

October 25, 2010



Mr. Ken Robinson
City of Flagstaff
Cinder Lake Landfill
211 W Aspen Ave
Flagstaff, AZ 86001

**Subject: Gas Generation Evaluation Review
Cinder Lake Landfill**

Dear Mr. Robinson:

R. W. Beck, Inc. has prepared this letter report in accordance with our April 2010 Proposal: Gas Generation Evaluation for Cinder Lake Landfill (City of Flagstaff Purchase Order Number: 144501). The report summarizes field testing, gas modeling, and addresses the four main objectives of the study as defined in the Request for Quote, dated March 30, 2010. The four main objectives are:

- Does the value of Q_{LFG} meet or exceed typical thresholds to validate proceeding with future opportunities in landfill gas ventures with potential partners?
- What is the approximate porosity of waste in-place, typical daily cover, and alternative daily cover found at the Landfill; additionally what is the effective porosity and how does that influence landfill gas emissions (and methane oxidation)?
- What influence does the atmospheric pressure have on the effect of Q_{LFG} ?
- Is the installation of the collection pipes at elevation 6690 warranted?

Abstract

The purpose of the Gas Generation Evaluation study was to estimate the landfill gas generation potential of the Cinder Lake Landfill. In addition, the four objectives listed above were investigated.

The landfill gas generation potential was estimated using an R. W. Beck computer model. Field data collected as part of a field test performed in the summer of 2010 was used to estimate model inputs and validate model outputs. This information was particularly interesting because of the large amount of paper sludge that has been disposed of in the Landfill.

The results of the gas generation evaluation have found good gas generation potential. Based on the model projections, there is enough gas to justify pursuing landfill gas to energy opportunities, which may include power generation or direct use in an industrial boiler.



Table of Contents

	Page
Abstract.....	1
Field Testing.....	2
Well Drilling.....	2
Landfill Gas Rig Testing.....	3
Gas Model.....	4
Input Variable Summary.....	6
Objective 1.....	12
Objective 2.....	13
Objective 3.....	13
Objective 4.....	14
Closing.....	14

Field Testing

Due to the large amount of paper sludge that has been disposed of in the Cinder Lake Landfill and the unknown effect that the sludge may have on landfill gas generation, a field test was completed to 1) obtain site specific data to better understand the landfill's gas characteristics and 2) validate the landfill gas model. The field study was completed between July 19, 2010 and August 6, 2010.

Well Drilling

Geomechanics Southwest, Inc. drilled three wells between July 19th and 20th. The first well (Well #1) was drilled 50 feet into the landfill. The other two wells (Well #2 and Well #3) were drilled 30 feet into the landfill. The locations of the wells are shown on the attached drawing, Figure 1. A well construction diagram is attached as Figure 2.

The wells were drilled with a CME-75HT truck-mounted drill rig equipped with a 4-1/4" ID x 8-1/4" OD continuous flight hollow-stem auger. Two-inch PVC wells were installed in each borehole with slotted screen from bottom of well to five feet below grade. The upper five feet of the well was bentonite sealed to prevent air-intrusion during the verification pump testing.

During well drilling, the R. W. Beck field engineer recorded characteristics of the drill cuttings. These logs are attached.



The age of the waste at each well location was noted because of its relevance to landfill gas production. Older waste likely has less gas production potential because some of the gas has already been released. Well #2 was drilled into waste that has been placed within the past three years. Well #1 and Well #3 were drilled into waste that was over 8 years and 12 years old, respectively. During drilling it was also noted that in Well #3 native soils were encountered in the bottom 10 feet of the boring.

Landfill Gas Rig Testing

After installation of the test wells, a portable landfill gas test rig, which included a blower and condensate knockout, was used on each well for approximately four days. The following data was gathered from the test rig:

- Outside Temperature – Temperature was recorded near the test rig using a thermometer.
- Barometric Pressure – Barometric pressure readings are taken to evaluate the effect atmospheric pressure has on the LFG flow through the gas well. Values were obtained from the Doney Park weather station archives.
- Hours of Operation on Current Well – Pressure produced from the landfill and the vacuum applied with an active collection system will equalize over time. This recording provides data to evaluate the vacuum that may be expected under a complete active collection system.
- CH₄ – Methane concentrations at the well provide an indication of the stage of waste decomposition in the area. Typically, during the most active methane generation period, methane concentrations are around 50%.
- O₂ – Oxygen is an indicator of over pulling the vacuum from the well. Oxygen levels should be lower than 1%. Higher oxygen levels may indicate that air is being pulled through the surrounding soils, reducing the methane concentration.
- CO₂ – Carbon dioxide concentrations are also an indicator of the stage of decomposition. A typical value during active methane generation will be approximately 40 to 50%.
- H₂S – Hydrogen sulfide was recorded on LFG Well #1. It is an additional parameter provided by the gas meter that does not affect the gas generation modeling.
- Landfill Gas Temperature – LFG temperature provides an indication of the biological activity in the waste. Generally LFG temperatures are around 80 to 100 degrees Fahrenheit.
- Velocity – Velocity measurements are used to determine LFG flow. Velocity is converted to flow and is to be maximized while not increasing O₂ above 1%. This allows for an estimation of LFG to be delivered from a particular collection point. This value can help to estimate an aggregate LFG flow that could potentially be delivered to a destruction device. This value will vary depending on age of waste, porosity of waste, and depth of well.
- Vacuum – Vacuum is used to determine how hard LFG can be pulled (maximizing flow) while limiting O₂ intrusion. This value will vary depending on similar factors as for velocity.



Table 1 below summarizes the recorded data. Field Logs from the Landfill Gas Well Testing are also attached.

Table 1
LFG Field Work Summary

LFG Well	Age (yr)	Depth (ft)	CH4 (%)	O2 (%)	CO2 (%)	LFG Temp (F)	Well Velocity (ft/min)	Well Flow (SCFM)
1	8+	50	50.1%	1.5%	N/A	83	400	21
2	3	30	56.4%	2.9%	39.6%	92	1,687	87
3	12+	30	49.2%	1.9%	35.2%	81	243	12

In summary the field test results showed very good gas generation. The field data was used to validate the gas model described in the following section.

