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NATURAL GAS VEHICLE FUEL SURVEY

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COMPRESSED NATURAL GAS VEHICLE FUEL SURVEY

FINAL REPORT

SwRI® Project No. 18.19236

Prepared for:

Coordinating Research Council, Inc.
5755 North Point Parkway, Suite 265
Alpharetta, GA 30022

May 27, 2014

SOUTHWEST RESEARCH INSTITUTE®

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EXECUTIVE SUMMARY

With recent advances in tight gas production methods from shale formations, the estimated reserves of natural gas in the United States have increased from approximately 175 trillion cubic feet (TCF) in 1999 to over 320 TCF in 2012. In response to the corresponding drop in natural gas prices, several automakers have introduced new models of natural gas vehicles (NGVs) for medium-duty and heavy-duty use and are working to expand the markets for NGVs in the United States. A key challenge to automakers in their plans for market expansion is the lack of data on compressed natural gas (CNG) quality at existing refueling stations and in regions where new CNG stations would be built. Data on water vapor in CNG is of particular interest because of its potential to corrode NGV fuel systems and to form hydrates that can plug fuel valves. The quality of natural gas delivered by transmission pipelines and local distribution companies to CNG stations varies, depending on factors such as available gas supplies, the amount of processing performed on the gas, and supplies drawn from storage during high-demand months. The recent increase in "shale gas" production in the United States has increased these variations since the last published study of pipeline gas compositions.

To help automakers and other stakeholders understand the geographic variations in natural gas quality that NGVs may encounter, Southwest Research Institute (SwRI) has obtained data on pipeline natural gas quality and CNG quality at CNG stations across the United States. The goals of this project were to provide the Coordinating Research Council with data on natural gas quality at transmission pipelines, local distribution company pipelines, and CNG dispensers, and to provide CRC with an understanding of any geographic variations in natural gas components and parameters affecting NGV performance.

To understand long-term historical trends in pipeline gas quality, literature searches were performed for appropriate data using SwRI Library resources and online search engines. The most recent published report on nationwide pipeline natural gas compositions was 20 years old. Results of a ten-year-old unpublished survey of nationwide gas quality were also found, but more recent data were found describing gas composition variations within state boundaries. Data were also collected from transmission and distribution companies that post daily gas composition data on public-access websites for use in custody transactions. A subset of online data representing several regions of the country was analyzed for short-term changes in pipeline gas quality. Parameters affecting NGV performance were computed from the gas compositions and analyzed for variations in time and for differences between regions of the country.

The current quality of CNG supplies was assessed through onsite sample collection. Experience in the natural gas industry has found that gas samples must be collected at source pressure and properly handled to avoid corrupting the sample composition before analysis. Since there are currently no standard methods for collecting samples from CNG dispensers at pressure, a sampling manifold was designed and built to collect CNG samples for laboratory analysis. The manifold was designed to carry CNG from the dispenser, through a gas-liquid separator, through multiple sample cylinders in parallel, and into an NGV fuel tank. Any compressor oils or other liquids in the stream were separated from the CNG and collected for separate identification. The manifold and sample cylinders were assembled and leak-tested at SwRI before being taken to the field.

SwRI staff visited a total of 23 CNG stations across the country to gather samples and collect data. Station operators were surveyed to gather data on equipment configurations, known quality issues with gas entering the station, station throughput, and customer feedback on vehicle performance. Portable moisture analyzers were used to directly measure moisture levels in the natural gas supplies entering the CNG stations and in the dispensed CNG. Finally, gas and liquid samples were collected from the station dispensers and sent to laboratories for analysis.

