FREEZING CLIMATE DESIGN OF WET GAS PIPE SYSTEMS-APPLICATION TO LANDFILL GAS COLLECTION SYSTEMS

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ABSTRACT

Ambient temperatures below freezing can have a detrimental impact on piping systems carrying gases which contain vapor phase or liquid phase water (wet gas). Landfill Gas (LFG) commonly contains both vapor and liquid phase water. LFG collection system design nearly always assumes that the LFG is saturated. Impacts of freezing ambient conditions include high condensate generation and ice formation. This paper discusses alternative methods of design and construction to protect LFG systems in cold climates.

Ice formation in a gas pipeline can take the form of hoarfrost or common ice. Hoarfrost is most likely the result of vapor phase water freezing out of the gas stream, similar to snow, and builds up on the pipe walls causing restriction or complete clogging of the pipe. This condition results from extremely cold ambient temperatures, which do not allow the vapor phase water to condense into liquid water before turning to ice. For less extreme temperatures, the vapor phase water will condense to liquid water before freezing, but with similar detrimental effects to the piping system.

The most common method of avoiding freezing water in LFG systems is to bury the collection pipe below the frost line. While this approach is simple in concept, it can be an expensive solution, especially if the frost line is below 5 feet in depth, and/or the pipe is buried in refuse. Trench safety practice and OSHA rules dictate that trenches over 5 feet in depth be either shored, or laid back, if construction personnel are to work in the trench. Both of these options are relatively expensive. An added complication and cost arises when excavating in refuse, because of the potential disposal and leachate handling costs among others. Generally, excavating to depths over 5 feet is to be minimized or avoided if possible. Also, because LFG systems are often a liability to the owner of the system, initial costs of installation is often of primary importance.

An alternative to burying the pipe below the frost line is to insulate the pipe. This alternative can be attractive if the calculated thickness of the insulation is not excessive. Several factors must be considered in the calculation of the insulation thickness. These factors include:

1. LFG temperature at the well
2. Design temperature at the pipe discharge
3. Assumed or known temperature of pipe backfill
4. LFG composition
5. LFG flowrate
6. Gas pipe diameter and length
7. Gas pipe material (if material has insulating properties) and thickness
8. Insulation material
9. Heat tracing (if used)

Design calculations for the insulation are based on heat transfer principals. In the approach described herein, a certain amount of the initial LFG heat is allowed to be lost through the walls of the collection piping, but is not allowed to exceed that which would cause the temperature of the gas to fall below the freezing point of water (32° F).

INTRODUCTION

In the design of wet gas piping systems in cold climates, consideration should be given to the potential of the moisture in the gas freezing and accumulating, causing ice blockage inside the pipe. This is especially true where the nominal frost depth is below the depth of the proposed pipeline which is typical of the northern states of the US.

Landfill gas is usually considered saturated with water for design purposes, and in reality, nearly always contains enough moisture to be of concern to designers of LFG systems in cold climates. The moisture content of saturated gas is a function of gas temperature.

Freezing of moisture in LFG systems can be prevented in a number of ways, including:

- Removing water at the well head
- Adding enough heat to prevent freezing
- Reducing heat loss by insulating the pipe

Removing water from the gas stream at the well head would require either large quantities of absorbent or desiccant, or large amounts of energy in the form of refrigeration. Neither of these options is practical.

Adding heat electrically using heat tape or mechanically using hot water or glycol solution can be practical. Both of these options would have to be used in conjunction with pipe insulation in order to be effective.

Insulation alone can be effective in many cases because heat is added to the flow along the LFG header system via additional flow from the LFG wells. An analysis can be performed to determine if insulation alone can be used, and to determine how much heat must be added if insulation alone is not adequate. For insulation to be effective, the system requires LFG flow. If the system is shutdown, freezing can occur.

An analysis is presented herein which yields a required insulation R-value to prevent freezing of water and water vapor in the LFG pipe. If the required R-value is so high that the thickness of the insulation is prohibitive, (as determined by the designer), then the method can be reworked using a given R-value, and solved for required heat input. The method described herein requires the following variables to be measured, estimated, given, or assumed.

- Pipe parameters (diameter, length, R-value)
- Flow parameters (LFG composition, flowrate temperature)
- Soil parameters (temperature)

Soil temperature is a function of many different variables, including air temperature, soil depth, soil density, and soil water content. The analysis of soil temperature is not within the scope of this paper. The analysis presented herein uses assumed soil temperatures. Local building officials, or agriculture departments (US department of Agriculture, Soil Conservation Service) may be consulted for local soil temperature profiles. Mathematical models are also available (see attachment).

