INGAA Key Initiative: Transportation and Storage of Renewable Natural Gas

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FINAL REPORT

Submitted to:
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INGAA Key Initiative:
Transportation and Storage of Renewable Natural Gas

1. INTRODUCTION

Renewable Natural Gas (RNG or biomethane) offers much potential for decarbonizing energy supplies in North America. RNG is a product derived from the microbial conversion of organic material (biomass) to a mixture of gaseous compounds (biogas), further cleaned or "conditioned" to produce a final product which primarily contains methane (RNG). RNG is suitable for the pipeline grid, given proper conditioning.

Individual gas companies make their own decisions regarding suitable RNG practices for their pipeline network. This Document provides a ***SAMPLE*** RNG Quality Specification and ***SAMPLE*** Verification and Monitoring Programs for the biogas sources of 1) Live Animal Manure (LAM) Anaerobic Digestion (AD) and industrial-grade food waste AD, and, 2) Landfills and Wastewater Treatment Sludge AD. Other AD systems are also addressed. These ***SAMPLE*** Documents serve as models only. This Document does not intend to imply that the offered ***SAMPLE*** Specification and Verification and Monitoring Programs are suitable for every gas company. Rather, it may serve as an industry-wide reference covering basic biogas and RNG characteristics, parameters of consideration with respect to trace constituents, conditioning unit technologies and measurement techniques that can be used in contracts interconnection agreements or company-specific specifications/gas quality programs. This Document does not comment on or endorse specific methods or designs of cleanup technology employed to produce RNG. Values or numbers found in the ***SAMPLES*** provided in this report are not intended to take precedence over company preference, existing contract or tariff values. *It is strongly advised that individual company natural gas quality tariffs and other parameters be considered in evaluating the suitability of any proposed gas product for introduction to the pipeline network. Conditions for RNG introduction may vary between natural gas companies and interconnection points. Readers are strongly advised to examine market, pipeline and end-user conditions to evaluate individual RNG projects to their pipeline network.*

2. CHAPTER 1: BACKGROUND: DESCRIPTION OF BIOGAS

2.1 What is "Biogas"

"Biogas" is a very general term, but has come to represent a gaseous product which results from the biologically-mediated (microbial) conversion or breakdown of organic waste, under oxygen-deprived (anaerobic) conditions. Biogas may contain compounds which are products of full conversion of an organic substrate, and/or it may contain products of partial conversion (i.e., intermediate compounds on the pathway to full conversion). However, and importantly, depending upon the biomass source, biogas may also contain compounds which are simply volatilizing from the biomass substrate. In the context of the topic at hand, biogas refers to a product of anaerobic digestion which contains a mixture of methane, carbon dioxide and other inert gases, sulfur compounds and a variety of "trace constituents" which are biomass-source dependent. Biogas must be cleaned or "conditioned" to be suitable for inclusion to the natural gas pipeline network. Synthesis gas (syngas) or gas produced through gasification processes is *not biogas*, by definition; the analytical profiles of syngas are different from biogas. Syngas may be considered a "renewable natural gas", but it is not produced through biological action. This paper will cover syngas briefly.

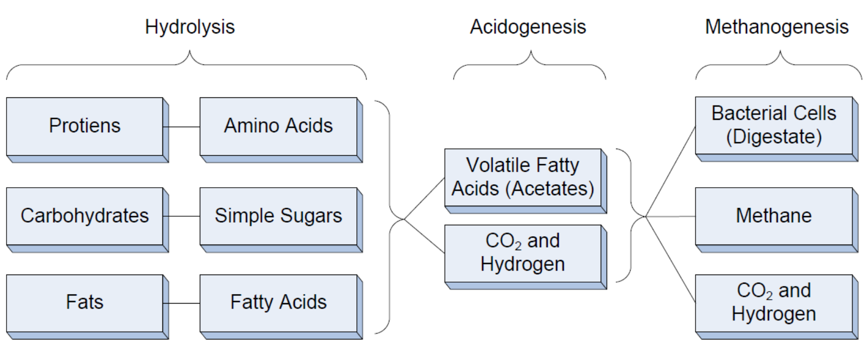
2.2 How is Biogas Created?

Biogas is created through the naturally-occurring microbial breakdown of organic compounds under conditions where oxygen is not present (anaerobic). These conversions occur widely in nature, under a variety of conditions. Plant and animal material, as well as other organic substances, break down through selected pathways, depending upon the presence of certain bacteria and conditions in the environment. Bacteria perform a wide variety of processes in nature, one of which is the conversion of organic matter to methane (through methanogenesis).

Harnessing the energy potential in biogas is an old practice. In the 10th Century, baths in Assyria were heated by burning biogas produced by the breakdown of organic matter, although the mechanism was not understood. In the 17th century, Jan Baptita Van Helmont of Belgium discovered that decaying organic matter produced flammable gas. In 1808, the British chemist Sir Humphry Davy discovered that methane gas was present in cow manure. The first known plant to use proper anaerobic digesters was built in a leper colony in Bombay, India in 1859. Today, the most common use for anaerobic digestion is on farms for the digestion and minimization of animal waste, so that farming operations limit waste disposal to their land and surrounding water bodies. Often, the biogas generated from the digesters is collected and burned in generators for production of electricity, which can be used on the farm or locally. This is also true of biogas generated from wastewater treatment sludge digesters or landfills.

Anaerobic digestion of organic material describes the process whereby carbon-based compounds are broken down by naturally-occurring bacteria through four major processes: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Bacteria are clever; they occupy niche environments, performing specific roles in the production of methane. The entire process is sensitive to the balance of all populations in the progression. *Hydrolysis* is the process in which carbohydrates, proteins and fats are converted/broken down to sugars, fatty acids, and amino acids. These are the basic foods for all bacterial populations which do the further conversion. *Acidogenesis* is the process by which the sugars, fatty acids, and amino acids are converted by a distinct set of bacteria to (mostly) carbon dioxide, ammonia, and carbonic acids; a small amount of methane is also produced. *Acetogenesis* is a parallel and competing process not associated with methane production; it is performed by another set of distinct bacteria which create acetic acid and carbon dioxide, but no methane. The final process, performed by yet another set of bacteria, is *methanogenesis*, where a mixture of larger amounts of methane and smaller amounts of carbon dioxide gases are produced (Figure 1). The entire process is, in fact, delicate, as the bacterial species which perform the various reactions do not thrive under similar conditions and fiercely compete. Therefore, overgrowth or dominance of one set of bacteria in the chain of reactions can lead to poor methane production, concurrent with excess production of carbon dioxide, etc.

Figure 1: Biological Conversion of Substrates to Methane



It is also important to remember that bacteria are able to partially convert compounds, of all sorts, to different compounds without fully driving the digestion to completion. In other words, compounds may be degraded to “intermediates”, which then accumulate in the liquids or gases, without producing methane. If the anaerobic digester is not operated optimally, with all bacterial populations in balance, excess quantities of carbon dioxide and other inerts, at least, can be expected. Additionally, bacteria are able to convert elemental sulfur to hydrogen sulfide under anaerobic conditions. Bacteria which perform tasks such as these are commonly found in the bovine gut, wastewater treatment systems and in other sources of biomass generally used for methane production. This process is separate from the creation of methane and it occurs concurrent with methane production. Therefore, it is typical that hydrogen sulfide is also found in biogas generated from digestion of organics.

Anaerobic digestion can occur in any closed system environment where oxygen in limited. “Anaerobic Digesters” (ADs) are, basically, tanks, vessels, ponds or pits which are confined, possess moisture (water) and are very limited in oxygen. The process of methane production ceases in the presence of oxygen. Moisture is also important for AD to occur, as bacteria thrive in moist environments. ADs vary in size, shape and configuration. Some ADs are operated at higher temperatures, and some at moderate temperatures. Mixing methods vary as well. A landfill also can be considered a “digester” in that landfills are highly anaerobic, fully contained and possess varying amounts of moisture (depending upon weather, contained materials, and operation). Give the correct conditions, bacteria can produce methane from organic waste materials deposited in the landfills. It is important to remember that materials deposited in landfills serve as sources for all types of gases, and the gases are not necessarily the result of bacterial action. Materials as common as paint thinners, solvents, nail polish removers, common household cleaning products, small amounts of industrial liquid waste, contaminated soils, oils/greases and other daily-used products are deposited in landfills through trash disposal. Compounds associated with these wastes can simply volatilize and are “sucked up” in the landfill gas collection system. These compounds are not created through the microbial production of methane, but are gathered along with methane in the gas collection system. Therefore, biogas from landfills (and wastewater treatment sludge ADs) contain biologically-produced methane *and* other compounds which are not produced necessarily through microbial action. These compounds are categorized as “trace constituents” and will be discussed in Chapter 2.

Figure 2: Anaerobic Digestion of Waste to Biogas

2.2 Influencing Factors in Methane and Biogas Production

The most dominant factors which influence the quantity and quality of biogas produced from a digester are: 1) the ability of the AD to control parameters which drive the entire process described above to the most desired compound, methane (see Figure 1), and, 2) the biomass source. If the digester is not operating optimally, the digester will produce a gas which contains larger quantities of inerts (carbon dioxide, etc.,), which will need to be removed. Therefore, there is less yield of methane in the biogas. Yields of methane from all digester designs, including landfills, vary widely, from 68% methane to 40% methane (or less). The remainder of the gas in the mixture is, generally, unwanted inert gases such as carbon dioxide and lesser amounts of nitrogen and oxygen, sulfur compounds (predominantly hydrogen sulfide) and smaller quantities of "trace constituents". Landfill biogas can contain greater amounts of nitrogen due to the process of biogas extraction. Carbon monoxide, helium and hydrogen are generally absent. Methane, sulfurs and inert gases are categorized as the "**Major Component**" gases; they heavily influence the BTU and Wobbe Number of the gas. In raw biogas, they are present in percent quantities. Table 1, from the California Council on Science & Technology Report, 2018, lists percentages of the major component gases in raw biogas. A biogas which contains high quantities of inerts possesses a lower BTU.

<u>Table 1: General Proportions of Major Component Gases in Biogas</u>
Source: CCST (2018)

Gas Composition	Source of Gas			
	WWTP	**Landfill**	**Animal/ Agricultural Waste**	**Municipal Waste**
Methane (CH4, vol. %)	55-70% [1] 60-67% [3] 59.6% [6] 60% [7]	45-60% [1] 47-62% [3] 35-65% [4] 44% [5] 45% [7]	50-70% [1] 55-58% [3] 60-70% [4] 68% [7]	50-60% [2]
Carbon dioxide (CO2, vol. %)	30-45% [1] 33-38% [3] 39.1% [6] 33% [7]	35-40% [1] 32-43% [3] 15-50% [4] 40.1% [5] 32% [7]	30-50% [1] 37-38% [3] 30-40% [4] 26% [7]	34-38% [2]
Nitrogen (N2, vol. %)	<2% [3] 0.9% [6] 1% [7]	0-3% [1] 1-17% [3] 5-40% [4] 13.2% [5] 17% [7]	0-3% [1] 1-2% [3] 1% [7]	0-5% [2]
Oxygen (O2, vol. %)	None [1] <1% [3] 0.2% [6] 0% [7]	0-2% [1] <1% [3] 0-5% [4] 2.6% [5] 2% [7]	<1% [3] 0% [7]	<1% [2]
Heating Value (BTU/scf)	500-640 [1]	410-550 [1]	450-650 [1]	450-550 [2]

[1] (Lampe, 2006), [2] (Bailón Allegue & Hinge, 2012), [3] (Rasi, 2009), [4] (Persson, Jonsson, & Wellinger, 2006), [5] (Jaffrin, Bentounes, Joan, & Makhlouf, 2003), [6] (Osorio & Torres, 2009), [7] (Favre, Bounaceur, & Roizard, 2009)

Trace Constituents are small, but significant, quantities of elements or compounds present in the resulting biogas; these compounds may or may not be a result of bacterial conversion to methane. The presence of trace constituents is biomass-source dependent; these compounds can vary widely, number in the hundreds, and can pose great concern, even in small quantities. Trace constituents can simply be volatilized from the biomass, or are products of bacterial digestion which are separate and distinct from methane production. This is discussed in later sections.

