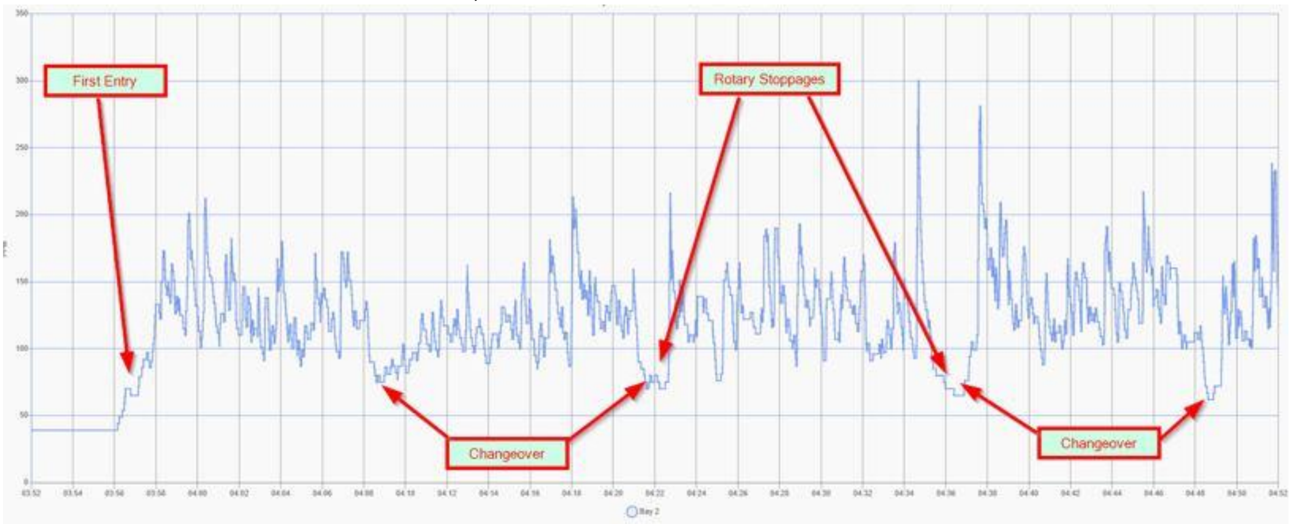

Figure 26 - Animal Breathing Pattern

What Arcoflex does is compute tonnes CO2E per year per animal and develops a herd average for comparison purposes. This will assist deriving tonnes of abatement. The calculations are complex but avoid modelling. Please see Annex C for details.

8.7 PPM and g/Cow/Day

One of the significant challenges we face is being able to compare our results with other white papers on the subject. Our contention is that ppm is an absolute and measurable metric. If a supplement or methodology results in halved ppm then it has reduced the CO2E loading by half. The question becomes: what is that metric. We like ppm because we can measure it directly. g/cow/day must involve either explicit cow physical measurement or modelling.

For example, 4.5 tonnes CO2E per year equals 12,300g per cow per day. Which metric is useful.

9. Methane Capture Methodology – Loafing Barns and Feedlots

The rise of feedlot and loafing barn sites present new opportunities to measure methane levels 24 hrs of the day. Whilst perhaps not as consistent as dairy data, it would still provide an important validation for feed supplement efficacy calculations. There are several opportunities:

Figure 27. Alternate Monitoring Positions

- Watering troughs offer a sheltered location to mount sensors.
- Portable feed bins offer a similar opportunity when sensors can be hidden.
- Portable feed bins and troughs can be used with sheep, beef cattle and goats.
- Robotic milkers offer obvious mounting points for sensors.

The expectation is that there are viable monitoring points with such animal scenarios but little research has been conducted to validate expected outcomes. An area ripe for further investigation.

10. Conclusion

The world is trying to move to a more carbon neutral future and agriculture takes centre-stage as one of the key contributors to carbon abatement regimes. Measuring enteric methane has been a significant challenge for the industry and an appropriate methodology has eluded the world until now. Arcoflex, in conjunction with Farming the Sky (FtS), has evolved the world's only commercially viable methane monitoring methodology and stands ready to assist the industry to achieve its low carbon targets.