Gas Model

Landfill gas modeling was completed using the LFG generation model developed by R.W. Beck. The model uses inputs that have been developed by R.W. Beck based on our experience completing LFG models, studies, and reviews of actual LFG generation data for over 100 landfill sites. Model output should be used for planning purposes; however, it is an approximation based on field observations, data provided by the City of Flagstaff, and our experience with other projects. Model output provides an annual prediction of collected LFG generation (cubic feet/minute), energy value (MMBtu/hour), and electricity power output (kilowatts). Provided in the attached Figures 3A, 3B, and 3C are graphs showing LFG generation and collection. It is assumed that collection would begin in 2011. Several inputs go into the model, which include:

- **Historical and Future Annual Waste Tonnages:** Historical tonnage values were provided by Flagstaff for the years 1965 through 2009. There was a dramatic decrease in waste generation from 2008 to 2009 of approximately 155,000 tons to 117,000 tons, respectively. Based on the significant reduction in waste generation, starting in 2010, a base value of 120,000 tons per year is used. Three separate models were run using different growth rates of zero growth, a one percent growth, and a three percent growth. The closure date is based on the ultimate capacity, which is approximately 10.7 million tons.
- **Landfill Closure Date:** Based on the growth rate, the estimated landfill closure date varies.
- **No growth (0%):** 2063
- **One percent:** 2052
- **Three percent:** 2042
- **Percentage of Decomposable Waste:** The City provided R.W. Beck with a waste characterization study from 2004. This study was used to establish an approximate organic



percentage of the waste stream. Based on the values found in the 2004 waste audit a value of 60% decomposable waste was used for the model generation.

- **Moisture Content:** Moisture monitoring of the waste was performed in 2007 and showed a range of 27% to 32% moisture content. The annual rainfall for the area is approximately 17 inches. The measured moisture contents are relatively high for an area of 17 inches of rainfall per year. The above expected monitored value of moisture content is likely related to the moisture in the paper sludge that is placed in the landfill. A moisture content of 30% will be used for the model calculation.
- **Biochemical Methane Potential:** The biochemical methane potential (BCMP) of a given volume of waste (cubic foot of methane per pound of dry organic waste, ft³ methane/lb) is a measure of the amount of methane per cubic foot of dry organic waste. Testing on actual values of methane potential from waste is limited and variable. Values are estimated based on waste characterization studies and LFG collection system data. Generally, the standard input value for the model for BCMP is 11.5 ft³ methane/lb. For LFG modeling at the Cinder Lake Landfill, a value of 11 ft³ methane/lb of dry organic waste was used due to the expected lower organic/BCMP value of the entire waste mass resulting from disposal of paper sludge. This value is considered slightly conservative.
- **Generation Rate:** The generation rate of the LFG (cubic foot per pound of waste per year, ft³ LFG/lb/year) is affected by the moisture content of the waste. The LFG will produce more gas sooner with higher moisture content. Industry reports state that moisture content is the most important variable in waste degradation, and therefore, LFG generation. For Cinder Lake Landfill, a value of 0.19 ft³ LFG/lb/year was used. This value is derived by evaluating various other sites with similar characteristics as Cinder Lake. Although, the area is considered arid, the monitored value of the moisture content of the waste will drive the production of LFG. The moisture content at 30% is higher than what would normally be used for a landfill in an arid region. However, the placement of paper sludge may account for the 30% moisture content. Values seen at landfills in climates that receive more precipitation have generation rate values around 0.24 ft³ LFG/lb/year. The generation rate value used in the model is based on values obtained from similar sites and are considered in line with industry standards. It should be considered slightly conservative and may not accurately represent Cinder Lake Landfill but provides a close approximation. Over time, the data obtained from an active collection system will aid in providing a more representative value for the generation rate.
- **Generation Period:** Typical values for the generation period are 40 years under dry tomb conditions (i.e. no leachate recirculation). The generation period used for the Cinder Lake Landfill model is 40 years.
- **BCMP Ratio:** The BCMP Ratio is a ratio between LFG produced and recoverable LFG. It indicates the quality of LFG generated and is a factor of moisture and BCMP. Values of BCMP ratio that are approximately 0.850 indicate a strong generation rate and can result in higher LFG collected. As stated above, a higher moisture content will increase the rate of



LFG generation. This means that in the years following waste placement (3-6 years) the majority of the LFG will have been generated and then rapidly decrease in generation. With a lower moisture content, the generation of LFG will be over a longer period of time, but the volume of LFG will be lower per year.

Input Variable Summary

- Waste acceptance: 1965 – 2044
- Moisture content: 30%
- BCMP: 11 ft³ methane/lb dry organic waste
- Generation rate: 0.19 ft³ LFG/lb/year
- Generation period: 40 years
- BCMP Ratio: 0.632
- Total tons: 10,700,000
- Scenario 1 (0%) – 1965 – 2063
- Scenario 2 (1%): 1965 – 2052
- Scenario 3 (3%): 1965 – 2042



Table 2A – No Growth
 LFG Generation Summary¹

Year	Summary		
	Generated (SCFM)	Collected (SCFM)	Collection Efficiency (%)
2012	1,477	1,108	75
2015	1,465	1,099	75
2020	1,454	1,090	75
2025	1,439	1,079	75
2030	1,423	1,067	75
2035	1,411	1,058	75
2040	1,402	1,051	75
2045	1,394	1,045	75
2050	1,391	1,043	75
2055	1,391	1,043	75
2060	1,391	1,043	75
2065	1,175	1,058	90
2070	776	698	90
2075	530	477	90
2080	348	313	90

¹ LFG values are given in standard cubic feet per minute (SCFM)



Table 2B – 1% Growth
 LFG Generation Summary¹

Year	Summary		
	Generated (SCFM)	Collected (SCFM)	Collection Efficiency (%)
2012	1,479	1,109	75
2015	1,477	1,108	75
2020	1,499	1,124	75
2025	1,531	1,148	75
2030	1,573	1,180	75
2035	1,629	1,222	75
2040	1,696	1,272	75
2045	1,772	1,329	75
2050	1,859	1,394	75
2055	1,568	1,412	90
2060	1,038	935	90
2065	719	647	90
2070	476	428	90
2075	292	263	90
2080	158	142	90

¹ LFG values are given in standard cubic feet per minute (SCFM)



Table 2C – 3% Growth
 LFG Generation Summary¹

Year	Summary		
	Generated (SCFM)	Collected (SCFM)	Collection Efficiency (%)
2012	1,484	1,113	75
2015	1,503	1,127	75
2020	1,597	1,198	75
2025	1,744	1,308	75
2030	1,944	1,458	75
2035	2,203	1,653	75
2040	2,524	1,893	75
2045	2,087	1,878	90
2050	1,390	1,251	90
2055	982	884	90
2060	659	593	90
2065	412	371	90
2070	223	201	90
2075	83	75	90
2080	7	6	90

¹LFG values are given in standard cubic feet per minute (SCFM)

We have assumed 75% landfill gas collection efficiency while the landfill is open, which assumes gas collection wells and piping will be installed soon after waste reaches final grades and is covered with intermediate cover. Once the landfill is closed, a collection efficiency of 90% is assumed because the working face will be closed up and gas can be collected from the entire landfill. The remaining 10% to 25% of landfill gas not collected is assumed to be lost into the atmosphere.