The following is a brief discussion of some important thermodynamic concepts.

Enthalpy (H) and Temperature (T)

Enthalpy is the heat content (H) of a fluid (liquid or gas), and is composed of internal energy (E) and flow energy (PV). Enthalpy is not the same as heat energy locked up in the individual molecules which is released during combustion of the gas, hence, the enthalpy of methane is not approximately 1000 BTU per cubic foot. For a given pressure, enthalpy is a function of fluid temperature. Within the narrow temperature ranges used in LFG problems, and assuming the LFG behaves as an ideal gas, ($PV=NRT$) enthalpy may be assumed to be directly proportional to temperature. The enthalpy of various gases can be obtained from thermodynamic references, are summarized in **Table 1** of the Appendix.

In wet gas systems, the steam in landfill gas when cooled will condense to form water. Further cooling will cause the condensate to freeze. Unlike the methane and carbon dioxide which stay a gas throughout the cooling process, steam can undergo several phase changes, with a loss of enthalpy at each phase change.

LMTD

Log mean temperature difference (LMTD) is the driving force which causes heat to flow from the gas to the surrounding environment. The greater the temperature difference between the ambient air or soil, and the LFG in the pipe, the greater the rate of heat loss through the pipe wall and insulation material.

R-Value

The R-value is a characteristic of pipe and pipe insulation materials. It is the resistance to heat flow and is the inverse of the heat transfer coefficient (U). R-value is most often used for insulation problems, and U for heat exchanger problems. For each inch of thickness, HDPE has a R-value of approximately 0.29 (hr. ft^2 °F)/BTU.

Once an required R-value has been calculated, it can be compared with the pipe R-value. If the pipe R-value in insufficient, insulation will be required, and the type and thickness of the insulation will have to be determined.

METHODOLOGY

Using the principles demonstrated herein, the designer can formulate many different methodologies to arrive at the same conclusions, or to solve for different variables. The methodology described below is but one example of how to use the principles to calculate pipe resistance R-value. This methodology will also be used in the example problem given in the Appendix.

To begin, draw a schematic diagram of the LFG header system and define each pipe segment. If practical, use only one pipe segment per well, (i.e., Well 1 corresponds to Segment 1, etc.). For each pipe segment, show pipe segment length, diameter, and R-value. Assign a soil temperature (T_3) for each segment. Show all wells with corresponding LFG flowrate, composition and temperature as shown in Figure 1 of the Appendix.

Starting at the upstream well of the header system, perform the following steps:

1) Assign allowable temperature drop in segment, and temperature at end of the segment (T_2) based on allowable temperature drop. The allowable temperature drop through a segment is somewhat arbitrary, and can be adjusted based on economic or other considerations. A good starting point is to allow a linear drop in temperature along the entire header from a high corresponding to the weighted average gas temperature to a low of 32°F.

2) If applicable, calculate the weighted average temperature of flows from this segment and upstream segments. To simplify this calculation, assume conservatively that water vapor does not condense.

3) Using the % H_20 column in Table 1, determine water vapor percentage at downstream end of pipe segment based on temperature T_2.

4) Using Table 1, calculate the mass flowrate of water vapor and condensate water through the pipe Segment.

5) Using Table 1, calculate the mass flowrate of all other gases through the pipe segment.

6) If applicable, combine upstream mass flowrates of all components to obtain total mass flowrate.

7) Using Table 1, determine enthalpies at the upstream (well head), and downstream (just prior to next well) ends of the pipe segment for each component of the LFG, including condensate.

8) Calculate heat loss through pipe wall for each component of the LFG including condensate, and sum all losses.

9) Calculate the LMTD through the pipe segment.

10) Calculate the required R-value for the segment.

11) Repeat steps 1-10 for each pipe segment down the header system.