Our methodology allows for methane assessments to move from one of modelling to one of empirical data measurement. All source data will be accessible for slicing and dicing to suit any data interest. Our approach is not based on modelling but direct measurement. We have found the most appropriate sensor and methodology for measure enteric methane in an agricultural setting. This is unique and game changing. This solution not only assesses carbon-reducing feed supplement efficacy but it is also the only solution capable of providing ongoing monitoring for low carbon regime audits. Arcoflex and FtS are here to help create and protect the low-carbon, sustainable future for dairies and cattle.

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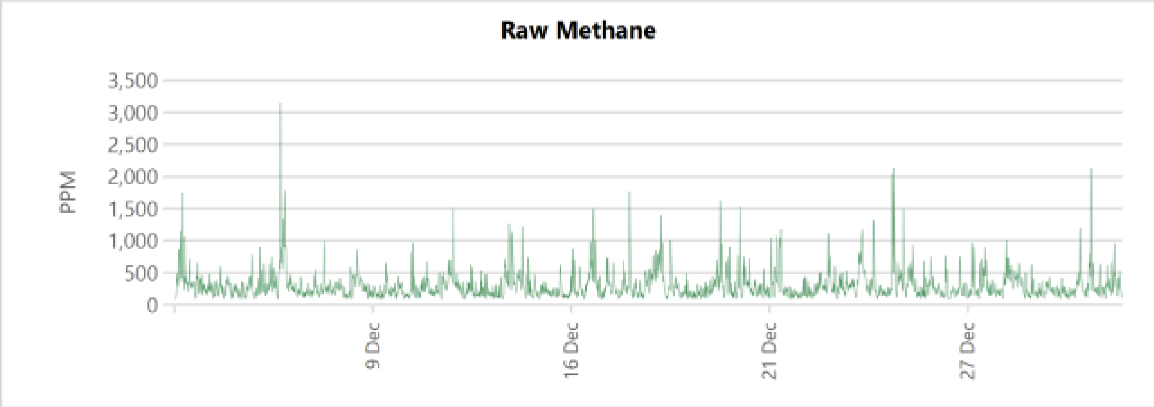
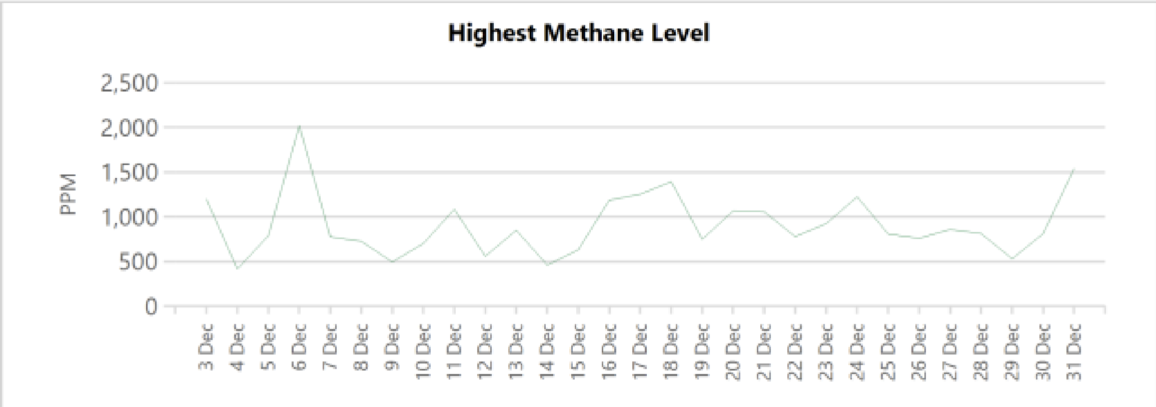
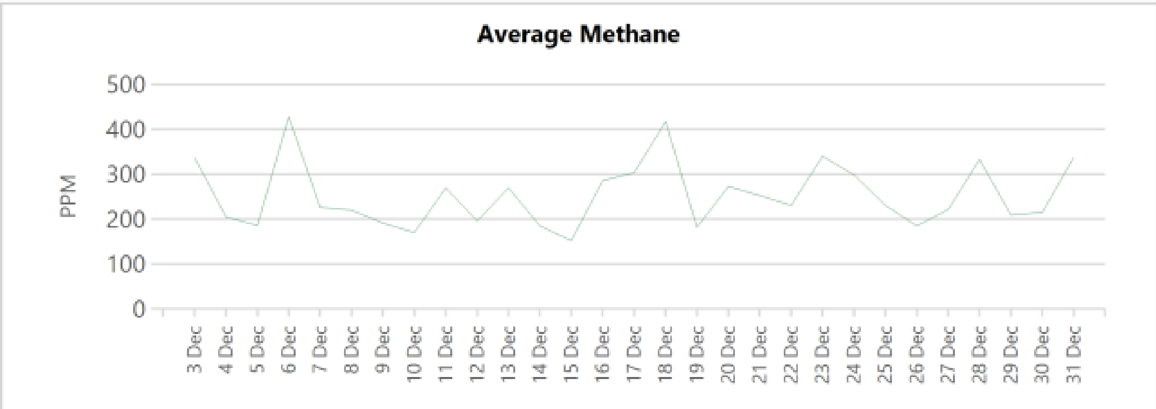
Annex A – Animal Profiling Example