The energy content of the LFG in millions of British Thermal Units (MMBTU) per hour is converted at approximately 500 BTUs per cubic foot of LFG. For LFG, kilowatts (kW) are calculated at 1 kW equal to 11,000 BTUs.



Table 3A – No Growth
MMBTU/Hour and Kilowatts Collected

Year	Baseline	
	MMBTU/hr	Kilowatts
2012	33	3,021
2015	33	2,996
2020	33	2,974
2025	32	2,943
2030	32	2,910
2035	32	2,886
2040	32	2,867
2045	31	2,850
2050	31	2,845
2055	31	2,845
2060	31	2,845
2065	32	2,885
2070	21	1,905
2075	14	1,300
2080	9	854



Table 3B – 1% Growth
MMBTU/Hour and Kilowatts Collected

Year	Baseline	
	MMBTU/hr	Kilowatts
2012	33	3,025
2015	33	3,022
2020	34	3,066
2025	34	3,131
2030	35	3,217
2035	37	3,332
2040	38	3,470
2045	40	3,624
2050	42	3,802
2055	42	3,850
2060	28	2,549
2065	19	1,764
2070	13	1,168
2075	8	718
2080	4	388



Table 3C – 3% Growth
 MMBTU/Hour and Kilowatts Collected

Year	Baseline	
	MMBTU/hr	Kilowatts
2012	33	3,035
2015	34	3,074
2020	36	3,267
2025	39	3,567
2030	44	3,976
2035	50	4,507
2040	57	5,163
2045	56	5,122
2050	38	3,411
2055	27	2,410
2060	18	1,618
2065	11	1,012
2070	6	547
2075	2	203
2080	0	18

Objective 1

Does the value of Q_{LFG} meet or exceed typical thresholds to validate proceeding with future opportunities in landfill gas ventures with potential partners?

Based on the landfill gas model results, there is enough gas to justify pursuing landfill gas to energy opportunities. Using the output results from the scenario assuming one percent growth, the modeled flow rates would be able to run three CAT 3516 landfill gas generators (the most common landfill gas generator in the US) for the majority of the life of the landfill. The model indicates there is capacity to add a generator for a total of four over the final 20 years. The estimated LFG flow required to operate a CAT 3516 is approximately 300 SCFM. Three generators would provide 2.4 megawatts of power (800 kW each) that would be sold to a utility and placed on the electrical grid.

Direct use of the landfill gas, via a pipeline to an industrial end user, is also worth evaluating. The viability of a direct use project depends largely on the distance and route to the end user, as well as the end user's energy needs.



Objective 2

What is the approximate porosity of waste in-place, typical daily cover, and alternative daily cover found at the Landfill; additionally what is the effective porosity and how does that influence landfill gas emissions (and methane oxidation)?

The porosity of municipal refuse is generally highly variable, depending on the waste composition, density, and stage of decomposition. Typical porosity values range from 30 to 40%.¹ During the well drilling the cuttings were observed and did not show signs that would indicate higher, or lower, porosity within the waste than typically observed at landfills. The paper sludge within the landfill does not appear to reduce the porosity based on the observations during the drilling and the fact that good gas generation was observed during the gas well testing.

Current methane oxidation calculations assume landfill soils reduce methane concentrations ten percent through an oxidation reaction in the soils. This means that approximately ten percent of the methane that escapes through the landfill surface is converted to carbon dioxide through natural processes in the soils. This value is typically used when calculating a facility's greenhouse gas emissions and is the generally accepted value for these evaluations. Studies are under way to more accurately represent the actual methane oxidations. However, values will vary from site to site depending on soil characteristics and porosity (channels for LFG to escape) among other factors.

Objective 3

What influence does the atmospheric pressure have on the effect of Q_{LFG} ?

Generally it is accepted in the landfill gas industry, that a landfill under passive venting (i.e. avenues for LFG escape such as gas vents) will be influenced by atmospheric pressure changes. The landfill acts as a flexible vessel and as pressure (a high atmospheric pressure) is applied it will force the LFG out of the vessel and increase Q_{LFG} . It is assumed that the high pressure will force more of the LFG through the openings. The opposite is true as a low atmospheric pressure system passes the landfill. The Q_{LFG} will be lower during these events. A similar example would be pressing down on an air filled balloon, creating a higher flow through the opening.

Under an active gas system (i.e. system under vacuum for collection), the effect of changes in the atmospheric pressure can have varying impacts on the Q_{LFG} . The applied vacuum from the compressor station (e.g. flare skid blowers) will be impacted by the changes in pressure. If a high pressure system moves through, the applied vacuum may actually decrease. The Q_{LFG} may vary slightly, but would largely remain unaffected. The issues with atmospheric pressure changes will have an impact on LFG composition and balancing the wellfield to deliver optimum flow. Attached are Figures 4 through 6 that compare barometric pressures and LFG velocities

¹ McBean, E. A., F. A. Rovers, and G. J. Farquhar, 1995. *Solid Waste Landfill Engineering and Design*. Englewood Cliffs, New Jersey: Prentice Hall PTR.



Mr. Ken Robinson
October 25, 2010
Page 14

from the three wells observed during the testing. The sample size for this is relatively limited and a correlation may become more apparent over a larger sample.

Objective 4

Is the installation of the collection pipes at elevation 6690 warranted?

Based on discussions with Flagstaff staff, there is to be approximately 15 to 30 more feet of additional waste placed over the 6690 elevation. Because this additional waste will be placed before an active gas collection system is in place, it does not appear the installation of the pipes is warranted. This is because once final elevation is reached vertical wells can be drilled into the landfill for landfill gas management. Since no active gas collection system is currently in place, there is no benefit in putting in the collection pipes a few years ahead of the vertical wells and this would also have the potential to increase the flow of gas venting into the atmosphere. Furthermore, it is our experience that horizontal gas collectors are prone to failure due to settlement and leachate accumulation in the piping. Vertical wells typically last longer and are a more cost effective design for this scenario.

Closing

R.W. Beck would like to thank the City of Flagstaff for the opportunity to complete the LFG field study and LFG generation modeling. If you have any questions, please feel free to contact me via email at mevans@rwbeck.com or telephone at (651)-289-2511.

