Biomethane RNG History and Background

Western Gas Measurement Short Course
Hyatt Regency SFO Airport
San Francisco, CA
May 4 – 7, 2026

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Outline

- Three Energy Transitions in North America
- Comparisons of Biogas and Biomethane
  - How it is produced
  - How it is cleaned
- Trace Constituents in Biomethane
- Risk of Trace Constituents to Receptors
- Creation of a Defendable Specification
- Sampling & Laboratory Testing of Trace Constituents
- Verification and Monitoring Programs for RNG

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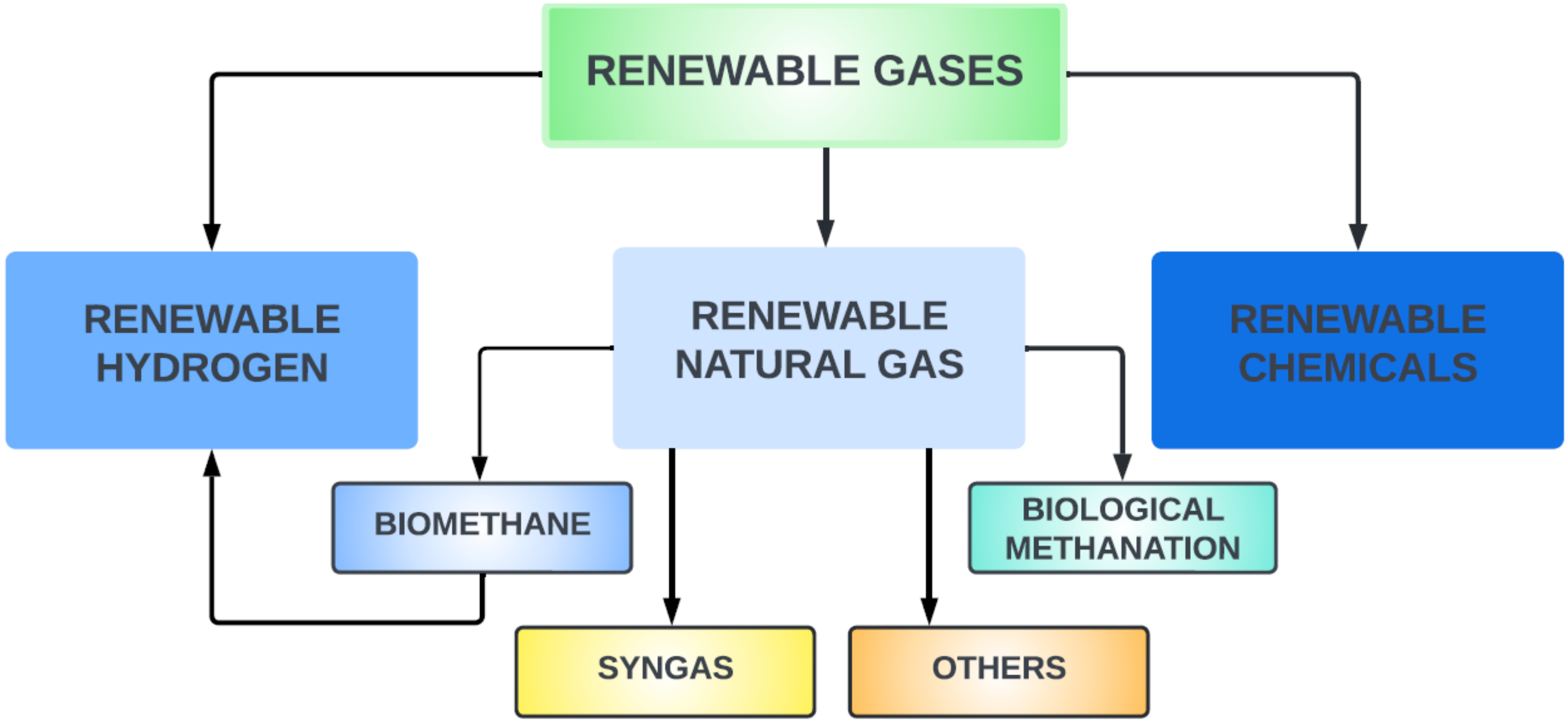
Renewable Gases: Definition?



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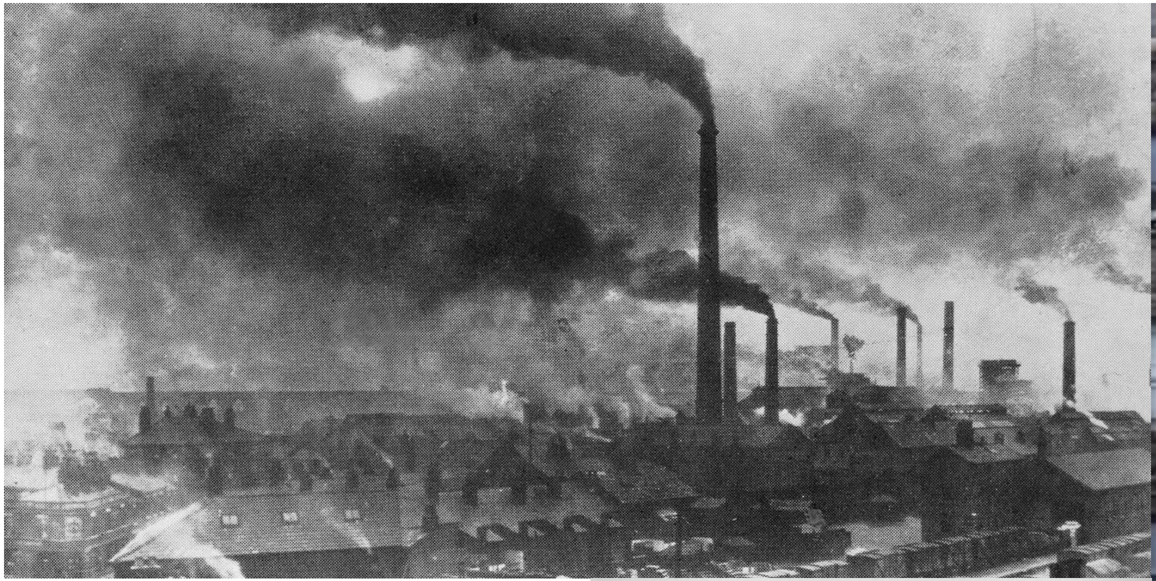
ENERGY HARNESSING:
It Started With Coal/Wood



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First (Gaseous) Fuel Transition

LOCALIZED PRODUCTION

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GASEOUS FUEL COMPOSITIONS

CONSTITUENT	TOWN GAS
BTU	480 - 550
WOBBE	N/A
Methane (C1)	27.5- 30.7%
Ethane (C2)	N/A
Propane (C3)	N/A
Butanes+ (C4)	N/A
Carbon Dioxide	16.3 - 19.9%
Carbon Monoxide	1.0 - 6.9%
Oxygen	Combo with N2: 0.6 - 5%
Nitrogen	Combo with O2: 0.6 - 5%
Hydrogen	46.3 - 55%
Hydrogen Sulfide	N/A
Total Sulfur	N/A
TRACE CONSTITUENTS	Many - but not considered

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Second Gaseous Fuel Transition

NETWORK OF PIPES CONNECTING THE SYSTEM

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GASEOUS FUEL COMPOSITIONS

CONSTITUENT	TOWN GAS	NATURAL GAS
BTU	480 - 550	950 - 1110
WOBBE	N/A	1234 - 1400
Methane (C1)	27.5- 30.7%	78 - 98%
Ethane (C2)	N/A	Up to 9%
Propane (C3)	N/A	Up to 5% (Limit 2%)
Butanes+ (C4)	N/A	Up to 4.8% (Limit 1.5%)
Carbon Dioxide	16.3 - 19.9%	2 - 3%
Carbon Monoxide	1.0 - 6.9%	N/A
Oxygen	Combo with N2: 0.6 - 5%	0.2 - 1%
Nitrogen	Combo with O2: 0.6 - 5%	3 - 6% (Limit 4%)
Hydrogen	46.3 - 55%	Up to 7% (Limits vary or N/A)
Hydrogen Sulfide	N/A	.25 - 1 gr/100scf
Total Sulfur	N/A	1 - 20 gr/100scf
TRACE CONSTITUENTS	Many - but not considered	Few

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GENERAL TERMS AND CONDITIONS

26. QUALITY

26.1 SPECIFICATIONS

Unless otherwise stated in an Agreement, natural gas delivered by or on behalf of Shipper to Natural at any Receipt Point, and natural gas delivered by Natural to or for the account of Shipper at any Delivery Point, shall be of pipeline quality and shall conform to the following specifications:

(a) OXYGEN

The oxygen content shall not exceed ten parts per million (10 ppm) by volume of uncombined oxygen, and the parties shall make reasonable efforts to maintain the gas free from oxygen.

(b) HYDROGEN SULFIDE

The hydrogen sulfide content shall not exceed one-quarter (1/4) grain per hundred (100) cubic feet of gas.

(c) MERCAPTANS

The mercaptan content shall not exceed one-quarter (1/4) grain per one hundred (100) cubic feet of gas.

(d) TOTAL SULFUR

The total sulfur content, including mercaptans and hydrogen sulfide, shall not exceed one-half (1/2) grain per one hundred (100) cubic feet of gas.

(e) CARBON DIOXIDE

The carbon dioxide content shall not exceed two percent (2%) by volume.

a) be free of objectionable elements or compounds that will render the gas unusable for its commonly used applications;
b) be commercially free from dust, gums, gum-forming constituents, or other liquid or solid matter which might become separated from the gas in the course of transportation through the pipeline or which could cause inaccurate measurement;

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Natural Gas Tariff Language

MAJOR COMPONENTS

- **BTU, WOBBE**
- **Inert Gases**
  - Carbon Dioxide
  - Oxygen
  - Nitrogen
  - Helium
  - Carbon Monoxide
- **Sulfur Compounds**
  - Hydrogen Sulfide
  - Mercaptans
  - Total Sulfur

Physical Attributes

- Moisture
- Hydrocarbon Dewpoint
- Temperature
- Characteristics upon burning

COVERED IN TARIFF LANGUAGE

TRACE CONSTITUENTS/"Objectionable Material"

NOT WELL DEFINED

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Natural Gas Quality Verification and Monitoring

- Installed instrumentation monitoring gas quality in **real-time, on-line, 24/7/365**
  - GC (C1 – C12): BTU, Wobbe, Inerts, HDP
  - Sulfur analyzer/H_2S
  - Oxygen analyzer
  - Moisture analyzer
  - Temperature
- SCADA interface
- Recorded database/legacy recording
- Shut-in conditions defined
- All major components measured
- Used for legal defense

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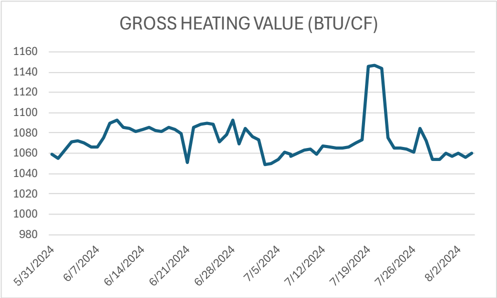
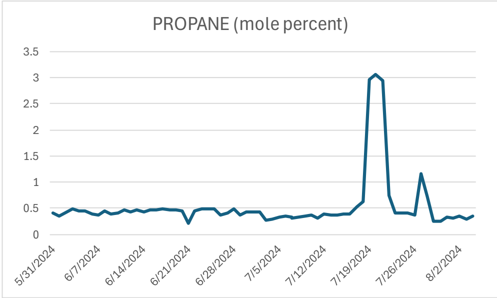
LOCATION DESCRIPTION	GROSS HEATING VALUE (BTU/CF)	SPECIFIC GRAVITY	WOBBE (calc)	CRICOND ENTHERM (deg F)	NITROGE N (mole percent)	CARBON DIOXIDE (mole percent)	METHANE (mole percent)	ETHANE (mole percent)	PROPANE (mole percent)	NORMAL BUTANE (mole percent)	ISO BUTANE (mole percent)	PENTANE (mole percent)	ISO PENTANE (mole percent)	NEO PENTANE (mole percent)	HEXANES PLUS (mole percent)	PRODUCT ION DATE	POSTING DATE
NORTHERN ARE	1059	0.6111	1354.7	-51.6	1.5611	0.6998	89.4707	7.7937	0.4112	0.0338	0.014	0.0036	0.0086	0.0004	0.0033	5/31/2024	6/1/2024
NORTHERN ARE	1059	0.6111	1354.7	-51.6	1.5611	0.6998	89.4707	7.7937	0.4112	0.0338	0.014	0.0036	0.0086	0.0004	0.0033	5/31/2024	6/2/2024
NORTHERN ARE	1054.5	0.606	1354.6	-55.7	1.4419	0.6476	90.3558	7.1641	0.3452	0.0226	0.0122	0.0025	0.0052	0.0001	0.003	6/1/2024	6/3/2024
NORTHERN ARE	1070.9	0.6222	1357.6	-38.1	1.8189	0.7557	87.3067	9.5551	0.494	0.036	0.0141	0.0035	0.0087	0.0004	0.0071	6/3/2024	6/4/2024
NORTHERN ARE	1072.3	0.6216	1360	-59.8	1.7223	0.7247	87.3305	9.716	0.455	0.0282	0.0122	0.0027	0.0066	0.0003	0.0016	6/4/2024	6/5/2024
NORTHERN ARE	1069.8	0.6184	1360.4	-59.1	1.6112	0.6976	87.97	9.2275	0.4373	0.0254	0.0144	0.004	0.0103	0.0005	0.002	6/5/2024	6/6/2024
NORTHERN ARE	1066	0.6152	1359.1	-65	1.5595	0.6806	88.5505	8.7772	0.3823	0.027	0.0095	0.0027	0.0088	0.0006	0.0013	6/6/2024	6/7/2024
NORTHERN ARE	1066.6	0.613	1362.3	-60.9	1.438	0.6014	88.9515	8.5754	0.3759	0.0301	0.0108	0.0035	0.0111	0.0009	0.0016	6/7/2024	6/8/2024
NORTHERN ARE	1075.2	0.6219	1363.4	-59.7	1.6459	0.6792	87.2299	9.9452	0.4445	0.03	0.0116	0.003	0.0089	0.0005	0.0015	6/8/2024	6/9/2024
NORTHERN ARE	1090	0.6277	1375.8	-57.7	1.4681	0.5741	85.8959	11.6242	0.3881	0.0264	0.0068	0.0033	0.0109	0.0009	0.0015	6/9/2024	6/10/2024
NORTHERN ARE	1092.5	0.6286	1378	-54.7	1.3977	0.5762	85.7419	11.8334	0.4	0.0269	0.0087	0.0032	0.0093	0.0007	0.0021	6/10/2024	6/11/2024
NORTHERN ARE	1085.2	0.6244	1373.3	-55.2	1.4142	0.5948	86.6812	10.7857	0.4768	0.0241	0.0093	0.0029	0.008	0.0007	0.0023	6/11/2024	6/12/2024
NORTHERN ARE	1084.5	0.6233	1373.7	-59.8	1.3906	0.5671	86.8052	10.7749	0.4275	0.0182	0.011	0.0011	0.0026	0	0.002	6/12/2024	6/13/2024
NORTHERN ARE	1081.2	0.6238	1369	-53	1.5278	0.6354	86.8079	10.5238	0.4647	0.0214	0.0117	0.0018	0.0026	0	0.0031	6/13/2024	6/14/2024
NORTHERN ARE	1083.2	0.6219	1373.5	-59.5	1.344	0.5615	87.1208	10.5028	0.4272	0.0256	0.0108	0.0016	0.0038	0	0.002	6/14/2024	6/15/2024
NORTHERN ARE	1085.6	0.626	1372.1	-56	1.4901	0.629	86.3443	11.0276	0.4709	0.0204	0.011	0.0016	0.0028	0	0.0023	6/15/2024	6/16/2024
NORTHERN ARE	1082.2	0.6219	1372.3	-50.4	1.3633	0.592	87.1839	10.3449	0.4687	0.0248	0.0112	0.0025	0.0054	0	0.0033	6/16/2024	6/17/2024
NORTHERN ARE	1081.3	0.6223	1370.8	-51	1.3898	0.6284	87.137	10.33	0.4777	0.0183	0.0119	0.0016	0.002	0	0.0035	6/17/2024	6/18/2024
NORTHERN ARE	1085.1	0.6247	1372.9	-55.1	1.4271	0.6034	86.6154	10.8468	0.4648	0.0225	0.0092	0.0026	0.0058	0	0.0025	6/18/2024	6/19/2024
NORTHERN ARE	1084	0.6236	1372.7	-55.9	1.4058	0.5957	86.8249	10.6648	0.4724	0.0191	0.0098	0.0018	0.0034	0	0.0025	6/19/2024	6/20/2024
NORTHERN ARE	1079.2	0.6189	1371.9	-51.3	1.2779	0.5736	87.7865	9.874	0.44	0.0256	0.0105	0.0028	0.006	0	0.0032	6/20/2024	6/21/2024
NORTHERN ARE	1050.5	0.5923	1364.9	-62.5	0.6271	0.4913	92.9583	5.6868	0.2114	0.0111	0.0087	0.0009	0.0022	0	0.0023	6/21/2024	6/22/2024
NORTHERN ARE	1085.2	0.6251	1372.6	-60.6	1.4576	0.6053	86.5011	10.9492	0.4459	0.0188	0.0149	0.0019	0.0039	0	0.0014	6/22/2024	6/23/2024
NORTHERN ARE	1088.7	0.6282	1373.6	-56.5	1.5241	0.6205	85.969	11.3282	0.484	0.0275	0.0366	0.0025	0.0059	0	0.0018	6/23/2024	6/24/2024
NORTHERN ARE	1089.4	0.6297	1372.9	-56	1.5759	0.6442	85.7193	11.4829	0.495	0.029	0.0463	0.0019	0.004	0	0.0018	6/24/2024	6/25/2024
NORTHERN ARE	1088.8	0.6278	1374.2	-56.9	1.4946	0.6097	86.0143	11.3386	0.4815	0.0259	0.0243	0.0028	0.0069	0	0.0016	6/25/2024	6/26/2024
NORTHERN ARE	1071.1	0.6111	1370.1	-58.7	1.0788	0.5453	89.2933	8.6719	0.3682	0.0196	0.0145	0.002	0.0043	0	0.0024	6/26/2024	6/27/2024





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<u>Third</u> Gaseous Fuel Transition

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Biogas

- Biogas = the product of biological degradation of organic materials to methane, CO_2 and other trace gases under anaerobic conditions (without air).

- May contain gases which are not biologically created (volatilized from the starting biomass)
  - Landfill gas
  - Wastewater treatment sludge anaerobic digestion

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Many Sources of Biogas

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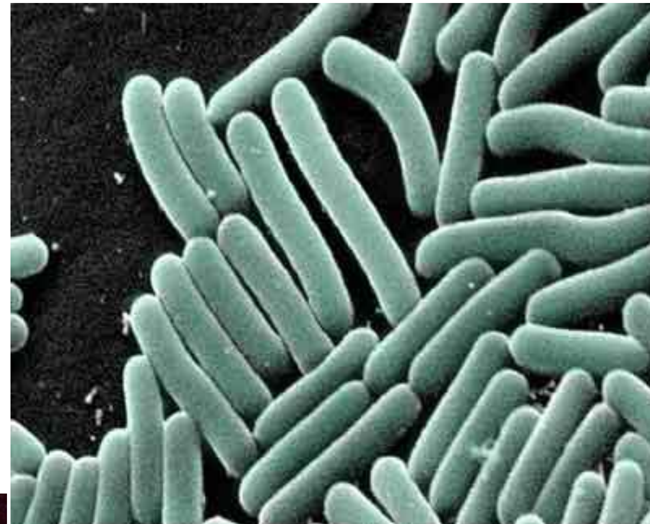
Microbes Do The Work!