Cow Profile for ID: 982 [redacted]

From: 03/12/2023 To: 31/12/2023 Site: [redacted]

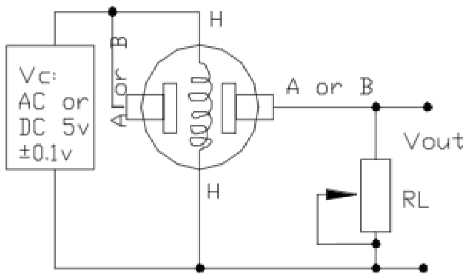






Annex B - On Farm Methane Sensor Calibration

The calculation of precise methane values is not difficult but relies on consistent electrical circuitry. Here is the standard circuit of the Arcoflex sensor and the key attributes involved:



- V_C – the known voltage applied across the sensor.
- R_S – the resistance of the sensor.
- R_0 – the resistance of the sensor in clean air.
- R_L – the load resistance the output voltage is developed against.

Figure B1: Sensor Circuit

B1 The Voltage Supply V_C

The manufacturer has a very strict supply range requirement for the sensor. If it is too high, it will damage the Tin Oxide coating. In our case, it is also the basis for methane calculation accuracy. To this end, a small voltage regulator is provided with each sensor and tuned to exactly 5.0V DC. Our tolerance is +/- 0.01V (not just +/- 0.1V) and this represents a final tolerance of less than 0.2%.

B2 The Load Resistor R_L

The value of the load resistor is vital to correct sensor operation but not important to calculation accuracy. The supplied gas curves from the manufacturer are drawn as a ratio of R_0 to R_S. Arcoflex computes R_Z from the known values of R_L and V_C. We can measure the load resistor (of 10kΩ) to +/- 10Ω. This is a tolerance of less than 0.1%. The conclusion is that the value of the load resistor to net sensor inaccuracy is also small.

B3 Sensor Resistance in Clean Air R_0

Clean air resistance is the most variable aspect of the calculation for gas density. The charts convert R_S/R_0 as a logarithmic ratio to parts per million. The manufacturer provided us with calculations that we could automate. We need to compute this on site in real time:

$$log(Y) - log(Y_1) = \frac{log(Y_2) - log(Y_1)}{log(X_2) - log(X_3)}(log(X) - log(X_1))$$

Using $R_S/R_0 = 1$ and PPM = 1000 and the $R_S/R_Z = 0.58$ for ppm = 5000, the formula simplifies to:

$$PPM = 1000(\frac{R_S}{R_0})^{-2.95}$$

Using the example shown, we have determined that the there are three distinct ratio slopes in different ppm ranges, each with differing degrees of accuracy. Our version of this formula prioritises the range between 200 ppm and 1000 ppm. If we detect a number near the high end of the range, we use a different gradient that is more sensitive for 1000 ppm to 3000 ppm.

To compensate for expected age drift, we recompute R_0 every day at 11.00am and 11.00pm, when there is no methane present. If methane is detected, the calibration is aborted and will be retried later. Every sensor is compared daily with its peers to make sure that we detect errant sensors quickly.