Sincerely,

R. W. BECK, INC.



Matthew Evans, P.E.
Project Manager

MJE/kb



Attachment 1
FIGURES



An SAIC Company

LANDFILL GAS SAMPLING 2010—SITE PLAN CINDER LAKE LANDFILL
 MSW LOCATIONS
 2' CONTOURS

LEGEND:

- EXISTING GAS PROBE
- EXISTING VADOSE ZONE WELL
- LFG TEST WELL

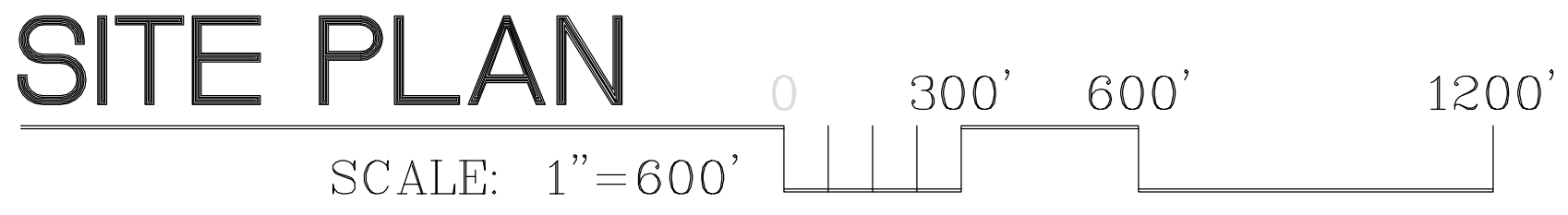
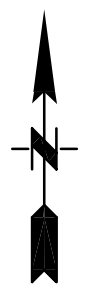
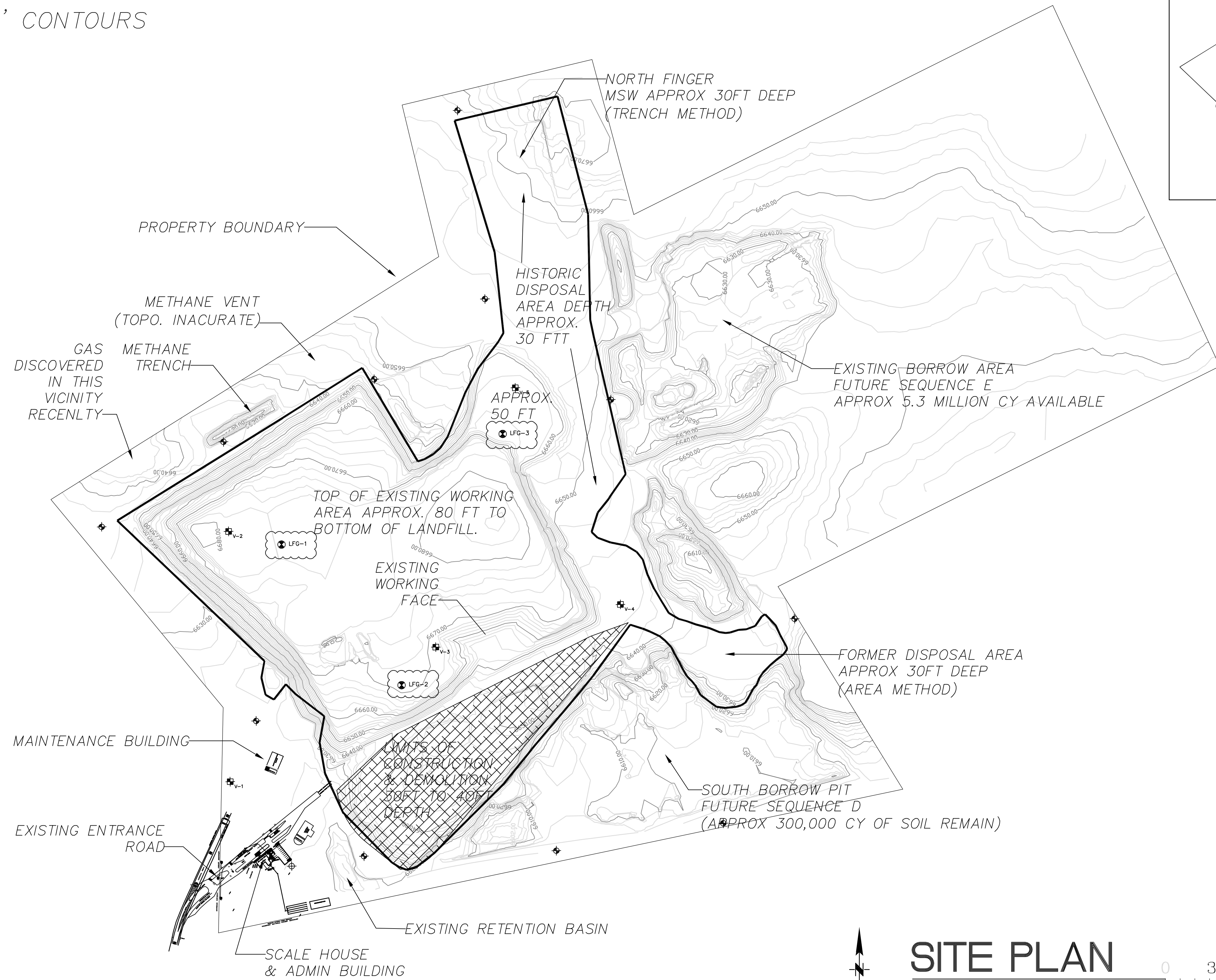
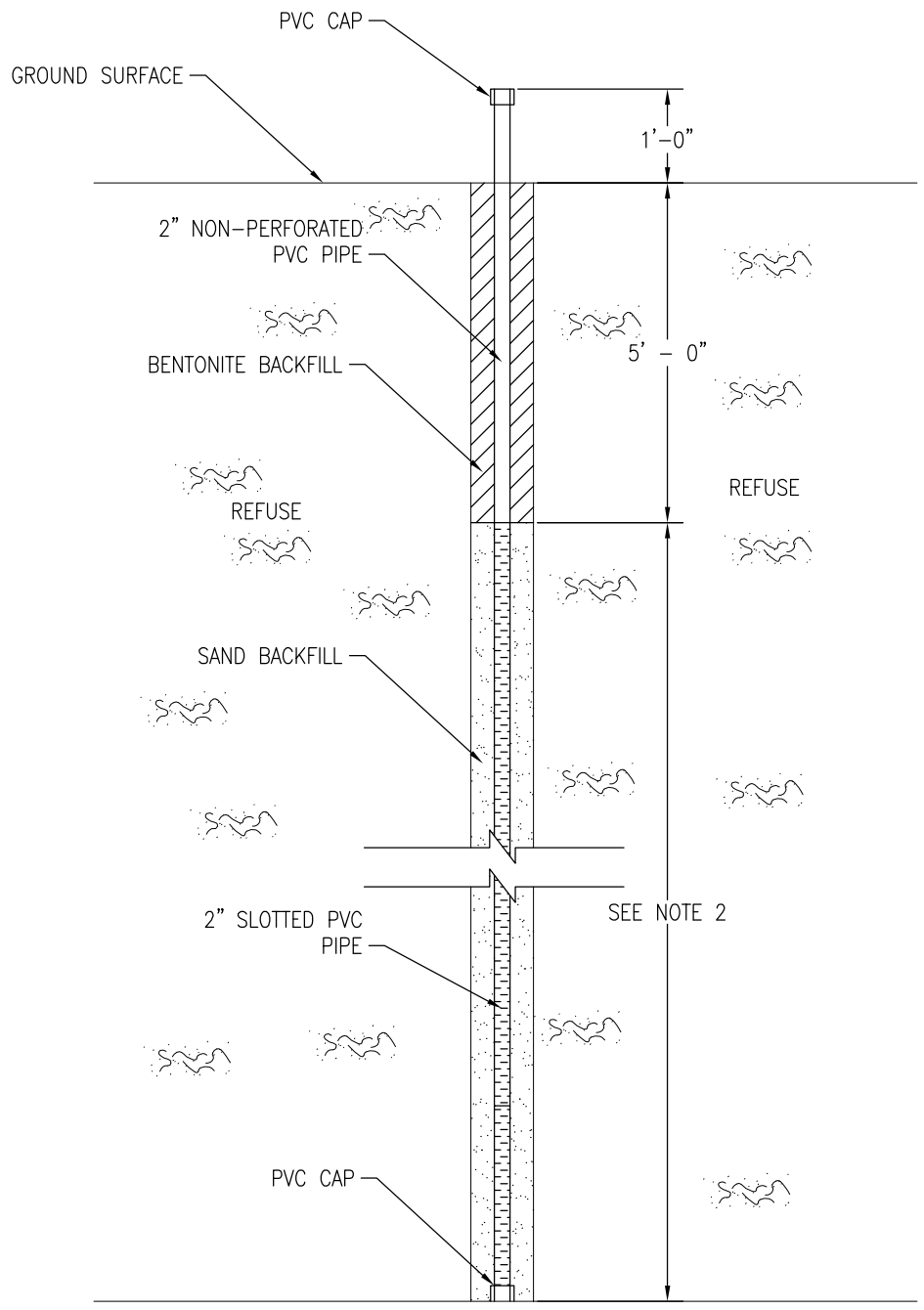