3. CHAPER 2: DESCRIPTION OF BIOGAS SOURCES/BIOMASS

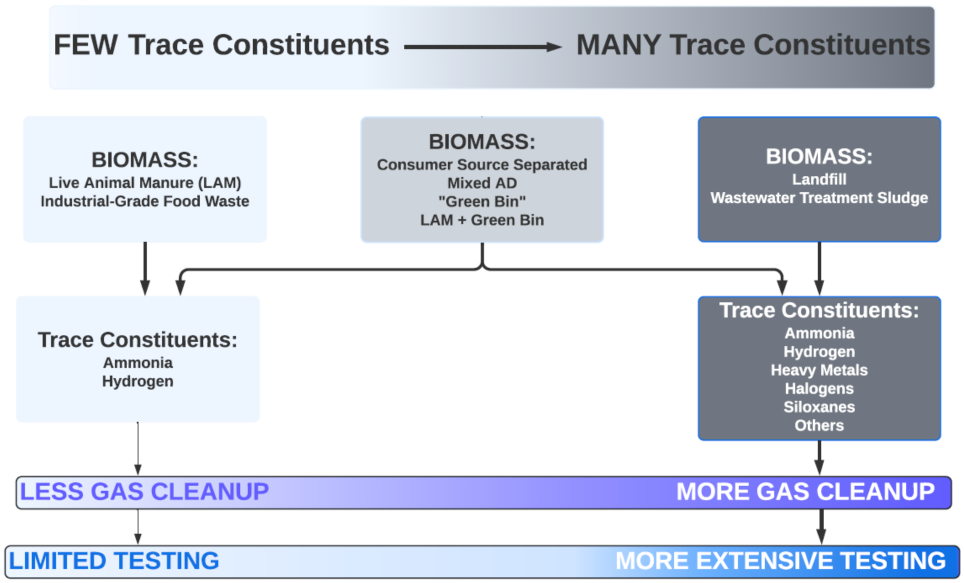
3.1 Overview

"Source biomass" is the starting material used for the digestion process which produces biogas. Bacteria are extremely clever and perform many degradative processes, with only a certain set able to convert organic material to methane. Mentioned previously, a set of anaerobic bacteria degrade simple organic compounds to completion through a series of steps; each step is mediated by different bacteria. Organic material which is "simple" (easy to digest/broken down, not physically complex, not containing metals, inert compounds, halogens, etc.) will be readily converted to methane, given proper conditions. Examples of simple organic material are manure from animals and industrial-grade food waste. Industrial-grade food waste is a term for the scraps, residuals, and imperfect products from food production, etc.; this food/waste has never been in contact with humans/animals. Agricultural waste can also be considered in this category. Conversely, "complex" biomass sources contain a wide variety of organics and inorganics in the mixture; these compounds may be broken down by bacteria to smaller compounds, but the process does not necessarily produce methane. In fact, some bacteria will break down certain classes of compounds into MORE TOXIC compounds (methane is not produced). Additionally, these types of biomasses offer sources of organic release by way of simple volatilization. Gases trapped in the biomass material are simply released upon gas collection, especially when the source is heated. Examples of complex biomass include landfill materials and wastewater treatment sludge. "Green Bin" programs offer an interesting challenge. While mostly containing simple biomass, the public will often comingle materials and organics which, when digested, produce trace constituents not allowed in the natural gas pipeline grid. Self-segregated organic waste programs often produce biogas containing a wide variety of undesirable trace constituents. Therefore, post-consumer biomass collection programs are considered on a case-by-case basis for categorization.

Figure 3: Biogas Quality is Biomass Dependent

Despite source of biomass, *the resulting biogas must be cleaned to standards set for inclusion to the pipeline grid.* Cleaned biogas is referred to as "Renewable Natural Gas" (RNG) or biomethane. As will be discussed in subsequent sections below, raw biogas quality varies widely but can be readily ranked from "most easy to clean" to "hardest to clean". If the biomass source is simple, few trace constituents will be present in the biogas, and cleanup to RNG specifications will be less complicated/expensive. If the source biomass contains many compounds, materials and types of organics/inorganics, the resulting biogas will more difficult to clean to the RNG specification because more trace constituents need to be removed.

Figure 4: Schematic of Biogas Cleanup Required, Depending Upon Biomass Source (Simple to Complex)



Biogas (and subsequently RNG) differs substantially from natural gas in that it does not contain heavy hydrocarbons (extended hydrocarbons), so the BTU and Wobbe Number will be inherently lower than typical natural gas supplies. According to the American Gas Association Report 4A, physical characteristics may be compromised if the gas has a Wobbe Number on the lower end of acceptability. This is addressed also in the *White Paper on Natural Gas Interchangeability and Non-Combustion End Use*, constructed by the NGC+ Interchangeability Work Group (February 28, 2005). Consistent application of BTU value and Wobbe Number are important for continuing gas performance and quality. In the case of Wobbe Number, biogas must be stripped of most inerts, leaving mostly methane, in order to produce RNG with an acceptable Wobbe Number (CCTS, 2018).

3.2 Anaerobic Digestion (AD) of Live Animal Manure

Live Animal Manure (LAM) can come from cows, cattle, hogs or other animals. There are a wide variety of arrangements to collect manure, which is then placed into tanks or ADs. ADs vary widely in design and configuration, but the intent is to create an environment whereby the organic waste is digested completely to methane, as efficiently as possible. Controlled AD is the most effective way to produce high quality biogas (high percentage of methane in the gas) because both conditions of bacterial growth and biomass quality control can be monitored and maintained under optimal conditions. Manure is very good digester substrate because it has tremendous buffering capacity. This means that the digester can absorb a variety of materials while maintaining optimal methane-production conditions. This becomes important when other types of organics are introduced and digested (see below). However, manure itself does not produce the volumes of biogas generally needed to make a cost-effective program. Manure is carbon poor, as most energy has been used by the animal. ADs on farms are generally used for the purposes of waste reduction, so that the impacts of animal farming are curtailed and waste by-products can be reused productively (solid and liquids). Many farms use digestion technology for manure waste minimization, with raw biogas driving gen-sets for on-site electricity production.

LAM AD produces a relatively clean biogas which mostly contains inerts, sulfur compounds (hydrogen sulfide) and the trace constituents of ammonia and small amounts of hydrogen. Ammonia is readily produced when urine mixes with manure. Therefore, the cleanup systems required for high quality RNG production are relatively straightforward and less expensive than those used with more complex biogas.

3.3 AD of Industrial-Grade Food Waste/Agricultural Waste

Industrial-grade food waste is human and animal food which has not been in contact with consumers, coming directly from manufacturing facilities or distribution centers where consumers have not interacted, used or collected the organics. Examples are food products directly from the manufacturer, such as residual cookies, bakery products, vegetable products (pre- or post-processed), farm residuals, yogurts and ice cream, out-of-date food products for animals and humans, and other organics which have not been in direct contact with the consumer. Fats, Oils and Greases (FOG) from restaurants and food production are "high value" wastes. These organics are of high value with respect to methane production through AD (high percentage of methane in the biogas), as the organics are easy-to-degrade, energy-rich and easily managed. Volumes of biogas from the AD process are also increased dramatically. Agricultural waste could include meat and animal by-products, slaughterhouse waste and animal carcasses. Additionally, energy grasses and crops yield high quantities of methane and have been used in Europe for this purpose for over 20 years.

Of particular interest is the mixing of industrial-grade food waste and suitable agricultural waste with LAM. The benefit is obvious, as LAM has tremendous buffering capacity and can absorb the variations in feed biomass. More importantly, the production of biogas is greatly increased, as these biomass materials serve as readily-digestible carbon sources. If the AD is operated optimally, vast quantities of biogas may result.

As with LAM AD, digestion of industrial-grade food waste produces a relatively clean biogas which mostly contains inerts, sulfur compounds (hydrogen sulfide) and the trace constituents of ammonia and small amounts of hydrogen. Therefore, the cleanup systems required for high quality RNG production are relatively straightforward and less expensive than those used with complex biogas.

3.4 AD of "Green Bin" Wastes

"Green Bin" waste is the organic portion of material collected as part of self-separated waste by consumers and the public. These materials are digested in AD systems, similar to industrial-grade food waste AD; yields in biogas can be high, with biogas containing high percentages of methane. In many cities, the public is encouraged to source-separate "organic" material, so that it can be collected in green bins and used in community-based ADs. Source separation also occurs in many cafeterias, school settings and other institutions where consumers self-select bins into which materials are disposed. While the intent is good, it has been found that these programs can be confusing and often cause the unintentional (and intentional) mixing of materials. Examination of wastes coming from households shows that consumers mix all sorts of materials with organics in their green bins, including fuel oils, solvents, metals and plastics. This is also the case in other community-based self-sort programs.

Green bin waste can also be comingled with LAM waste, to increase yields in biogas production and quality (higher percentage of methane in the gas). The resulting biogas may or may not be more complex than LAM AD only or industrial-grade food waste AD with respect to the trace constituents profile. Therefore, the producer and gas company may wish to fully examine the biogas for the presence of additional trace constituents, beyond ammonia and hydrogen. Included in this testing should be examination for halogens, heavy metals, siloxanes and perhaps others.

3.5 Combined AD Programs

Combined AD programs are those digesters which accept waste from a wide variety of sources, generally based in LAM digestion. Because of the high yield in biogas quantity and quality (high percentage of methane associated with the gas), these programs are very attractive. However, mixing organic wastes and other materials in a digester may yield a biogas which contains a wide variety of trace constituents which will need to be removed to meet gas quality specifications (see Green Bin waste). Careful examination of source biomass material and full profile analytical data will dictate the type of cleanup program required for high quality RNG production. It also dictates the extent to which the gas must be tested to verify that the cleaned RNG meets gas quality specifications. This is a special consideration in combined AD programs.

3.6 Landfills

Landfill biogas or landfill gas (LFG) is generated from the degradation and volatilization of materials contained in a landfill; anything that has been deposited in the landfill may be released into the biogas, depending upon conditions in the landfill. Methane is created biologically in landfills; operation of the landfill influences methane yields. Moisture within the landfill, age of the waste, temperature, strict anaerobic conditions, quality and quantity of organics, contamination by toxic compounds, competitive biological reactions and other factors dictate the quality of the resulting biogas (percent of biogas total which is methane). Landfills can vary widely in quality production, often producing a biogas containing only 40-55% methane. Inert gases must be stripped, yielding low gas volumes. Nitrogen is found in larger quantities in landfills due to air intrusion during the biogas extraction process.

“Landfill gas”, rather than “biogas”, is an appropriate term for this raw product. It is, in fact, a mixture of gases, some of which are produced biologically and some released through simple volatilization. Bacteria are able to convert many compounds, most of which do not result in methane production. The following language is derived from the US EPA’s Landfill Methane Outreach Program (LMOP) website: (https://www.epa.gov/lmop/frequent-questions-about-landfill-gas):

“What components make up landfill gas? *By volume, LFG is about 50 percent methane and 50 percent carbon dioxide and water vapor. It also contains small amounts of nitrogen, oxygen, and hydrogen, less than 1 percent non-methane organic compounds (NMOCs), and trace amounts of inorganic compounds. Some of these compounds have strong, pungent odors (for example, hydrogen sulfide). NMOCs consist of certain hazardous air pollutants (HAPs) and volatile organic compounds (VOCs), which can react with sunlight to form ground-level ozone (smog) if uncontrolled. Nearly 30 organic hazardous air pollutants have been identified in uncontrolled LFG, including benzene, toluene, ethyl benzene, and vinyl chloride. Exposure to these pollutants can lead to adverse health effects.”*

The above EPA quotation is important because it reenforces databases which show that landfill gas can contain a wide variety of known and unknown constituents. Within the context of RNG production, landfill gas is particular because of its trace constituent profile. Hundreds of trace constituent compounds are found in landfill gas; not all of these constituents pose risk to the gas pipeline, end use or human health and safety. It is particularly important to remove *selected sets* of trace constituents, as they are known to be problematic to the pipeline grid. Cleaned biogas/RNG is NOT “free of all trace constituents”. Rather, the most impactful trace constituents have been removed to currently-known “safe levels” or gas company required levels. Identifying and targeting selected compounds is an evolving field, particularly in the fields of pipeline safety and end-use impacts. Research and field observation add to the body of data from which assessments are made. At the time of writing this document, researchers and the gas industry have limited data specific to long term impacts of RNG trace constituents on the pipeline (metal or plastic). Over time, RNG specifications may be revised and refined. Removal of these constituents is expensive, and testing of resulting RNG is more extensive. Therefore, the industry wishes to target the most impactful trace constituents, while allowing for this new product to enter the pipeline grid safely.

Landfill RNG can contain ammonia, hydrogen, siloxanes, heavy metals, halogens and other trace constituents.

3.7 Wastewater Treatment Sludge AD

Treatment of wastewater is conducted under aerobic conditions; publicly-owned treatment works (POTWs) receive wastewaters from households and industries in a community. The water is placed into large vessels and slowly mixed, under aerobic (with air) conditions, to completely digest the wastes to carbon dioxide and water. This process does not produce biogas containing methane. Rather, the sludge from the main, aerobic treatment process (bio-bodies, non-digested residuals in the water, etc.) are collected and further reduced in volume through AD. This way, the wastewater treatment (WWT) plant minimizes the quantity of organic/inorganic sludge destined for disposal in landfills.

Wastewater treatment sludge contains a wide variety of organics and inorganics from the processing of water which flows through the treatment plan. Anything which is flushed down toilets, released through industry processing or collected during rain events is subject to digestion at the facility. Many compounds are present in the tank sludge; these compounds many be released during the anaerobic digestion process to produce methane. As such, biogas which is produced from wastewater treatment sludge is considered similar to landfill gas. This biogas can contain ammonia, hydrogen, halogens, heavy metals, siloxanes and other compounds which may be of concern. Cleanup of this biogas can be expensive and verification programs are more robust.

3.8 Sources NOT APPROVED for Upgrade and Usage in Natural Gas Pipelines

All companies considering the introduction of RNG to their pipeline grid should **carefully consider the source of the biogas**. Some sources are simply too risky or unsuitable for upgrade. These sources include biogas derived from a landfill or site which is a regulated or not regulated, active or "former; not active; de-listed" Federal or State-led Superfund, *or of similar site status*. This includes all Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and all Resource Conservation and Recovery Act (RCRA) sites, whether Federal or State governance/oversight. Included are all Federal or State-led Superfund site: active, interim-action, closed or de-listed. All National Priorities List (NPL) sites are included, active, interim-action, closed or de-listed, and all Federal or State-led Department of Defense (DOD) sites (Installation Restoration Program) governed at the state or Federal level. All state-led cleanup programs for site cleanup are included, as state-led programs are named differently across US states and federal district, including insular areas. All known, permitted and deemed hazardous waste repositories are included, including former, fully permitted hazardous waste repositories, including RCRA Subtitle C landfills. *All landfills or sites considered for upgrade to the pipeline should be thoroughly reviewed for appropriateness for an RNG injection to the pipeline project, and denial is at the discretion of the overseeing gas company, based on site history, risk to pipeline/consumers/end-use equipment or other tangible/non-tangible impacts to the gas company and its pipeline network.* Seeking advise as to the appropriateness of upgrading any high-risk biogas source is strongly recommended.