The gas samples were analyzed by an offsite laboratory using ASTM methods to quantify hydrocarbons, sulfur compounds, and diluent (non-burning) components. The liquid samples were returned to SwRI for a qualitative analysis of any liquids collected from the CNG streams. Because of the manifold sampling approach, quantitative liquid analysis was not considered feasible, but the liquid samples were analyzed to identify water, compressor oils, or other hydrocarbons separated from the CNG stream. The moisture data and gas analyses were combined and used to determine gas quality parameters for the CNG at each station. These parameters and levels of moisture and sulfur in the CNG were compared to typical pipeline limits and other recommended limits for pipeline gas.

Several conclusions about natural gas quality and CNG quality across the country were drawn from the results of this study.

- From the early 1990s to the early 2000s, differences in gas quality among supplies in different regions of the U.S. became smaller, but then became broader between 2003 and the present. This diversity in gas quality is attributed to the increasing variety of natural gas sources, particularly shale gas supplies.
- Within each geographic region defined for this study (Pacific, Rockies, Central, and Eastern regions), CNG samples from some stations were distinctly higher in heating value and Wobbe index (a parameter related to natural gas engine performance) than other stations in the same region. Overall, however, the average heating values and Wobbe indices for each region were not statistically different from one another.
- Fluctuations in gas quality at a single location have been observed over periods of months, weeks, and days due to changes in supply and seasonal variations.
- The Natural Gas Council *White Paper on Natural Gas Interchangeability and Non-Combustion End Use* has recommended limits on quality parameters for natural gas pipelines so that gas supplies from different sources are interchangeable with one another at the point of use. A recent survey has also listed typical limits on quality parameters for gas supplies that pipelines accept from producers and processors. The gas samples collected from CNG stations for this project complied with all of these limits except for moisture content. However, daily gas quality data from pipeline websites show that these limits can be exceeded for several days at a time.
- At about one-fourth of the CNG stations visited during this project, the moisture content of the dispensed CNG was significantly greater than the moisture content of the natural gas entering the stations. Despite the fact that only two of the 23 stations were receiving natural gas with moisture levels exceeding the recommended limit, four stations were dispensing CNG with moisture levels exceeding the limit. These findings were supported by liquid sample analyses and data from onsite equipment. Moisture in dispensed CNG and its potential effects

on NGV fuel systems may be of concern to NGV manufacturers and other stakeholders in the CNG industry.

- All of the liquid samples collected from the CNG stations were found to contain trace amounts of heavy hydrocarbons left behind after the lighter CNG components flashed off from the liquid sample cylinders. Only four of the 22 trace hydrocarbon samples resembled known compressor oils, but the others contained hydrocarbons with similar carbon numbers to compressor oils. The small amounts of liquid prevented quantitative estimates of the relative fractions of heavy components in the CNG.

1. INTRODUCTION

1.1 The Need for Data on CNG Quality

With recent advances in tight gas production methods from shale formations, the estimated reserves of natural gas in the United States have increased from approximately 175 trillion cubic feet (TCF) in 1999 to over 320 TCF in 2012 (U.S. Energy Information Administration, 2014). The corresponding drop in natural gas prices has encouraged the use of compressed natural gas (CNG) as an alternative fuel in the transportation sector, particularly for commercial vehicles and light-duty personal vehicles. Several automakers have introduced new NGVs for medium-duty and heavy-duty use and are working to expand the markets for NGVs in the United States (James, 2013; Stenquist, 2013). NGVs can be attractive to consumers for their low fuel prices on an energy-equivalent basis relative to gasoline (Wiley and Hunt, 2011) and for the availability of natural gas compressors for home refueling (Stenquist, 2013).

Some challenges exist for NGVs, however. One key challenge to automakers in their plans to expand the market for NGVs is the lack of data on CNG quality at existing refueling stations and in regions where new CNG stations could be built. To be accepted by transmission pipelines for transportation around the United States, natural gas must meet gas quality tariff requirements, including limits on moisture content, limits on sulfur content, and other limits intended to avoid pipeline corrosion and maintain pipeline integrity. However, in times of high demand, pipelines may be forced to accept gas that exceeds their tariff requirements and blend the “out-of-spec” gas with other gas supplies to return it to acceptable levels. If blending is inadequate, the gas received by a local distribution company (LDC) may still deviate from the original tariff requirements. In some cases, if the gas has been received by the end-user directly from production sites, it may not have met these requirements to begin with.