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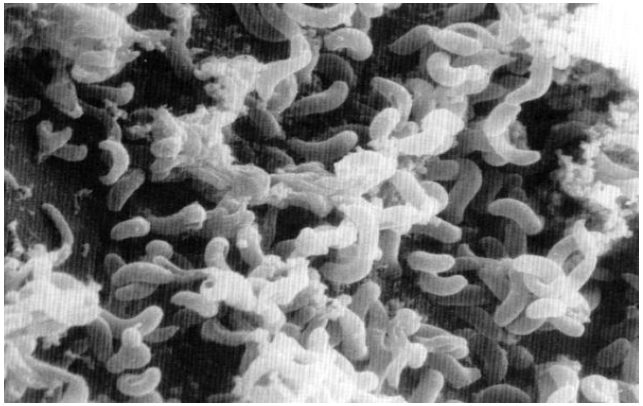
Anaerobic Digestion (AD) of Waste to Produce Biogas is a Multi-Step Process

It is MEDIATED by Multiple Microorganisms:

- Hydrolytic - Acidogenic
- Sulfate - Reducing
- Denitrifying
- Acetogenic
- Syntrophic
- Acetoclastic Methanogenic



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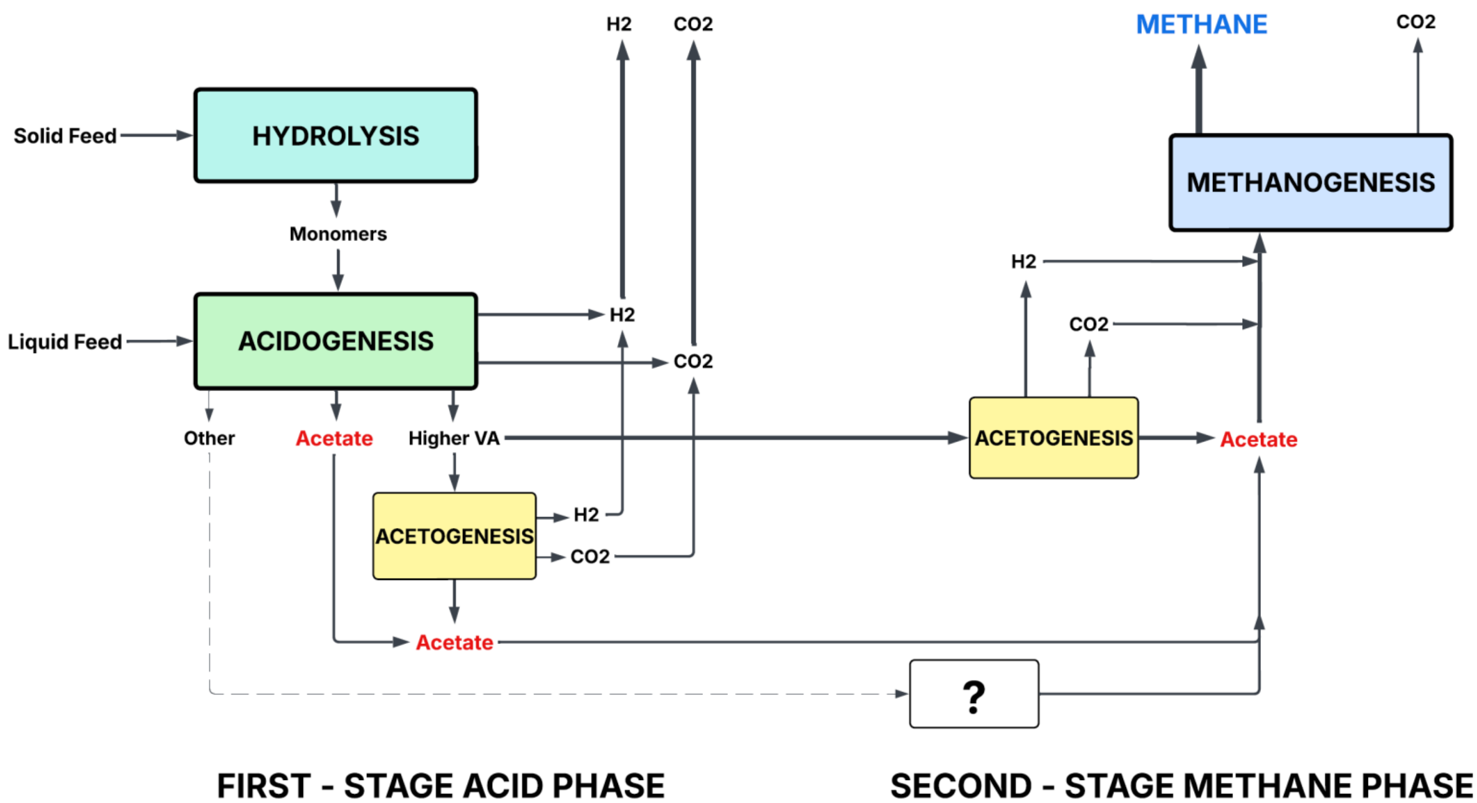
Digestion to Methane is a Two-Phase Process



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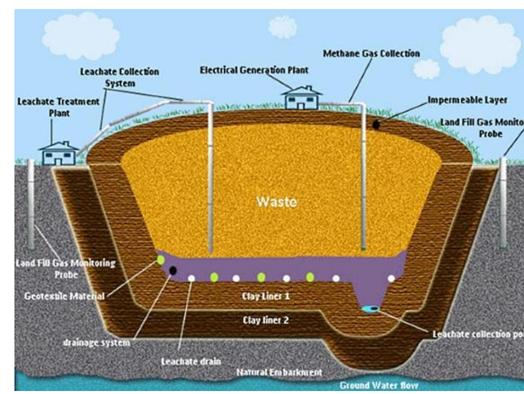
Anaerobic Digester Design Influences Biogas Quality

Quality of Raw Biogas:

- Specific to types of materials digested (feedstock)
- Influenced by digester process/design
  - Lagoon to landfill to high design AD
- Needs to be upgraded or "conditioned" to pipeline quality biomethane (RNG)

Image : Ville de Québec



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GASEOUS FUEL COMPOSITIONS

CONSTITUENT	TOWN GAS	NATURAL GAS	RAW BIOGAS
BTU (Higher Heating Value)	480 - 550	950 - 1110	537 - 570
WOBBE	N/A	1234 - 1400	612 - 676
Methane (C1)	27.5- 30.7%	78 - 98%	40 - 65%
Ethane (C2)	N/A	Up to 9%	N/A
Propane (C3)	N/A	Up to 5% (Limit 2%)	N/A
Butanes+ (C4)	N/A	Up to 4.8% (Limit 1.5%)	N/A
Carbon Dioxide	16.3 - 19.9%	2 - 3%	27 - 50%
Carbon Monoxide	1.0 - 6.9%	N/A	N/A
Oxygen	Combo with N2: 0.6 - 5%	0.2 - 1%	0 - 1%
Nitrogen	Combo with O2: 0.6 - 5%	3 - 6% (Limit 4%)	0.5 - 10%
Hydrogen	46.3 - 55%	Up to 7% (Limits vary or N/A)	Depends
Hydrogen Sulfide	N/A	.25 - 1 gr/100scf	600 - 7,000 ppm
Total Sulfur	N/A	1 - 20 gr/100scf	3 - 18 gr/100scf
TRACE CONSTITUENTS	Many - but not considered	Few	VERY MANY and VARIED

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Biogas Clean-Up to Biomethane

- All BIOGAS must be cleaned or “conditioned” to pipeline quality BIOMETHANE
  - A gas which is “interchangeable” with natural gas
- There are numerous ways to condition biogas
- The biogas is cleaned to a “pipeline quality specification”

BIOMETHANE is NOT NATURAL GAS

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Where Do We Start?

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GASEOUS FUEL COMPOSITIONS

CONSTITUENT	TOWN GAS	NATURAL GAS	RAW BIOGAS
BTU (Higher Heating Value)	480 - 550	950 - 1110	537 - 570
WOBBE	N/A	1234 - 1400	612 - 676
Methane (C1)	27.5- 30.7%	78 - 98%	40 - 65%
Ethane (C2)	N/A	Up to 9%	N/A
Propane (C3)	N/A	Up to 5% (Limit 2%)	N/A
Butanes+ (C4)	N/A	Up to 4.8% (Limit 1.5%)	N/A
Carbon Dioxide	16.3 - 19.9%	2 - 3%	27 - 50%
Carbon Monoxide	1.0 - 6.9%	N/A	N/A
Oxygen	Combo with N2: 0.6 - 5%	0.2 - 1%	0 - 1%
Nitrogen	Combo with O2: 0.6 - 5%	3 - 6% (Limit 4%)	0.5 - 10%
Hydrogen	46.3 - 55%	Up to 7% (Limits vary or N/A)	Depends
Hydrogen Sulfide	N/A	.25 - 1 gr/100scf	600 - 7,000 ppm
Total Sulfur	N/A	1 - 20 gr/100scf	3 - 18 gr/100scf
TRACE CONSTITUENTS	Many - but not considered	Few	VERY MANY and VARIED

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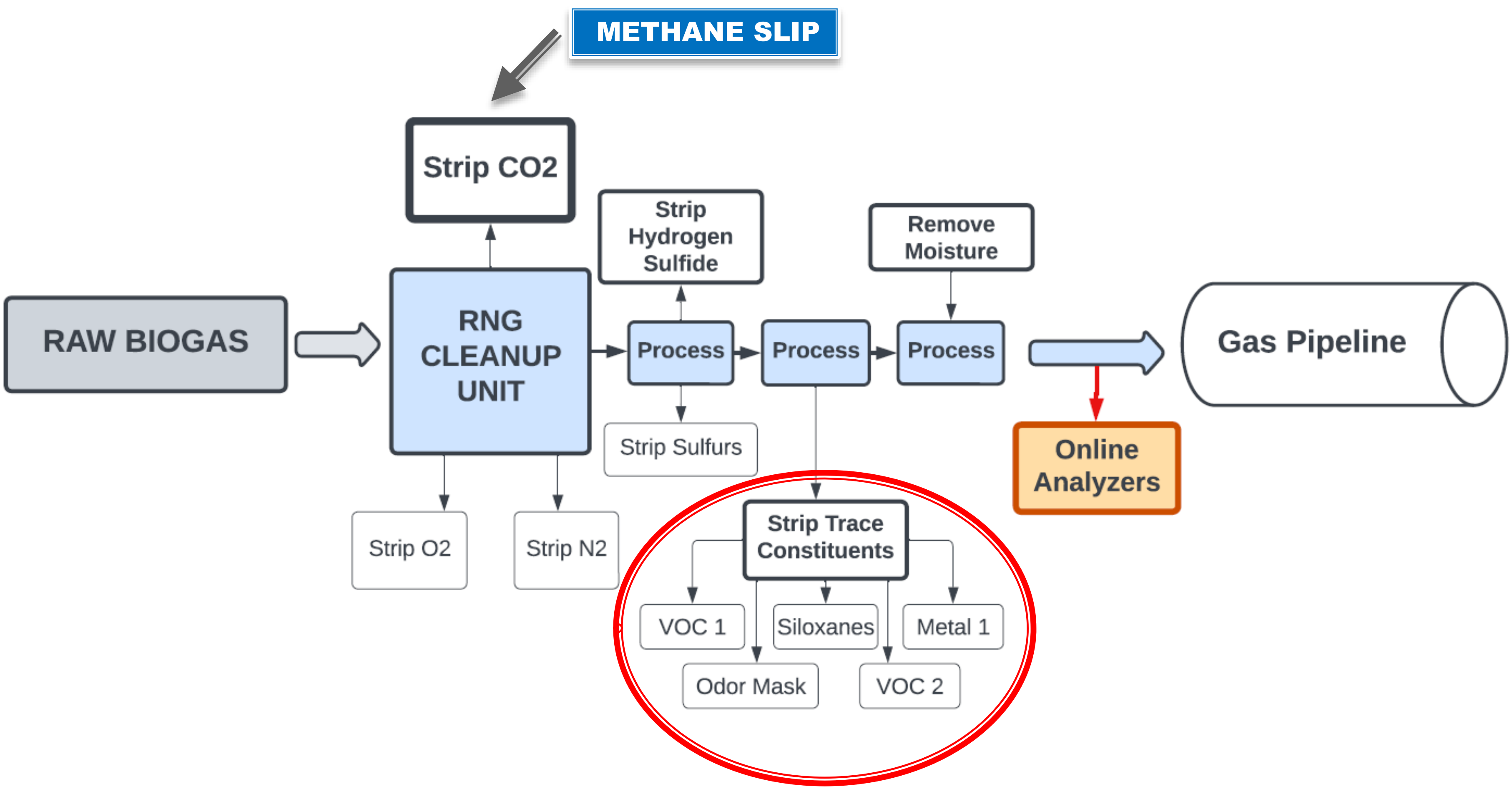
METHANE SLIP
Strip CO2
RAW BIOGAS
RNG CLEANUP UNIT
Strip Hydrogen Sulfide
Process
Strip Sulfurs
Process
Remove Moisture
Process
Gas Pipeline
Online Analyzers
Strip O2
Strip N2
Strip Trace Constituents
VOC 1
Siloxanes
Metal 1
Odor Mask
VOC 2

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For the Natural Gas Industry
and
with respect to the
MAJOR COMPONENTS,
Biomethane RNG
is treated
ON PAR with Natural Gas
(“Look to the Tariff Language”)

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GASEOUS FUEL COMPOSITIONS

CONSTITUENT	TOWN GAS	NATURAL GAS	RAW BIOGAS	RENEWABLE NATURAL GAS (BIOMETHANE)
BTU (Higher Heating Value)	480 - 550	950 - 1110	537 - 570	<995 (950-970 Spec.)
WOBBE	N/A	1234 - 1400	612 - 676	Depends (1279 Spec.)
Methane (C1)	27.5- 30.7%	78 - 98%	40 - 65%	N/A
Ethane (C2)	N/A	Up to 9%	N/A	N/A
Propane (C3)	N/A	Up to 5% (Limit 2%)	N/A	N/A
Butanes+ (C4)	N/A	Up to 4.8% (Limit 1.5%)	N/A	N/A
Carbon Dioxide	16.3 - 19.9%	2 - 3%	27 - 50%	Goes With Tariff
Carbon Monoxide	1.0 - 6.9%	N/A	N/A	N/A
Oxygen	Combo with N2: 0.6 - 5%	0.2 - 1%	0 - 1%	Goes With Tariff
Nitrogen	Combo with O2: 0.6 - 5%	3 - 6% (Limit 4%)	0.5 - 10%	Goes With Tariff
Hydrogen	46.3 - 55%	Up to 7% (Limits vary or N/A)	Depends	Goes With Tariff
Hydrogen Sulfide	N/A	.25 - 1 gr/100scf	600 - 7,000 ppm	Goes With Tariff
Total Sulfur	N/A	1 - 20 gr/100scf	3 - 18 gr/100scf	Goes With Tariff
TRACE CONSTITUENTS	Many - but not considered	Few	VERY MANY and VARIED	Your RNG Specification

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Organic Biomass is Abundant

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Many Types of Anaerobic Digesters…

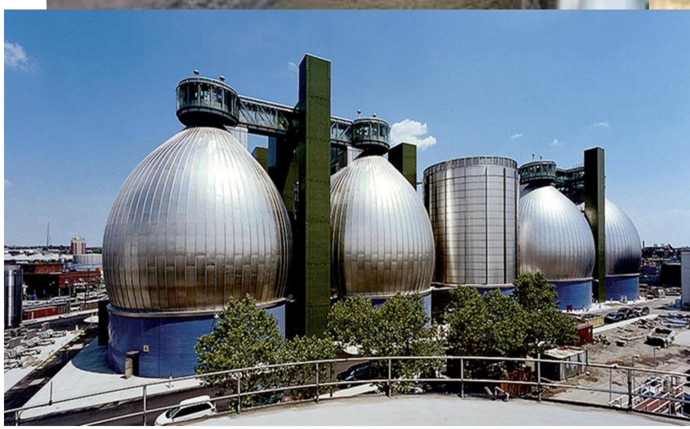
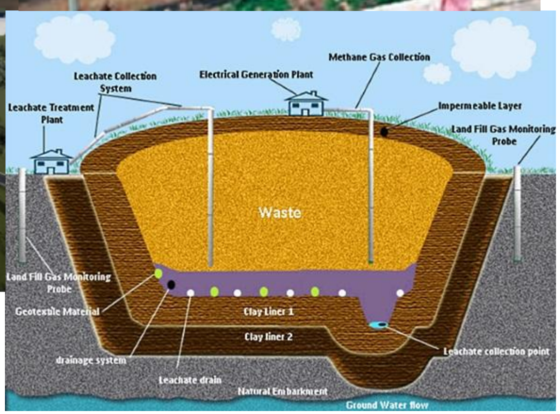


Image : Ville de Québec



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What Goes into the Anaerobic Digester, May Come Out of the Digester…

- Halogens
- Siloxanes
- Heavy Metals
- Odorant Masking Agents
- ??? Emerging Contaminants

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Biomass Source

Limited Trace Constituents

Animal Waste, Industrial-Grade Food Waste (Pre-Consumer), Agricultural Waste, etc.

Many Trace Constituents

Landfill, Wastewater Treatment Sludge

Post-Consumer?













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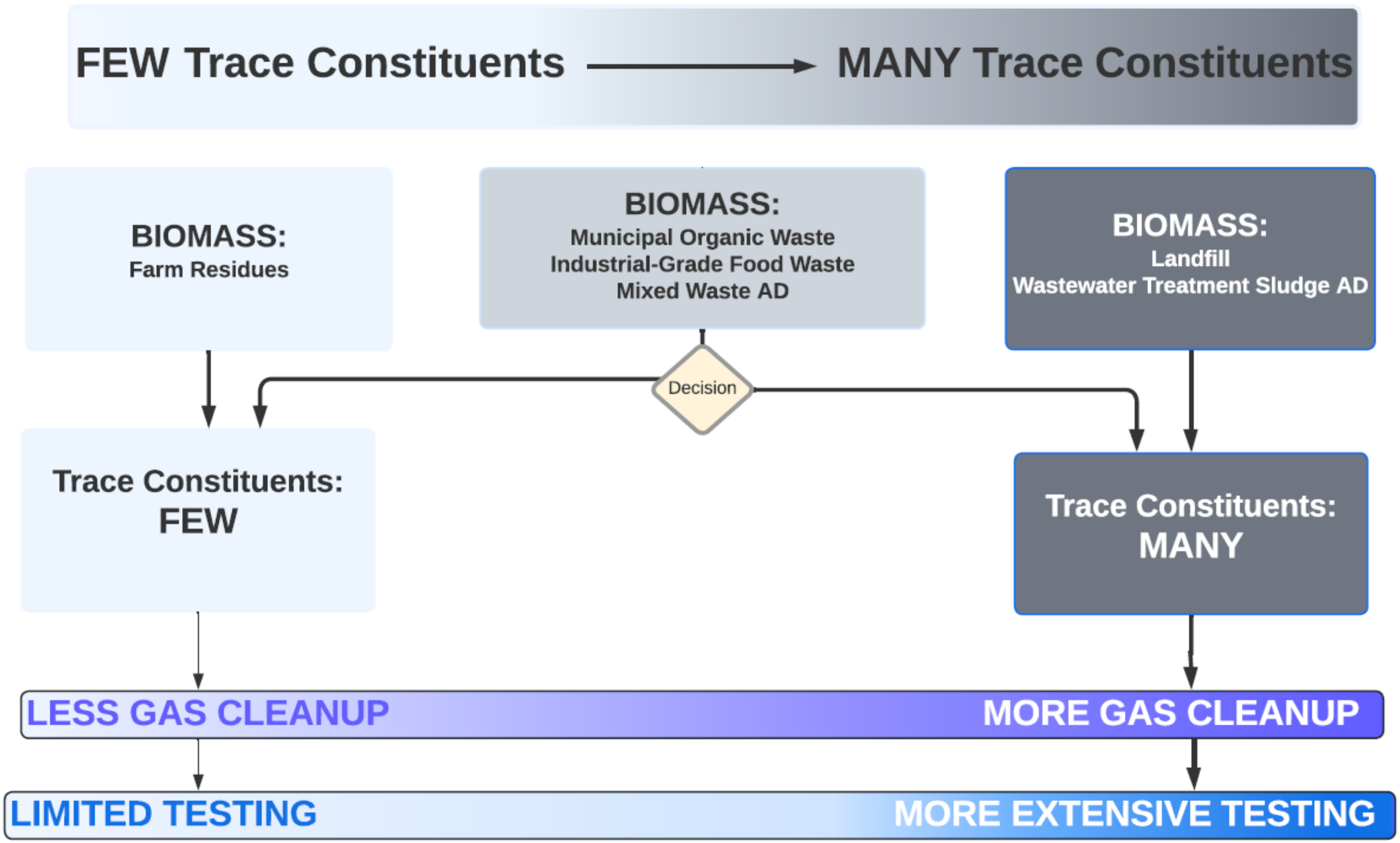
FEW Trace Constituents
MANY Trace Constituents
BIOMASS:
Farm Residues
BIOMASS:
Municipal Organic Waste
Industrial-Grade Food Waste
Mixed Waste AD
BIOMASS:
Landfill
Wastewater Treatment Sludge AD
Decision
Trace Constituents:
FEW
Trace Constituents:
MANY
LESS GAS CLEANUP
MORE GAS CLEANUP
LIMITED TESTING
MORE EXTENSIVE TESTING