3.9 Is Syngas a Form of Biogas?

Syngas or *synthetic methanation* is a process whereby raw materials are dried, thermally treated (pyrolyzed), filtered at high temperatures and cooled/cleaned. The "cleaned" gas then enters a methanation reactor, where the methane is then produced. The raw materials for syngas production are organic waste materials such as wood, agricultural products and farming residues. Municipal solid waste is also proposed as a raw material for the process. Syngas itself containing mostly hydrogen, carbon monoxide and carbon dioxide, with small amounts of methane. This gas is then converted to mostly methane via thermochemical methanation. The process is characterized by a high heat demand utilizing a sensitive chemical catalyst at increased pressure conditions. Of importance, a wide and yet undefined number of trace constituent compounds are also created/carried through in the process.

Syngas is considered a renewable natural gas product if cleaned properly, meeting the requirements for inclusion to natural gas systems. However, by definition, it is not a "biogas", in that it was not created through the anaerobic digestion of waste. The analytical boundaries and parameters associated with upgraded biogas (RNG) have been researched, and consensus is being developed as to the trace constituents of concern. Syngas differs from biologically-produced RNG because the process of methane creation is radically different. *Full characterization of syngas has not been fully executed, especially within the trace constituents group*. Syngas RNG will possess a chemical profile (in both major component profile and trace constituent profile) which is different from RNG produced through biological degradation of organic materials. Therefore, the RNG quality specifications for syngas are yet to be developed, and those listed this document do not apply.

4. CHAPTER 3: TRACE CONSTITUENTS OF CONCERN

4.1 Overview of Topic

Biogas must be upgraded, cleaned or "conditioned" to pipeline quality standards; this is achieved through stripping of unwanted gases (mostly inerts) from the biogas, thereby concentrating the methane and other constituents in the resulting product. Gas quality parameters are grouped into two basic categories: Major Components and Trace Constituents.

Major Components are parameters which are found in nearly all natural gas tariffs found in North America; the natural gas industry is familiar with this set of parameters. They include:

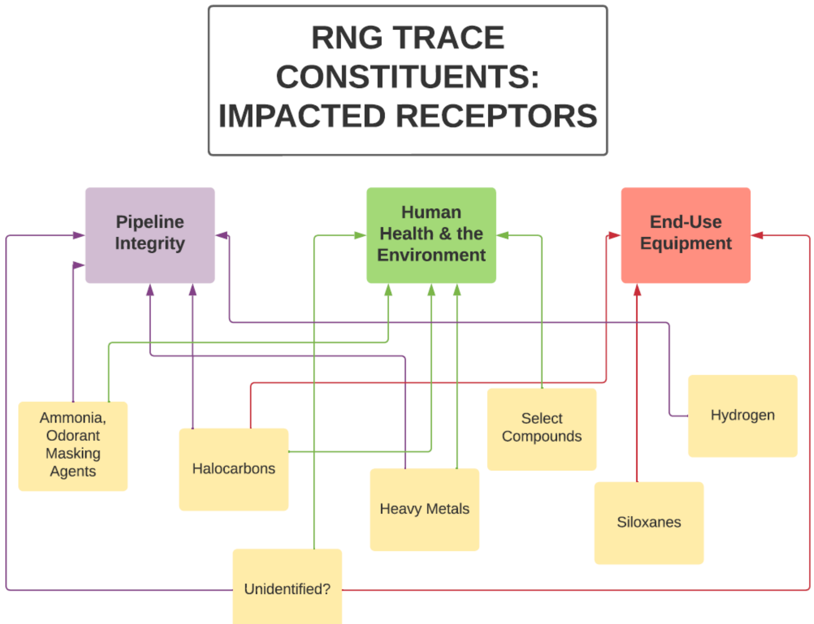
- BTU
- Wobbe Number
- Extended Hydrocarbons (do not apply to RNG)
- Inert Concentrations (CO_2, O_2, N_2 and Total Inerts)
- Sulfurs (H_2S, Total Sulfurs)
- Moisture/Water Vapor
- Temperature

Trace Constituents are another set of parameters not typical to natural gas supplies, generally found in lower concentrations. However, these parameters are very important due to their potential impacts to pipeline integrity, end-use equipment and human health and the environment (known as the "receptors"). As discussed previously, the trace constituents profiles vary between biogas sources, and can be grouped as follows:

- LAM (Live Animal Manure) AD, Industrial-grade food waste AD, and co-digestion AD of these biomass sources
- Landfill gas, and Wastewater treatment (WWT) sludge AD

NOTE: Post-consumer organics AD (Green Bin AD, and Combined or Mixed Waste AD) may or may not contain trace constituents of concern and must be evaluated individually. Some trace constituents impact more than one "receptor", as shown in the Figure 5, below.

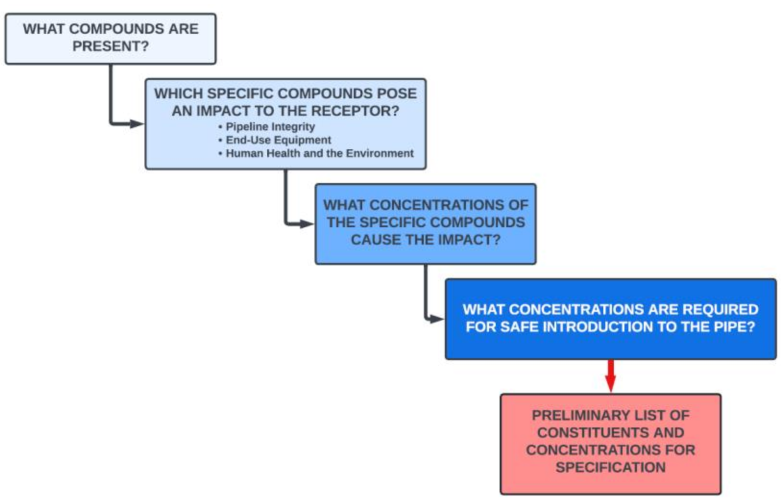
Figure 5: RNG Trace Constituents: Impacted Receptors



Understanding the risks and impacts of a specific constituent or sets of constituents on the specific "receptor" is a step-by-step process. The following schematic shows the steps involved in examining:

- **WHAT COMPOUNDS ARE PRESENT** in the RNG?
- **WHICH** of the **COMPOUNDS** in the RNG **POSE A POTENTIAL IMPACT** TO THE RECEPTOR?
- **WHAT CONCENTRATIONS** of the compounds **CAUSE THE IMPACT**?
- **WHAT CONCENTRATIONS ARE REQUIRED** for safe delivery to the receptor(s)?

Figure 6: Determining Constituents of Concern and Safe Concentrations for RNG



Studies and research have been executed to understand the types of constituents found in the various sources of raw biogas; concentrations of constituents were examined to understand the quantity of the constituents in each biogas source, and examination of threshold concentrations (maximum concentrations) against the impacts to various receptors has been performed, to the best of knowledge at the time of this report preparation. The "receptors" are the impact points (what "receives" the damage): pipeline integrity, end-use equipment or human health and the environment. It is important to remember that this field is still developing, and best judgement is used in identifying impactful constituents. Moreover, the maximum allowable limits for each constituent are based upon current known risks and "safe values". The following sections detail the identified constituents of concern for each of the receptors, with attention to the Trace Constituents. Table 2 shows the trace constituents and the receptor of concern.

Table 2: Trace Constituents and Receptors: Areas of Concern

PARAMETER	ABBREVIATION	LIMIT (MAX.)	UNIT	TRACE CONSTITUENT RISK RECEPTOR		
				Human Health and Environment	Pipeline Integrity and Operations	End-Use Equipment
Ammonia	NH_3	0.001	% vol.		X	
Hydrogen	H_2	*	% vol.		X	
Siloxanes	Si	0.5	mg Si/m³			X
Chlorine Total	Cl	10	mg/m³	X	X	X
Fluorine Total	F	1	mg/m³	X	X	X
Mercury	Hg	0.08	mg/m³	X	X	X
Arsenic	As	0.19	mg/m³	X		
Copper	Cu	0.6	mg/m³	X		
*Hydrogen limit should be evaluated by Operator, considering their pipeline system and in coordination with INGAA Hydrogen Document						

4.2 Impact to Pipeline Integrity and Operations: Constituents of Concern

Integrity of the metal pipelines within a natural gas transmission system is of chief concern to the gas pipeline industry. Of greatest focus is the presence of compounds or agents which may weaken, crack, pit or deteriorate the steel pipeline. Through careful examination of constituents found in biogas from all sources, the following constituents have been identified, by source, which impact pipeline integrity:

Live Animal Manure/Industrial-Grade Food Waste/Agricultural Waste:

Ammonia
Hydrogen

Landfill Gas/Wastewater Treatment Sludge AD/Mixed AD:

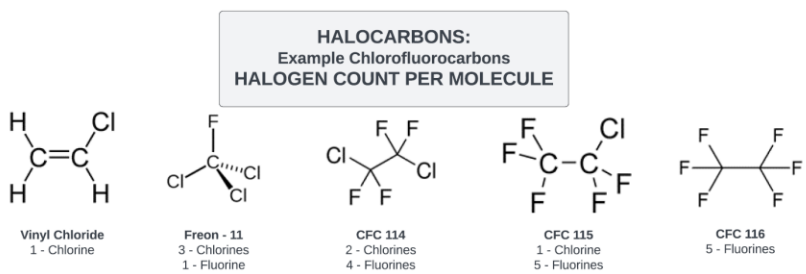
Ammonia
Hydrogen
Halogens (chlorine and fluorine halogens)
Mercury

Ammonia is a powerful odorant masking agent at increasing concentrations; this is considered in the category of pipeline integrity. Ammonia is produced through the mixture of manure and urine, and is expected with digesters which utilize these waste biomass products. In higher concentrations, ammonia can impact downstream gas processing equipment. Combustion of ammonia can form nitrogen oxides, potentially impacting end use operations and could cause the exceedance of air permit requirements in the compression and transport of natural gas.

Hydrogen can be present in two forms; atomic hydrogen (H), and/or diatomic hydrogen (H_2). Atomic hydrogen stress can cause stress cracking or metal embrittlement; this has been well documented. As with most trace constituents in the gas, the conditions for corrosion/pipe deterioration are accelerated or exacerbated by a confluence of both chemical and physical conditions in the pipeline at any time. Such is the case with atomic hydrogen in gas supplies. The presence of hydrogen sulfide in the gas accelerates the permeation of atomic hydrogen into the iron lattice. Other concerns are with reactions between hydrogen and sulfur and chlorine/fluorine-containing compounds, especially in the presence of water, forming sulfuric and hydrochloric/hydrofluoric acids. Diatomic hydrogen is a more stable form and less likely to react within the pipeline. However, a major concern relates to the permeability of hydrogen gas through non-metallic piping systems or mechanical connections (threads, pipe unions, flanges, etc.). Long term impacts to plastic distribution pipeline are poorly understood, and insufficient information exists as to potential impacts of hydrogen concentrations. Impacts of increasing concentrations of hydrogen to pipeline materials and associated components is actively being studied, as it is anticipated that the transportation and use of hydrogen will grow over time. The topic of introduction of hydrogen to the pipeline is active at the time of this report preparation. Therefore, appropriate and safe concentrations of hydrogen to the pipeline system are still in flux. INGAA is developing a Transportation and Storage of Hydrogen document to review these considerations.

Halocarbons are organic compounds containing carbon, hydrogen, and one or more halogen element (chlorine, fluorine, or bromine, etc.). They are also considered volatile organic compounds (VOCs). When a halocarbon compound is broken apart through combustion or other mechanisms, the **halogen** portion (chlorine: Cl^-, fluorine: F^-, etc.) is released, to combine with hydrogen, creating an acid (hydrochloric or hydrofluoric acid). These acids create potential negative impacts to all three "receptors": pipeline integrity, burner-tip, and human health and the environment. Acids instigate or exacerbate internal corrosion of metal pipelines, could potentially impact the burner tip performance, and impact indoor air quality/outdoor air emissions. A single halocarbon compound can contain many halogens (the agents of concern). Of particular concern are the chlorofluorocarbons (CFCs). This set of compounds, known to deteriorate ozone and are found as refrigerants, are ubiquitous in landfills and are typically found in biogas and RNG. These molecules can contain numerous halogens, serving as sources of chlorine and fluorine (see below). Often, there is only a focus on the halocarbon, vinyl chloride. Vinyl chloride is a known carcinogen, but with respect to impacts to pipeline integrity and end-use, it contributes far less chlorine and no fluorine. Therefore, the total concentration of Cl^- and F^- elements (the halogens) are measured in the gas versus total halocarbon concentrations.