FIGURE 1
 Site Map
 Cinder Lake Landfill - LFG Study
 City of Flagstaff, AZ





NOTES:

1. A TOTAL OF THREE BOREHOLES WERE COMPLETED FOR THE GAS GENERATION EVALUATION PROJECT.
2. BOREHOLE 1 SLOTTED PIPE LENGTH IS 45- FEET. BOREHOLE 2 AND BOREHOLE 3 SLOTTED PIPE LENGTHS ARE 25- FEET.

Figure 2
WELL BORING PROFILE
GAS GENERATION EVALUATION
Cinder Lake Landfill, Flagstaff, AZ



Figure 3A - No Growth
LFG Generation/Collection - Cinder Lake Landfill, Flagstaff, AZ

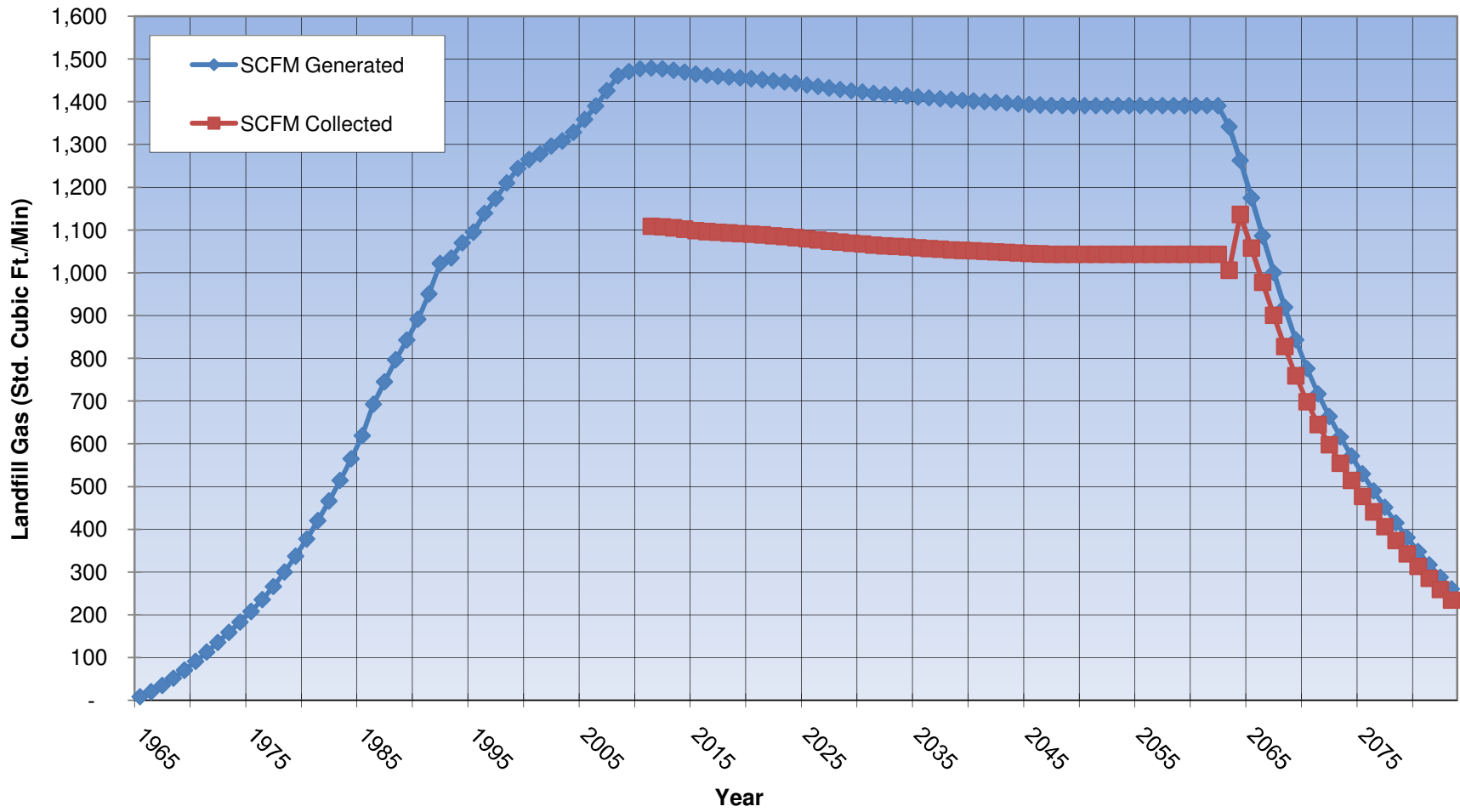


Figure 3B - 1% Growth
LFG Generation/Collection - Cinder Lake Landfill, Flagstaff, AZ