APPENDIX 1 - SAMPLE PROBLEM

TABLE 1- - LFG THERMODYNAMIC DATA

		Enthalpies (BTU/lb.)					
Temp. (°F)	%H_2O	H_{CH4}	H_{CO2}	H_{O2}	H_{N2}	H_{H2O} (gas)	H_{H2O} (liq)
32	0.6	246	82	106	124	1076	0
40	0.8	250	84	108	126	1080	8
50	1.3	255	86	110	128	1084	18
60	1.8	260	88	112	130	1088	28
70	2.6	265	90	114	132	1092	38
80	3.6	270	92	116	134	1097	48
90	5.0	275	94	118	136	1101	58
100	6.8	280	96	120	138	1105	68
110	9.1	285	98	122	140	1110	78
120	12.1	290	100	124	142	1114	88
130	15.9	295	102	126	144	1118	98

Molecular Weights (lb./lb.mol)				
CH_4	CO_2	O_2	N_2	H_2O
16	44	32	28	18

SAMPLE PROBLEM

The analytical procedure is illustrated using a sample problem which was designed to be representative of a typical section of a LFG network, and includes 2 LFG wells with varying LFG temperatures and gas composition. The header pipe size varies, as does the soil temperature in each segment. Refer to Table 1 above and Figure 1.

SEGMENT 1

STEP 1

Calculate weighted average well temperature

$$T_A = \frac{90^\circ F \times 80CFM + 70^\circ F \times 120CFM}{80CFM + 120CFM} = 78^\circ F$$

Calculate temperature at downstream end of segment 1 (T_2). Use 32° at downstream end of segment 2.

$$T_2 = \left[\frac{78^\circ - 32^\circ}{200' + 1{,}200'} \times 1200' \right] + 32^\circ = 71^\circ$$

STEP 2

N/A

STEP 3

From Table 1, the approximate water vapor content of LFG at the downstream end of pipe segment 1 is approximately 2.6%.

STEP 4

Calculate mass flowrate of water vapor and condensate water.

Mass flowrate of both water phases (M_{H_2O}) =

$$80\,\frac{\text{ft}^3}{\text{min}}\times\frac{60\text{min}}{\text{hr}}\times 0.05\times\frac{18\text{lb}}{\text{lb}\cdot\text{MOL}}\times\frac{\text{lb}\cdot\text{MOL}}{379\text{ft}^3}=11.40\,\frac{\text{lb}}{\text{hr}}$$

Mass flow rate of water vapor $\left(M_{H_2O_G}\right)$ =

$$11.40\times\frac{2.6\%}{5.0\%}=5.93\,\frac{\text{lb}}{\text{hr}}$$

Mass flow rate of liquid water $\left(M_{H_2O_L}\right)$ =

$$11.40-5.93=5.47\,\frac{\text{lb}}{\text{Hr.}}$$

STEP 5

Calculate M for all other gases

$$M_{CO_2}=\frac{80\ \text{ft}^3}{\text{min}}\times\frac{60\text{min}}{\text{hr}}\times 0.45\times\frac{44\text{lb}}{\text{lb}\cdot\text{MOL}}\times\frac{\text{lb}\cdot\text{MOL}}{379\text{ft}^3}=250.76\,\frac{\text{lb}}{\text{hr}}$$

$$M_{CH_4}=\frac{80\text{ft}^3}{\text{min}}\times\frac{60\text{min}}{\text{hr}}\times 0.5\times\frac{16\text{lb}}{\text{lb}\cdot\text{MOL}}\times\frac{\text{lb}\cdot\text{MOL}}{379\text{ft}^3}=101.32\,\frac{\text{lb}}{\text{hr}}$$

STEP 6

N/A

STEP 7

Determine upstream & downstream enthalpies of all components using Table 1

$$H^{90}_{H_2O_G}=1{,}101\frac{\text{BTU}}{\text{lb}}\qquad H^{71}_{H_2O_G}=1{,}093\frac{\text{BTU}}{\text{lb}}$$

$$H^{90}_{H_2O_L}=58\frac{\text{BTU}}{\text{lb}}\qquad H^{71}_{H_2O_L}=39\frac{\text{BTU}}{\text{lb}}$$

$$H^{90}_{CO_2}=94\frac{\text{BTU}}{\text{lb}}\qquad H^{71}_{CO_2}=90\frac{\text{BTU}}{\text{lb}}$$

$$H^{90}_{CH_4}=274\frac{\text{BTU}}{\text{lb}}\qquad H^{71}_{CH_4}=266\frac{\text{BTU}}{\text{lb}}$$

STEP 8

Calculate heat loss for each component.