Figure 7: Examples of Halocarbons (Note Presence of Chlorine and Fluorine Halogens)



Mercury, and other heavy metals, may cause toxicological and environmental problems, but the primary impact to pipeline integrity is the potential corrosion of aluminum metal and alloys used to construct gas processing equipment. Mercury is present in most natural gas fields in concentrations from

<10 ppb to >1 ppm as elemental (metallic), organic, and also inorganic compounds. This is particularly problematic because heavy metals, such as mercury, may concentrate in cryogenic liquids and other processing fluids. It can poison catalysts used in downstream process units, and can damage downstream equipment through liquid-metal embrittlement (LME), a form of corrosion leading to crack initiation and propagation primarily in equipment constructed from aluminum.

NOTE REGARDING BIOLOGICALS: Biologicals fall under the category of Particulate Matter with respect to natural gas tariff specifications, with the language, "Commercially free of…". Particulate matter, such as biologicals, dust, gums, objectionable odors, solids, liquids, etc., can be introduced into the gas pipeline network from a variety of sources. In the case of RNG production, particulate matter may be carried along from the production process into the final RNG gas product. Specific microbes contained in RNG may induce/exacerbate pipeline corrosion (microbial induced corrosion or "MIC"). MIC has been found to influence almost 40% of internal corrosion in pipelines. Other gas constituents can influence MIC, especially the presence of water, CO_2, H_2S and O_2. However, and importantly, research clearly indicates that the quantity of MIC-producing microbes in RNG is *equal to or less than* the number found in geologic natural gas sources (GTI, 2009). As part of the RNG Verification and Monitoring Program, below, use of EM/EA coupons is suggested. Refer to NACE Standard Test Method: TM0212-2018, "*Detection, Testing, and Evaluation of Microbiologically Influenced Corrosion on Internal Surfaces of Pipelines"* for more information.

4.3 Impacts to End-Use Equipment: Constituents of Concern

Impacts of constituents on end-use equipment is another aspect of concern to the natural gas transmission industry. Constituents carried in natural gas or RNG may be innocuous to the pipeline or to human health and the environment, but be highly impactful upon combustion at the burner tip. Through careful examination of constituents found in biogas from all sources, the following constituents have been identified which impact end-use equipment:

Live Animal Manure/Industrial-Grade Food Waste/Agricultural Waste:

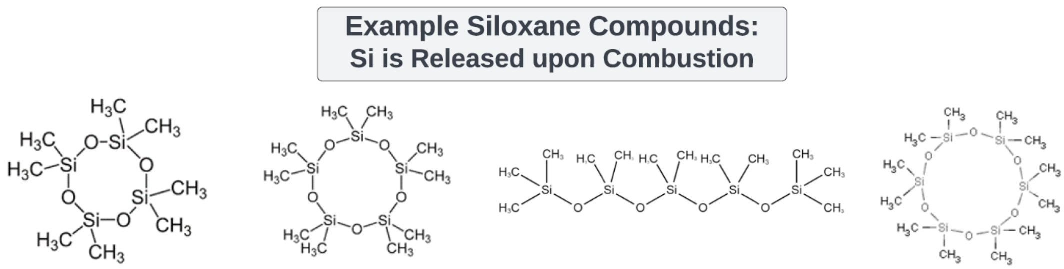
None

Landfill Gas/Wastewater Treatment Sludge AD/Mixed AD:

Siloxanes
Halogens (chlorine and fluorine halogens)
Mercury

Siloxanes are a family of man-made compounds containing oxygen and silicon (O-Si-O) bonds, with methyl (carbon and hydrogen, CH_3) groups bound to the silicon atoms. Siloxanes exist as different congeners, and are often referred to by abbreviations such as L2, D4, etc. with the number indicating the number of silicon atoms and the letter indicating the structure (linear, L or cyclic, D). Due to the increase in silicon-containing personal hygiene, health care and industrial products, the presence of siloxane in landfill and wastewater treatment waste streams has increased; they are generally not present in biogas produced from live animal manure (LAM), industrial-grade food waste or agricultural residues. However, if the above mention wastes are mixed with wastes from Green Bin programs, the presence of siloxane is increased due to erroneous admixtures with plastics and other potentially hazardous substances. As the silicon-containing waste stream is digested, siloxane compounds are created; these volatilize and become entrained in the biogas. When this gas is combusted under high heat and pressure (burner tip), silicon dioxide is formed. This silica dust damages internal combustion engines, turbines, and add-on air pollution control devices. Accurate expression of siloxane concentrations is in units of mg Si/m^3 of gas. Because the concern is post-combustion silica formation potential, which is proportional to mass of Si, siloxane content should be represented in mg Si/m^3 whenever possible (similar to concentration of halogens in the halocarbon compounds, described above.)

Figure 8: Representative Siloxane Compounds



D4 **D5** **L5** **D6**

The CCST Report (2018) performed an exhaustive review of available information specific to allowable concentrations of siloxane in natural gas-fueled equipment. The following language comes from the report (page 48-49).

"Some manufacturers of natural gas-fueled equipment have instituted specifications for maximum allowable siloxane concentration to ensure proper operation (see Table 10. Surveys of maximum siloxane concentration in end-use equipment., and Figure 11). Operators *do not provide methodological details about how such specifications were developed* (e.g., any testing data are proprietary). This information gap makes it *difficult to use engine manufacturer specifications as a basis to place a limit on maximum allowable siloxane concentration for pipeline injection*."

It is also noted in the CCST report that "some hypersensitive equipment (mainly fuel cells) are known to have activated carbon filters to polish the gas prior to use, even during regular natural gas service." The conclusion of this analysis by the CCST author team is stated: "The methods and data used to develop manufacturer standards are typically not available in public domain. As such, these are not useful for detailed modeling of potential impacts. However, any siloxane standard should consider manufacturer specifications." See below for "Table 10 and Table 11" from the CCST report.

Table 10. Surveys of maximum siloxane concentration in end-use equipment.

End-Use Application	Manufacturer	Maximum siloxane conc. [mg Si/m³] (evaluated as D4 for biomethane at 990 BTU/scf)	Source
Reciprocating Engine	Various Caterpillar Jenbacher Waukesha Deutz	10 – 36 3.5 10 9 5	[1] [3] [2] [6] [2]
Combustion Turbine	Unknown (without Recuperation) Unknown (with Recuperation) Solar Turbines	10 5 5-10	[1] [1] [8]
Micro-turbine	Unknown Ingersoll-Rand Microturbines Capstone Microturbines	0.6 0.046 0.023	[1] [2] [2] [4]
Stirling Engine	STM Power	1.96	[5]
Fuel Cell	Fuel Cell Energy	4.66	[5]
Vehicle Fuel	Cummins Various (recommended)	14 0.1	[1] [7]

[1] (Pierce, 2015)
[2] (Wheless & Pierce, 2004)
[3] ("Caterpillar G36000- G3300 Fuels," n.d.)
[4] ("Application guide, Landfill/Digester Gas Use with the Capstone MicroTurbine," 2004)
[5] (Lampe, 2006)
[6] ("Gaseous Fuel Specification for Waukesha Engines," 2014)
[7] (Kramer, Ferrera, Kühne, Moreira, & Magnusson, 2015)
[8] Personal communication

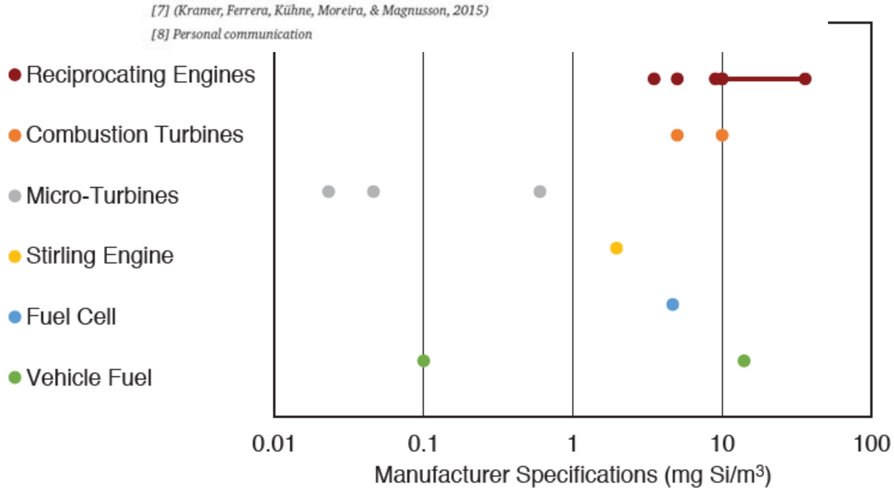


Figure 11. Survey of siloxane specifications reported by manufacturers of combustion equipment.

The CCST report also concludes and states that siloxanes can be removed at relatively small cost before injections into pipelines. Experimental studies find that siloxane removal technologies are effective at reducing siloxane concentrations to levels at or below 0.1 mg Si/m^3; this is verified through existing databases from companies which are performing Verification and Monitoring programs, as described below (Attachment 2), on a routine basis.

Ammonia, described earlier.

Halocarbons (halogens), described earlier.

Mercury, described earlier.

4.4 Impacts to Human Health and the Environment: Constituents of Concern

Constituents which cause impacts to human health and the environment are of concern to both the transmission of the gas and the end-use of the gas. There are a number of points where impact can occur with respect to human health and the environment:

- Worker on the pipeline, working with gas within the pipe (pre-combustion)
- Consumer/end-user in an indoor air environment (off-gases from combustion)
- Post-combustion off-gases from compressor drivers (i.e., turbines, reciprocal compressor drivers or downstream power generation combustion), possibly causing air permit deviations.

The field of impacts to human health and the environment is complex, and considers many parameters. However, "safe concentrations" are advised by the EPA, NIOSH, OSHA and other governing agencies. Biogas and subsequent RNG may contain a wide variety of compounds, but the vast majority are not covered under regulation or cited as problematic. Therefore, a discrete set of compounds is the focus, known to be present in RNG and of potential concentrations of concern:

<u>Live Animal Manure/Industrial-Grade Food Waste/Agricultural Waste:</u>

None

<u>Landfill Gas/Wastewater Treatment Sludge AD/Mixed AD:</u>

Halogens (chlorine and fluorine halogens)
Mercury
Arsenic
Copper

Halocarbons (halogens), described earlier.

Heavy metal concentrations are of particular concern when dealing with RNG generation because volatile metals may be released through the degradation of metal-containing products, batteries, etc. They are carried by small particulate matter in the gas stream, and impact the quality of emissions. Heavy metals may cause toxicological and environmental problems. From a human health and environment perspective, particular heavy metals can be highly toxic and impact air quality.

5. CHAPTER 4: BASIC BIOGAS UPGRADE PROCESSES FOR RNG PRODUCTION

5.1 Overview of RNG Upgrading

Raw biogas must be upgraded or "conditioned" to a pipeline quality specification prior to injection into the pipeline grid. Conditioning units are engineered and designed with the RNG quality specification in mind. Therefore, the RNG quality specification must be *finalized prior to design of the cleanup unit*, as removal of individual components in the biogas may require additional technology or process engineering. Each RNG project is unique to a certain extent. Depending upon the complexity and constituents in the raw biogas, conditioning units vary in design. Most consist of a "technology train" of units, designed to remove specific constituents or gas components. However, most RNG production plants utilize a central technology, which is further augmented by other processes, aimed at refining the raw biogas to the specific requirements stated in the RNG Quality Specification. For this reason, it is highly disruptive and expensive to the RNG producer (and the project in general) if the RNG specification changes or is modified to a more stringent gas quality requirement after the unit has been engineered. The RNG producer seeks to configure a cleanup unit which meets RNG quality specifications for the least cost, both capital and operating.

Therefore, the RNG quality specification serves as the basis for design and should be carefully considered when engaging in RNG upgrade projects.

There are five (5) basic, commercially-available, operational RNG conditioning technologies which serve as the foundation to RNG upgrade plants; a sixth is offered but is generally not employed. One of these technologies is selected as the central unit and other technologies or units are added, based upon the gas quality requirement. If the raw biogas is complex, with many trace constituents, or if the RNG quality requirement demands low concentrations of constituents in the final product, the RNG production facility may consist of multiple additional polishing units. For the most part, the central conditioning unit is concerned with the removal/stripping of bulk CO_2 from the raw biogas, to result in a gas which is predominantly methane. Commercially-available technologies are described in greater detail in the excellent summary report by the Swedish Gas Center (*Biogas Upgrading – Review of Commercial Technologies*, 2013), including descriptions of the theory behind the separation mechanism, the upgrading process as a complete system, operational issues and how these are solved, and financial data.

The SGC Report shows that for mid-scale applications, the most common options are all viable. The European market values a low “methane slip”; this is the quantity of methane which is expelled with the unwanted off-gases such as CO_2. According to the report, all scrubbing technologies performed well and have similar costs of investment and operation. The simplicity and reliability of the water scrubber has made this the preferred choice in many applications, but the high purity and very low methane slip from amine scrubbers are important characteristics. Regarding PSA and membrane units, the investment cost for these are on par with scrubbers. Furthermore, recent developments in membrane units have also made it possible to reach low methane slips with this technology. Cryogenic upgrading remains problematic, especially with regards to costs.

5.2 Biogas Scrubbers

5.2.1 Amine Scrubbers

Removal of CO_2 from gas is not a new process; it has been utilized for the removal of sour gas (CO_2 and hydrogen sulfide) from natural gas supplies. With regards to RNG conditioning, a selected amine binds to the CO_2, removing it from the gas. This is most commonly performed using a water solution of amines (molecules with carbon and nitrogen), with the reaction product being either in the molecular or ion form. A variety of amines may be used in the RNG conditioning process, with some preferred over others. There is usually gas sweetening (H_2S removal) upstream of the amine unit, to avoid smell and material issues downstream. Other units may be required upstream or downstream of the amine scrubber, depending on required gas quality.