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Landfill Raw Biogas

	TEST#1		TEST#2		TEST#3	
Time:						
Component	**ppm (v)**	**mg/m^3**	**ppm (v)**	**mg/m^3**	**ppm (v)**	**mg/m^3**
Propene	**6.30**	**11.0**	**5.60**	**9.70**	**6.50**	**11.0**
Dichlorodifluoromethane (CFC 12)	**1.60**	**7.70**	**1.50**	**7.30**	**1.60**	**7.90**
Chloromethane	<0.83	<1.70	<0.58	<1.20	<0.63	<1.30
1,2-Dichloro-1,1,2,2-tetrafluoroethane	<0.25	<1.80	**0.25**	**1.70**	**0.25**	**1.80**
Vinyl Chloride	**3.40**	**8.60**	**3.20**	**8.10**	**3.70**	**9.40**
1,3-Butadiene	<0.81	<1.80	<0.57	<1.30	<0.61	<1.40
Bromomethane	<0.44	<1.70	<0.31	<1.20	<0.33	<1.30
Chloroethane	**2.00**	**5.40**	**2.00**	**5.20**	**2.20**	**5.90**
Ethanol	**28.0**	**52.0**	**17.0**	**31.0**	**18.0**	**34.0**
Acetonitrile	<1.10	<1.80	<0.75	<1.30	<0.81	<1.40
Acrolein	<1.50	<3.40	<1.10	<2.40	<1.10	<2.60
Acetone	<7.80	<19.0	<5.50	<13.0	<5.90	<14.0
Trichlorofluoromethane (CFC 11)	<0.32	<1.80	<0.23	<1.30	<0.25	<1.40
2-Propanol (Isopropyl Alcohol)	**3.90**	**9.60**	**3.70**	**9.10**	**4.20**	**10.0**
Acrylonitrile	<0.82	<1.80	<0.58	<1.30	<0.62	<1.40
1,1-Dichloroethene	<0.47	<1.90	<0.33	<1.30	<0.35	<1.40
Methylene Chloride	**5.70**	**20.0**	**5.30**	**18.0**	**5.90**	**20.0**
3-Chloro-1-propene (Allyl Chloride)	<0.58	<1.80	<0.41	<1.30	<0.44	<1.40
Trichlorotrifluoroethane (CFC 113)	<0.24	<1.80	**0.25**	**1.90**	**0.26**	**2.00**
Carbon Disulfide	<1.20	<3.80	<0.85	<2.70	<0.92	<2.90
trans-1,2-Dichloroethene	<0.46	<1.80	<0.32	<1.30	<0.35	<1.40
1,1-Dichloroethane	**3.80**	**15.0**	**3.70**	**15.0**	**4.10**	**17.0**
Methyl tert-Butyl Ether	<0.52	<1.90	<0.36	<1.30	<0.39	<1.40
Vinyl Acetate	<5.20	<18.0	<3.60	<13.0	<3.90	<14.0
2-Butanone (MEK)	**2.40**	**7.00**	**2.20**	**6.50**	**2.60**	**7.60**
cis-1,2-Dichloroethene	**3.70**	**15.0**	**3.50**	**14.0**	**3.80**	**15.0**
Ethyl Acetate	**2.50**	**9.00**	**2.40**	**8.50**	**2.60**	**9.30**
n-Hexane	**11.0**	**39.0**	**11.0**	**37.0**	**12.0**	**42.0**
Chloroform	**0.70**	**3.40**	**0.68**	**3.30**	**0.72**	**3.50**
Tetrahydrofuran (THF)	**29.0**	**84.0**	**27.0**	**79.0**	**29.0**	**87.0**
1,2-Dichloroethane	**4.60**	**19.0**	**4.30**	**18.0**	**4.60**	**19.0**
1,1,1-Trichloroethane	<0.34	<1.90	<0.24	<1.30	<0.26	<1.40
Benzene	**5.80**	**18.0**	**6.00**	**19.0**	**6.80**	**22.0**
Carbon Tetrachloride	<0.28	<1.80	<0.20	<1.30	<0.22	<1.40
Cyclohexane	**3.80**	**13.0**	**3.60**	**12.0**	**4.00**	**14.0**
1,2-Dichloropropane	<0.40	<1.90	<0.28	<1.30	<0.30	<1.40
Bromodichloromethane	<0.27	<1.80	<0.19	<1.30	<0.21	<1.40
Trichloroethene	**0.99**	**5.30**	**1.00**	**5.40**	**1.10**	**5.70**
1,4-Dioxane	<0.51	<1.80	<0.35	<1.30	<0.38	<1.40
Methyl Methacrylate	<0.92	<3.80	<0.65	<2.70	<0.70	<2.90
n-Heptane	**6.30**	**26.0**	**6.20**	**25.0**	**6.80**	**28.0**
cis-1,3-Dichloropropene	<0.42	<1.90	<0.30	<1.30	<0.32	<1.50
4-Methyl-2-pentanone	<0.45	<1.80	<0.31	<1.30	<0.34	<1.40
trans-1,3-Dichloropropene	<0.40	<1.80	<0.28	<1.30	<0.30	<1.40
1,1,2-Trichloroethane	<0.34	<1.90	<0.24	<1.30	<0.26	<1.40
Toluene	**59.0**	**220**	**55.0**	**210**	**59.0**	**220**
2-Hexanone	<0.45	<1.90	<0.32	<1.30	<0.34	<1.40
Dibromochloromethane	<0.22	<1.90	<0.15	<1.30	<0.16	<1.40
1,2-Dibromoethane	<0.24	<1.90	<0.17	<1.30	<0.18	<1.40
n-Butyl Acetate	<0.39	<1.90	<0.27	<1.30	<0.30	<1.40
n-Octane	**3.40**	**16.0**	**3.60**	**17.0**	**3.70**	**17.0**
Tetrachloroethene	**2.10**	**14.0**	**2.20**	**15.0**	**2.20**	**15.0**
Chlorobenzene	**0.97**	**4.50**	**1.10**	**5.10**	**1.10**	**5.20**
Ethylbenzene	**2.90**	**12.00**	**3.30**	**14.0**	**3.30**	**14.0**
m,p-Xylenes	**7.50**	**32.00**	**8.80**	**38.0**	**8.80**	**38.0**
Bromoform	<0.18	<1.80	<0.12	<1.30	<0.13	<1.40
Styrene	<0.43	<1.80	<0.30	<1.30	<0.32	<1.40
o-Xylene	**1.90**	**8.30**	**2.30**	**10.0**	**2.20**	**9.60**
n-Nonane	**1.80**	**9.30**	**2.10**	**11.0**	**2.10**	**11.0**
1,1,2,2-Tetrachloroethane	<0.27	<1.80	<0.19	<1.30	<0.20	<1.40
Cumene	<0.37	<1.80	<0.26	<1.30	<0.28	<1.40
alpha-Pinene	**2.50**	**14.0**	**2.90**	**16.0**	**2.80**	**16.0**
n-Propylbenzene	<0.38	<1.90	<0.26	<1.30	<0.29	<1.40
4-Ethyltoluene	<0.37	<1.80	<0.26	<1.30	<0.28	<1.40
1,3,5-Trimethylbenzene	<0.37	<1.80	<0.26	<1.30	<0.28	<1.40
1,2,4-Trimethylbenzene	<0.37	<1.80	**0.46**	**2.20**	**0.33**	**1.60**
Benzyl Chloride	<0.73	<3.80	<0.51	<2.70	<0.55	<2.90
1,3-Dichlorobenzene	<0.31	<1.90	<0.22	<1.30	<0.23	<1.40
1,4-Dichlorobenzene	<0.31	<1.90	<0.22	<1.30	<0.23	<1.40
1,2-Dichlorobenzene	<0.31	<1.90	<0.22	<1.30	<0.23	<1.40
d-Limonene	**1.40**	**7.50**	**2.00**	**11.00**	**1.70**	**9.50**
1,2-Dibromo-3-chloropropane	<0.19	<1.80	<0.13	<1.30	<0.14	<1.40
1,2,4-Trichlorobenzene	<0.25	<1.80	<0.17	<1.30	<0.19	<1.40
Naphthalene	<0.33	<1.80	<0.23	<1.20	<0.25	<1.30
Hexachlorobutadiene	<0.17	<1.80	<0.12	<1.30	<0.13	<1.40

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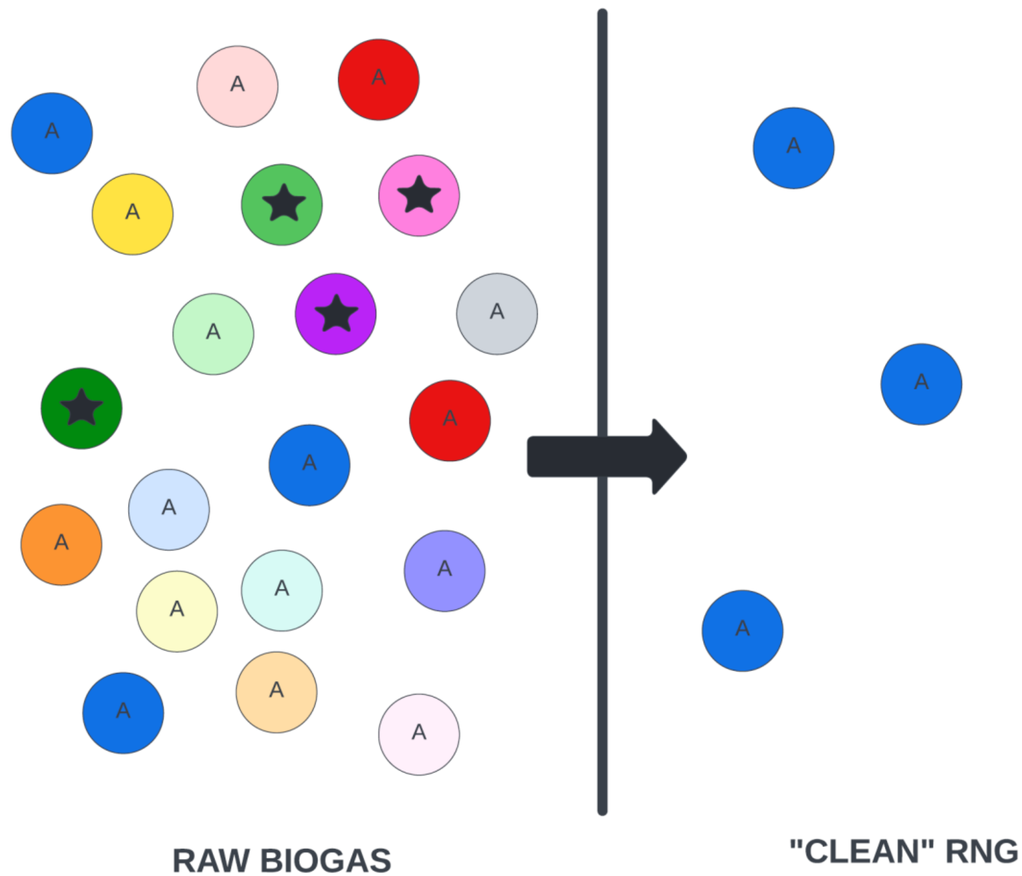
Biogas Cleanup:
"What We Think is Happening"



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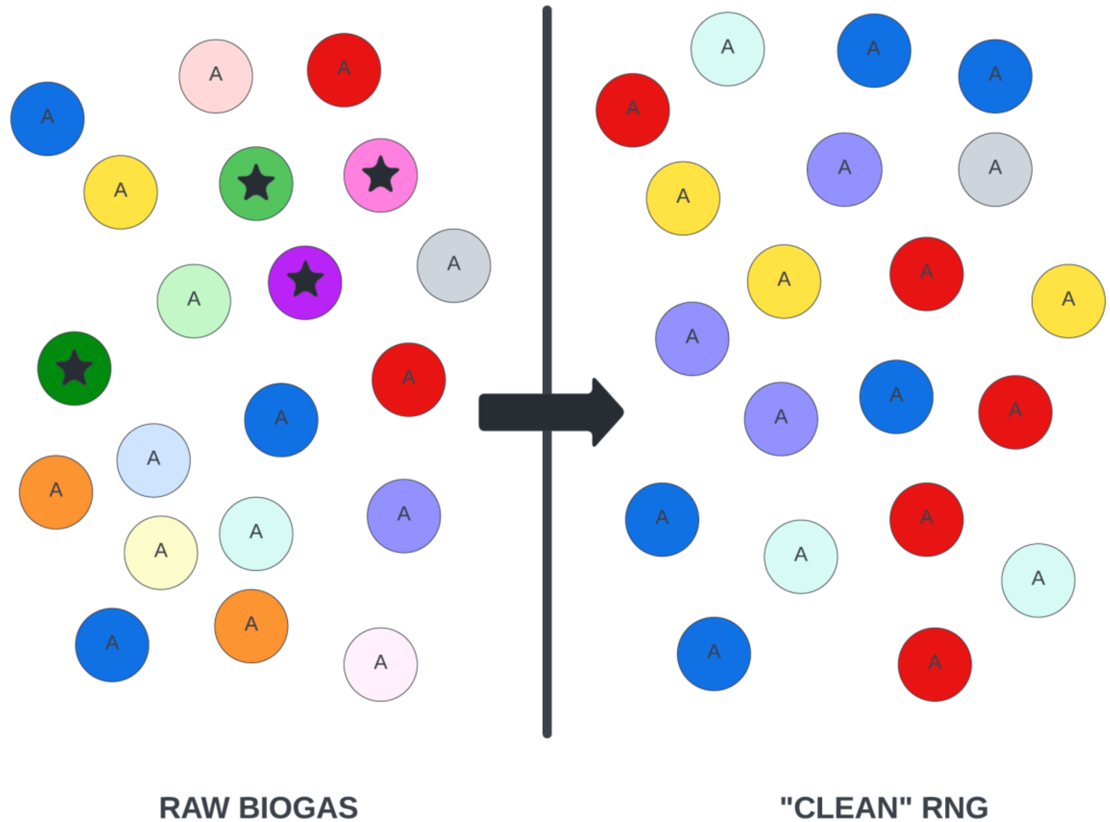
Biogas Cleanup: "The Reality"



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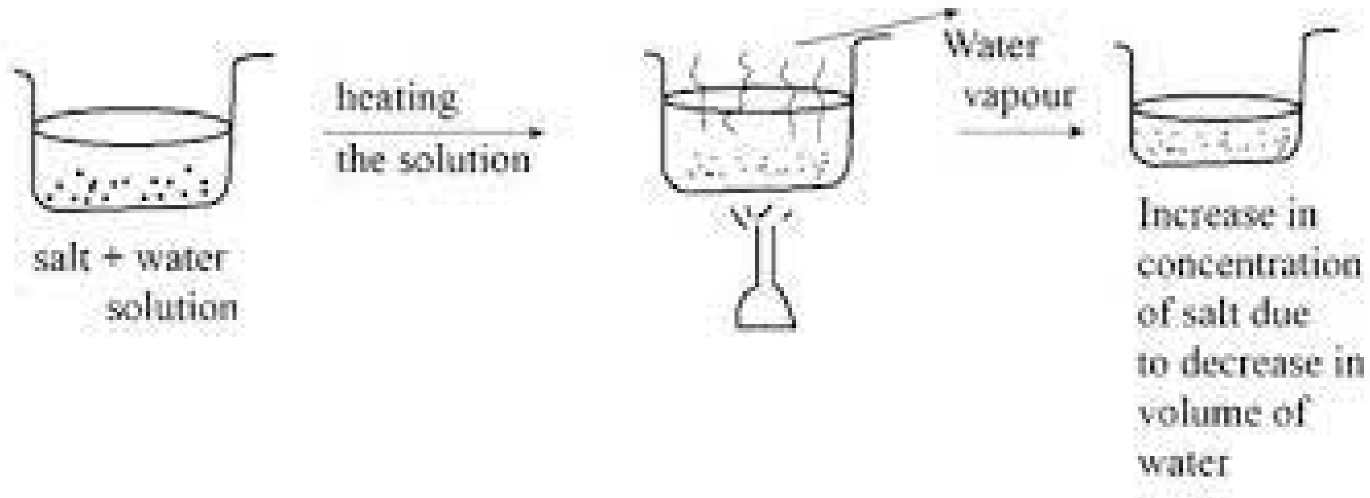
heating
the solution
Water
vapour
salt + water
solution
Increase in
concentration
of salt due
to decrease in
volume of
water

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Landfill Biogas Profile

4 Samples Retrieved

Biogas

Analyte	**Mean**	**Median**	**Standard I**	**Range**	**Minimum**	**Maximum**	**Count**
Benzene	1.05	1.07	0.0827	0.161	0.96	1.12	3
Carbon Tetrachloride	0.435	0.293	0.253	0.441	0.286	0.73	3
Toluene	32.7	31.4	13.3	26.4	20.2	46.6	3
trans-1,3-Dichloropropene	0.467	0.467	0.108	0.152	0.391	0.543	2
Tetrachloroethene	0.540	0.494	0.164	0.318	0.404	0.722	3
Chlorobenzene	1.35	1.33	0.473	0.946	0.882	1.83	3
Ethylbenzene	78.0	78.0	25.7	36.3	59.8	96.1	2
m/p-Xylenes	71.7	71.7	N/A	0.0	71.7	71.7	1
Styrene	7.48	7.77	2.24	4.45	5.11	9.56	3
o-Xylene	67.6	67.6	22.6	31.9	51.7	83.6	2
1,1,2,2-Tetrachloroethane	0.313	0.313	N/A	0.0	0.313	0.313	1
Isopropylbenzene	15.7	15.1	5.54	11.0	10.5	21.6	3
2-Chlorotoluene	2.52	2.34	0.37	0.66	2.28	2.94	3
n-Propylbenzene	20.2	19.6	4.3	8.5	16.3	25	3
1,3,5-Trimethylbenzene	81.1	72.5	39.1	76.9	47.0	123.9	3
tert-Butylbenzene	12.9	12.9	N/A	0.00	12.9	12.9	1
1,2,4-Trimethylbenzene	238	248	90.2	180	144	323	3
sec-Butylbenzene	12.1	12.1	3.78	7.55	8.30	15.85	3
bis(2-Chloroethyl)ether	0.838	0.838	N/A	0.00	0.838	0.838	1
1,3-Dichlorobenzene	0.368	0.368	0.00187	0.00265	0.367	0.370	2
1,4-Dichlorobenzene	93.9	102	36.2	70.9	54.3	125	3
p-Isopropyltoluene	242	249	80.3	160	158	318	3
Benzyl Alcohol	148	148	N/A	0.00	148	148	1
1,2-Dichlorobenzene	2.36	2.45	0.562	1.11	1.76	2.88	3
n-Butylbenzene	12.1	11.4	2.93	5.76	9.52	15.3	3
N-nitroso-di-n-propylamine	6.06	6.06	N/A	0.00	6.06	6.06	1
2,4-Dimethylphenol	1.27	1.27	N/A	0.00	1.27	1.27	1
1,2,4-Trichlorobenzene	1.99	1.75	0.509	0.933	1.64	2.57	3
Naphthalene	151	154	11.3	22.0	139	161	3
1,2,3-Trichlorobenzene	0.410	0.346	0.130	0.234	0.326	0.560	3
2-Methylnaphthalene	18.9	15.1	10.9	20.7	10.5	31.2	3
1-Methylnaphthalene	9.60	7.35	5.49	10.3	5.59	15.9	3
Acenaphthene	2.70	1.99	1.98	3.774	1.16	4.94	3
4-Nitrophenol	1.90	1.928	0.0672	0.125	1.82	1.95	3
Dibenzofuran	1.04	0.703	0.812	1.51	0.458	1.97	3
Diethylphthalate	0.390	0.390	N/A	0.00	0.390	0.390	1
Fluorene	1.10	1.10	0.842	1.19	0.508	1.70	2
Phenanthrene	0.869	0.869	N/A	0.00	0.869	0.869	1
Di-n-butylphthalate	0.747	0.747	0.248	0.351	0.572	0.923	2

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Landfill RNG Profile

Biomethane

Analyte	Mean	Median	Standard I	Range	Minimum	Maximum	Count
Benzene	2.24	1.03	2.67	5.55	0.686	6.24	4
Carbon Tetrachloride	0.796	0.796	0.00709	0.0100	0.791	0.801	2
1,2-Dichloropropane	0.514	0.514	N/A	0.00	0.514	0.514	1
Trichloroethene	0.602	0.602	N/A	0.00	0.602	0.602	1
Toluene	1.74	1.09	1.67	3.15	0.488	3.64	3
Ethylbenzene	1.15	1.15	N/A	0.00	1.15	1.15	1
m/p-Xylenes	1.42	1.42	N/A	0.00	1.42	1.42	1
o-Xylene	1.19	1.19	N/A	0.00	1.19	1.19	1
Isopropylbenzene	0.412	0.412	N/A	0.00	0.412	0.412	1
n-Propylbenzene	0.49	0.49	N/A	0.00	0.49	0.49	1
1,3,5-Trimethylbenzene	1.31	1.31	N/A	0.00	1.31	1.31	1
1,2,4-Trimethylbenzene	2.62	2.62	2.36	3.34	0.954	4.29	2
sec-Butylbenzene	0.47	0.47	N/A	0.00	0.47	0.5	1
1,4-Dichlorobenzene	1.19	1.19	1.11	1.6	0.41	2.0	2
p-Isopropyltoluene	13.6	13.6	9.78	14	6.66	20.5	2
n-Butylbenzene	0.45	0.45	N/A	0.00	0.45	0.45	1
Naphthalene	5.35	5.35	2.34	3.31	3.69	7.00	2
2-Methylnaphthalene	0.775	0.775	0.19	0.271	0.640	0.911	2
1-Methylnaphthalene	0.408	0.408	N/A	0.00	0.408	0.408	1
Diethylphthalate	0.500	0.500	N/A	0.000	0.500	0.500	1
Di-n-butylphthalate	0.729	0.589	0.339	0.633	0.483	1.12	3

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Need to Clean the Biogas to "High Quality RNG"

- Biomethane RNG is not the same as "natural gas"
  - No extended hydrocarbons
  - Lower BTU/lower Wobbe
  - AGA Report 4A
  - NGC+ Whitepaper
- Many parameters to "pipeline quality"
  - Physical and chemical parameters
- Removal of constituents can cost $
- ***An RNG Specification Is Needed***
- *An RNG Specification is NOT an RNG Tariff*

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Trace Constituents Evaluation

1) Assess ***what*** compounds are present
2) ***Which*** compounds poses a risk (to "*Receptors*")
    - **3 Risk Receptors:**
        - **Human Health & the Environment (NIOSH, OSHA, EPA, Env. Canada, European Lit., etc.)**
        - **Pipeline Integrity**
        - **End-Use Equipment**
3) Do the ***concentrations*** pose a risk to the receptor?
4) ***What concentration is required*** for safe introduction to the pipeline network?