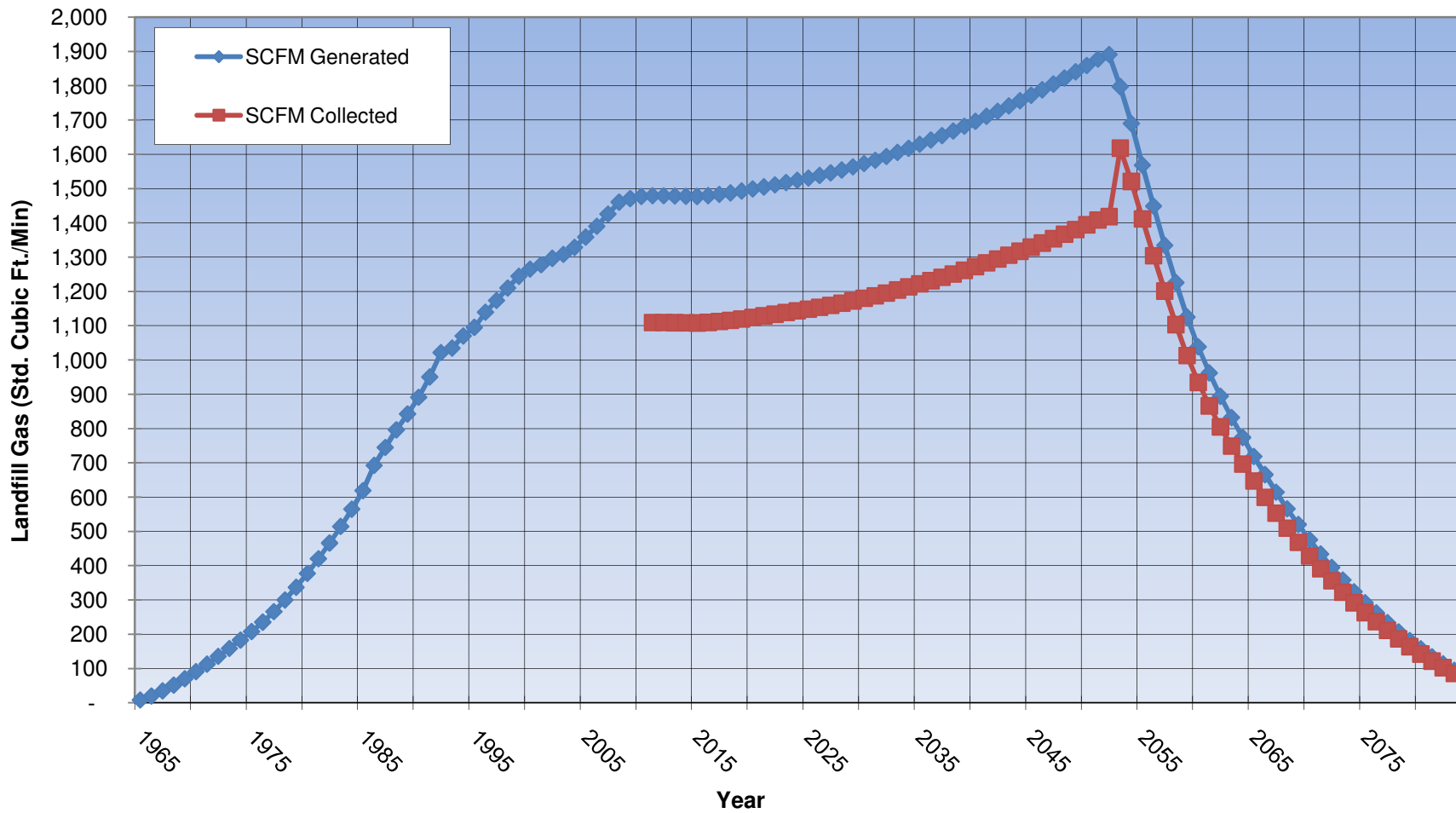


Figure 3C - 3% Growth
LFG Generation/Collection - Cinder Lake Landfill, Flagstaff, AZ