Natural gas quality is known to vary among different LDCs around the country. At the beginning of this project, the most recent comprehensive nationwide survey of gas quality and quality limits available to the public was over 20 years old (Liss et al., 1992). With the recent increase in “shale gas” production in the United States, variations in gas quality wider than those seen in the 1992 report can be expected. Also, the use of water in hydraulic fracturing fluids for shale gas production may require separation of water from the produced gas and dehydration of the gas stream (AGA, 2013). If pipelines must accept shale gas that has not been adequately processed and are unable to lower the moisture level by blending it with water-dry supplies, this moisture may lead to corrosion of hardware in NGV fuel systems, the formation of methane hydrates that can plug valves, and the overload of gas drying and dehydration equipment in refueling systems.

To help automakers and other interested parties understand the variations in natural gas quality across the United States, data are needed on the current levels of moisture and other components of concern found in the natural gas transmission and distribution systems and in the CNG currently being dispensed at CNG stations.

1.2 Goals of This Project

In this project sponsored by the Coordinating Research Council (CRC) and co-funded by the American Gas Association (AGA), Southwest Research Institute (SwRI) has obtained data on pipeline natural gas quality and CNG quality at CNG stations across the United States. Some data were gathered through searches for recent gas composition data from transmission and distribution pipelines. The remaining data are from analysis of gas samples from CNG stations in cities across the United States. The samples were collected in different parts of the continental United States to provide data on natural gas from different gas producers and LDCs.

One goal of the project was to provide CRC with data on natural gas quality at three different points within the natural gas infrastructure: transmission pipelines, LDC pipelines, and CNG stations (specifically, the CNG dispenser). A second goal of the project was to provide CRC with an understanding of variations in natural gas compositions around the country. It should be understood that the dispenser samples are "snapshots" of gas quality at each location at the time of the sample, while the literature search has provided data on variations in gas quality over time.

1.3 Report Organization

The project was divided into five technical tasks. In the first task, existing data were gathered on natural gas quality and components of interest within transmission and LDC pipeline networks. Websites of libraries and natural gas organizations were searched for prior natural gas quality surveys. The online search also collected current gas quality data from transmission and distribution companies. The data are compiled in Appendix A of this report, while trends in the data are reviewed in Section 2.

The second task was to prepare equipment for onsite and offsite analysis of CNG. Portable analyzers were purchased to measure moisture levels in LDC pipelines and CNG dispensers at the refueling stations. Other natural gas components of interest and possible compressor oils in the CNG streams were analyzed by dedicated laboratories. Sample cylinders were purchased to collect gas and liquid samples onsite and transport them to labs for these analyses. The gas cylinders were passivated to prevent loss of sulfur compounds in the CNG samples during transport. Sampling manifolds were also designed and built to collect representative gas and liquid samples during refueling of an NGV. Finally, the equipment performance was verified at SwRI and nearby locations before use, and SwRI field personnel were trained on the specific analysis and sampling methods to be used. The equipment and its uses are discussed in Section 3.

In the third project task, SwRI, CRC, and AGA arranged access to CNG stations in eleven metropolitan areas for sampling. With assistance from AGA, SwRI identified owners and operators of CNG stations in these locations. CRC, AGA, and SwRI then contacted the owners to solicit their participation. Once permission was gained, SwRI worked with the station owners to identify equipment and assistance needed from their staff, select CNG stations for sampling, and schedule the visits.