	TEST#1		TEST#2		TEST#3	
Time:						
Component	ppm (v)	mg/m³	ppm (v)	mg/m³	ppm (v)	mg/m³
Propene	6.30	11.0	5.60	9.70	6.50	11.0
Dichlorodifluoromethane (CFC 12)	1.60	7.70	1.50	7.30	1.60	7.90
Chloromethane	<0.83	<1.70	<0.58	<1.20	<0.63	<1.30
1,2-Dichloro-1,1,2,2-tetrafluoroethane	<0.25	<1.80	0.25	1.70	0.25	1.80
Vinyl Chloride	3.40	8.60	3.20	8.10	3.70	9.40
1,3-Butadiene	<0.81	<1.80	<0.57	<1.30	<0.61	<1.40
Bromomethane	<0.44	<1.70	<0.31	<1.20	<0.33	<1.30
Chloroethane	2.00	5.40	2.00	5.20	2.20	5.90
Ethanol	28.0	52.0	17.0	31.0	18.0	34.0
Acetonitrile	<1.10	<1.80	<0.75	<1.30	<0.81	<1.40
Acrolein	<1.50	<3.40	<1.10	<2.40	<1.10	<2.60
Acetone	<7.80	<19.0	<5.50	<13.0	<5.90	<14.0
Trichlorofluoromethane (CFC 11)	<0.32	<1.80	<0.23	<1.30	<0.25	<1.40
2-Propanol (Isopropyl Alcohol)	3.90	9.60	3.70	9.10	4.20	10.0
Acrylonitrile	<0.82	<1.80	<0.58	<1.30	<0.62	<1.40
1,1-Dichloroethene	<0.47	<1.90	<0.33	<1.30	<0.35	<1.40
Methylene Chloride	5.70	20.0	5.30	18.0	5.90	20.0
3-Chloro-1-propene (Allyl Chloride)	<0.58	<1.80	<0.41	<1.30	<0.44	<1.40
Trichlorotrifluoroethane (CFC 113)	<0.24	<1.80	0.25	1.90	0.26	2.00
Carbon Disulfide	<1.20	<3.80	<0.85	<2.70	<0.92	<2.90
trans-1,2-Dichloroethene	<0.46	<1.80	<0.32	<1.30	<0.35	<1.40
1,1-Dichloroethane	3.80	15.0	3.70	15.0	4.10	17.0
Methyl tert-Butyl Ether	<0.52	<1.90	<0.36	<1.30	<0.39	<1.40
Vinyl Acetate	<5.20	<18.0	<3.60	<13.0	<3.90	<14.0
2-Butanone (MEK)	2.40	7.00	2.20	6.50	2.60	7.60
cis-1,2-Dichloroethene	3.70	15.0	3.50	14.0	3.80	15.0
Ethyl Acetate	2.50	9.00	2.40	8.50	2.60	9.30
n-Hexane	11.0	39.0	11.0	37.0	12.0	42.0
Chloroform	0.70	3.40	0.68	3.30	0.72	3.50
Tetrahydrofuran (THF)	29.0	84.0	27.0	79.0	29.0	87.0
1,2-Dichloroethane	4.60	19.0	4.30	18.0	4.60	19.0
1,1,1-Trichloroethane	<0.34	<1.90	<0.24	<1.30	<0.26	<1.40
Benzene	5.80	18.0	6.00	19.0	6.80	22.0
Carbon Tetrachloride	<0.28	<1.80	<0.20	<1.30	<0.22	<1.40
Cyclohexane	3.80	13.0	3.60	12.0	4.00	14.0
1,2-Dichloropropane	<0.40	<1.90	<0.28	<1.30	<0.30	<1.40
Bromodichloromethane	<0.27	<1.80	<0.19	<1.30	<0.21	<1.40
Trichloroethene	0.99	5.30	1.00	5.40	1.10	5.70
1,4-Dioxane	<0.51	<1.80	<0.35	<1.30	<0.38	<1.40
Methyl Methacrylate	<0.92	<3.80	<0.65	<2.70	<0.70	<2.90
n-Heptane	6.30	26.0	6.20	25.0	6.80	28.0
cis-1,3-Dichloropropene	<0.42	<1.90	<0.30	<1.30	<0.32	<1.50
4-Methyl-2-pentanone	<0.45	<1.80	<0.31	<1.30	<0.34	<1.40
trans-1,3-Dichloropropene	<0.40	<1.80	<0.28	<1.30	<0.30	<1.40
1,1,2-Trichloroethane	<0.34	<1.90	<0.24	<1.30	<0.26	<1.40
Toluene	59.0	220	55.0	210	59.0	220
2-Hexanone	<0.45	<1.90	<0.32	<1.30	<0.34	<1.40
Dibromochloromethane	<0.22	<1.90	<0.15	<1.30	<0.16	<1.40
1,2-Dibromoethane	<0.24	<1.90	<0.17	<1.30	<0.18	<1.40
n-Butyl Acetate	<0.39	<1.90	<0.27	<1.30	<0.30	<1.40
n-Octane	3.40	16.0	3.60	17.0	3.70	17.0
Tetrachloroethene	2.10	14.0	2.20	15.0	2.20	15.0
Chlorobenzene	0.97	4.50	1.10	5.10	1.10	5.20
Ethylbenzene	2.90	12.00	3.30	14.0	3.30	14.0
m,p-Xylenes	7.50	32.00	8.80	38.0	8.80	38.0
Bromoform	<0.18	<1.80	<0.12	<1.30	<0.13	<1.40
Styrene	<0.43	<1.80	<0.30	<1.30	<0.32	<1.40
o-Xylene	1.90	8.30	2.30	10.0	2.20	9.60
n-Nonane	1.80	9.30	2.10	11.0	2.10	11.0
1,1,2,2-Tetrachloroethane	<0.27	<1.80	<0.19	<1.30	<0.20	<1.40
Cumene	<0.37	<1.80	<0.26	<1.30	<0.28	<1.40
alpha-Pinene	2.50	14.0	2.90	16.0	2.80	16.0
n-Propylbenzene	<0.38	<1.90	<0.26	<1.30	<0.29	<1.40
4-Ethyltoluene	<0.37	<1.80	<0.26	<1.30	<0.28	<1.40
1,3,5-Trimethylbenzene	<0.37	<1.80	<0.26	<1.30	<0.28	<1.40
1,2,4-Trimethylbenzene	<0.37	<1.80	0.46	2.20	0.33	1.60
Benzyl Chloride	<0.73	<3.80	<0.51	<2.70	<0.55	<2.90
1,3-Dichlorobenzene	<0.31	<1.90	<0.22	<1.30	<0.23	<1.40
1,4-Dichlorobenzene	<0.31	<1.90	<0.22	<1.30	<0.23	<1.40
1,2-Dichlorobenzene	<0.31	<1.90	<0.22	<1.30	<0.23	<1.40
d-Limonene	1.40	7.50	2.00	11.00	1.70	9.50
1,2-Dibromo-3-chloropropane	<0.19	<1.80	<0.13	<1.30	<0.14	<1.40
1,2,4-Trichlorobenzene	<0.25	<1.80	<0.17	<1.30	<0.19	<1.40
Naphthalene	<0.33	<1.80	<0.23	<1.20	<0.25	<1.30
Hexachlorobutadiene	<0.17	<1.80	<0.12	<1.30	<0.13	<1.40

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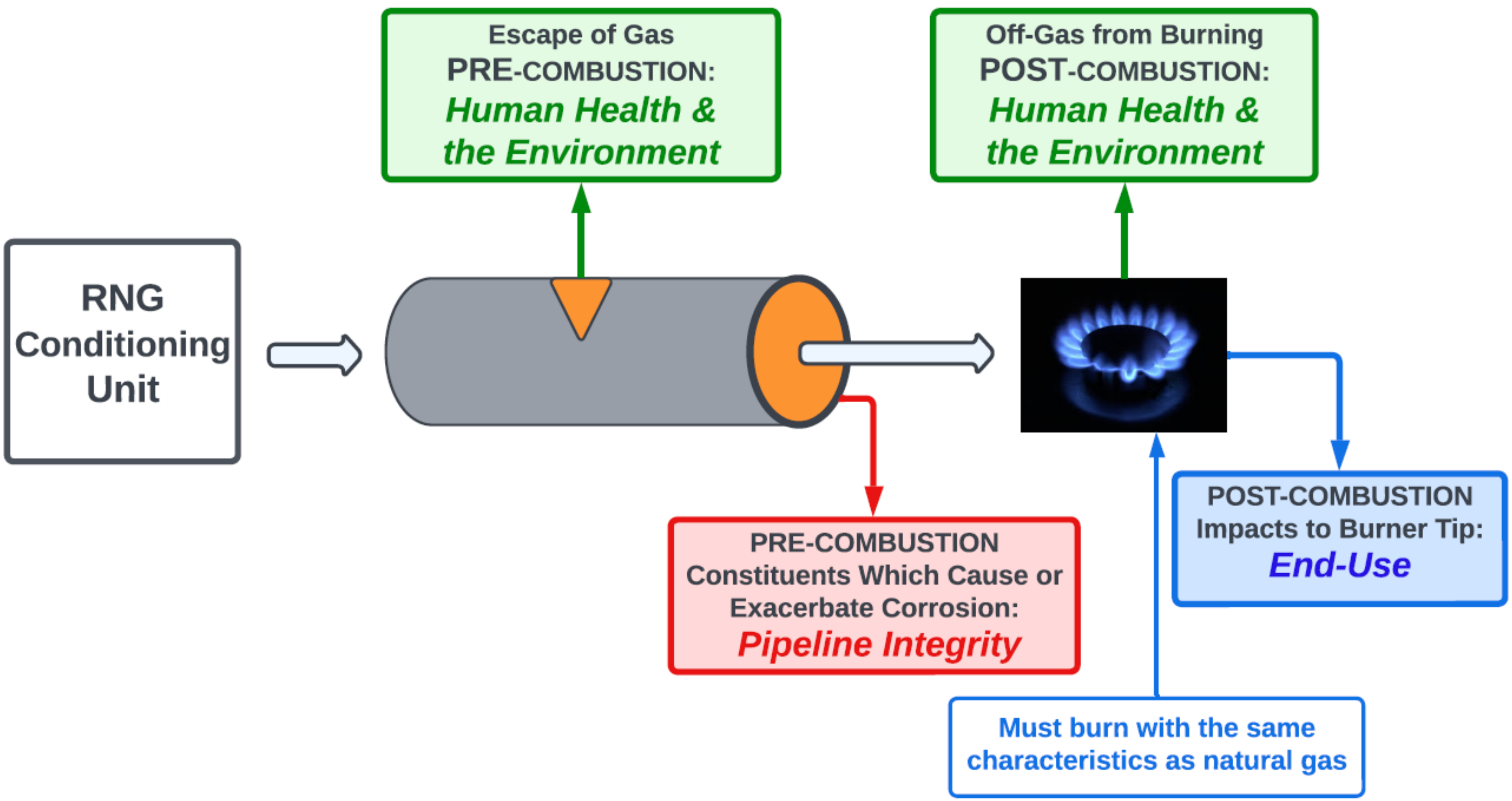
Three Risk Receptors



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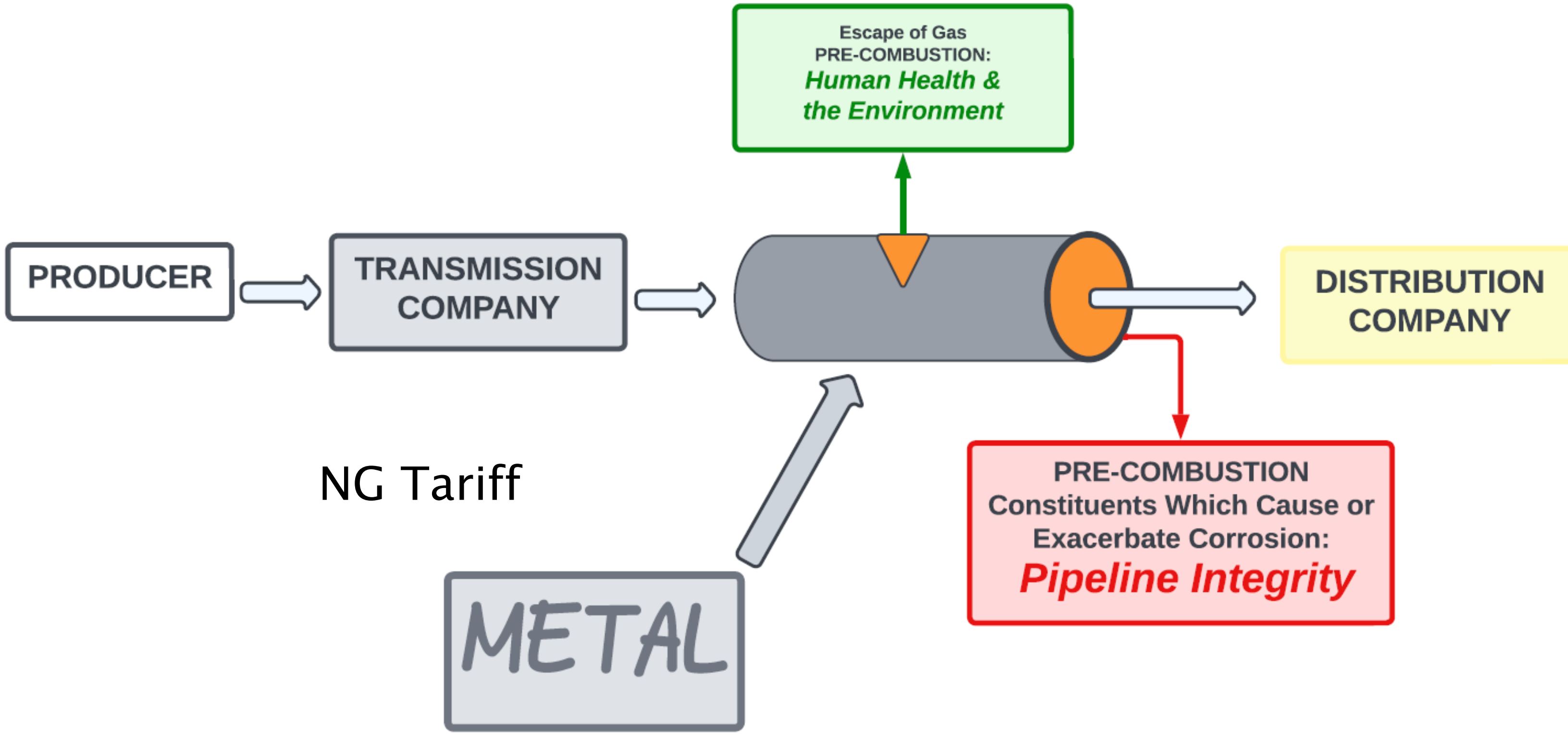
Gas Quality Concerns in Natural Gas: Transmission System



HIGH PRESSURE, HIGH VOLUME,
BLENDING OF GASES IS ALLOWED

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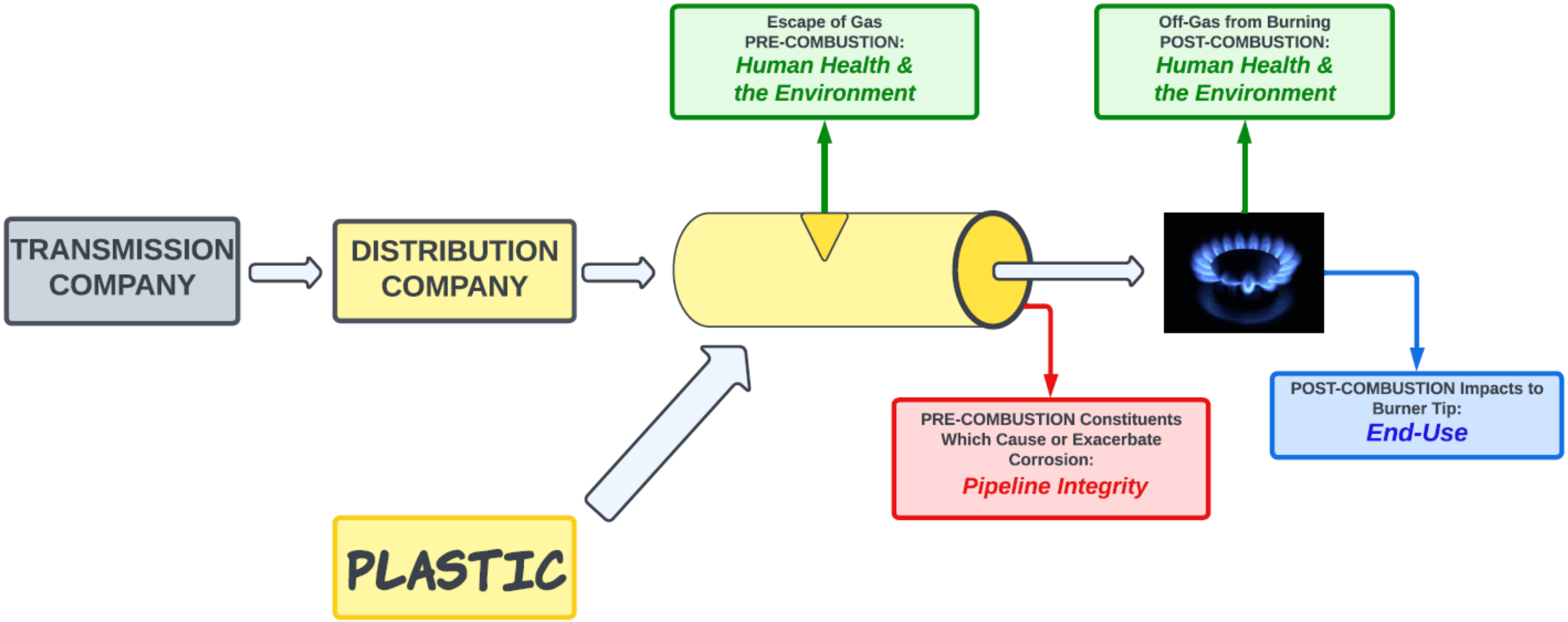
Gas Quality Concerns in Natural Gas: Distribution System