$$\Delta H_{H_2O_G} = (1{,}101 - 1{,}093)\frac{\text{BTU}}{\text{lb}} \times \frac{5.93\ \text{lb}}{\text{hr}} = 47\frac{\text{BTU}}{\text{hr}}$$

$$\Delta H_{H_2O_{G-L}} = (1{,}101 - 58)\frac{\text{BTU}}{\text{lb}} \times \frac{5.47\ \text{lb}}{\text{hr}} = 5{,}705\frac{\text{BTU}}{\text{hr}}$$

$$\Delta H_{H_2O_L} = (58 - 39)\frac{\text{BTU}}{\text{lb}} \times \frac{5.93\ \text{lb}}{\text{hr}} = 113\frac{\text{BTU}}{\text{hr}}$$

$$\Delta H_{CO_2} = (94 - 90)\frac{\text{BTU}}{\text{lb}} \times \frac{250.76\text{lb}}{\text{hr}} = 1{,}003\frac{\text{BTU}}{\text{hr}}$$

$$\Delta H_{CH_4} = (274 - 266)\frac{\text{BTU}}{\text{lb}} \times \frac{101.32\ \text{lb}}{\text{hr}} = 811\frac{\text{BTU}}{\text{hr}}$$

Calculate total heat loss

$$\Delta H_t = (47 + 5{,}705 + 113 + 1{,}003 + 811)\frac{\text{BTU}}{\text{hr}} = 7{,}679\frac{\text{BTU}}{\text{hr}}$$

STEP 9

Calculate LMTD

$$\text{LMTD} = \frac{(T_1 - T_3) - (T_2 - T_3)}{\text{Ln}\left(\dfrac{T_1 - T_3}{T_2 - T_3}\right)} = \frac{(90 - 10) - (71 - 10)}{\text{Ln}\left(\dfrac{90 - 10}{71 - 10}\right)} = 70^\circ\ \text{F}$$

STEP 10

Calculate segment 1 R-value

$$R = \frac{(A_{\text{pipe}})(\text{LMTD})}{\Delta H_t} = \frac{\Pi\left(\dfrac{6}{12}\right)(200)\,\text{ft}^2\,(70^\circ\ \text{F})}{7{,}679\,\dfrac{\text{BTU}}{\text{hr}}} = \frac{2.86\ \text{hr}\cdot\text{ft}^2\cdot{}^\circ\ \text{F}}{\text{BTU}}$$

SEGMENT 2

STEP 1

T_2 = 32° (determined in segment 1 step 1)

STEP 2

Calculate weighted average temperature of flows from Segment 1 and Segment 2.
Flow in Segment 1 = 80 CFM (given)
Flow in Segment 2 = 120 CFM (given)
Temperature in Segment 1 = 71 °F (from segment 1 step 1)
Temperature in Segment 2 = 70 °F (given)

Calculate new T_1

$$T_1 = \frac{(80)(71)+(120)(70)}{80+120} = 70.4^\circ$$

STEP 3

From Table 1, % H_2O @ 32°F = 0.6%

STEP 4

$$M_{H_2O} = \frac{120\text{ft}^3}{\text{min}} \times \frac{60\text{min}}{\text{hr}} \times 0.026 \times \frac{18\text{lb}}{\text{lb}\cdot\text{MOL}} \times \frac{\text{lb}\cdot\text{MOL}}{379\text{ft}^3} = 8.89\,\frac{\text{lb}}{\text{hr}}$$

$$M_{H_2O_G} = 8.89 \times \frac{0.6\%}{2.6\%} = 2.05\frac{\text{lb}}{\text{hr}}$$

$$M_{H_2O_L} = 8.89 - 2.05 = 6.84\,\frac{\text{lb}}{\text{hr}}$$

STEP 5

$$M_{CO_2} = 120 \times 60 \times 0.40 \times 44 \times \frac{1}{379} = 334.35\frac{\text{lb}}{\text{hr}}$$

$$M_{CH_4} = 120 \times 60 \times 0.50 \times 16 \times \frac{1}{379} = 151.98\frac{\text{lb}}{\text{hr}}$$

$$M_{N_2} = 120 \times 60 \times 0.063 \times 28 \times \frac{1}{379} = 33.51\frac{\text{lb}}{\text{hr}}$$

$$M_{O_2} = 120 \times 60 \times 0.01 \times 32 \times \frac{1}{379} = 6.08\,\frac{\text{lb}}{\text{hr}}$$

STEP 6

Combine upstream mass flows.