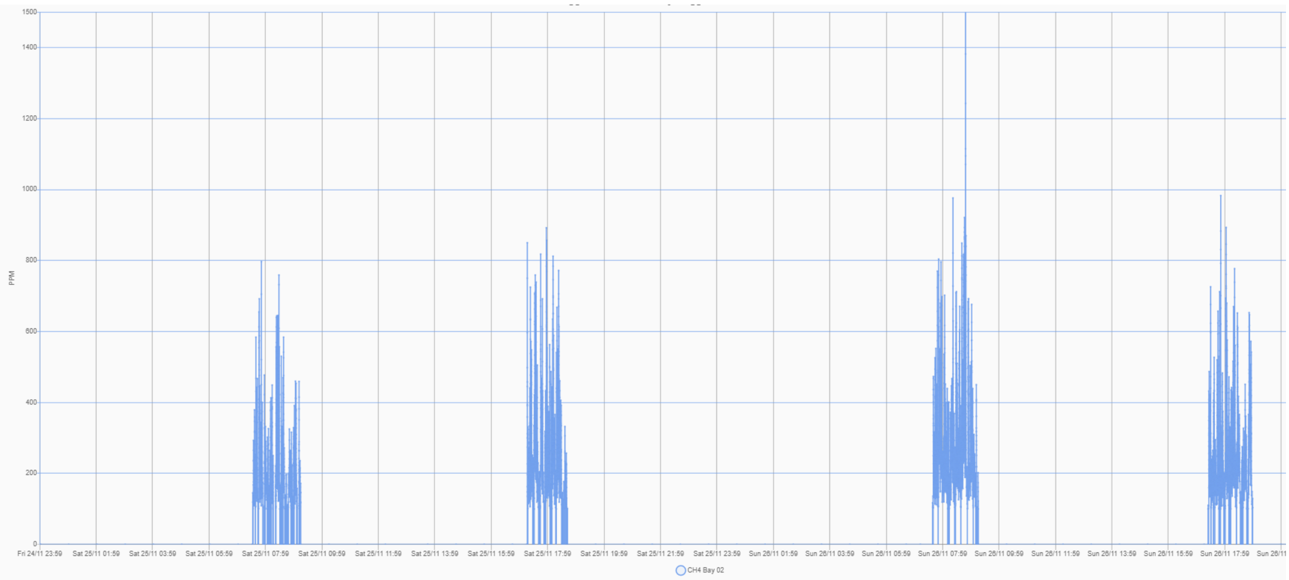


Figure B2. Methane Presence Chart

The sensor works by measuring the voltage drop across the load. By knowing the supply voltage and load resistance, the sensor resistance can be determined. From the recorded R_S/R_0 ratio, we compute ppm but we achieve much here. Here is the summary:

- The sensors are supplied with a highly accurate V_C of 5.0V DC, +/- 0.01 V.
- The sensors are provided with accurately known load resistors (+/- 10Ω) for ppm calculations.
- Our testing rig allows us to remove the heater circuit, allowing us to measure the native sensor resistance when cold and then measure that resistance as the sensor warms up. This will help us determine the minimum heating time required for correct sensor operation.
- We will be able to measure sensor response times, relative to temperature.
- We will be able to measure the ppm response for Propane and Methane and verify manufacturer charts. These charts are logarithmic in nature but are not of high quality. Whilst our components may be +/- 0.1%, provided charts do not offer accuracy more than +/- 5%. We will work with the manufacturer on greater quality but at the end of the day, the cows do not ‘cooperate’ directly.

B4 Sensor Sensitivity Resolution

Using manufacturer charts, it is possible to assess how accurate we can expect to be for a given clean air voltage detected. This has two purposes: (1) to assess how accurate each measuring range can be, and (2) to help determine when a sensor passes outside acceptable measuring parameters. Empirical testing has resulted in the table show in Figure 24 below.

By designing circuitry appropriately, we found that we can influence detection accuracy. Widening V_0 range appears to offer greater granularity but the nature of the logarithmic curve is such that it reduced sensitivity. It flattens the curve, reducing overall sensitivity. Whilst this seems counterintuitive, our experiments confirmed that the 0.3V to 1V range was the most appropriate and has been developed in cooperation with Winsen Electronic.

Vo (Clean Air)	Resolution Target			
	1 ppm	5 ppm	10 ppm	20 ppm
0.3V – 1V	0 – 2,000 ppm	0 – 5,000 ppm	0 – 9,000 ppm	0 – 10,000 ppm
0.3V – 2V	0 – 1,000 ppm	0 – 3,000 ppm	0 – 5,000 ppm	0 – 8,000 ppm

Figure B3. Methane Resolutions Possible

The consequence of higher accuracy is a lower upper limit for accurate detection. We discovered that we could increase low level accuracy at some expense to accuracy above 3000 ppm Remembering that the usual range of methane for healthy cows is from 400 – 1500 ppm, it was important to concentrate on these lower ranges for higher accuracy.