LOW PRESSURE, SEASONAL VARIATION IN VOLUMES,
NO "EASY" BLENDING OF GASES

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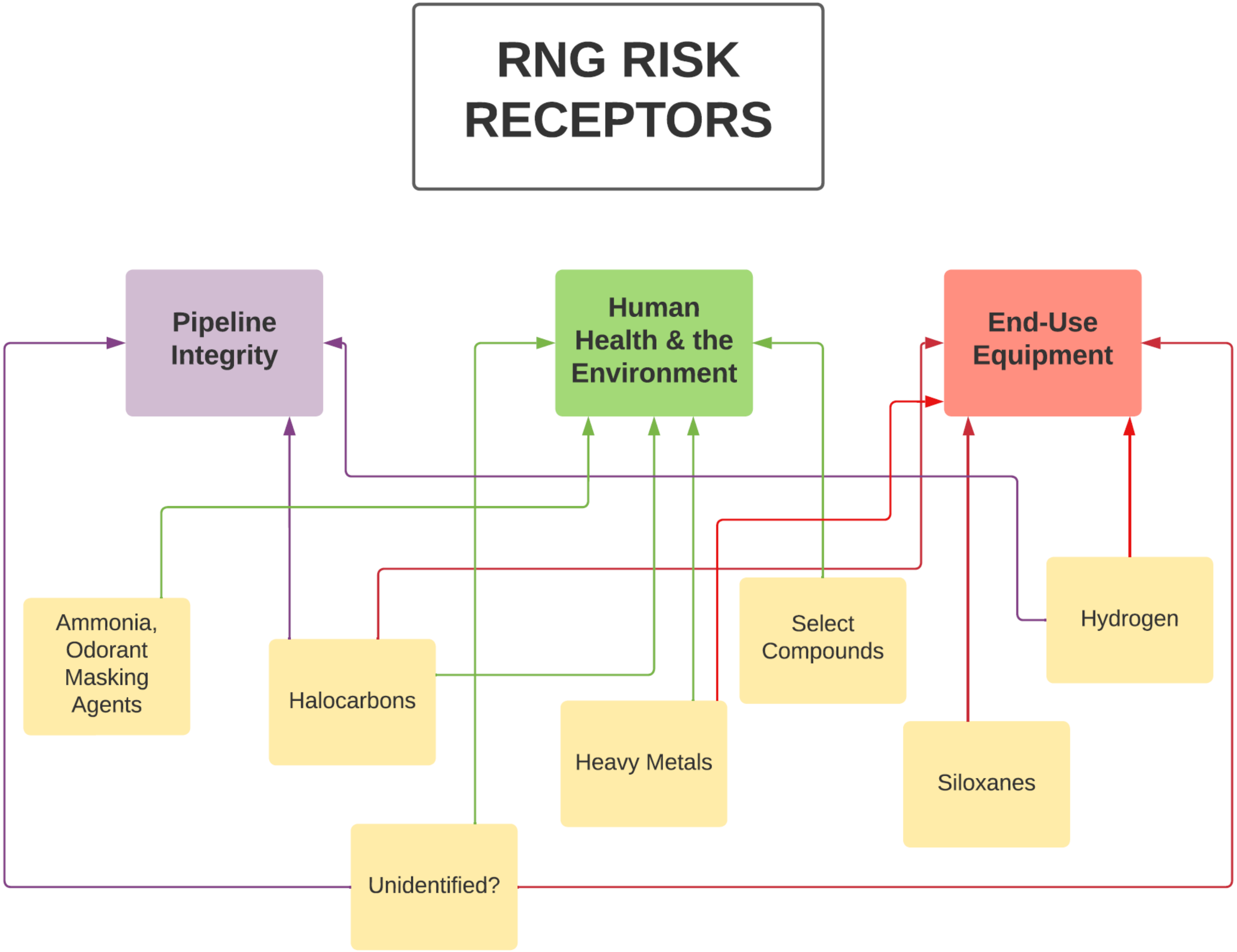
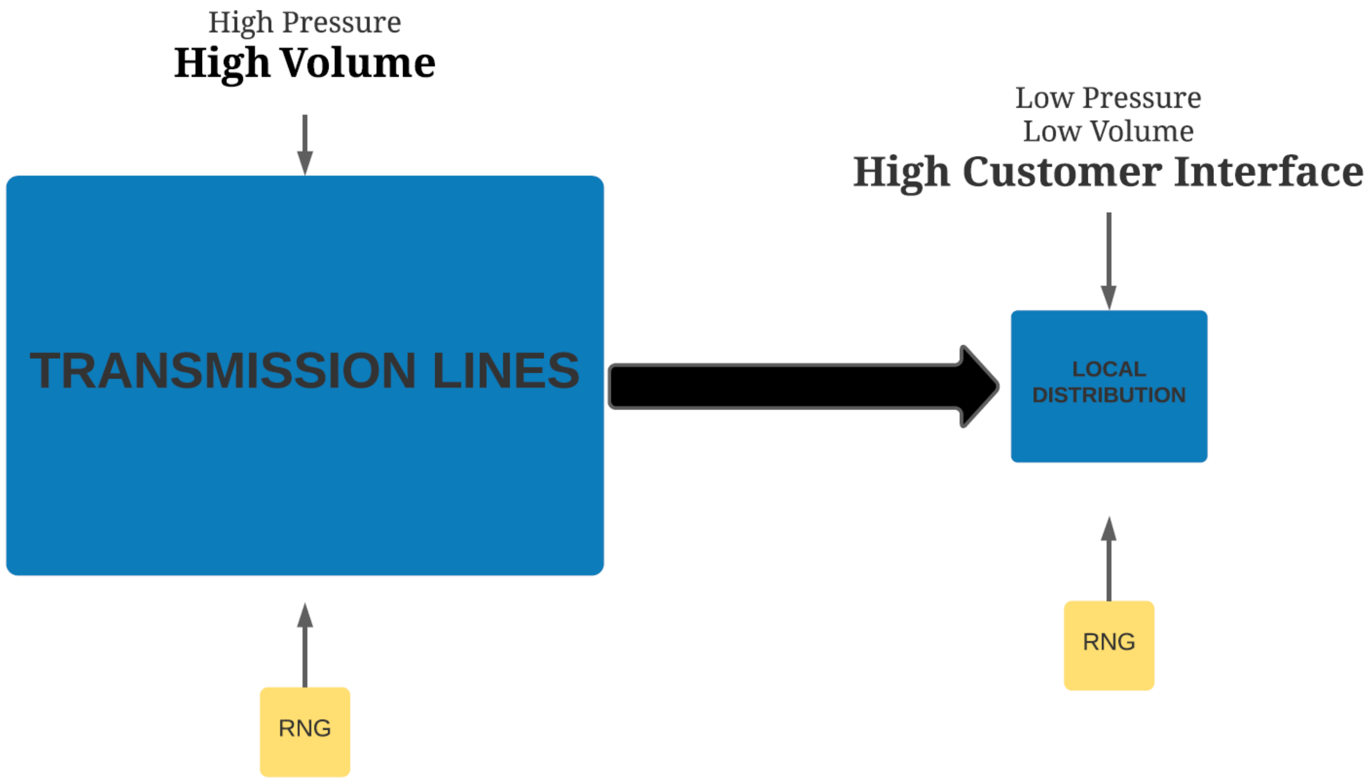
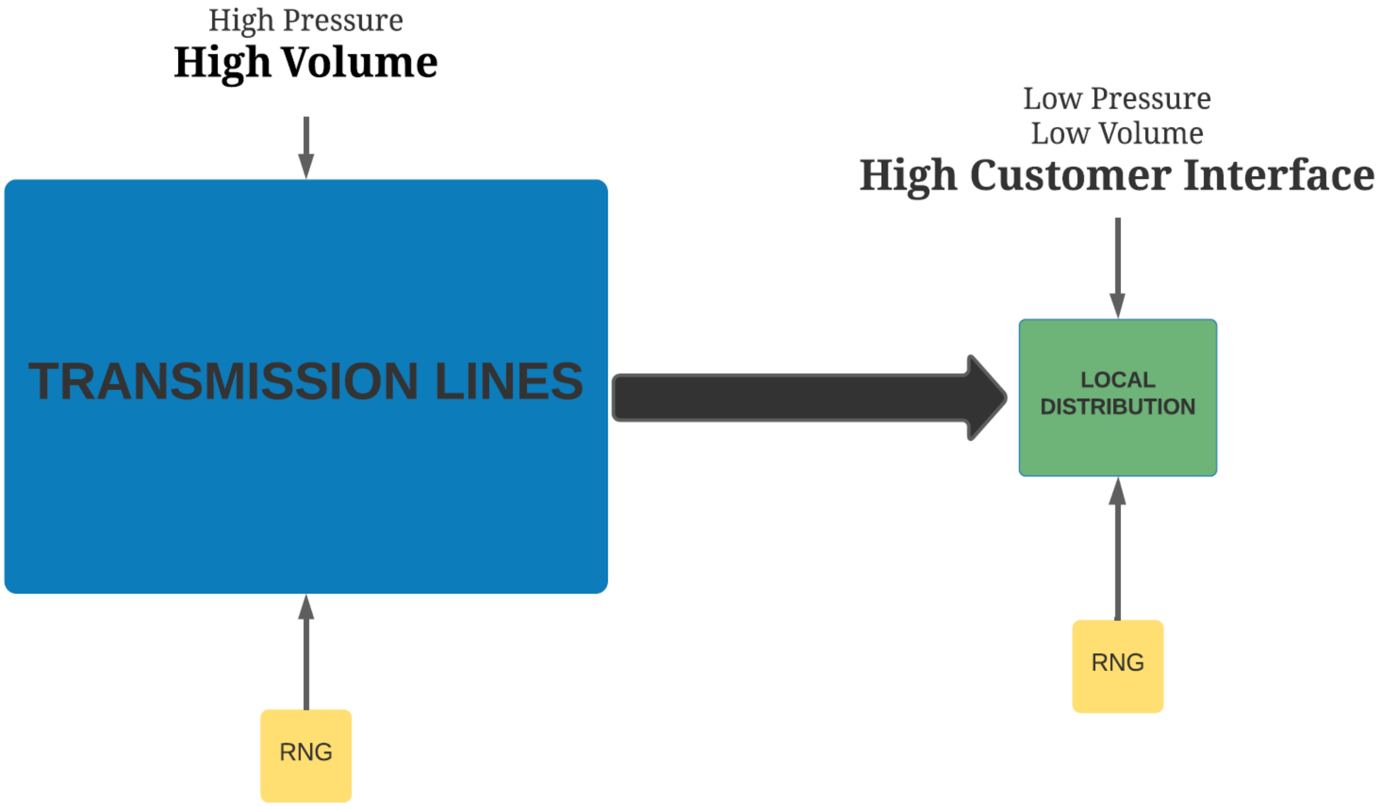

RNG RISK RECEPTORS
Pipeline Integrity
Human Health & the Environment
End-Use Equipment
Ammonia, Odorant Masking Agents
Halocarbons
Select Compounds
Hydrogen
Heavy Metals
Siloxanes
Unidentified?

REEthink

Specifications and Dilution



Specifications and Dilution



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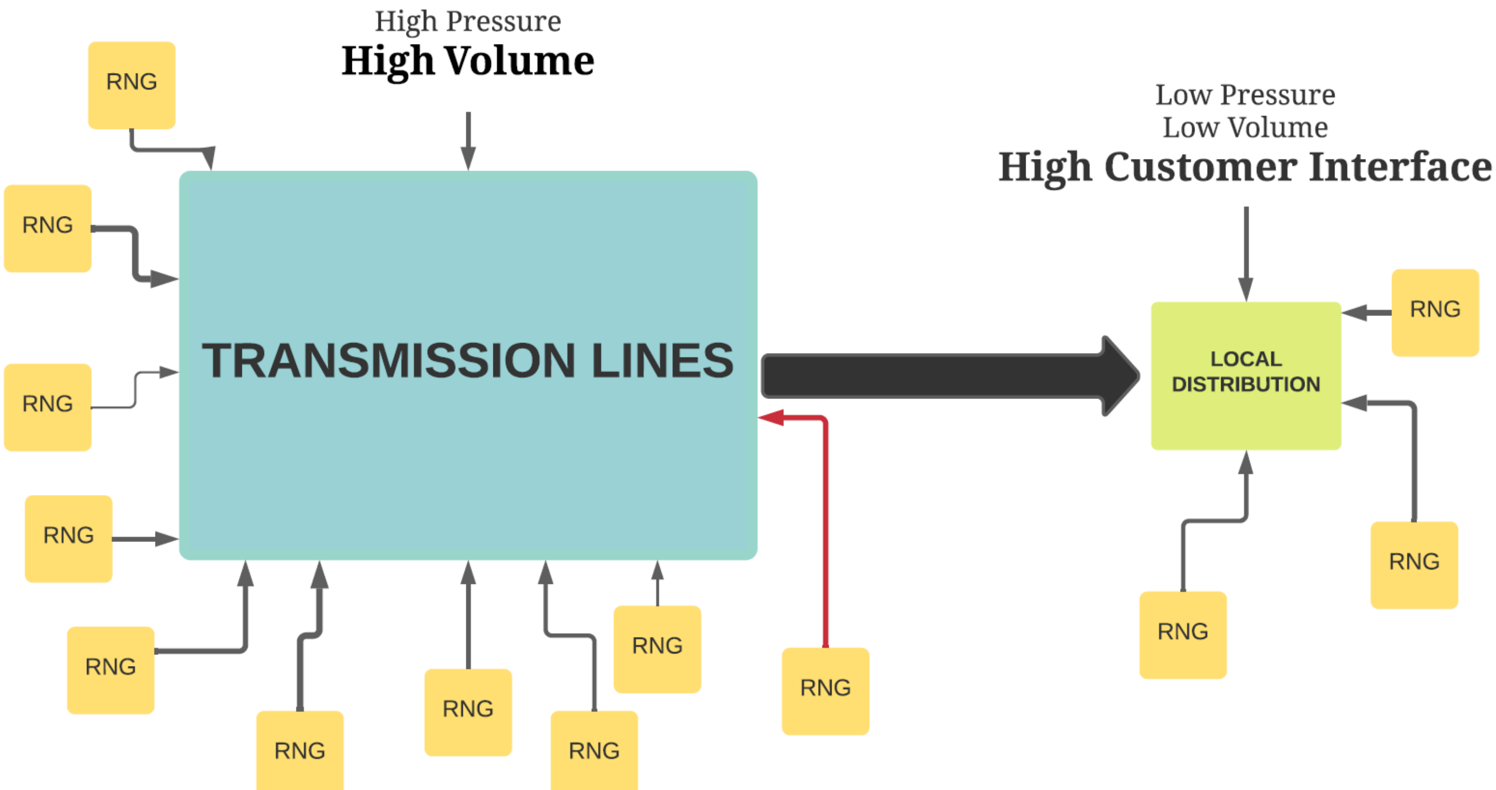
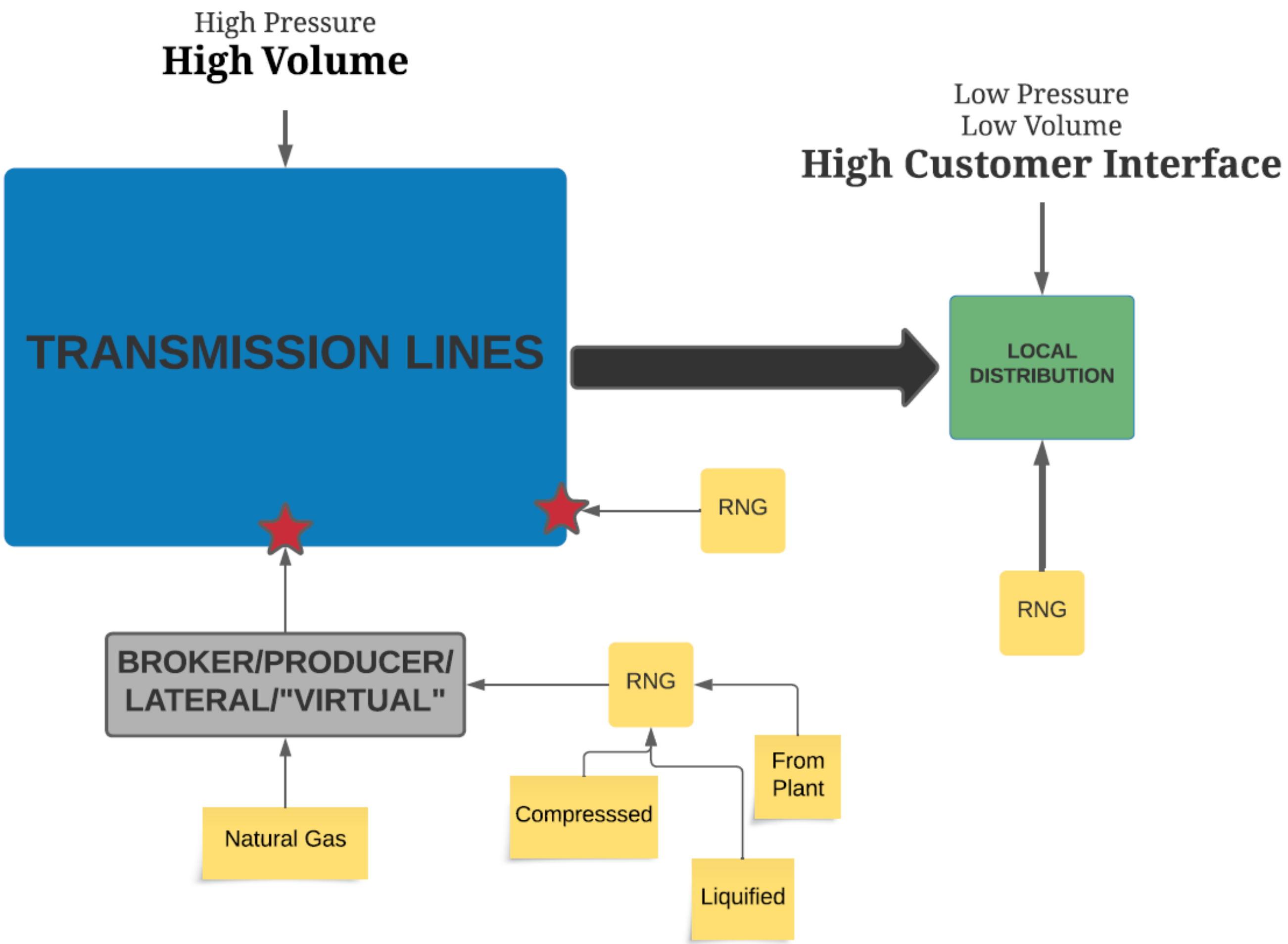
Specifications and Dilution



Dilution Before Entering Transmission Line



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We need a
SPECIFICATION
for the
TRACE CONSTITUENTS

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What Makes A Defendable Biomethane Specification?