5.2.2 Water Scrubbers

A water scrubber is a physical scrubber that uses the fact that CO_2 has much higher solubility than methane in water. In a water scrubber, carbon dioxide is separated from the raw biogas and dissolved into the water in the absorption column by using high pressure, normally 6-10 bar. The CO_2 is then released from the water again in the desorption column, by addition of air at atmospheric pressure. Volatile organic substances and ammonia may also be captured in the condensate. Other units may be required upstream or downstream of the water scrubber, depending on required gas quality.

5.2.3 Organic Physical Scrubbers

Organic physical scrubbing is similar to water scrubbing, but the CO_2 in the biogas is absorbed in an organic solvent (a glycol). As with each of the scrubbing units, there are advantages and disadvantages.

Other units may be required upstream or downstream of the organic physical scrubber, depending on required gas quality.

5.3 Membrane Technology

A membrane is a dense filter that can separate the components in a gas (or a liquid) to the molecular level. Membranes were used for landfill gas in early upgrading projects in the US, beginning in the 1990's. These early units were built with less selective membranes, with a much lower methane recovery demand. However, to be able to combine high methane recovery with high methane concentration requires more selective membranes and suitable design. The membranes used today for biogas upgrading retain most of the methane, while most of the CO_2 permeates through the membrane. This results in RNG which possesses a higher percentage of methane, with higher BTU and Wobbe. During the process of CO_2 separation, water vapor, hydrogen and oxygen may also be removed. Other units/filters may be required upstream or downstream of the central filter system, depending on required gas quality.

5.4 Pressure Swing Absorption (PSA)

Pressure swing adsorption (PSA) is a dry method used to separate gases via physical properties. Explaining PSA on a macro level, the raw biogas is compressed to an elevated pressure and fed into an adsorption column which retains the CO_2 but not the methane. When the column material is saturated with CO_2, the pressure is released; the CO_2 is then desorbed and led into an off-gas stream. For continuous production, several PSA columns are needed, opening and closing consecutively. PSA unit characteristics include feeding pressure, purging pressure, adsorbent, cycle time and column interconnectedness, among other things. Other units/filters may be required upstream or downstream of the PSA system, depending on required gas quality.

5.5 Cryogenic Technology

Cryogenic processes make use of exceptionally low temperatures in order to separation of gases. For the purposes of RNG production, the cryogenic units operate at temperatures well below -50 °C; this is the temperature where common gases become a liquid. The best developed cryogenic technologies available today are being used to remove trace impurities from landfill gas and other complex biogases; trace constituents are removed based upon liquefaction temperature. The gas is often purposely liquified for specific end use. Cryogenic technology is deeply rooted in the liquid nitrogen industry, but the SGA states: "Cryogenic upgrading is an interesting possibility, but … the technology still has some important operational issues to resolve."

5.6 Other Technologies for Trace Constituent Removal

5.6.1 Nitrogen

Nitrogen (N_2) is difficult and expensive to remove from biogas given the similar diameters of N_2 and methane molecules. Membrane systems and PSA systems are capable of removing some N_2 from the biogas stream, but often secondary nitrogen-rejection systems, using additional adsorbents, are required to meet RNG quality specifications. Nitrogen is commonly found in landfill gas, as ambient air seeps into the landfill, contributing to increased concentrations in the biogas.

5.6.2 Oxygen

Stand-alone oxygen (O_2) removal systems remove O_2 through a catalytic reactor. Membrane separators and PSA do remove some O_2, but removal may not be sufficient to meet RNG quality specifications. However, some PSA systems have been reported to be effective in removing nearly all O_2.

5.6.3 Siloxane/VOC Removal

For projects with smaller gas flows or projects with higher gas flows but relatively low concentrations of VOCs and siloxanes, a non-regenerative carbon medium is typically used to remove siloxane and VOC contaminants. Companies that specialize in the removal of specific compounds will analyze gas samples and prepare a site-specific carbon medium ‘recipe’ best suited for removing them. Under normal operation, gas quality is monitored to determine when the medium is saturated and replacement is necessary. These types of media can be disposed of in a landfill, and no other special handling is required.

For higher gas flows or projects with high concentrations of VOCs or siloxanes, a regenerative process is required. As with the non-regenerative systems, a medium is used to capture the contaminants, but instead of disposing of media once saturated, the media are regenerated through a temperature or PSA process. VOCs and siloxanes de-sorb with a change in pressure or temperature, and are directed to a flare for combustion.

5.6.4 Mercury/Metals

Mercury and other metals are difficult to remove from biogas. A standard activated carbon has low affinity for elemental mercury, which leads to low saturation loading. To increase the adsorption capacity, the activated carbon is impregnated with chemicals that react with mercury. Mercury removal can be achieved using either non-regenerative or regenerative adsorbents, as described above.

6. CHAPTER 5: RNG QUALITY PROGRAM

6.1 RNG Specification

RNG specifications are created from knowledge rooted in understanding the impacts/risks associated with the various receptors previously mentioned *and* referenced concentrations of specific constituents which clearly indicate impact. For each company, ONE specification is prepared, so that there is consistency and harmony throughout. A specification is not a “wish list” of constituents and concentrations. A proper RNG specification is carefully constructed, and follows the criteria below, so that it is defendable, reasonable and cost-effective to instate, and is rooted in science and reality, rather than emotion. The following six (6) points are the key elements of a good, defendable RNG Specification:

1) **Evidenced-Based**: The specification should be rooted in science, research, modeling and historical precedence. This is a critical aspect of a specification, so that it covers only the constituents and parameters which are relevant to actual impacts to the above-mentioned receptors. Otherwise, the specification may simply indicate a misunderstanding of the subject and be too broad and difficult to defend or instate.

2) **Referenced**: The specification should share consensus within the industry and be in line with the shared body of knowledge. A “referenced specification” indicates a level of assurance, so that the product is created from the best available knowledge on the topic, and that other major, reputable influencers/industry bodies of expertise agree with list of constituents and the clean-up levels required.

3) **Reasonable**: The specification should be easy to understand, be rational, be in line with applicable and high-quality research results, and be in consensus with industry and scientific experts. The applicable statement is, "Does this make sense?", or, "Are we asking the correct questions?"

4) **Justifiable**: Through the examination of databases, scientific papers, datasets or analytical reviews, can the list of proposed compounds be justified and are the gas quality standards reasonable? Why were the constituents on the list chosen? What were the cleanup values based on? What can we reasonably expect from a gas conditioning program? Is the specification too restrictive, which will cost more money to achieve? These questions, and more, serve as a basis for the critical evaluation of a specification.

5) **Verifiable**: This aspect of the specification is very important in that is considers whether the proposed analytical boundaries can, in fact, be confirmed through approved methods. This parameter of the specification is to ensure that the required concentrations are not outside of high-quality testing ranges. In other words, the required specification values need to be within the constraints of appropriate analytical methods.

6) **Achievable**: The specification should be achievable by best available demonstrated technologies for cleanup of raw biogas to quality RNG.

The RNG Quality Specification is then supported by a thorough gas quality Verification and Monitoring Program, discussed in Section 5.2.

The RNG Quality Specification should be accompanied by a Guidance Document or similar, to completely describe and justify all gas quality parameters required in the RNG specification, as well as detail the methods for field or on-line testing, sampling methods, laboratory analytical methods and other details specific to the application of the RNG specification. This way, the specification can be applied across the company and there is no question as to accuracy of results. Analysis of specific constituents within specific matrices (biogas/RNG/gases) is performed through specific analytical methods, using specific analytical procedures for sample collection (see Attachment 3 as example). A Guidance Document example has not been included in this document.

The following is a ***SAMPLE*** RNG QUALITY SPECIFICATION**. Each constituent and corresponding required value for cleanup is supported by the footnote reference document**. These references can be found in the Section 9 of this report. NOTE: RNG Quality Specifications can vary widely across the transmission sector of the natural gas industry in the US. Some are exceptionally conservative and some make wide allowances for variances. The circumstances by which each gas company decides on their RNG Quality Specification is specific to the company. Each gas company should carefully consider conditions specific to their company, with special attention to the following:

- Current natural gas tariff governing the injection location – allowances and variances
- Injection location
- Nearest off-take points
- Condition of the pipeline/special circumstances with respect to integrity concerns
- Volumes of gas injected into the system
- Volumes of gas within the system
- Pipe material, age, etc.
- Company policies, practices, etc.
- Sensitive end-users and proximity to injection point
- Locations and numbers of additional RNG facilities on the pipe

- Source of RNG
- History with RNG producer
- Others specific to the pipeline network

The ***SAMPLE*** RNG Quality Specification (Table 3) was created by REEthink, Inc. This RNG Quality Specification (below) has been adopted by a number of leading transmission companies in the US and Canada; the values are well supported, reasonable, justifiable, attainable, cost-effect and scientifically-based (see above). *It is offered as an example only*.

Table 3: ***Sample*** RNG Gas Quality Specification

PARAMETER	ABBREVIATION	PROPOSED VALUE	Tariff Limit or Assigned Value	UNIT
Heating Value[1]	HV	970	As Per Tariff Requirement	BTU/scf
Wobbe Number[1]		1297	As Per Tariff Requirement	BTU/scf
Carbon Dioxide	CO_2		As Per Tariff Requirement	% vol.
Oxygen	O_2		As Per Tariff Requirement	% vol.
Nitrogen	N_2		As Per Tariff Requirement	% vol.
Total $CO_2 + N_2 + O_2$			As Per Tariff Requirement	% vol.
Total Inerts			As Per Tariff Requirement	% vol.
Hydrogen Sulfide	H_2S		As Per Tariff Requirement	grains/100scf
Total Sulfur	S		As Per Tariff Requirement	grains/100scf
Moisture Content	H_2O		As Per Tariff Requirement	lbs/MMscf
Temperature			As Per Tariff Requirement	Fahrenheit
Objectionable Matter/Particulates/Biologicals			Commercially Free Of..	
Ammonia[2,3]	NH_3		0.001%	% vol.
Hydrogen[2,3]	H_2		*	% vol.
Siloxanes[1]	Si		0.5	mg Si/m^3
Chlorine Total[4,7]	Cl		10	mg/m^3
Fluorine Total[4,7]	F		1.0	mg/m^3
Mercury[2,3,4,7]	Hg		0.08	mg/m^3
Arsenic[2,3,4,7]	As		0.19	(mg/m^3)[5]
Copper[2,3,7]	Cu		0.6	(mg/m^3)[6]

*Hydrogen limit should be evaluated by Operator, considering their pipeline system and in coordination with INGAA Hydrogen Document

[1] CCST Report, June, 2018
[2] Rule 30, SoCal
[3] Rule 21, PG&E
[4] CGA, 2011
[5] 0.06 ppmv
[6] 0.23 ppmv
[7] BNQ 3672-100/2012

6.2 Verification Plan and Monitoring Programs

6.2.1 Overview

Gas quality Verification and Monitoring Programs are an essential and integral part of an RNG project. "Verification", as termed in this *SAMPLE* program, refers to a (up to) one month period of RNG testing aimed at confirming gas quality to specification requirements prior to pipeline injection. Likewise, the term "Monitoring" refers to confirming that the gas maintains high quality, through continuous, on-line analysis, and sampling for laboratory analysis, for a period of three (3) years and beyond.

Using the Verification and Monitoring Programs, 3 goals are achieved:

1. The gas company is able to monitor consistent quality and routine production of the RNG product over a trial period of time,
2. The RNG provider/cleanup unit operator is able to verify that the product is consistent and safe for pipeline introduction, and,
3. Both parties may better understand the changes required to the gas production process or gas injection system necessary to optimize the introduction of RNG to the pipeline network.

This period of examination also serves the following purposes:

1. Provides confidence to the gas company that the conditioning/cleanup system is reliable and operates consistently at high levels of performance.
2. Provides a dataset to the gas company to support a level of confidence in the quality of the product delivered to the pipeline grid.
3. Provides operational security and predictability in the performance of the conditioning system.
4. Allows the gas company to leverage the success of the projects towards additional RNG projects.
5. Educates both the gas company and the producer as to the parameters, characteristics and idiosyncrasies of the specific project, so that all understand and support the effort with transparency.

6.2.2 Description of Programs

Verification and Monitoring Programs are used to confirm that the conditioning unit is performing optimally, and that the RGN produced is of the pipeline quality required for inclusion to the pipeline network. This is an essential component to an RNG program. Because RNG cleanup systems vary, and conditions for RNG production are tailored to each project, it is important that gas quality is monitored in the short, medium and long term. The *Sample Programs* attached to this Document include the testing and analysis scheduling for the first three (3) years of the conditioning unit operation, and beyond, in perpetuity for the length of the project. Attached are two (2) *Sample* Programs: one for the biomass sources of LAM and Industrial-Grade Food Waste (Attachment 1) and one for the biomass sources of Landfill and WWT Sludge (Attachment 2).

The *Sample* Verification and Monitoring programs include a *pre-injection* Verification program for each biomass source and a *continuing* Monitoring program for each biomass source.

The Verification and Monitoring programs consider RNG produced from **two distinct biomass sources**: 1) LAM and industrial-grade food waste, and, 2) Landfill and WWT sludge. RNG produced from consumer-separated "Green Bin" AD and mixed AD, as well as LAM + Green Bin projects should be considered carefully, as constituents consistent with landfill and WWT sludge AD may be present. These projects should be examined on a case-by-case basis, with expanded and comprehensive laboratory testing until data proves the biogas source does not contain trace constituents of concern. Table 4 shows the testing required for each trace constituent in the RNG Quality Specification, by biogas source. RNG sampling and laboratory testing protocols are shown in Attachment 3.