For example, using a V_o range of 0.3 – 2V we can achieve an accuracy of 1 ppm but only for below 1000 ppm. This is considered completely acceptable when you take into the account the natural variability of animal breathing patterns and the manner of collection.

B5 Scientific Validation and Sensor Uncertainty

Whilst we have confidence in our measurements, it was appropriate to seek external validation. To test our measurements, we engaged the services of a NATAA accredited lab (Ektimo) [21]. We needed an assessment of our sensor measuring capability. Using reference gases and a tuned gas chromatograph, the staff at Ektimo verified our measuring capability. In assessing a small range of sensors, Ektimo was able to offer the following conclusion:

"When calculated per sensor, the numbers provided give an indicative ***standard relative uncertainty of 8-12%*** *for the precision. If we want an expanded value (standard deviation covers 68% of cases, expanded covers 95%), we will double it to get an* ***expanded relative uncertainty of 16-24%.*** *The typical thing to do in this case is to take the worst-case sensor, 24%, as it is inclusive of all other sensors with lower uncertainties/higher precision. This suggests that applying the same conditions to a sensor should give repeat readings that fall within ±24% of each other 95 times out of 100. Our sensors will be able to identify the difference between 100 ppm (range would be ~75-125 ppm), 1000 ppm (range would be ~750-1250 ppm), and 3000 ppm (range would be ~2250-3750 ppm)."*

This degree of certainty and margin for error is entirely acceptable. We are dealing with animals and a wide range of variables and we're averaging 100's of animals to produce the farms herd value. We are easily able to detect change and that is the purpose of the exercise.

Over time we will provide ever increasing numbers of sensors to assess. We will be able to reduce the margin of error and increase certainty but even at these levels, the results are very encouraging. Given we are measuring animal breath in highly variable circumstances, to achieve this level of accuracy is pleasing. No other published study boasts this degree of accuracy.

Annex C – Computing Net CO2E from CH_4 Monitoring

Methane is delivered in eructation pulses: it builds up and then releases. There is not a consistent concentration per breath and in-between breaths (from the lungs) do not contribute methane – just the usual CO2 and O2. This makes the calculation of a precise amount methane quite difficult because we need to try to assess the regular amount of methane from the total breath output from the animal. Our aim is to reduce the amount of modelling so that we arrive at a values-based outcome.

Step 1 – The Weight of Methane.

The molecular mass of methane is well-known [1]: **16.04 g/mol**. This is computed by adding up the atomic mass of each atom in the molecule. One cubic metre of methane at 25°C weighs 0.657kg but we are not talking about pure methane, rather, a concentration in air.

This rises to about 0.717kg at 0°C so it is easy to compute an adjustment for temperature if required. However, as we are talking about quickly cooling animal breath, which starts at 38°C, so the number at 25°C is a reasonable one to choose. This is the weight of pure methane, not what the animal eructates. For our purposes, we have chosen this as a static number in calculations.

Step 2 – The Weight of Methane at the Measured Concentration

A cow respiring normally, exhales air from its lungs, containing a measured concentration of methane. There is a simple, straight-line calculation to convert PPM to mg/m^3 as follows:

Concentration (mg/m^3) = concentration (ppm) x molecular weight / 24.45 [15]
…where 24.45 = molar volume of air in litres at 1 atmosphere and 25C [14]

So, for example: at 600 ppm, there are 393.6 mg per cubic metres of exhaled air.
at 1200 ppm, there are 787.2 mg per cubic metres of exhaled air.

This formula is used in our calculations.

Step 3 – How Much Air Does a Cow Exhale

- Eructation, as previously discussed, comes in waves as not every breath is laced with the same amount of methane. Much of this is to do with the biology and physiology of the animal but we find some animals emit higher counts of eructation than others. Because we are looking for change, the absolute value is less of significance than choosing a base marker from which to assess change. Precise calculations and justifications of CO2E will come from the scientists but we will base our calculations on these directly measured PPM values. This appears reasonable and results in CO2E values sufficiently near those estimated in the referenced papers.
- Lung size and respiration rates vary from reference to reference. We based our calculations on an article in Canadian Cattlemen (2016) because it represents the middle ground [16]:
    - Average lung size is **12.5 litres** (12-13 cited most often).
    - Respiration rates are estimated at **30 breaths per minute [26]**.
    - This computes as 43,200 breaths per day or **15.78 million** breaths per year.
    - This figure assumes a healthy cow of an average physical size of 400-450 kg.
    - An animal that must walk up a hill to milk will breathe harder and with less eructation.
    - As with humans, we assume only **80%** of their total lung capacity is exhaled.
    - Weather has a significant impact on respiration rates as you would expect.