$$M_{H_2O_G} = \frac{2.05\text{ lb}}{\text{hr}} + \frac{5.93\text{ lb}}{\text{hr}} = 7.98\frac{\text{lb}}{\text{hr}}$$

$$M_{H_2O_L} = 6.84 + 5.47 = 12.31\frac{\text{lb}}{\text{hr}}$$

$$M_{CO_2} = 334.35 + 250.76 = 585.11\frac{\text{lb}}{\text{hr}}$$

$$M_{CH_4} = 151.98 + 101.32 = 253.30\frac{\text{lb}}{\text{hr}}$$

$$M_{N_2} = 33.51\frac{\text{lb}}{\text{hr}}$$

$$M_{O_2} = 6.08\frac{\text{lb}}{\text{hr}}$$

STEP 7

$$H^{71}_{H_2O_G} = 1{,}093\frac{\text{BTU}}{\text{lb}} \qquad H^{32}_{H_2O_G} = 1{,}076\frac{\text{BTU}}{\text{lb}}$$

$$H^{71}_{H_2O_L} = 39\frac{\text{BTU}}{\text{lb}} \qquad H^{32}_{H_2O_L} = 0\frac{\text{BTU}}{\text{lb}}$$

$$H^{71}_{CO_2} = 90\frac{\text{BTU}}{\text{lb}} \qquad H^{32}_{CO_2} = 82\frac{\text{BTU}}{\text{lb}}$$

$$H^{71}_{CH_4} = 266\frac{\text{BTU}}{\text{lb}} \qquad H^{32}_{CH_4} = 246\frac{\text{BTU}}{\text{lb}}$$

$$H^{71}_{N_2} = 132\frac{\text{BTU}}{\text{lb}} \qquad H^{32}_{N_2} = 124\frac{\text{BTU}}{\text{lb}}$$

$$H^{71}_{O_2} = 114\frac{\text{BTU}}{\text{lb}} \qquad H^{32}_{O_2} = 106\frac{\text{BTU}}{\text{lb}}$$

STEP 8

$$\Delta H_{H_2O_G} = (1{,}093 - 1{,}076) \times 7.98 = 136 \frac{\text{BTU}}{\text{hr}}$$

$$\Delta H_{H_2O_{G\text{-}L}} = (1{,}093 - 39) \times 6.84 = 7{,}209 \frac{\text{BTU}}{\text{hr}}$$

$$\Delta H_{H_2O_L} = (39 - 0) \times 12.31 = 480 \frac{\text{BTU}}{\text{hr}}$$

$$\Delta H_{CO_2} = (90 - 82) \times 585.11 = 4{,}681 \frac{\text{BTU}}{\text{hr}}$$

$$\Delta H_{CH_4} = (266 - 246) \times 253.30 = 5{,}066 \frac{\text{BTU}}{\text{hr}}$$

$$\Delta H_{N_2} = (132 - 124) \times 33.51 = 268 \frac{\text{BTU}}{\text{hr}}$$

$$\Delta H_{O_2} = (114 - 106) \times 6.08 = 49 \frac{\text{BTU}}{\text{hr}}$$

$$\Delta H_t = 136 + 7{,}209 + 480 + 4{,}681 + 5{,}066 + 268 + 49 = 17{,}889 \frac{\text{BTU}}{\text{hr}}$$

STEP 9

$$\text{LMTD} = \frac{(71^\circ - 5^\circ) - (32^\circ - 5^\circ)}{\text{Ln}\left[\frac{71^\circ - 5^\circ}{32^\circ - 5^\circ}\right]} = 44^\circ$$

STEP 10

$$R = \frac{\left(\Pi \frac{10}{12} \times 1{,}200\right)\text{Ft}^2\left(44^\circ \text{F}\right)}{17{,}889 \frac{\text{BTU}}{\text{hr}}} = \frac{7.73\ \text{hr} \cdot \text{ft}^2 \cdot {}^\circ\text{F}}{\text{BTU}}$$

Disclaimer: The information provided in this paper is intended to convey a set of principals which may be used to determine pipe insulation thermal criteria. Pier review was not rigorous. Many simplifying assumptions were made. Readers and users of the information contained herein are advised to check the work thoroughly before using, and use at your own risk. GCE Inc. accepts no responsibility based on the use of this material.