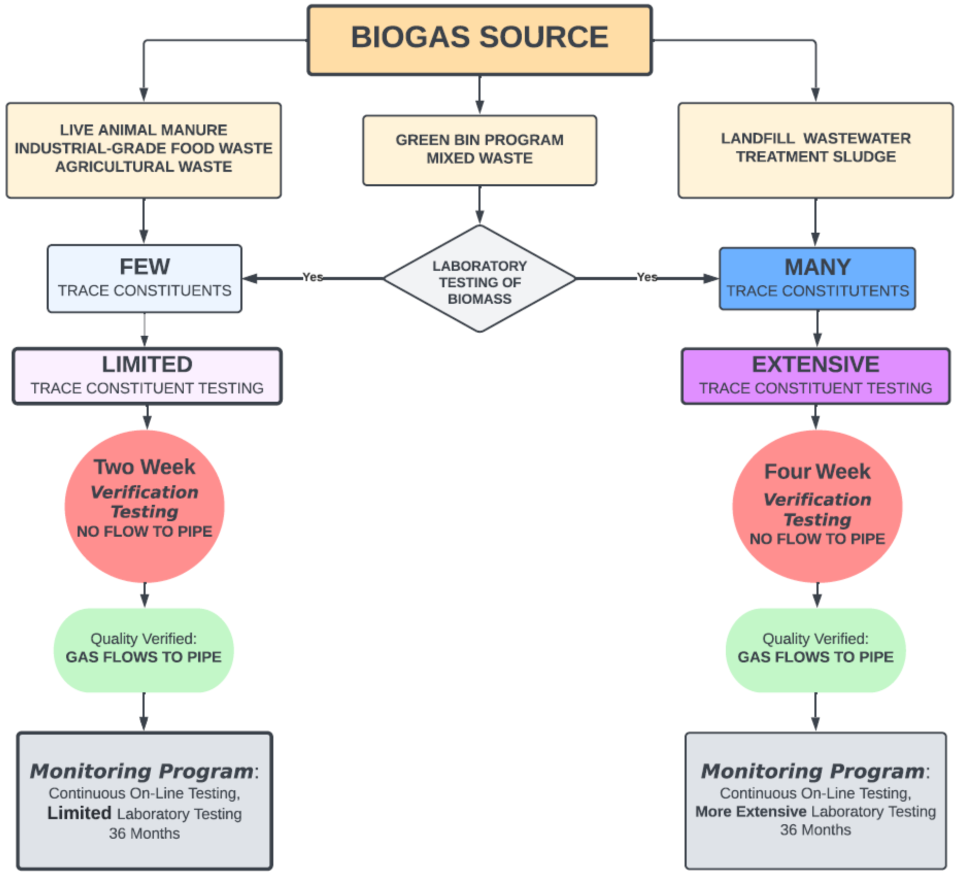
Table 4: Verification and Monitoring Testing Required by Biogas Source

TRACE CONSTUTENT	VERIFICATION AND MONITORING TESTING REQUIRED BY BIOGAS SOURCE				
	Landfill	Wastewater Treatment Slude AD	Green Bin AD (GBAD)	Live Animal Manure	Mixed Waste AD
Ammonia	X	X	X	X	X
Hydrogen	X	X	X	X	X
Siloxanes	X	X	Check Analytical		Check Analytical
Chlorine Total	X	X	Check Analytical		Check Analytical
Fluorine Total	X	X	Check Analytical		Check Analytical
Mercury	X	X	Check Analytical		Check Analytical
Arsenic	X	X	Check Analytical		Check Analytical
Copper	X	X	Check Analytical		Check Analytical

Check Analytical = Carefully review biomass source/biogas quality for indications of trace constituents associated with landfills, WWT, etc.; check RNG with Verification Testing associated with landfill, WWT, etc.

The Verification and Monitoring Protocols are different for the sources of RNG because of the testing regime associated with the trace constituents; LAM and industrial-grade food waste does not contain many of the trace constituents found in landfill and WWT biogas. Therefore, testing is less extensive. RNG from landfill and WWT sludge AD is more comprehensively tested for a wider variety of constituents. Each testing regime should be accompanied with detailed, specific language covering the parameters of the testing program, to be included in the interconnect agreement or legal document for the project. Figure 9 shows a Decision Tree, indicating the level of complexity associated with the Verification and Monitoring Programs, by biogas source (limited testing versus extensive testing of RNG over the period of the Program).

Figure 9: Decision Tree: Biogas Source and Applicable Verification and Monitoring Program



Verification and monitoring of gas quality should be considered an integral part of the project rather than an unexpected "add on". Monitoring through laboratory testing can be expensive, and turn-around times for analytical testing, especially for trace constituents, can be lengthy (3 weeks or more). Laboratory analyses can be expedited, but there is an upcharge. It is highly recommended that all costs associated with field sampling and laboratory analysis be carefully estimated and discussed with both gas company and RNG developers *prior to execution of the project*. This ensures that this important aspect to the RNG project does not "come as surprise"; adjustments to the Program may be necessary, depending upon specific company needs. Costs include field sampling (i.e., personnel, equipment, outside contractors, etc.), sample shipment costs, analytical costs per sample, report preparation (if needed), and review of data/verification. Verification and Monitoring Programs can be reduced in size and scope. *It is recommended that an RNG producer perform the entire Verification and Monitoring Program as written for its first project to the gas company system. Once the RNG producer has been vetted through the Program (or a major part of the Program), a reduced Verification and Monitoring Program may be appropriate*. This way, the gas company is secure that RNG production can be achieved safely and routinely *from the specific producer*, allowing subsequent projects with that producer to be more streamlined.

6.3 On-line Analytical Testing of RNG

The following on-line instrumentation should be installed by the gas company as part of the RNG program, at the point of injection into the pipeline. This instrumentation is used in conjunction with the Verification and Monitoring Program. The RNG supplier should install separate instrumentation and all equipment should be calibrated and checked frequently for identical analytical results. This redundant system allows for dual verification of gas quality and serves to protect the gas company and its assets.

Operators should work with their Gas Measurement Engineering Departments when selecting equipment, installation requirements and sample probe locations. Instrumentation packages are at the discretion of the gas company.

Suggested On-Line Instrumentation:

- Gas Chromatograph (GC) – 5-minute cycle suggested; SCADA interface and programs for calculations for Wobbe, inerts (Method ASTM D1945/1946)
- Oxygen Analyzer
- Sulfur Analyzer (H_2S included)
- Moisture Analyzer

At discretion of gas company:

- Redundant H_2S Analyzer
- CO_2 Analyzer
- Hydrogen Analyzer
- Mercury Analyzer
- Installation of a GC/Mass Spectrometer

As field instrumentation improves over time, some laboratory testing may be replaced with in-field, on-line instrumentation, for real-time, continuous testing of the RNG for the specific parameter.

6.4 Laboratory Testing of Trace Constituents

Constituents which cannot be tested in real time through installed on-line instrumentation must be determined through field sampling and laboratory analysis. Field sampling techniques and protocols are specific to the laboratory analysis required. It is essential that the correct field sampling technique be used for sample collection, and quality assurance/quality control procedures are followed. Collection of samples in the field must be performed using the correct equipment, technique, devise and protocol. Gas volumes are often required. It is advised to consult a qualified laboratory for proper sampling protocols prior to RNG sampling. A *Sample RNG Quality Parameters with Testing Methodologies* has been included (Attachment 3).

It is imperative that all trace constituent testing or testing which requires laboratory analysis (not measured through installed on-line analytical instrumentation) be performed with upmost quality and precision. Proper sample collection, sample handling and preservation, sample packaging (cooling, etc.) and sample delivery must be performed with care. It is therefore suggested that a qualified sample collection team be contracted for this job. Often, certified, accredited laboratories will collect samples for clients. The sample collection team will properly ship the samples to the most appropriate, accredited laboratories for analyses; analyses will be performed using the assigned methodology noted in this document. Samples will be sent to multiple laboratories, as RNG is a gaseous fuel and will be tested for a variety of constituents, some of which are deemed hazardous. Laboratories specialize in specific methods, using specific instrumentation. Refer to Attachment 3 for sample collection methods and the associated laboratory analysis for each trace constituent in the *SAMPLE* RNG Quality Specification. With respect to trace constituents, sample collection and management is integral to excellent laboratory data. If samples are not collected properly, time and money are wasted.

NOTE regarding Operator Qualification Compliance Plan:

If gas samples are collected by company employees or 3rd party contractors, the process is considered a *covered task* and must be part of an Operator Qualification Compliance Plan. Conformance with Department of Transportation (DOT) requirements set forth in 49 CFR § Subpart N is required. To ensure compliance with these regulations, the Company shall have a defined Operator Qualification Compliance Plan (Plan). This Plan defines how the Company will identify covered tasks that impact the safety or integrity of pipelines, qualifying individuals to perform those tasks, and managing the qualifications of pipeline personnel.

7. CHAPTER 6: RNG PRODUCERS

The field of RNG to the natural gas pipeline is still developing and companies participating in this space require guidance and assistance. Developers of RNG projects often are not aware of the constraints within the natural gas industry, with particular emphasis on gas quality and safety to pipeline infrastructure, end user requirements and human health and the environment concerns. It is therefore very important that developers be mindful, even at an early stage, of the full scope and requirements of the project. Early dialog between the gas company and the RNG producer is highly advised. With respect to the natural gas company, the following sample questions may aid in understanding RNG developer capabilities and prepare the potential developer for the breadth of the project. Level setting in this manner will help to minimize potential problems, such as lack of understanding of the full scope of the project, including all requirements, delays in schedule and project cost overruns. The following questions may be useful in helping the natural gas company assess the experience, capabilities and alignment of the potential RNG producer. The list is general in nature; the gas company should feel empowered to ask probing questions which reveal the level of experience and capabilities of the potential RNG producer:

1) Can our gas company visit a currently operating RNG unit which you have built? Can we see data from this unit? What is the source of biogas for your previous projects (is it the same as the proposed project?) Can you describe your previous experiences with construction, operation and maintenance?
2) Describe, in detail, the conditioning process you are proposing.
    a. Describe all primary and secondary processes.
    b. Detail the science behind the technology. How do you remove specific trace constituents to the required levels?
    c. With specific reference to the RNG Quality Specifications provided by our company, describe the anticipated outcomes (RNG quality) using your proposed process and list any anticipated limitations to performance.
    d. Describe your system with respect to retrofitting/improving/modifying if necessary for future improvements or requirements.
        i. In the future, biogas volumes may increase. Can your system adapt? Provide maximum volumes with current system and modifications to increase the volume. Also speak to limitations on the lower side of production.
3) Describe and detail the siloxane removal system for the process.
4) Describe the off-gas treatment process, if any, and the anticipated quality of off-gases from the process.
5) Describe and detail your SCADA system or engineering/process controls protocols.
6) Detail the requirements of the system in terms of utilities needs (electrical, water, etc.)
7) Detail the requirements of connection to the raw biogas source.
8) Detail the maintenance schedule typical to your system.
9) *Will you supply a performance guarantee?*
    a. *Performance guarantee for required RNG gas quality*
    b. *Performance guarantee for time required for system build/start up/gas verification/final delivery (make assumptions based upon gas company provided information)*

c. Others

10) Describe the on-line analytical equipment you will build into the program, so that gas continuously meets all RNG Quality Specification requirements.
    a. How will you verify gas quality?
    b. Describe on-line and laboratory testing you will be performing to quality the performance of your process.
    c. Have you built gas quality verification into your cost estimate?
11) Detail other features of your proposed conditioning program and system. What makes it superior?
12) Clearly explain and detail any contingencies to the process and limitations to your system.
13) Clearly explain any additional assumptions you made in preparing your proposal?

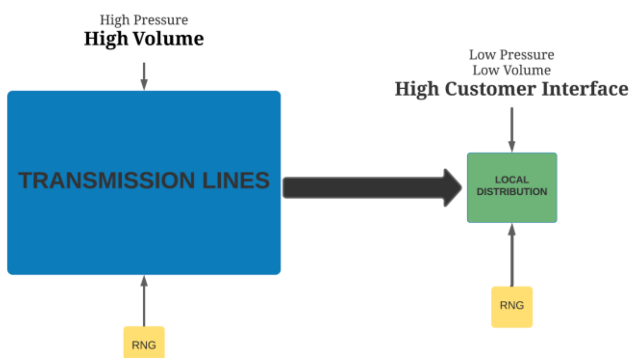
8. CHAPTER 7: INTERCONNECT AGREEMENTS

8.1 “Blending” of RNG with Natural Gas in the Pipeline

RNG which enters the pipeline network should always meet the RNG Quality Specification prepared by the gas company. Many natural gas tariffs permit blending of natural gas supplies, assuming that supplies vary with respect to the major components of natural gas (BTU, Wobbe, sulfurs, inerts, etc.). However, RNG contains a profile of trace constituents which are NOT found in natural gas supplies. It is projected that RNG will enter the pipeline, despite location, in greater quantities over time. Therefore, more concentrations of RNG will be present in the gas pipeline over time. Some constituents of concern pose immediate risk to the pipeline and associated receptors previously discussed. Others will, upon accumulation, become problematic. Due to the injection and off-take locations, it is hard to predict if RNG and natural gas will be sufficiently “blended”; database research and analysis of off-take gas where RNG is injected nearby upstream indicates that the “gas” neither fits a natural gas profile OR an RNG profile. The following schematics demonstrate the impacts of blending in the short and long term on a transmission system network. There is already evidence that there are impacts to odorization due to the levels of trace constituents entering the transmission network, by way of introduction of insufficiently cleaned RNG or other natural gas products (natural gas with excessive quantities of heavy hydrocarbons, etc.)