Some of the assertions of the Wageningen paper [17] involve the placement of bulky sensors and small tubes in places our experience with dairies suggests may not be optimal. What we can agree with is placement near the mouth in the dairy scenario. This is critical to the reliable capture for measurable readings. Whether this translates to *Greenfeed* [18] devices or barns is a different subject.

To summarise: **80% x 15.78 million breaths x 12.5 litres = 157,800** cubic metres of air per year

Step 4 – Compute the CO2E for Each Cow

Accepting the metrics above, we can now derive the final calculation for CO2E. We have mg/m^3 at each concentration and the number of breaths and we are assuming the Global Warming Potential (GWP) of methane as **28 times** that of CO2.

This number is controversial and is sometimes cited as high as 35. The consequence for calculation outcomes is dramatic. We are working from contemporary articles in National Geographic (2019) [19] and The U.S. Environmental Protection Authority [20], both of which choose 28.

We can now compute annual per-cow values at different concentrations:

Concentration (ppm)	Density (mg/m^3)	Methane (tonnes)	CO2E (tonnes)
100	65.6	0.01035	0.29
300	196.8	0.03106	0.87
600	393.6	0.06211	1.74
900	590.4	0.09316	2.61
1200	787.2	0.12422	3.48
1500	984.0	0.15523	4.35

Step 5 – Assessing the Model

The final phase is to assess what a "normal" animal is. Typically, the herds we are watching tend to yield around a 600 – 900 ppm range. Specific animals go up over 2000 ppm and some sick animals throw readings as high as 4000 ppm. The longer an animal is sick the more methane she will throw.

Armed with these metrics, you can see how cow size, lung capacity, health and respiration rate can dramatically affect these calculations. There will be a further difference for pasture fed vs barn vs supplemented feeding. Calves vs cows and large varieties vs smaller ones are also complicating factors.

Arcoflex has produced a number based on the above methodology and we welcome review and debate. What can be asserted with confidence is:

- Methane must be directly measured in ppm – these values are verifiable and sufficiently accurate.
- The model looks for percentage difference – regardless of the scale, that number is absolute.
- Arcoflex can assess the immediate health of an animal at each milking.
- The herd average is preferred – the herd value is far more important than the individual because of variations in breed health and environmental conditions.
- We can now add 5% for the accepted proportion of methane excreted in manure.

Annex D – Laboratory Testing of Arcoflex Sensors

In seeking to provide credibility for a unique sensor working in a unique environment, Arcoflex subjected its sensors to comparison with gas chromatography (GC) at the Ektimo laboratories in Mitcham, Melbourne [21]. As part of our manufacturing process, a sample set from every batch is taken to Ektimo to confirm construction integrity and sensor accuracy consistency.

Sensors are placed in a container and flooded with a specific volume of reference gas. The purpose of such a container is so that a sufficiently similar sample of the air that the sensors read can then be placed into GC for accurate analysis. There will always be some variability in the amount of reference gas inserted and the volume of air tested but this is weighed against the eventual implementation where we are attempting to collect breathing samples from an animal going about is normal business of eating.

Figure D1. Comparison with a Gas Chromatograph and Testing the Reference Gas

Our first mission was to test the mid-point for animal expected breathing ranges of 400 – 1500 ppm. This was conducted using 1000 ppm BOC reference methane. This reference gas was used to train the GC and then used to flood our sensors. The GC then took a sample of the same air placed over the sensors for comparison. The results from the first such test conducted in July 2023 are shown in Figure D2. These results show a consistency for our sensors to read about 15% too low. However, it is considered more appropriate to under-estimate than over-estimate. We can always bias the results if required.

The second test was to demonstrate that our sensors could detect very low levels of methane, down to as little as 50 ppm. A 100ppm BOC reference gas was used for this purpose. In the first of such tests (July 2023), the GC did confirm our detection of methane but found that we consistently read around 20% too high at this level. Again, this can easily be compensated in software but it was pleasing to see that we could reliably detect such low levels. At the time of writing, there was no other commercially available sensor for agricultural application that can do this. An uncertainty of +/- 10 ppm at 50 ppm is an outstanding achievement and well good enough to detect methane concentration changes.