1) Evidence-Based (science, research, modeling, historical precedence)
2) Referenced (consensus within the industry, shared body of knowledge)
3) Reasonable (does it make sense, industry experts, scientific experts)
4) Justifiable (database examination, comparison of datasets, analytical review)
5) Verifiable (analytical techniques available for reliable testing)
6) Achievable (it can be done with available technology)

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BIOMETHANE RNG TRACE CONSTITUENT SPECIFICATIONS			
Ammonia	NH_3	0.001%	% vol.
Hydrogen	H_2	Varies by Company	% vol.
Siloxanes	Si	0.5	mg Si/m3
Chlorine Total	Cl	10	mg/m3
Fluorine Total	F	10	mg/m3
Mercury	Hg	0.08	mg/m3
Arsenic	As	0.19	mg/m3[5]
Copper	Cu	0.6	mg/m3[6]

Other Trace Constituents may be Included, Depending upon Company Requirements

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Natural Gas Tariff Language

MAJOR COMPONENTS

- **BTU, WOBBE**
- **Inert Gases**
  - Carbon Dioxide
  - Oxygen
  - Nitrogen
  - Helium
  - Carbon Monoxide
- **Sulfur Compounds**
  - Hydrogen Sulfide
  - Mercaptans
  - Total Sulfur

Physical Attributes

- Moisture
- Hydrocarbon Dewpoint
- Temperature
- Characteristics upon burning

ON-SITE, REAL TIME MONITORING

TRACE CONSTITUENTS/"Objectionable Material"

FIELD SAMPLES

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Every TRACE CONSTITUENT in Your RNG SPECIFICATION Requires a SPECIFIC FIELD SAMPLE METHOD, which goes with a SPECIFIC LABORATORY METHOD

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FIELD SAMPLE METHOD

Performed with Accuracy and Precision

LABORATORY METHOD

REQUIRED FOR CONSTITUENT DETECTION AND QUANTIFICATION

High Quality, Defendable, Accurate Results

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Gas Quality Constituent	Assigned Value	Laboratory Equipment	Laboratory Method	Field Sampling Material or Devise	Comments
TRACE CONSTITUENTS					
Ammonia	0.001 vol% 10 ppmV	AAS/Ion Chromatography	OSHA ID-188 NIOSH 6015 EPA M26	Glass Tubes Glass Tubes Mod. EPA Method 26 (Impingers)	Analytical Method pairs with Sampling Method; EPA Method is impinger method
Hydrogen	0.1 Vol %	Gas Chromatography/Thermal Conductivity Detector	ASTM D1945/D1946	Tedlar Bag/Cylinder/Check with your Laboratory	
Siloxanes	0.5 mg Si/m3	Gas Chromatography/Mass Spectrometry	ASTM D8230-19	Tedlar bag - Analysis within 72 hours; Sample cylinder - check with your laboratory for holding times, options	ASTM recently approved method
Halocarbons - Halogens	Chlorine: 10 mg/m3 TOTAL Fluorine: 10 mg/m3 TOTAL	Gas Chromatography/Mass Spectrometry	EPA TO-15	5-L Tedlar Bag; Summa Canisters. Impinger method in field: EPA Method 26/26A	
Mercury	0.08 mg/m3	Atomic Adsorption Spectroscopy	ASTM D5954	Gold Plated Silica Beads	
Arsenic	0.19 mg/m3 or 0.06 ppmv	Atomic Adsorption Spectroscopy/ICAP	EPA Method 29 Modified	EPA Method 29	
Copper	0.60 mg/m3 or 0.23 ppmv	Atomic Adsorption Spectroscopy/ICAP	EPA Method 29 Modified	EPA Method 29	

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Field Sampling Is…

- Expensive!
  - Mobilization/Demobilization Costs
  - Personnel Time
  - Travel
  - Equipment
  - Expedited Shipping
- Highly Crucial to the Accuracy of the Laboratory Results
  - Correct method, correct medium, correct approach, attention to detail
  - Sampling gaseous fuel, low concentrations of constituents, etc.
- Field sampling method PAIRS with the laboratory method
- The key to product safety for the pipeline
- Used for legal defense

Review

MAJOR COMPONENTS:

REAL-TIME, ON-LINE MONITORING
24/7/365
SCADA INTERFACE
LONG TERM MONITORING (DATABASE CREATION)
SAME AS NATURAL GAS SUPPLIES
FIELD SAMPLE: SPECIFIC CIRCUMSTANCES

TRACE CONSTITUENTS:

FIELD SAMPLING

Specific sampling method for the required laboratory test

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Trace Constituents in Typical Biomethane RNG Specification

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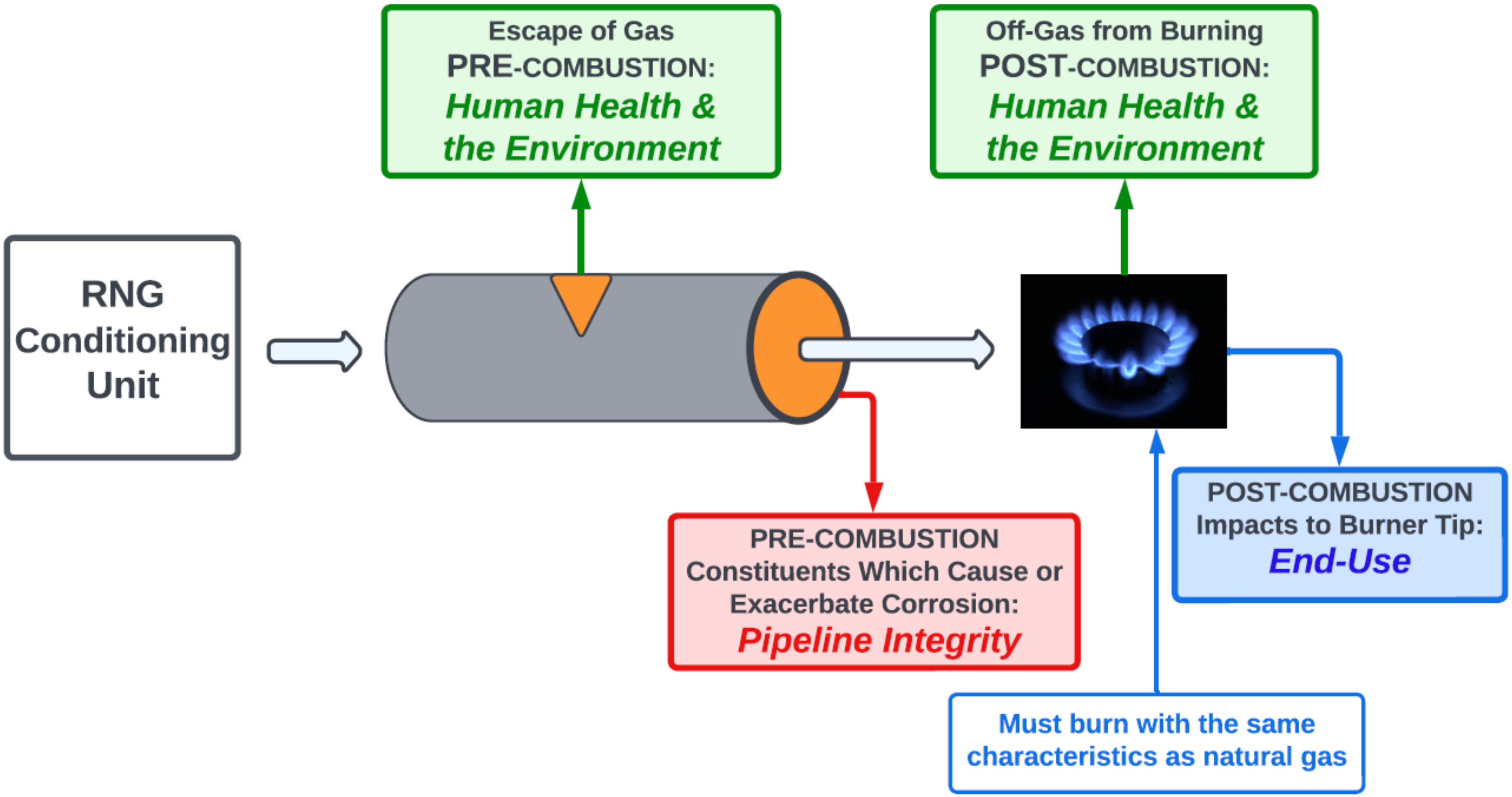
Three Risk Receptors



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Trace Constituent Risk Receptor			
Compound	**Human Health & Environment**	**Pipeline Integrity**	**End-Use Impact**
Ammonia	X	X	
Hydrogen		X	X
Siloxanes			X
Chlorine Total	X	X	X
Fluorine Total	X	X	X
Mercury			X
Arsenic	X		
Copper	X		

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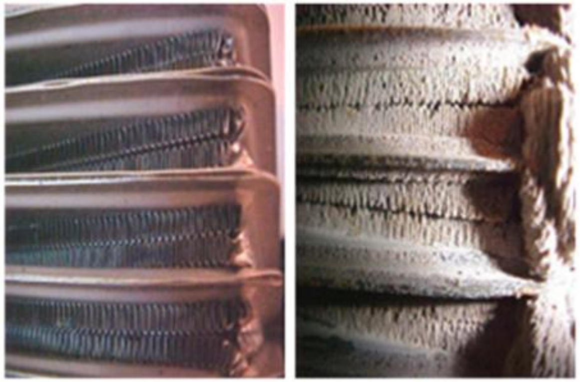
Ammonia

- Can be associated with manure systems
- Can be found in landfills, WWT sludge AD systems
- Tested in all biogas sources
- **IMPACT TO ODORANT PERFORMANCE**
- **Accelerates internal corrosion**
  - Ammonium chloride
- Field Sampling: Glass tubes with sorbent media
- Laboratory analysis:
  - OSHA ID-188
  - NIOSH 6015

Siloxanes

- Man-made chemicals found in products such as cosmetics, personal hygiene products, soaps, food additives, water-repellent clothing, defoamers and many other sources.
- There are many congeners (forms) containing various amounts of silicon - Si
- They are volatilized through the AD process.
- When combusted, the siloxane molecules are reduced to silica dust; this is extremely abrasive and damaging to internal engine components.
- The combustion process can also cause a build up around burner tips and on the tubes of heat exchangers.
- Found in many sources – landfill, WWT, etc.
- **IMPACT TO END-USED EQUIPMENT**



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Siloxanes

- Field Sampling: Glass tube with media, cylinder, Tedlar bag – CHECK WITH YOUR LABORTORY
- Laboratory Method: ASTM 8230-19

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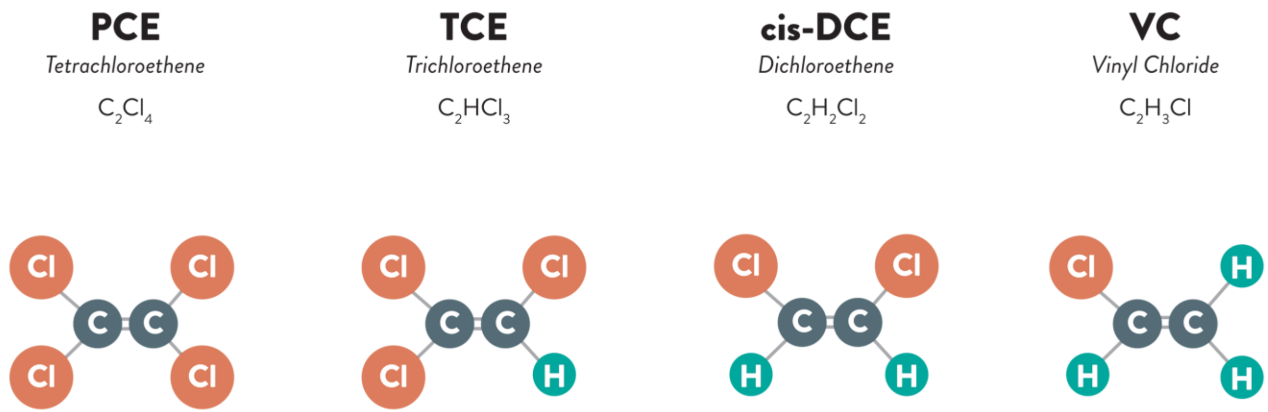
Halogens: Chlorine, Fluorine



$$2Cl^{-} + 2H^{-} \rightarrow 2\ HCl$$

Potential for hydrochloric acid

IMPACT ALL RECEPTORS

(HHE, end-use, pipeline integrity)

Found in landfill gas, WWT sludge AD

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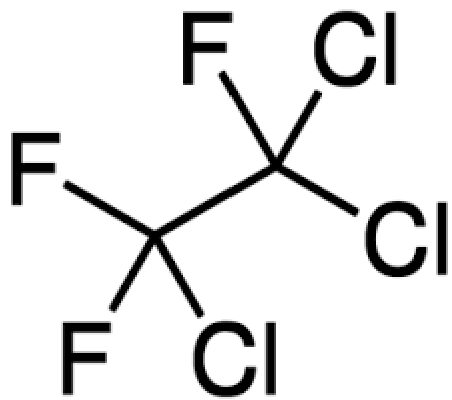
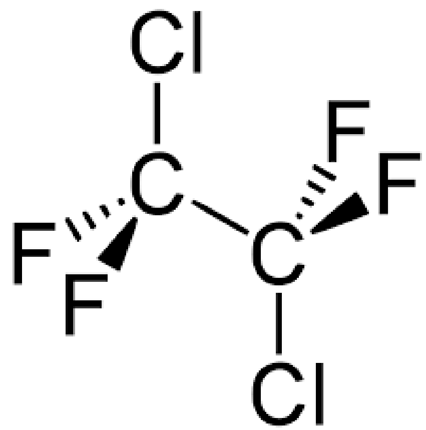
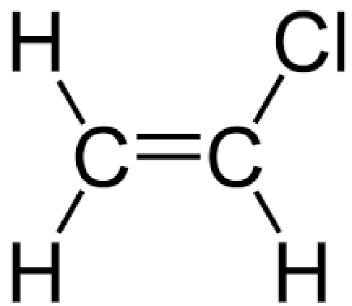
Count the Chlorine/Fluorine Molecules, Not the Compounds



CFC-113



CFC-114



Vinyl Chloride

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Halogens: Chlorine and Fluorine

- Field Sampling: Glass tube with media, Tedlar bag, check with laboratory
- Laboratory Method: TO-15
- Recorded as mg Si/m3

Component Name	LF1BG01TB ppmv	LF1BG02TB ppmv	LF1BG03TB ppmv	LF1BG04TB ppmv
Dichlorodifluoromethane (CFC-12)	**1.85**	**2.05**	**1.26**	**1.90**
1,2-Dichlorotetrafluoroethane (CFC-114)	BDL	BDL	**0.25**	**0.33**
1,1,2-Trichloro-1,2,2-trifluoroethane (CFC-113)	BDL	BDL	BDL	BDL
Trichlorofluoromethane (CFC-11)	**0.42**	**0.51**	**0.20**	**0.23**
Chloromethane	BDL	BDL	BDL	BDL
Dichloromethane (Methylene Chloride)	**2.18**	**2.48**	**0.93**	**1.15**
Chloroform	BDL	BDL	BDL	BDL
Carbon Tetrachloride	BDL	BDL	BDL	BDL
Chloroethane	BDL	BDL	**0.81**	**0.88**
1,1-Dichloroethane	**0.17**	**0.20**	**0.13**	**0.15**
1,2-Dichloroethane	**0.22**	**0.16**	**0.14**	**0.20**
1,1,1-Trichloroethane	BDL	BDL	BDL	BDL
1,1,2-Trichloroethane	BDL	BDL	BDL	BDL
1,1,2,2-Tetrachloroethane	BDL	BDL	BDL	BDL
Chloroethene (Vinyl Chloride)	**0.21**	**0.25**	**0.53**	**0.64**
1,1-Dichloroethene	BDL	BDL	BDL	BDL
cis-1,2-Dichloroethene	**0.28**	**0.32**	**0.36**	**0.45**
Trichloroethene	**0.31**	**0.30**	**0.26**	**0.38**
Tetrachloroethene	**0.20**	**0.21**	**0.21**	**0.28**
			BDL	BDL
1,2-Dichloropropane	BDL	BDL	BDL	BDL
			BDL	BDL
3-Chloropropene	BDL	BDL	BDL	BDL
cis-1,3-Dichloropropene	BDL	BDL	BDL	BDL
trans-1,3-Dichloropropene	BDL	BDL	BDL	BDL
			BDL	BDL
Bromomethane	BDL	BDL	BDL	BDL
1,2-Dibromoethane	BDL	BDL	BDL	BDL
			BDL	BDL
Chlorobenzene	BDL	BDL	BDL	BDL
1,2-Dichlorobenzene	BDL	BDL	BDL	BDL
1,3-Dichlorobenzene	BDL	BDL	BDL	BDL
1,4-Dichlorobenzene	BDL	BDL	BDL	BDL
1,2,4-Trichlorobenzene	BDL	BDL	BDL	BDL
Hexachloro-1,3-butadiene	BDL	BDL	BDL	BDL
Total TO-14 Halocarbon Components:	**5.85**	**6.49**	**5.09**	**6.59**

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Metals: Mercury, Arsenic and Copper

- Mercury:
  - **Impacts to end-use equipment** (corrosion and catalyst poisoning)
  - Rules 21 and 30 from California utilities
  - Reported value from internal research
  - Found in landfill gas/WWT sludge digestion biogas

- Arsenic and Copper:
  - **Impacts to human health and the environment**
  - Rules 21 and 30 from California utilities
  - Based on health risk reports from the state of CA
  - Found in landfill gas/WWT sludge digestion biogas

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Metals

- MERCURY
  - FIELD SAMPLING – Glass tube/other with gold-plated silica beads to which the mercury attaches
  - Need volumes of gas collected
  - LABORATORY ANALYSIS – ASTM D5954
- ARSENIC and COPPER
  - FIELD SAMPLING: EPA Method 29 Modified
  - NEW field collection method: OL-21G Glass tube with sorbent material
  - LABORATORY ANALYSIS: EPA Method 29

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RNG: Focus on Pipeline Corrosion

<u>As with natural gas</u>:

- Pipeline internal corrosion is attributed to a combination of factors occurring in the pipeline
- Complex interaction and rarely due to one factor
- Difficult to control and predict

Contributing factors (both natural gas and biomethane):

- Moisture (water in the pipe)
- CO2
- Hydrogen sulfide
- Oxygen
- Combinations
- Presence of a specific set of microbes (MIC microbes)

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Pipeline Microbiology

- Nothing is sterile.
- Bacteria are considered **particulate matter**, therefore "objectionable material".
- These bacteria instigate, exacerbate and/or accelerate corrosion of metal pipe through acid production and unique abilities to thrive under very harsh conditions.
- Metal begins to pit and weaken, dust/powder is produced.
- 40% of corrosion is a result of microbial action.

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Microbiologically-Influenced Corrosion (MIC)

- A *general term* which involves many types of microbes (bacteria and Archaea) which contribute to corrosion.
- They are *extremophiles*, thriving under conditions of high/low temperature, pressure, salinity, radiation, presence of toxic compounds and heavy metals, and pH ranges.
- Very “old” set of microbes.
- Very adaptable, clever and “tough” – have developed unique enzyme systems to cope with very hostile environments.
- Anaerobic – can thrive under conditions with no oxygen.
- They can create unique microenvironments which fluctuate; changes can occur quickly.

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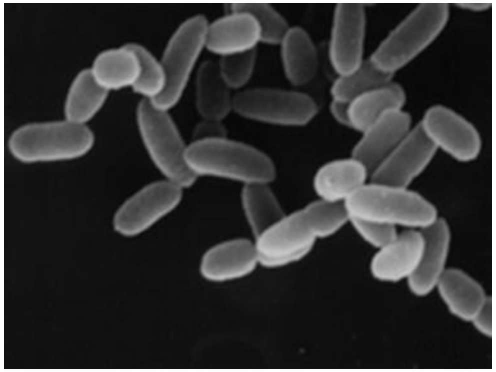
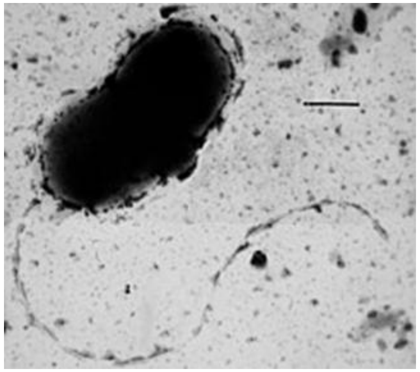
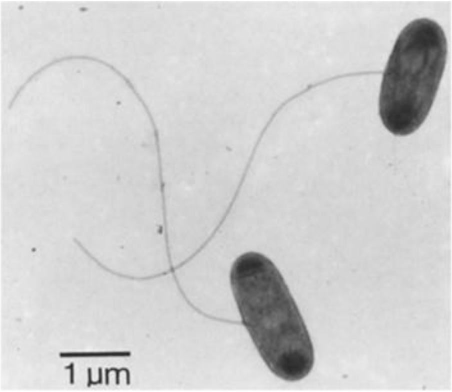
Microbes are Everywhere – in Natural Gas and in RNG

How do the bacterial/Archaea numbers compare:

RNG versus Natural Gas?







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Bacterial Counts in Natural Gas and RNG

- The number of bacteria/Archaea within the MIC set in RNG are less than or equal to those found in natural gas systems.
- Microbes are living and ONE cell can “bloom” to many, under the right conditions…therefore:

TOTAL BACTERIAL COUNTS ARE MEANINGLESS

- Conditions for microbial grown need to be monitored in all pipelines (water vapor control important).
- Microbial “blooms” can also be a confluence of other pipeline conditions: trace constituents for which we have no data.
- This parameter is covered the “Objectionable Material” clause, as microbes are particulate matter.