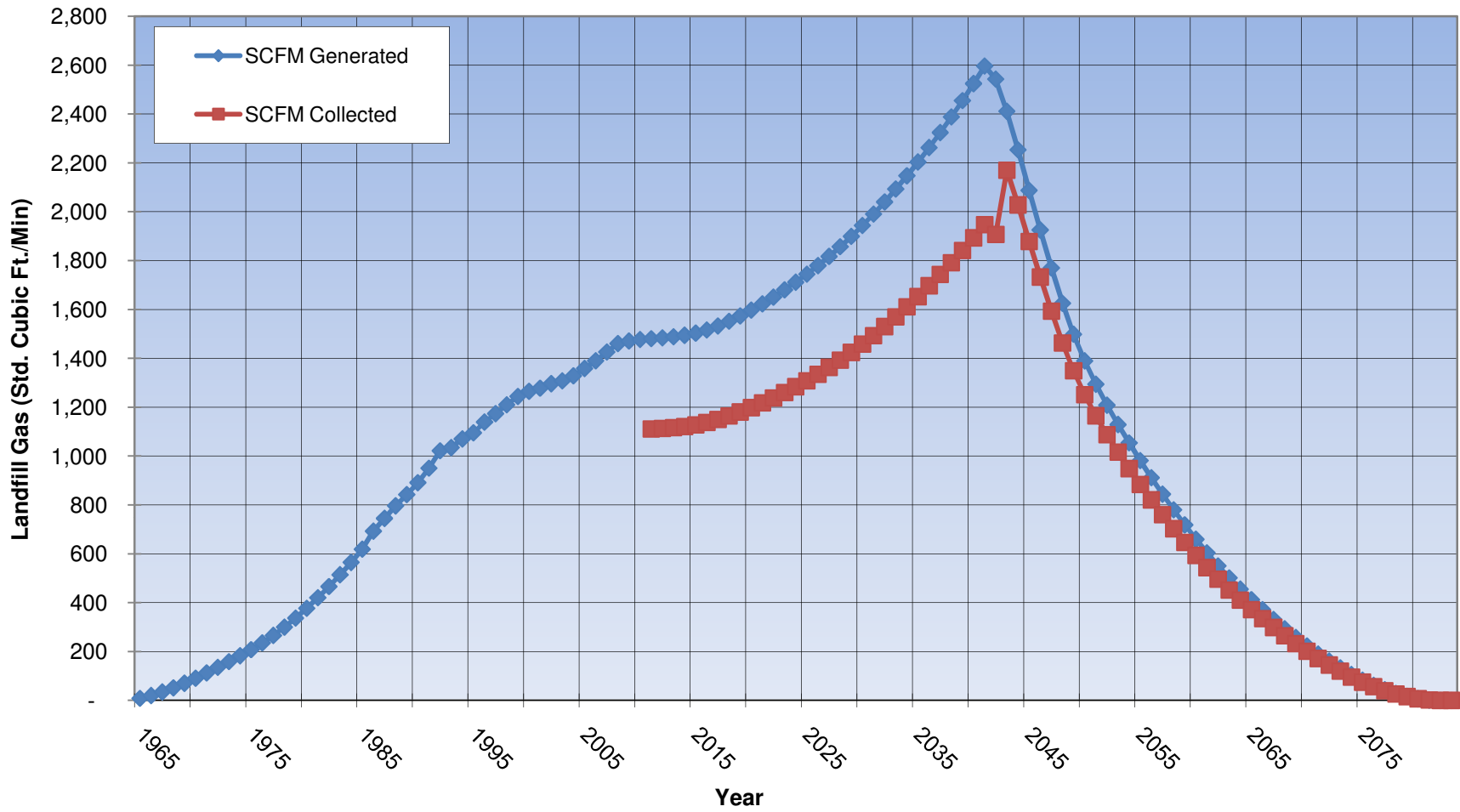


Figure 4
LFG Well 1 LFG Flow and Barometric Pressure Comparison

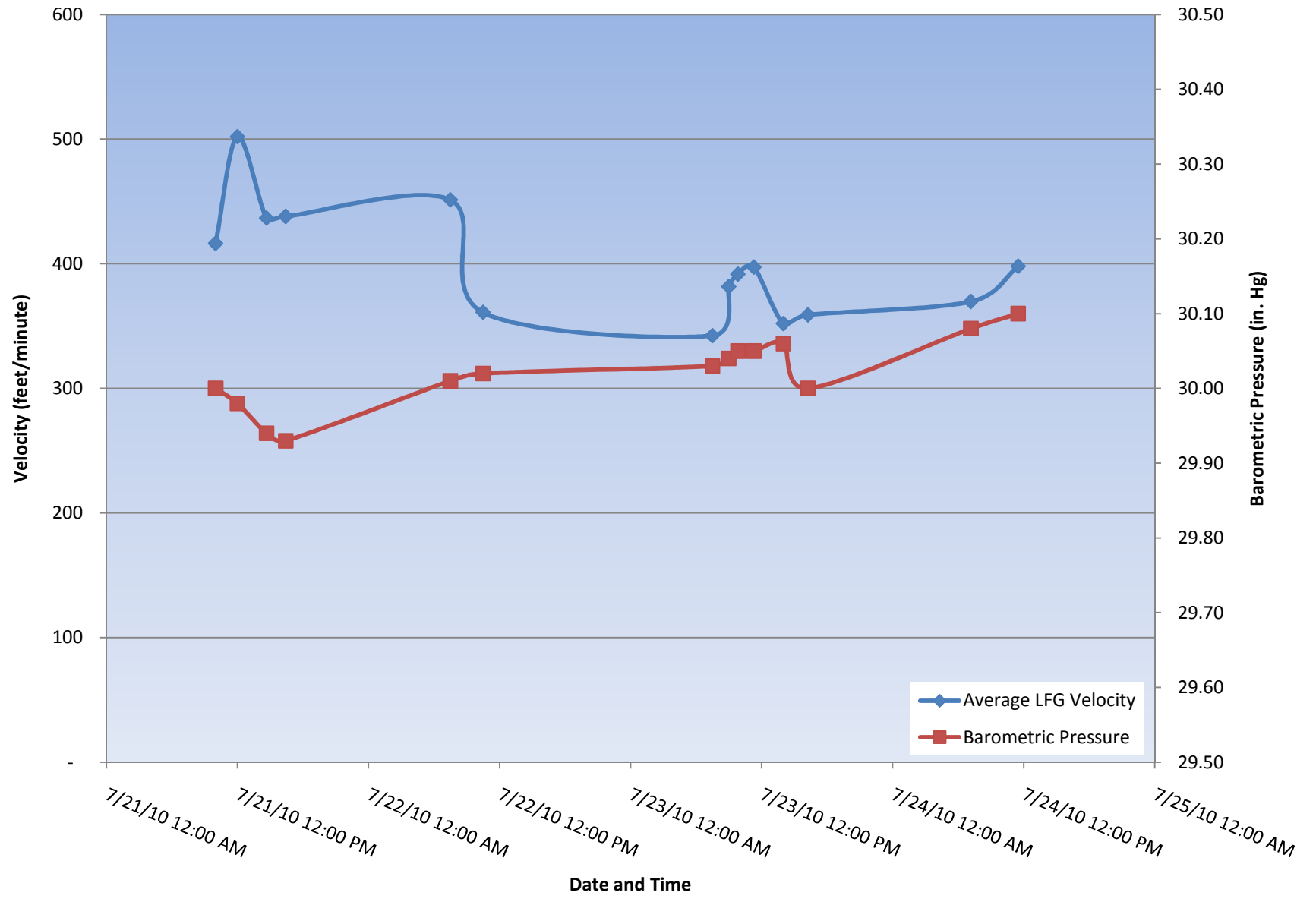


Figure 5
LFG Well 2 LFG Flow and Barometric Pressure Comparison

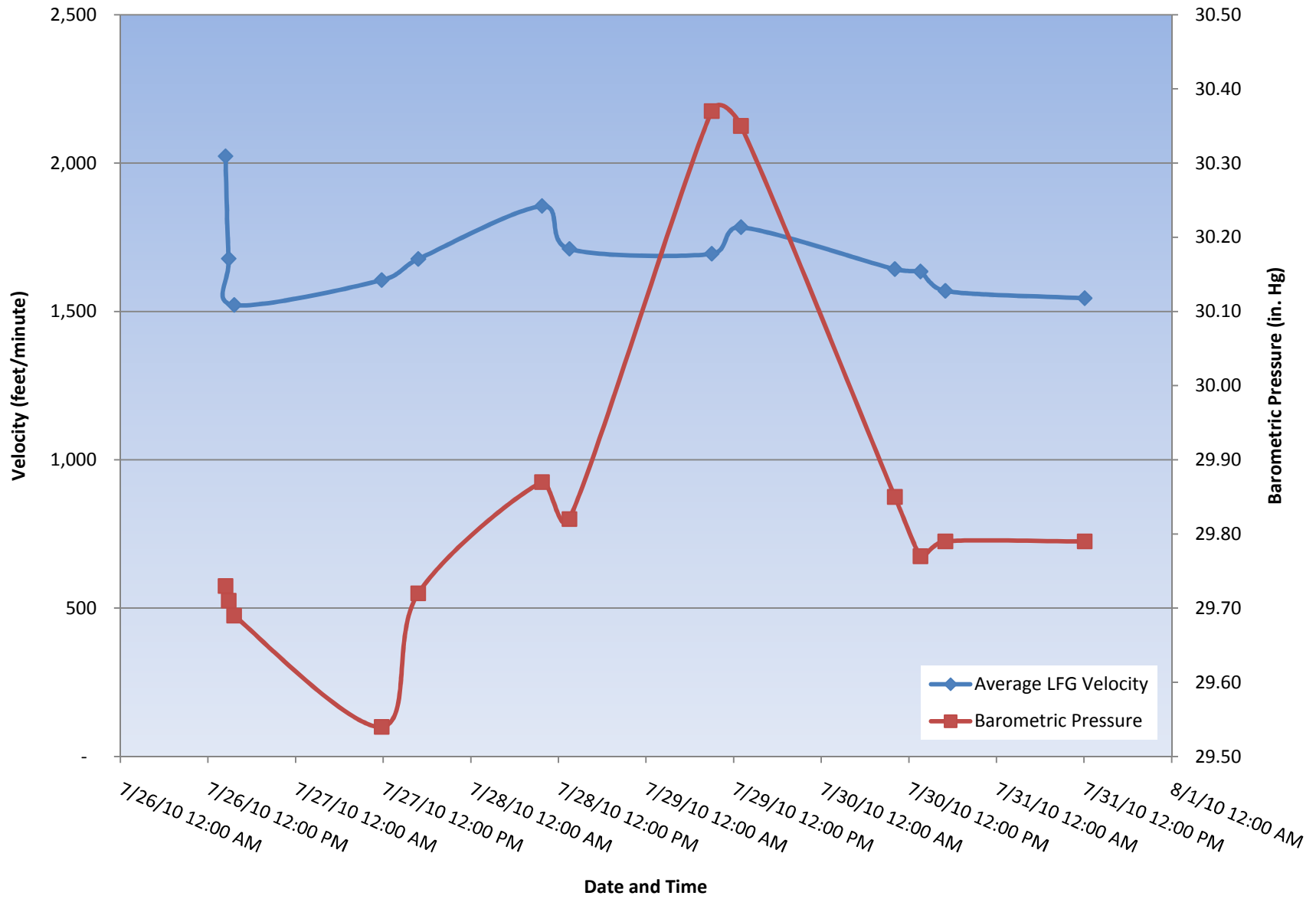