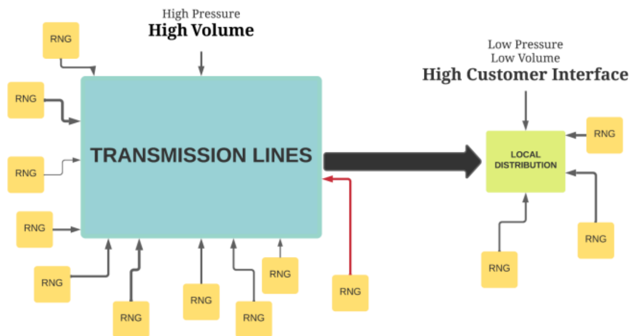
As shown in Figure 10, while the impacts of “blending” on the transmission system are “negligible” in the short term, the impacts to an LDC network can be realized quickly.

<u>Figure 10: Impacts of Off-Spec RNG on Transmission and LDC Pipeline (Blue+Yellow = Green), Present</u>



As more RNG enters the system, however, the impacts of trace constituents are more apparent (Figure 11). Some RNG sources will be more impactful than others. Special attention can be drawn to the injection point represented by the red arrow in the following schematic. At this point, the off-take is very close to the injection point and RNG cannot be masked through blending. This is already seen in some systems in the US. Due to potential impacts to pipeline integrity, the end-user and human health and the environment, using a scheme to “blend” undesirable constituents to meet gas quality specifications with respect to the trace constituents is not advised in the short or long term. RNG producers will only clean to the extent required by the gas company. Aside from contractual conflicts and prejudicial treatment of supplies depending upon injection point and gas flow, ONE RNG Quality Specification is advised, despite injection point or volumes, with variances used when needed.

Figure 11: Impacts of Off-Spec RNG on Transmission and LDC Pipeline, Projected Use Increased



9. CHAPTER 8: STORAGE

Most existing natural gas storage in the United States is in depleted natural gas or oil fields that are close to consumption centers. Conversion of a field from production to storage duty takes advantage of existing wells, gathering systems, and pipeline connections. Depleted oil and natural gas reservoirs are the most commonly used underground storage sites because of their wide availability.

In some areas, most notably the Midwestern United States, natural aquifers have been converted to natural gas storage reservoirs. An aquifer is suitable for gas storage if the water-bearing sedimentary rock formation is overlaid with an impermeable cap rock. The nature of the water in the aquifer may vary from fresh water to nearly saturated brines.

Salt caverns provide very high withdrawal and injection rates relative to their working gas capacity. Base gas requirements are relatively low. Most salt cavern storage facilities have been developed in salt dome formations located in the Gulf Coast states. Salt caverns have also been made (by a process called leaching) in bedded salt formations in Northeastern, Midwestern, and Southwestern states.

RNG impacts to underground gas storage should be considered. Little evidence or research exists stating impacts to storage field; few, if any, studies have been performed. Ideally, if an RNG Verification and Monitoring Program is in place and gas quality levels are meeting RNG Quality Specifications, RNG may not significantly influence internal corrosion concerns within the storage pool. However, a prudent operator should still prepare and instate an annual evaluation for internal corrosion. Internal corrosion programs should already be in place for evaluation of corrosive constituents in natural gas (H_2O, H_2S, CO_2, biologicals, etc.) during injection and withdrawal from the storage pool. This may involve the use of corrosion coupons, fluids analysis and gas sampling. This handled in a case-by-case basis, as each operator is different, depending upon how RNG gas is introduced to the storage system.

RNG trace constituents may have an impact on storage fields, but further studies should be considered to determine the impacts on permeability of the storage formation.

The potential health concerns of arsenic, mercury and copper interactions with water tables in certain storage formations is another topic of interest, although few studies have been performed to date.

10. REFERENCES

1. American Gas Association, AGA Report 4A, *Natural Gas Contract Measurement and Quality Clauses*, Catalog No. XQ0904, 2009

2. Swedish Gas Center, *Biogas Upgrading – Review of Commercial Technologies*, SGC Report 2013:270

3. Bureau de Normalisation du Quebec: BNQ 3672-100/2012, *Biomethane – Quality Specification for Injection into Natural Gas Distribution and Transmission Systems*

4. Canadian Gas Association (CGA), *Biomethane Guidelines for the Introduction of Biomethane into Existing Natural Gas Distribution & Transmission Systems*, February, 2011

5. California Air Resources Board and the Office of Health Hazard Assessment, California Environmental Protection Agency, *Recommendations to the California Public Utilities Commission Regarding Health Protective Standards for the Injection of Biomethane into the Common Carrier Pipeline*, May 15, 2013

6. California Council on Science & Technology (CCST), *Biomethane in California Common Carrier Pipelines: Assessing Heating Values and Maximum Siloxane Specifications*, June, 2018

7. Gas Technology Institute, *Pipeline Quality Biomethane: North American Guidance Document for Introduction of Dairy Waste Derived Biomethane into Existing Natural Gas Networks*, February, 2009

8. Gas Technology Institute, *Pipeline Quality Biogas: Guidance Document for Dairy Waste, Wastewater Treatment Sludge and Landfill Conversion*, December, 2009

9. Gas Rule No. 21, Pacific Gas & Electric, 2009

10. Gas Rule No. 30, Southern California Gas Company, 2011

11. MarcoGaz Working Group, *Injection of Gases from Non-Conventional Sources into Gas Networks, Final Recommendation*, January, 2006

12. NGC+ Interchangeability Work Group, *White Paper on Natural Gas Interchangeability and Non-Combustion End Use*, February, 2005

13. Pipeline Research Council International, Inc. (PRCI), *Emerging Fuels – Renewable Natural Gas State-Of-The-Art, Gap Analysis, Future Project Roadmap*, MEAS-15-03, Catalog No. PR306-20604-R01, Measurement Technical Committee of PRCI, prepared by GRTgaz, December, 2020 FINAL

11. ADDITIONAL RESOURCES

AgSTAR: Biogas Recovery in the Agriculture Sector | US EPA https://www.epa.gov/agstar
Anaerobic Digestion (AD) | US EPA https://www.epa.gov/anaerobic-digestion
Biogas Toolkit | US EPA https://www.epa.gov/agstar/biogas-toolkit
Pipeline Database: Major Transmissions Gas Pipeline Tariffs — The Coalition For Renewable Natural Gas (rngcoalition.com) https://www.rngcoalition.com/pipeline-database

Northeast Gas Association: Renewable Gas / Bio Gas
https://www.northeastgas.org/renewable_natural_gas.php
RIN Calculator | American Biogas Council https://americanbiogascouncil.org/resources/rin-calculator/
Renewable Natural Gas Database | Argonne National Laboratory (anl.gov)
https://www.anl.gov/es/reference/renewable-natural-gas-database
Alternative Fuels Data Center: Renewable Natural Gas Production (energy.gov)
https://afdc.energy.gov/fuels/natural_gas_renewable.html
WEF Biogas Data (resourcerecoverydata.org) https://www.resourcerecoverydata.org/
Renewable Natural Gas | World Resources Institute (wri.org)
https://www.wri.org/initiatives/renewable-natural-gas
Renewable Natural Gas (ca.gov) https://www.cpuc.ca.gov/renewable_natural_gas/
Renewable Natural Gas Projects & Policy | RNG Coalition https://www.rngcoalition.com/
Championing the Biogas Industry | American Biogas (americanbiogascouncil.org)
https://americanbiogascouncil.org/
Resources : Canadian Biogas Association https://biogasassociation.ca/resources/

SAMPLE RNG VERIFICATION and MONITORING PROGRAM GUIDELINES FOR INJECTION TO THE NATURAL GAS PIPELINE GRID: LAM and INDUSTRIAL-GRADE FOOD WASTE

	TARIFF - MAJOR COMPONENTS									
	PARAMETER and COMPANY APPROVED ON-LINE, CONTINOUS METHODOLOGY/EQUIPMENT									
	HHV	WOBBE	CARBON DIOXIDE	OXYGEN	NITROGEN	TOTAL INERTS (CO_2 + N_2 + O_2)	HYDROGEN SULFIDE	TOTAL SULFUR	MOISTURE CONTENT	DELIVERY TEMP
Tariff Limit or Assigned Value	As Per Tariff Require	As Per Tariff Require	As Per Tariff Require	As Per Tariff Require	As Per Tariff Require	As Per Tariff Require	As Per Tariff Require	As Per Tariff Require	AS Per Tariff Require	As Per Tariff Require
Referenced Method*	ASTM D1945/D1946	ASTM D3588	ASTM D1945/D1946	ASTM D1945/D1946	ASTM D1945/D1946	ASTM D1945/D1946	ASTM D6228/D5504	ASTM D6228/D5504	ASTM D1142 or ASTM D5454	RTD in meter tube thermo well
Sampling Method*	Online GC	Online GC	Online Analyzer	Online Analyzer	Online Analyzer	Online Analyzer	Online Analyzer	Online Analyzer	Online Analyzer	Online Analysis
RNG VERIFICATION PERIOD (2 WEEKS) GAS NOT INJECTED INTO PIPELINE										
WEEK 1 Testing	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous
WEEK 2 Testing	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous
(2 Weeks consistently meeting specification)										
Start-Up Sampling Events**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**
MONITORING PERIOD 1 (Month 2 -6) GAS FLOWS TO PIPE										
Continuous	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Bi-Weekly (5 Months)										
Total Month 2 - 6 Sampling Events**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**
MONITORING PERIOD 2 (Month 7 - 18)										
Continuous	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Monthly (Total Count)										
Bi-Annually										
Total Month 7 - 18 Sampling Events**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**
MONITORING PERIOD 3 (Month 19 - 36)										
Continuous	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Monthly										
Quarterly (Every 3 months for 18 months)										
Bi-Annually (Every 6 months for 18 Months)										
Total Month 19 - 36 Sampling Events**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**
MONITORING PERIOD 4 (In Perpetuity)										
Continuous	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

* Approved instrumentation and methodology only

** NOTE: All on-line analysis is continuous, always.

NOTES: Events or conditions that trigger addition laboratory analysis include: a significant reading of off-spec RNG as indicated by the continuous analyser(s), an expansion of the RNG generation process, an indication of a significant change in the RNG composition, addition of a new biomass source. NOTE THE FOLLOWING IMPORTANT INFORMATION: If any parameter measured through C*ontinuous Testing* exceeds the tariff limits or assigned values **for three (3) consecutive readings with on-line instrumentation, immediate shut-in of the RNG will occur**. Gas must be flared until the situation has been recified and the producer can verify gas quality standards for 24 hours minimum. Sampling methods and analytical test methods may be modified or changed over time, based upon updates in test methods and instrumentation. Proposed alternative test methods, especially for trace constituents, must be approved by the Company. The Company reserves the right to modify this program based upon testing results.

SAMPLE **RNG VERIFICATION and MONITORING PROGRAM GUIDELINES FOR INJECTION TO THE NATURAL GAS PIPELINE GRID:**
LAM and INDUSTRIAL-GRADE FOOD WASTE: LABORATORY TESTING SAMPLING EVENTS

	TRACE CONSTITUENTS		
	PARAMETER and TESTING BY THIRD PARTY LABORATORIES		
	HYDROGEN	AMMONIA	PARTICULATES/BIOLOGICALS
Tariff Limit or Assigned Value	0.30%	0.001%	Commerically Free of...
Referenced Method*	ASTM D1945/D1946	OSHA ID 188	Monitored by In-Line Coupon (Metal Pipes)
Sampling Method*	GC/TCD	Ion Chromatography	Filter as per protocol
RNG VERIFICATION PERIOD (2 Weeks) GAS <u>NOT</u> INJECTED INTO PIPELINE**			
WEEK 1 Testing: (1 Event X Triplicate Samples)	1	1	
WEEK 2 Testing: (1 Event X Triplicate Samples)	1	1	
(2 Test Sets Consistently Meeting Specification - one per week)			
Start-Up Sampling Events***	**2**	**2**	Check filter/coupon at completion
MONITORING PERIOD 1 (Month 2 - 6) GAS FLOWS TO PIPE			
Continuous			
Monthly (5 Months)	5	5	
Total Month 1 - 6 Sampling Events***	**5**	**5**	Coupon retreived at completion
MONITORING PERIOD 2 (Month 7 - 18)			
Continuous			
Monthly (Total Count)			
Bi-Annually (Every 6 months for 12 Months)	2	2	
Total Month 7 - 18 Sampling Events***	**2**	**2**	Coupon retreived at completion
MONITORING PERIOD 3 (Month 19 - 36)			
Continuous			
Bi-Annually (Every 6 months for 18 Months)	3	3	
Total Month 19 - 36 Sampling Events***	**3**	**3**	Coupon retrieved bi-annually
MONITORING PERIOD 4 (In Perpetuity)			
Annual Check***	**1**	**1**	Coupon retrieved annually or as indicated

* Approved methodology only

** NOTE: A full analytical profile of <u>all trace constituents in the RNG Specification</u> is to be performed once at the beginning of this Period

*** Event x Number Required = Total Sample Events; During each sampling event, samples are taken in TRIPLICATE for each parameter.