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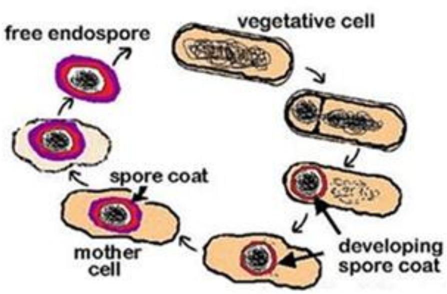
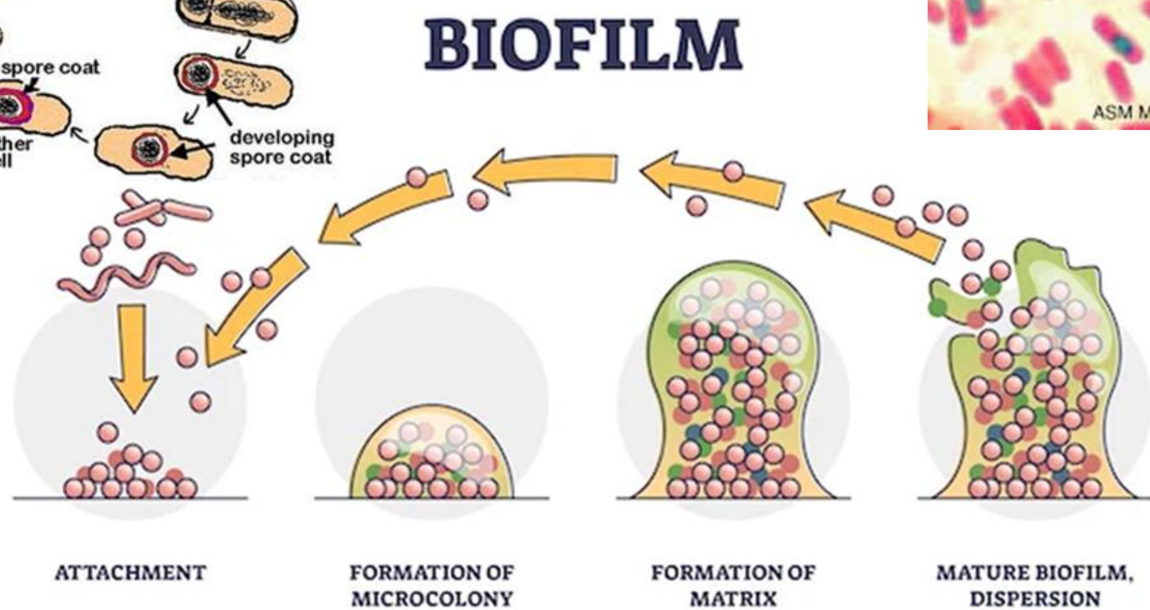
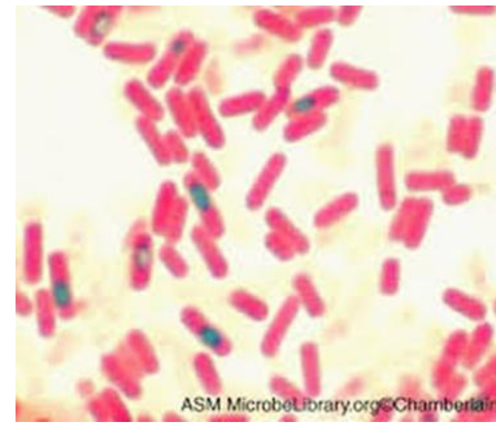
Microbes in the Pipeline: Biofilm Formation/Endospores







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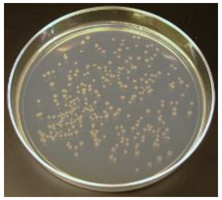
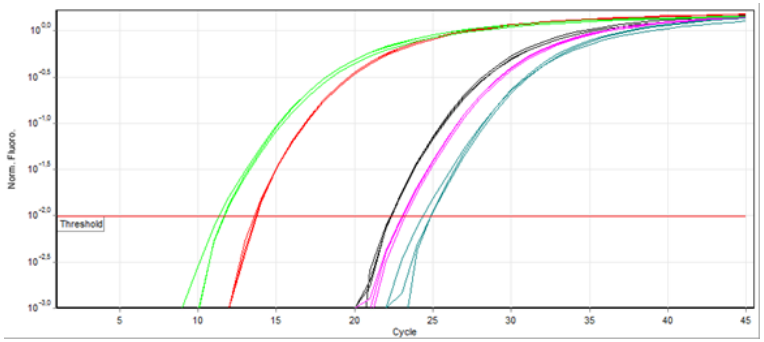
Microbial Counts – What Does it Mean?



- Plate counts are not accurate
- qPCR testing:
  - Only counts microbes in the flowing gas, not attached to the walls
  - **Does not** distinguish between live and dead cells
  - **Does not** count spores
  - **DOES NOT INDICATE CORROSION OR THE LIKELIHOOD OF CORROSION**
  - Not required for natural gas inclusion to the pipe
  - Some RNG specifications include nonsense language regarding "biologicals"
- Use of biocides: bacteria become resistant…doesn't work in the long run



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Use of High-Quality Industrial Filter and Monitoring Through EM/EA Coupons

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Specification alone is not sufficient…

Need a

Verification and Monitoring Program

for

GAS QUALITY ASSURANCE

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Verification and Monitoring Program = Quality Assurance

Verification =
"Does the gas meet the specification PRIOR to entering the pipeline?"

Monitoring =
"Is the gas quality consistent over time?"

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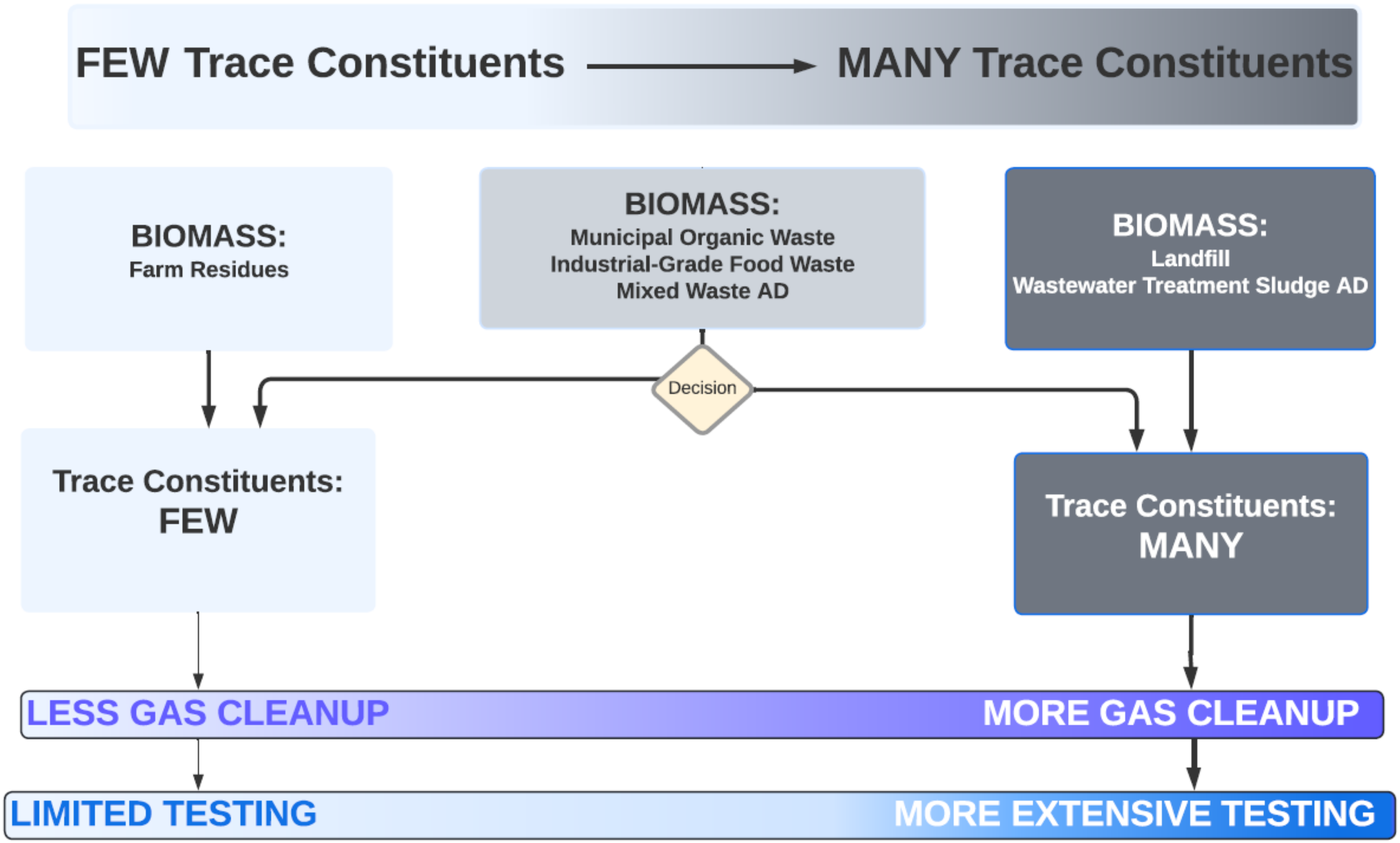
FEW Trace Constituents
MANY Trace Constituents
BIOMASS:
Farm Residues
BIOMASS:
Municipal Organic Waste
Industrial-Grade Food Waste
Mixed Waste AD
BIOMASS:
Landfill
Wastewater Treatment Sludge AD
Decision
Trace Constituents:
FEW
Trace Constituents:
MANY
LESS GAS CLEANUP
MORE GAS CLEANUP
LIMITED TESTING
MORE EXTENSIVE TESTING

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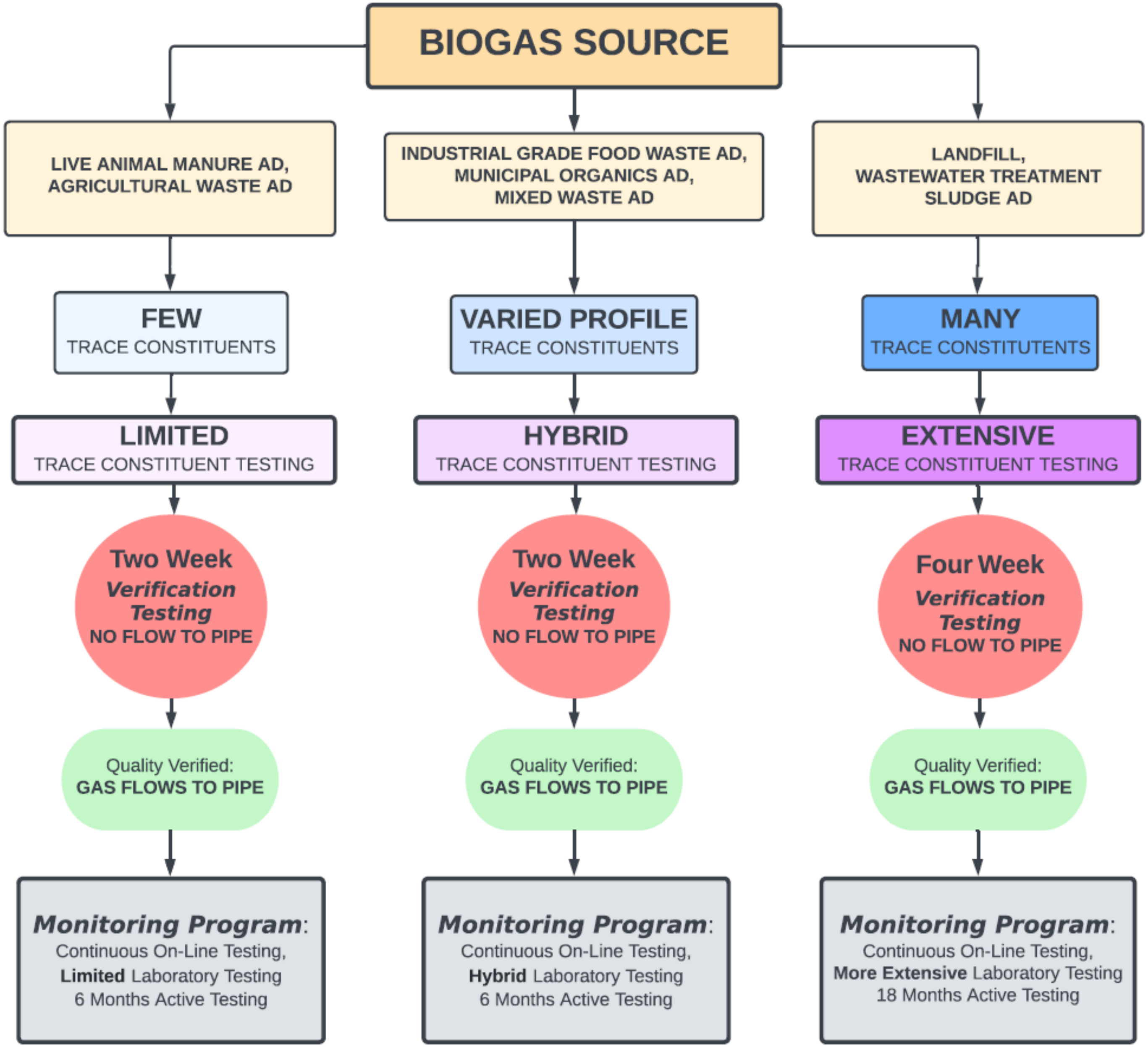
BIOGAS SOURCE
LIVE ANIMAL MANURE AD, AGRICULTURAL WASTE AD
INDUSTRIAL GRADE FOOD WASTE AD, MUNICIPAL ORGANICS AD, MIXED WASTE AD
LANDFILL, WASTEWATER TREATMENT SLUDGE AD
FEW
TRACE CONSTITUENTS
VARIED PROFILE
TRACE CONSTITUENTS
MANY
TRACE CONSTITUTENTS
LIMITED
TRACE CONSTITUENT TESTING
HYBRID
TRACE CONSTITUENT TESTING
EXTENSIVE
TRACE CONSTITUENT TESTING
Two Week Verification Testing NO FLOW TO PIPE
Two Week Verification Testing NO FLOW TO PIPE
Four Week Verification Testing NO FLOW TO PIPE
Quality Verified: GAS FLOWS TO PIPE
Quality Verified: GAS FLOWS TO PIPE
Quality Verified: GAS FLOWS TO PIPE
Monitoring Program: Continuous On-Line Testing, Limited Laboratory Testing 6 Months Active Testing
Monitoring Program: Continuous On-Line Testing, Hybrid Laboratory Testing 6 Months Active Testing
Monitoring Program: Continuous On-Line Testing, More Extensive Laboratory Testing 18 Months Active Testing

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BIOGAS SOURCES OF LIVE ANIMAL MANURE/AGRICULTURAL WASTE AD ONLY

	TRACE CONSTITUENTS
	PARAMETER and TESTING BY THIRD PARTY LABORATORIES
COMPONENT	AMMONIA
Specification Limit*	0.001% Vol
Analytical Method (Laboratory Testing)*	OSHA ID-188/see list
PLANT START-UP	
RNG Plant Operation Document	Y
RNG VERIFICATION PHASE (2 weeks)	
Start-up Testing WEEK 1: (1 Event x Triplicate Samples)	1
Start-Up Testing WEEK 2 : (1 Event per Week x Triplicate Samples)	1
Verification Sample Events**	**2**
MONITORING PERIOD 1 (MONTH 1 - 6)	
Monthly (Once a Month)	6
Total Monitoring Period 1 Sample Events**	**6**
MONITORING PERIOD 2 (Month 7 - 18)	
Quarterly (Every Three Months)	4
Total Monitoring Period 2 Sample Events**	**4**
MONITORING PERIOD 3 (Month 19 - 36)	
Bi-Annually (Twice Yearly)	2
Total Monitoring Period 3 Sample Events**	**2**
MONITORING PERIOD 4 (Length of Project)	
Annual Check **	**1**

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BIOGAS SOURCES LANDFILL/WWT SLUDGE AD

	TRACE CONSTITUENTS						
	PARAMETER and TESTING BY THIRD PARTY LABORATORIES*						
COMPONENT	**AMMONIA**	**SILOXANES**	**CHLORINE: TOTAL**	**FLUORINE: TOTAL**	**MERCURY**	**ARSENIC**	**COPPER**
Specification Limit*	0.001% Vol	0.5 mg SI/m3	10 mg/m3	10 mg/m3	0.08 mg/m3	0.19 mg/m3 or 0.06 ppmV	0.60 mg/m3 or 0.23 ppmv
Analytical Method (Laboratory Testing)*	OSHA ID-188/see list	ASTM D8230-19	EPA TO-15	EPA TO-15	ASTM D5954	EPA Method 29 Modified	EPA Method 29 Modified
PLANT START-UP							
RNG Plant Operation Document	Y	Y	Y	Y	Y	Y	Y
RNG VERIFICATION PHASE (Month 1)							
Start-up Testing WEEK 1: (1 Event x Triplicate Samples)	1	1	1	1	1	1	1
Weekly Testing WEEKS 2 - 4: (1 Event per Week x Triplicate Samples)	3	3	3	3	3	3	3
Verification Sample Events**	**4**	**4**	**4**	**4**	**4**	**4**	**4**
MONITORING PERIOD 1 (MONTH 2 -6)							
Bi-Weekly (Every Other Week, Total Count)	10	10	10	10	10	10	10
Total Monitoring Period 1 Sample Events**	**10**	**10**	**10**	**10**	**10**	**10**	**10**
MONITORING PERIOD 2 (Month 7 - 18)							
Monthly (Once a Month)	12	12	12	12	12	12	12
Quarterly (Every Three Months)							
Total Monitoring Period 2 Sample Events**	**12**	**12**	**12**	**12**	**12**	**12**	**12**
MONITORING PERIOD 3 (Month 19 - 36)							
Quarterly (Every Three Months)	4	4	4	4		4	4
Bi-Annually (Twice Yearly)					2		
Total Monitoring Period 3 Sample Events**	**4**	**4**	**4**	**4**	**2**	**4**	**4**
MONITORING PERIOD 4 (Length of Project)							
Annual Check **	**1**	**1**	**1**	**1**	**1**	**1**	**1**

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MAJOR COMPONENTS

Major Components

- These parameters and constituents are directly carried over from current natural gas tariffs.
- Natural gas tariffs vary across the US and even between pipeline companies.
- Some tariffs are specific to a particular end-user, producer or section of pipe.
- Transmission companies monitor gas supplies to their network.
- Measured on-line, real time 24/7/365.