Since July 2023, we improved sensor consistency even further by weeding out low performing sensors in bench tests before construction. The manufacturer has given us a range of metrics to check for and how to tweak electronics to suit such low readings. The use of highly accurate voltage sources helps.

At the conclusion of each round of testing, Ektimo summarises the results within the limits of the number of sensors submitted for each batch. After the latest round of testing, Ektimo have determined that our sensors have a relative uncertainty of 24% with a confidence level of 95% [29]. Given the use case involving intemperate animals, this is good enough. However, Arcoflex will seek to improve sensor consistency with each batch, improving the platform and rejecting higher quantities of mal-performing sensors.

Ektimo Test Result 31-07-2023

1000ppm Reference Gas Test

Test No.	Regime		Time	Sensor 1	Sensor 2	Sensor 3	Sensor 4	GC Result
	Pressure	Duration						
1	20 psi	6 seconds	11:11	571	530	714	560	
2			11:14	454	421	578	432	680
3			11:22	467	436	620	407	
4			11:27	529	527	800	465	
5			11:36	501	458	707	435	747

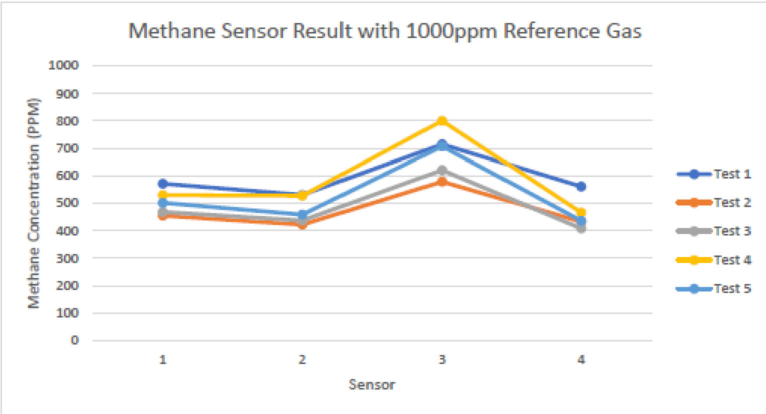


Figure D2. Arcoflex Sensor Consistency with 1000 ppm Reference Gas

100ppm Reference Gas Test

Test No.	Regime		Time	Sensor 1	Sensor 2	Sensor 3	Sensor 4	GC Result
	Pressure	Duration						
1	50 psi	10 seconds	11:46	65	65	68	50	
2			11:48	78	81	89	62	
3			11:53	67	69	77	53	50
4			12:01	71	74	80	59	45

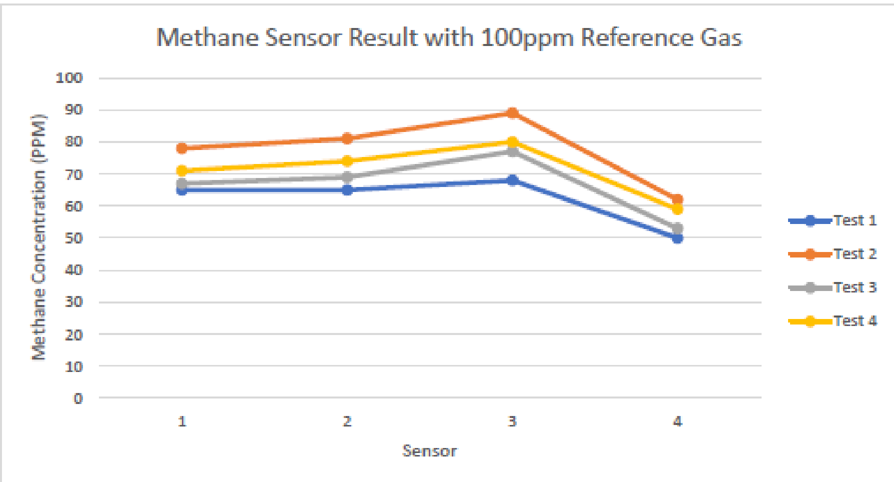


Figure D3. Arcoflex Sensor Comparison with 100 ppm Reference Gas