NOTES: Events or conditions that trigger addition laboratory analysis include: a significant reading of off-spec RNG as indicated by the continuous analyser(s), an expansion of the RNG generation process, an indication of a significant change in the RNG composition, addition of a new biomass source. NOTE THE FOLLOWING IMPORTANT INFORMATION: If any parameter measured through C*ontinuous Testing* exceeds the tariff limits or assigned values **for three (3) consecutive readings with on-line instrumentation, immediate shut-in of the RNG will occur**. Gas must be flared until the situation has been recified and the producer can verify gas quality standards for up to 24 hours minimum. Sampling methods and analytical test methods may be modified or changed over time, based upon updates in test methods and instrumentation. Proposed alternative test methods, especially for trace constituents, must be approved by the Company. The Company reserves the right to modify this program based upon results of sampling. The Company reserves the right to update laboratory methodologies, as newer, more accurate, less expensive approved approaches become available.

ATTACHMENT 2

SAMPLE RNG Plant Start-Up, Verification and Monitoring Program Guidelines for Injection to the Natural Gas Pipeline Grid:
Landfill and WWT Sludge

SAMPLE **RNG VERIFICATION and MONITORING PROGRAM GUIDELINES FOR INJECTION TO THE NATURAL GAS PIPELINE GRID: LANDFILL and WWT SLUDGE**

	TARIFF - MAJOR COMPONENTS									
	PARAMETER and COMPANY APPROVED ON-LINE, CONTINOUS METHODOLOGY/EQUIPMENT									
	HHV	**WOBBE**	**CARBON DIOXIDE**	**OXYGEN**	**NITROGEN**	**TOTAL INERTS (CO2 + N2 + O2)**	**HYDROGEN SULFIDE**	**TOTAL SULFUR**	**MOISTURE CONTENT**	**DELIVERY TEMP**
Tariff Limit or Assigned Value	As Per Tariff Require	As Per Tariff Require	As Per Tariff Require	As Per Tariff Require	As Per Tariff Require	As Per Tariff Require	As Per Tariff Require	As Per Tariff Require	AS Per Tariff Require	As Per Tariff Require
Referenced Method*	ASTM D1945/D1946	ASTM D3588	ASTM D1945/D1946	ASTM D1945/D1946	ASTM D1945/D1946	ASTM D1945/D1946	ASTM D6228/D5504	ASTM D6228/D5504	ASTM D1142 or ASTM D5454	RTD in meter tube thermo well
Sampling Method*	Online GC	Online GC	Online Analyzer	Online Analyzer	Online Analyzer	Online Analyzer	Online Analyzer	Online Analyzer	Online Analyzer	Online Analysis
RNG VERIFICATION PERIOD (Month 1) **GAS <u>NOT</u> INJECTED INTO PIPELINE**										
WEEK 1 Testing	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous
WEEKS 2 - 4 Testing	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous
(4 weeks consistently meeting specification)										
Start-Up Sampling Events**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**
MONITORING PERIOD 1 (Month 2 -6) **GAS FLOWS TO PIPE**										
Continuous	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Bi-Weekly (5 Months)										
Total Month 2 - 6 Sampling Events**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**
MONITORING PERIOD 2 (Month 7 - 18)										
Continuous	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Monthly (Total Count)										
Bi-Annually										
Total Month 7 - 18 Sampling Events**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**
MONITORING PERIOD 3 (Month 19 - 36)										
Continuous	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Monthly										
Quarterly (Every 3 months for 18 months)										
Bi-Annually (Every 6 months for 18 Months)										
Total Month 19 - 36 Sampling Events**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**	**Continuous**
MONITORING PERIOD 4 (In Perpetuity)										
Continuous	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

* Approved instrumentation and methodology only

** NOTE: All on-line analysis is continuous, always.

NOTES: Events or conditions that trigger addition laboratory analysis include: a significant reading of off-spec RNG as indicated by the continuous analyser(s), an expansion of the RNG generation process, an indication of a significant change in the RNG composition, addition of a new biomass source. NOTE THE FOLLOWING IMPORTANT INFORMATION: If any parameter measured through C*ontinuous Testing* exceeds the tariff limits or assigned values **for three (3) consecutive readings with on-line instrumentation, immediate shut-in of the RNG will occur**. Gas must be flared, etc. by the producer until the situation has been recified and the producer can verify gas quality standards for 24 hours minimum. Sampling methods and analytical test methods may be modified or changed over time, based upon updates in test methods and instrumentation. Proposed alternative test methods, especially for trace constituents, must be approved by the Company. The Company reserves the right to modify this program based upon testing results.

SAMPLE RNG VERIFICATION and MONITORING PROGRAM GUIDELINES FOR INJECTION TO THE NATURAL GAS PIPELINE GRID:

LANDFILL and WWT SLUDGE: LABORATORY TESTING SAMPLING EVENTS

	TRACE CONSTITUENTS								
	PARAMETER and TESTING BY THIRD PARTY LABORATORIES								
	HYDROGEN	AMMONIA	SILOXANES	CHLORINE: TOTAL	FLUORINE: TOTAL	PARTICULATES/BIOLOGICALS	MERCURY	ARSENIC	COPPER
Tariff Limit or Assigned Value	0.30%	0.001%	0.5 mg Si/m3	10 mg/m3	1 mg/m3	Commerically Free of...	0.08 mg/m3	0.19 mg/m3 or 0.06 ppmv	0.60 mg/m3 or 0.23 ppmv
Referenced Method*	ASTM D1945/D1946	OSHA ID-188	ASTM D8230-19	EPA TO-15	EPA TO-15	Monitored by In-Line Coupon	ASTM D5954	EPA Method 29	EPA Method 29
Sampling Method*	GC/TCD	Ion Chromatography	GC/MS	GC/MS	GC/MS	Filter as per protocol	AAS	AAS/ICAP	AAS/ICAP
RNG VERIFICATION PERIOD (Month 1) **GAS NOT INJECTED TO PIPELINE**									
WEEK 1 Testing: (1 Event x Triplicate Samples)	1	1	1	1	1		1	1	1
WEEKS 2-4 Testing: (1 Event per Week x Triplicate Samples)	3	3	3	3	3		3	3	3
(4 Test Sets Consistently Meeting Specification)									
Start-Up Sampling Events**	**4**	**4**	**4**	**4**	**4**	Check filter/coupon at completion	**4**	**4**	**4**
MONITORING PERIOD 1 (Month 2 - 6) **GAS FLOWS TO PIPE**									
Continuous									
Bi-Weekly (5 Months): (1 Event, 2x a Month)	10	10	10	10	10		10	10	10
Total Month 2 - 6 Sampling Events**	**10**	**10**	**10**	**10**	**10**	Coupon retrieved at completion	**10**	**10**	**10**
MONITORING PERIOD 2 (Month 7 - 18)									
Continuous									
Monthly (Total Count) (12 Months)	12	12	12	12	12		12	12	12
Total Month 7 - 18 Sampling Events**	**12**	**12**	**12**	**12**	**12**	Coupon retrieved at completion	**12**	**12**	**12**
MONITORING PERIOD 3 (Month 19 - 36)									
Continuous									
Monthly									
Quarterly (Every 3 months for 18 months)			6						
Bi-Annually (Every 6 months for 18 Months)	3	3		3	3		3	3	3
Total Month 19 - 36 Sampling Events**	**3**	**3**	**6**	**3**	**3**	Coupon retrieved bi-annually	**3**	**3**	**3**
MONITORING PERIOD 4 (In Perpetuity)									
Annual Check**	**1**	**1**	**1**	**1**	**1**	Coupon retrieved annually or as indicated	**1**	**1**	**1**

* Approved Company methodology only

** Event x Number Required = Total Sample Events; During each sampling event, samples are taken in TRIPLICATE for each parameter.

NOTES: Events or conditions that trigger addition laboratory analysis include: a significant reading of off-spec RNG as indicated by the continuous analyser(s), an expansion of the RNG generation process, an indication of a significant change in the RNG composition, addition of a new biomass source. NOTE THE FOLLOWING IMPORTANT INFORMATION: If any parameter measured through C*ontinuous Testing* exceeds the tariff limits or assigned values **for three (3) consecutive reading with on-line instrumentation, immediate shut-in of the RNG will occur**. Gas must be flared until the situation has been recified and the producer can verify gas quality standards for up to 24 hours minimum. Sampling methods and analytical test methods may be modified or changed over time, based upon updates in test methods and instrumentation. Proposed alternative test methods, especially for trace constituents, must be approved by the Company. The Company reserves the right to modify this program, based on results of testing over time. The Company reserves the right to update laboratory methodologies, as newer, more accurate, less expensive approved approaches become available.

ATTACHMENT 3

SAMPLE RNG GAS QUALITY *Sample RNG Quality Parameters with Testing Methodologies*

SAMPLE RNG QUALITY PARAMETERS WITH TESTING METHODOLOGIES*							Testing Required: Biogas Source			
Gas Quality Constituent	**Reference**	**Specific Tariff Limit or Assigned Value**	**Instrumentation***	**Analytical Method***	**Sampling Material or Devise**	**Comments**	**Landfill**	**WWT**	**MIX AD****	**LAM**
High Heating Value (HHV)	Published Tariff/Historical, 1	As Per Tariff Requirement	Online Gas Chromatograph - Company Approved	ASTM D1945/D1946	Continuous Online	Standard Procedure	X	X	X	X
Wobbe Number	Published Tariff/Historical, 1	As Per Tariff Requirement	Online Gas Chromatograph/Calculation - Company Approved	ASTM D3588	Continuous Online - Calculated	Standard Procedure	X	X	X	X
Carbon Dioxide (CO2)	Published Tariff/Historical	As Per Tariff Requirement	Online Gas Chromatograph	ASTM D1945/D1946	Continuous Online	Standard Procedure	X	X	X	X
Oxygen (O2)	Published Tariff/Historical	As Per Tariff Requirement	Online Gas Chromatograph	ASTM D1945/D1946	Continuous Online	Standard Procedure	X	X	X	X
Nitrogen (N2)	Published Tariff/Historical	As Per Tariff Requirement	Online Gas Chromatograph	ASTM D1945/D1946	Continuous Online	Standard Procedure	X	X	X	X
Total Inerts (CO2 + N2 + O2)	Published Tariff/Historical	As Per Tariff Requirement	Online Gas Chromatograph	ASTM D1945/D1946	Continuous Online	Standard, stated as Total Inerts	X	X	X	X
Hydrogen Sulfide	Published Tariff/Historical	As Per Tariff Requirement	Online Analyzer	ASTM D6228/D5504	Continuous Online	Standard Procedure	X	X	X	X
Total Sulfur	Published Tariff/Historial	As Per Tariff Requirement	Online Analyzer	ASTM D6228/D5504	Continuous Online	Standard Procedure	X	X	X	X
Moisture Content	Published Tariff	As Per Tariff Requirement	Online Analysis	ASTM D1142 or ASTM D5454	Continuous Online	Standard Procedure	X	X	X	X
Delivery Temperature	Published Tariff	As Per Tariff Requirement	Online Analysis	RTD in meter tube thermo well	Continuous Online	Temperature of the injection gas	X	X	X	X
Particulates/Biologicals	Published Tariff	Commerically Free Of...			Filter prior to gas introduction	HEPA filter recommended prior to gas introduction; Monitored by in-line EM/EA coupon	X	X	X	X
Ammonia	Ref. 2, 3	0.001 vol%	GC/NCD or Equiv.	OHSA ID-188	Mod. EPA Method 26		X	X	X	X
Hydrogen	Ref. 2, 3	0.3 vol%	Gas Chromatography/Thermal Conductivity Detector	ASTM D1945/D1946	Tedlar Bag	Specific to pipeline integrity; Measured with Major Components	X	X	X	X
Siloxanes	Ref. 1	0.5 mg Si/m3	Gas Chromatography/Mass Spectrometry	ASTM D8230-19	Tedlar bag - Analysis within 72 hours	ASTM approved method	X	X	X	
Halocarbons (Halogens)	Ref. 4, 5	Chlorine: 10 mg/m3 Fluorine: 1 mg/m3	Gas Chromatography/Mass Spectrometry	EPA TO-15***	5-L Tedlar Bag; Summa Canisters; Impinger method in field:USEPA Method 26/26A	Use impinger method for Cl and F quantification only	X	X	X	
Mercury	Ref.2, 3, 4, 5	0.08 mg/m3	Atomic Adsorption Spectroscopy	NIOSH D5954	Gold Plated Silica Beads		X	X	X	
Arsenic	Ref. 2, 3, 4, 5	0.19 mg/m3 or 0.06 ppmv	Atomic Adsorption Spectroscopy/ICAP	EPA Method 29 Modified	EPA Method 29		X	X	X	
Copper	Ref. 2, 3, 5	0.60 mg/m3 or 0.23 ppmv	Atomic Adsorption Spectroscopy/ICAP	EPA Method 29 Modified	EPA Method 29		X	X	X	

Reference 1 CCST Report, June, 2018
Reference 2 Rule 30, SoCal
Reference 3 Rule 21, PG&E
Reference 4 CGA, 2011
Reference 5 BNQ 3672-100/2012

* Sampling methods and analytical testing methods for trace constituents may be updated over time. Alternative methods must be approved by the Company.
** Must verify quality of biogas for AD source material in order to qualify for reduced Verification Testing
***TO-15 with calculation for total chlorine and fluorine, considering molecular weight and % of total compound, unless impinger method is used