BTU and Wobbe Number

- BTU = heating value of the gas (combination of gases)
  - Is in **all** Natural Gas Specifications
- Wobbe Number
  - Wobbe Number is based on the heating value and specific gravity of a gas, and it is related to the thermal output from a burner (BTU/hour)
  - "Heating value alone is not a sufficient indicator of the interchangeability of gases" – NGC+ Whitepaper
  - Not in all natural gas specifications
  - Very important in the "burn quality" of the gas
  - Don't want flame lifting, formation of CO, yellow-tipping and blowout

Compounds and Associated Heating Values	
Compound	**Heating Value (BTU/ft3)**
Methane	1,010
Ethane	1,770
Propane	2,516
Butane	3,225
Pentane	3,981
Hexane	4,667
Manufactured Gas	530

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BTU and Wobbe Number

- With RNG, BTU directly related to concentration of inerts (CO_2 and N_2) in the gas
- Always will have lower BTU and Wobbe Number… never 100% methane
- In the laboratory, the analytical test is ASTM D1945/D1946
- **On-line, real-time monitoring required**

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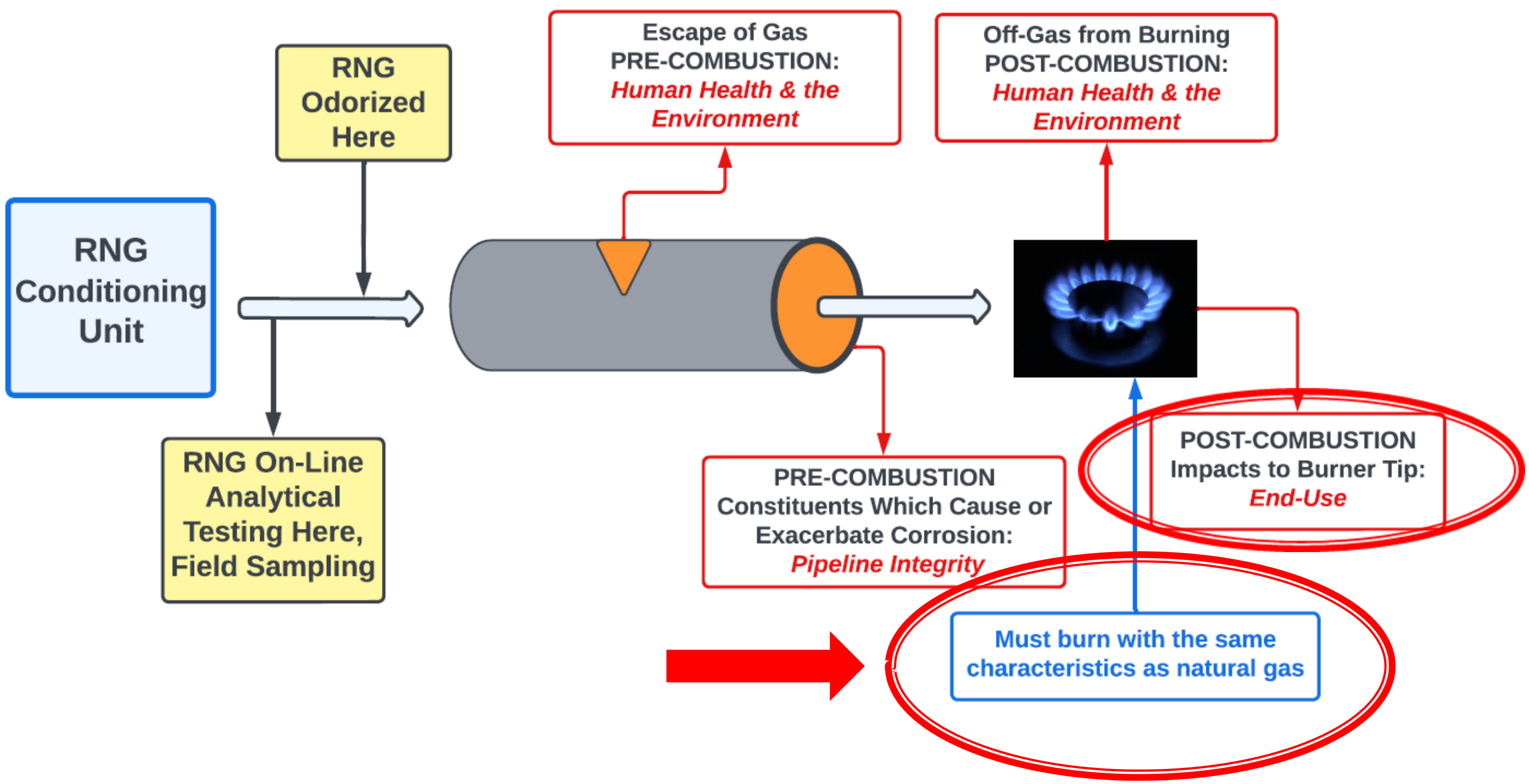
Impacts of BTU and Wobbe Number



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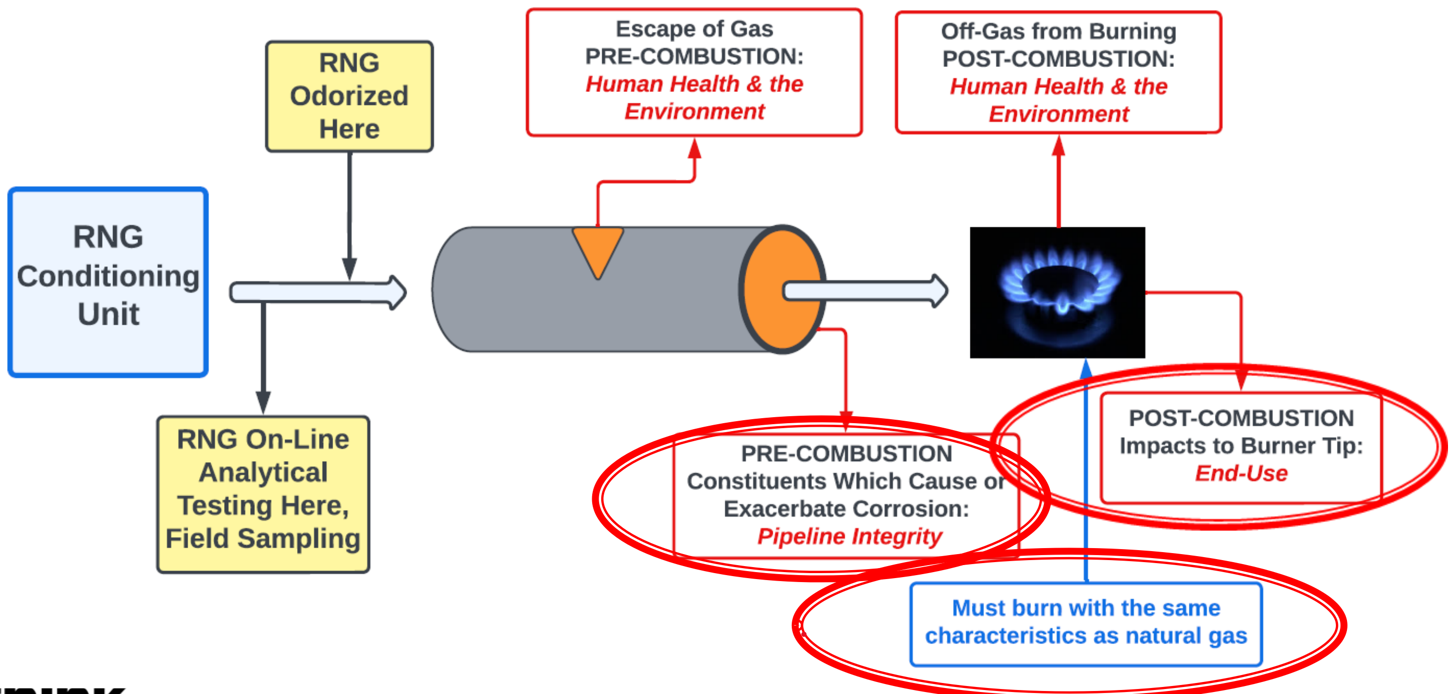
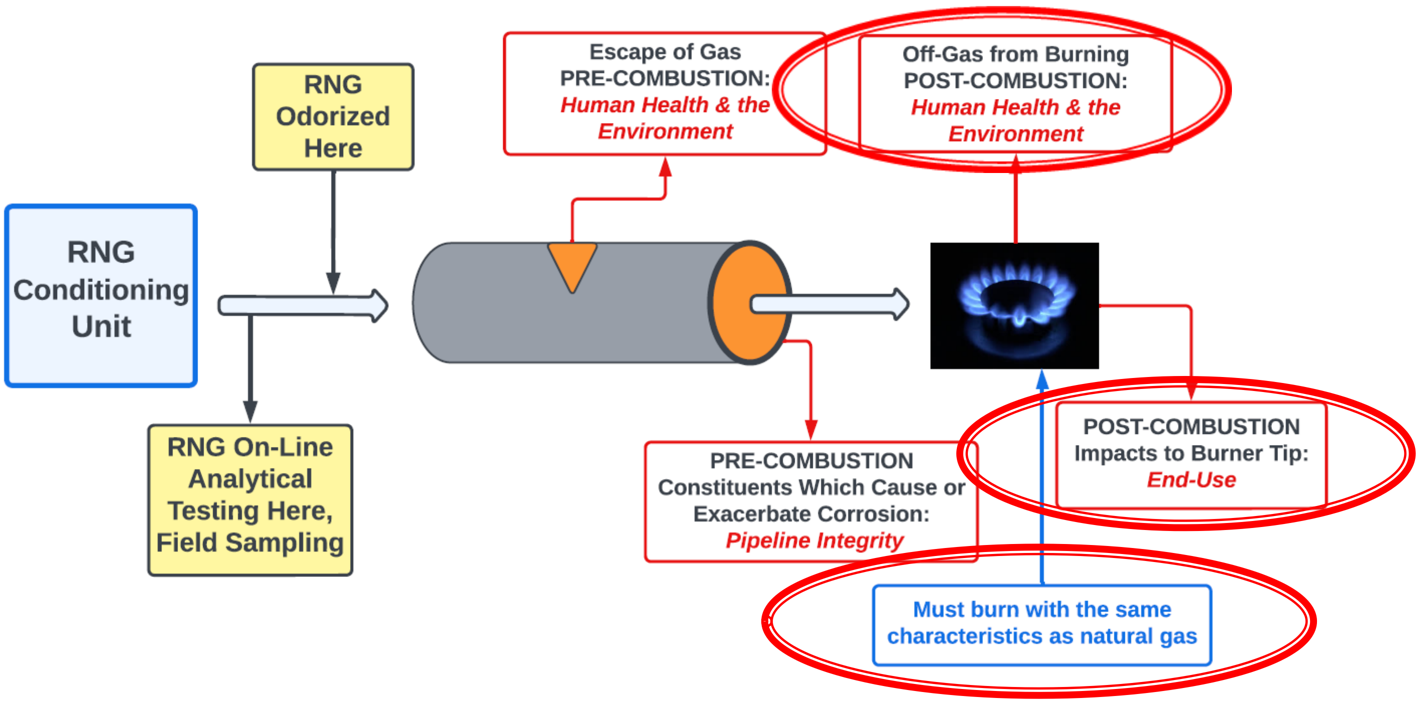
Inerts: Carbon Dioxide

- Dominates the gas profile, diluent
- In the presence of water, can form carbonic acid
- Can react with H_2S and oxygen – enhancing corrosion in metal pipes
- Laboratory testing: ASTM D1945/D1946
- **On-line, real-time monitoring required**



Inerts: Nitrogen

- Is a diluent
- Impacts gas used as feedstock (fuel cells, hydrogen production, natural gas liquefaction)
- Impacts compressibility of the gas
- Impacts emissions from burning: NOx
- Laboratory testing: ASTM D1945/D1946
- **On-line, real-time monitoring required**



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BTU, Wobbe Number, Inerts (CO_2, N_2):

ONE ONLINE INSTRUMENT:

Gas Chromatograph

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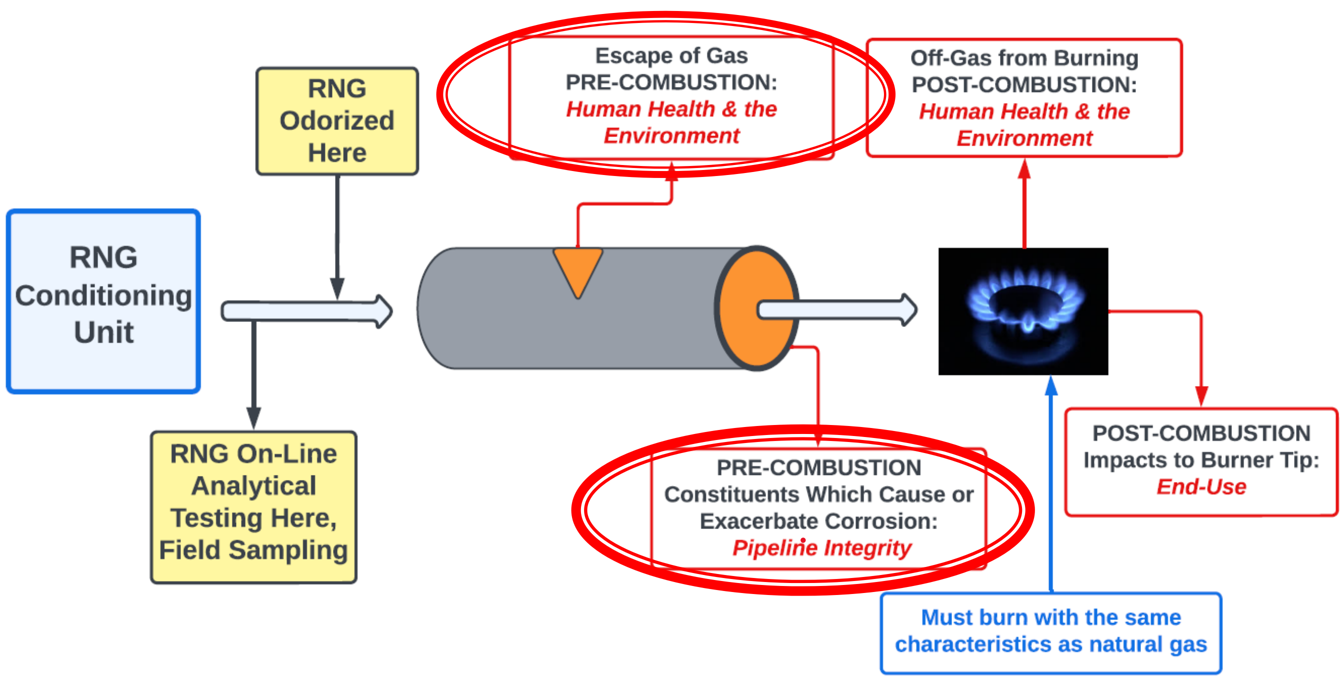
Inert: Oxygen

- A key element in the RATE and EFFECT of corrosion in metal pipes – VERY IMPORTANT CONSTITUENT TO MONITOR
- Difficult to remove in biogas
- In the presence of water and/or CO_2 or H_2S, corrosion is instigated or exacerbated
- Bacteria can grow in presence of oxygen, causing corrosion
- If there is leakage, combustion is possible
- Laboratory testing: ASTM D1945/D1946
- **On-line, real-time monitoring required**



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Oxygen:
ONE ONLINE INSTRUMENT

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Sulfur in Natural Gas or Biomethane

- Total Sulfur = the sum of the contribution of all sulfur-containing compounds in the gas, and is then calculated based on relative molecular weight of sulfur in the compound.
- Hydrogen sulfide is the primary sulfur compound of concern in raw biogas/RNG.
  - Generated through microbial decomposition of sulfur-containing compounds.
  - Found naturally in some water sources
- RNG units must be able to remove H_2S.

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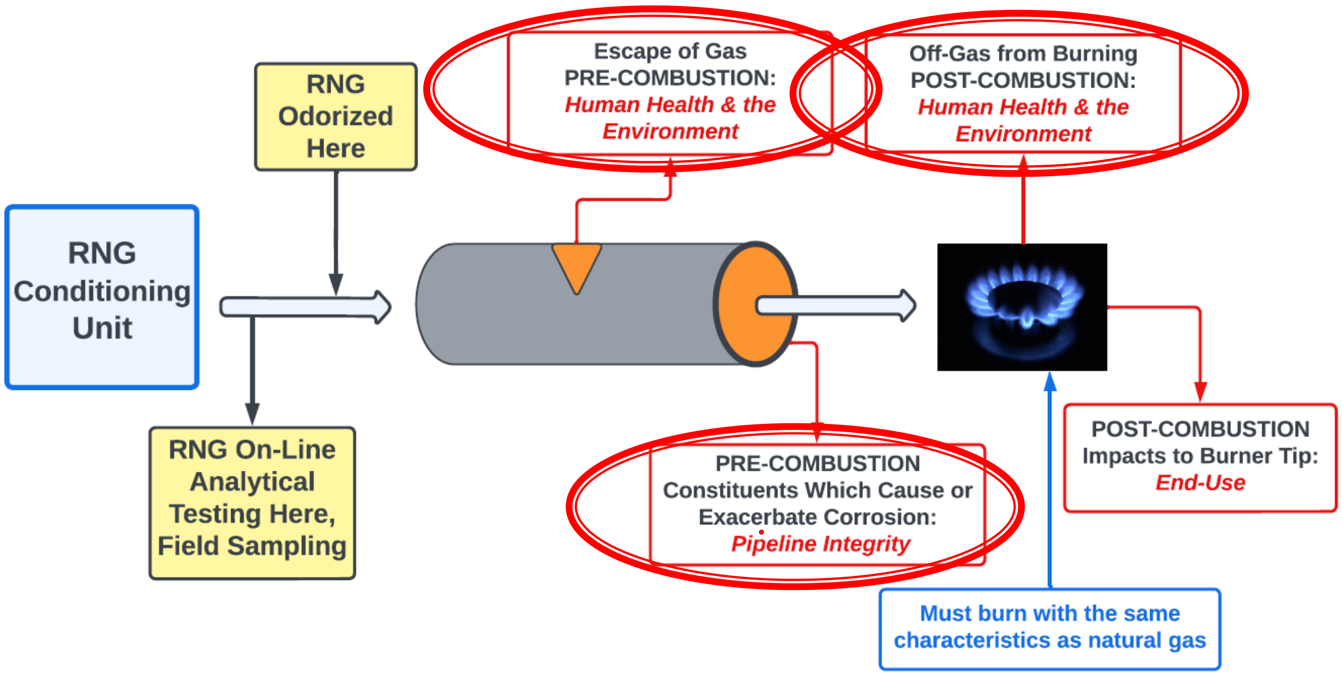
Inert: Sulfur/H_2S

- Highly corrosive and destructive to metal pipe.
- In the presence of water, sulfur compounds form sulfuric acid, a strong acid with aggressive corrosion potential
- Corrosion is exacerbated by the presence of CO_2 or O_2
- Combustion of gas with sulfur compounds produce SOx - emissions
- H_2S is also an irritant or potentially toxic to humans at high levels
- **On-line, real time monitoring required**



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Hydrogen Sulfide/Total Sulfur:

ONE ONLINE INSTRUMENT

(Total Sulfur – sometimes field sampling/laboratory testing)

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Moisture and Temperature in Natural Gas or Biomethane

- Moisture (water vapor) is a critical parameter for natural gas and RNG.
  - **Very important for metal pipelines; highly accelerates, exacerbates and induces corrosion, especially in presence of sulfur, bacteria or oxygen.**
  - Limited to prevent condensation and reduce hydrate formation (ice-like mixture of water and HCs formed at high pressures) – natural gas only
- Temperature
  - Ranges protect external coatings or pipe materials
  - Protects downstream gas processing and handling equipment
  - Differences in allowable temperatures: metal vs. plastic pipe

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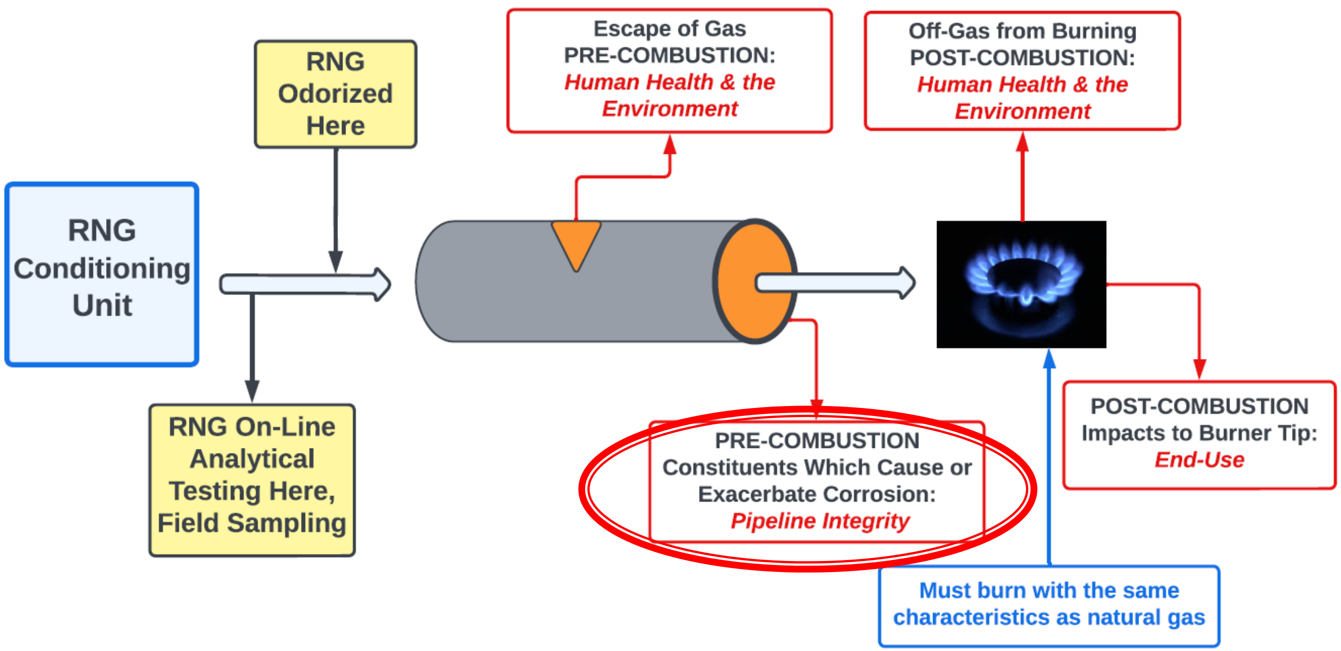
Parameter: Moisture Content

- Induces a highly corrosive and destructive environment to metal pipe.
- Water combined with CO_2 and H_2S, under certain conditions, can form acidic mixtures.
- Corrosion-causing bacteria thrive in wet environments.



Water Vapor and Temperature: Measurement

ONLINE INSTRUMENTS

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Conclusions

- Gaseous fuel supplies have changed over time.
- Gaseous fuel products may vary significantly.
- Natural gas and RNG are not the same – interchangeability requirements.
- A proper RNG specification is needed
- Major components measured on-line, real time.
- Proper field sampling and laboratory testing is key to trace constituent analysis.
- Verification and monitoring is necessary (natural gas industry is responsible).
- We are not done yet…industry must be ready to adjust for new constituents based on impacts to receptors.

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THANK YOU!

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