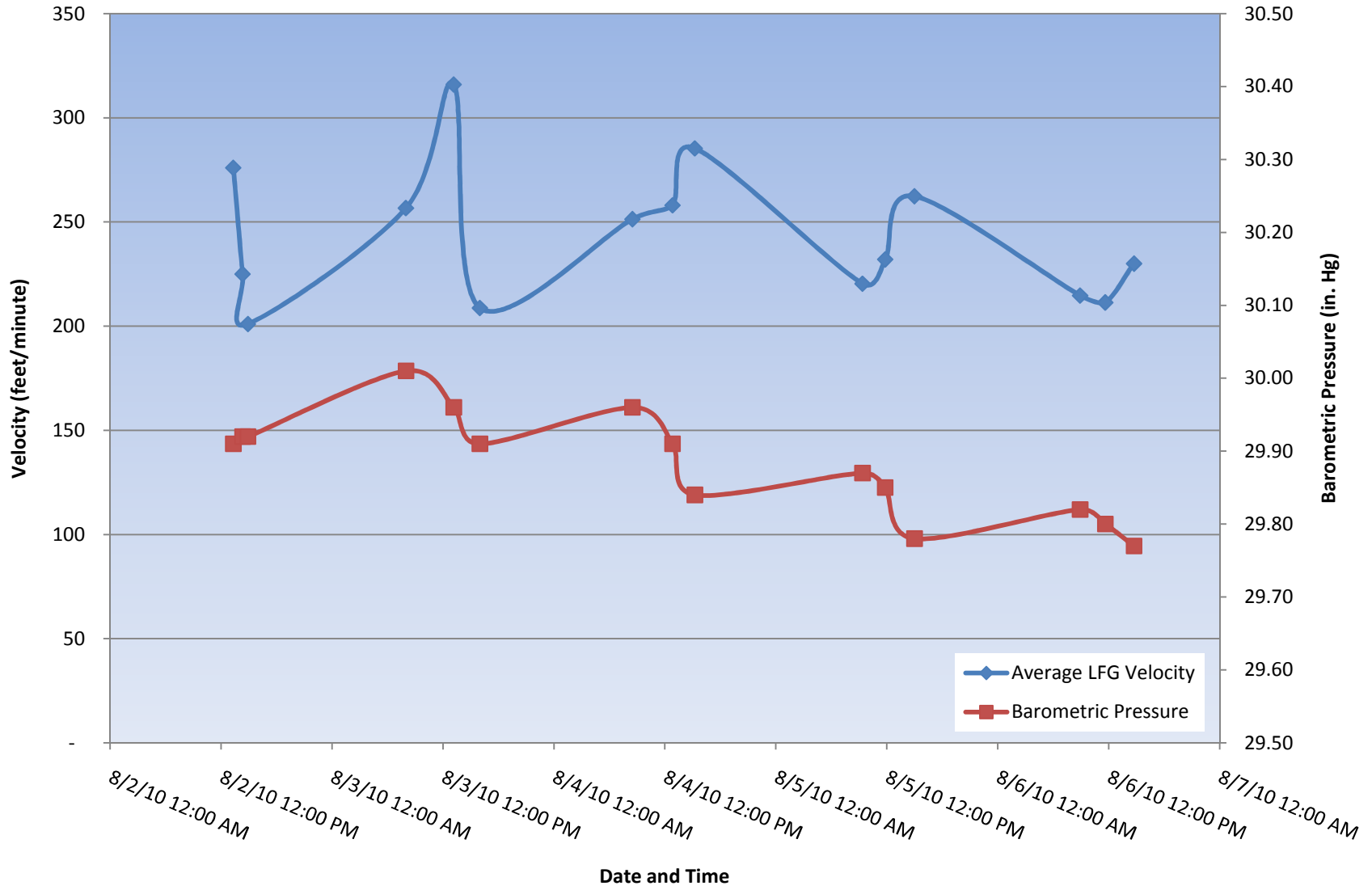


Figure 6
LFG Well 3 LFG Flow and Barometric Pressure Comparison



Attachment 2
BORING LOGS



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Attachment 3
LFG TEST FIELD DATA



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