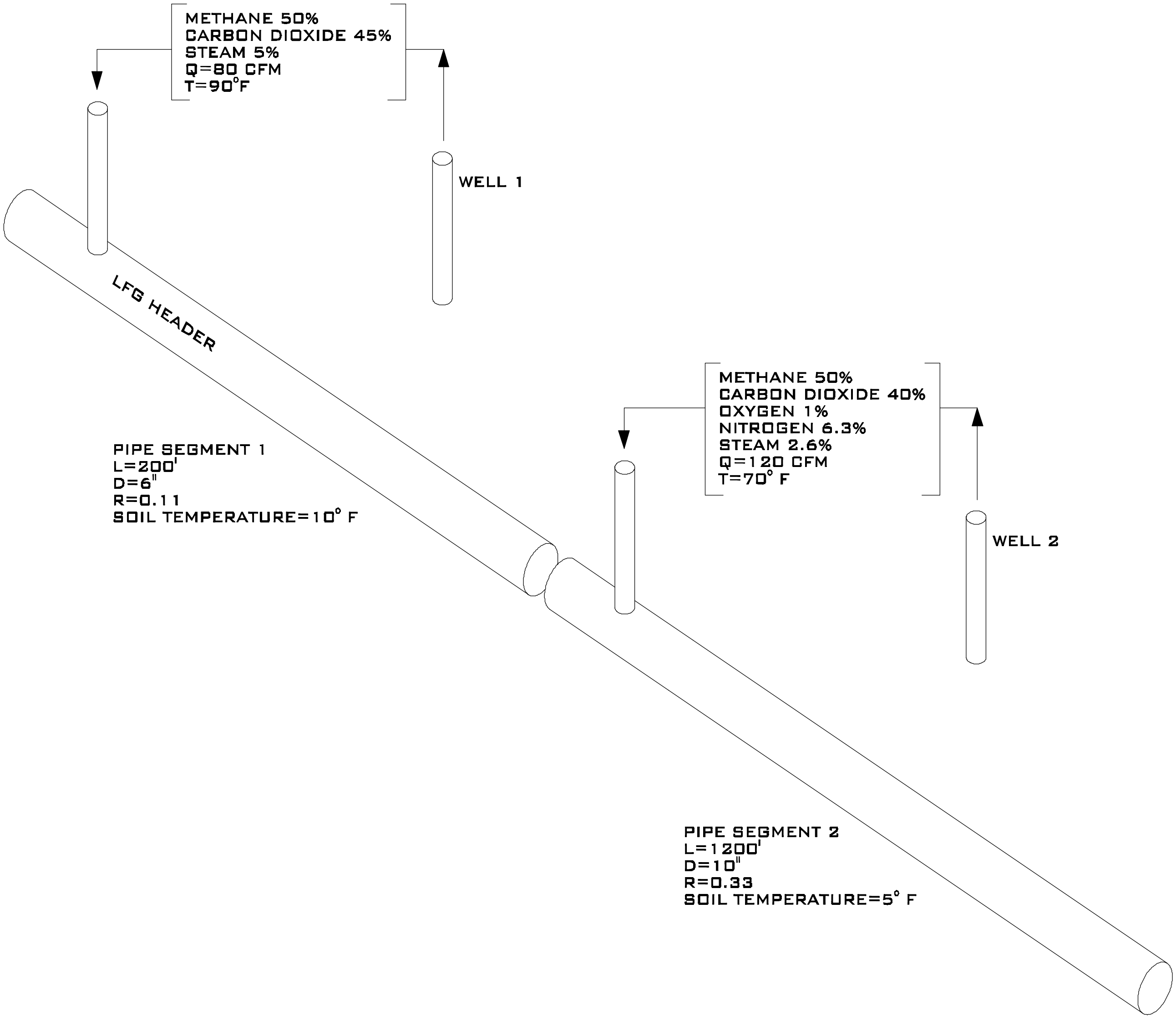
METHANE 50%
CARBON DIOXIDE 45%
STEAM 5%
Q=80 CFM
T=90°F
WELL 1
LFG HEADER
PIPE SEGMENT 1
L=200'
D=6"
R=0.11
SOIL TEMPERATURE=10° F
METHANE 50%
CARBON DIOXIDE 40%
OXYGEN 1%
NITROGEN 6.3%
STEAM 2.6%
Q=120 CFM
T=70° F
WELL 2
PIPE SEGMENT 2
L=1200'
D=10"
R=0.33
SOIL TEMPERATURE=5° F

FIGURE 1