In the fourth project task, SwRI staff visited the sites. Moisture levels were measured in the distribution gas entering the station and in the CNG dispensed at each station. Gas and liquid spot samples were also collected from the CNG dispenser at each station and sent to laboratories for analysis. Finally, SwRI staff conducted a brief survey of station staff to gain further insight into CNG quality at the stations and photographed station equipment and arrangements used to analyze and sample gas streams. Section 4 describes the stations visited and findings of the blinded survey. The survey results themselves are tabulated in Appendix D. Equipment layouts of all stations visited during the survey can be found in Appendix E, along with photographs of representative station equipment taken during the visits. Photos were taken of the equipment at all 23 stations, but are too numerous to include in this report, so the entire photo collection has been provided to CRC electronically.

The fifth project task involved analysis of the CNG samples, calculation of properties of interest, and analysis of geographic variations in these properties. To ensure accurate results, SwRI sent the CNG samples to SPL, Incorporated (SPL) for analysis according to ASTM standards. SPL analyzed the CNG samples for hydrocarbons, diluents, total sulfur content, and (as warranted) sulfur species, and sent the results to SwRI. Any liquid samples collected from the CNG dispensers were qualitatively analyzed by the Fuels and Lubricants Research Division of SwRI for components of interest, primarily compressor oils. The CNG analyses and onsite moisture measurements were used to calculate the Wobbe index, methane number, higher and lower heating values, and specific gravity of each CNG sample. Section 5 reviews the onsite moisture measurements, CNG analyses, and liquid analyses from each site, along with calculated CNG properties and geographic trends in CNG quality observed from the results. Finally, Section 6 presents conclusions of this survey.

2. REVIEW OF EXISTING GAS QUALITY DATA

At the beginning of this project, the most recent published report on nationwide natural gas quality was approximately 20 years old (Liss et al., 1992). As this project was being conducted, another report was released by the American Gas Association (AGA, 2013) that listed results of an unpublished survey of natural gas quality throughout the United States. However, that survey was ten years old at the time it was published in the AGA report. More recent regional data are available, as are data from individual pipelines. Studies have been published on gas quality variations within state boundaries (Singer, 2007), and some transmission and distribution companies post daily gas composition data on public-access websites for use in custody transactions.

For this project, a search was performed for the original survey data cited by the AGA document, and searches were performed for more recent data using resources of the SwRI Library and online search engines. The library website of the Gas Technology Institute (GTI) was particularly useful in obtaining historical data. An online search also found many transmission and distribution company websites that post current gas composition data, often stretching back three months. A subset of pipeline websites representing several regions of the country was polled to collect data on changes in natural gas quality over time.

This section summarizes trends in both gas composition data and properties of interest computed from the data. Subsection 2.1 introduces gas quality parameters of interest to the natural gas industry as well as NGV manufacturers, end-users, and other interested parties. The remaining subsections review trends in previous nationwide gas quality surveys and pipeline gas quality data from February to May 2013. All data gathered during this survey are presented graphically in Appendix A.

2.1 Key Gas Quality Parameters and Practical Limits

A variety of gas quality parameters were chosen for study by CRC. Some of these directly or indirectly affect NGV performance, while others are monitored by pipelines to avoid corrosion and keep the gas quality acceptable for a variety of end users. This subsection reviews the parameters of interest and discusses typical pipeline limits on these parameters.

2.1.1 Hydrocarbons

Hydrocarbons, compounds whose molecules are composed of only hydrogen and carbon atoms, are the natural gas components that produce energy through combustion. Natural gas is mostly composed of hydrocarbons ranging from methane (CH_4, with one carbon atom) through the hexanes (molecules with six carbon atoms and up to fourteen hydrogen atoms). The C_1 through C_6 hydrocarbons, described in this report as light hydrocarbons, often make up over 95 mole percent (95 mol%) of natural gas. Natural gas streams from different sources and processing plants will have different hydrocarbon compositions, and thus different properties of interest. For example, the amounts of ethane (C_2H_6), propane (C_3H_8), and heavier hydrocarbons relative to methane will affect the Wobbe index and methane number as described later.

For this report, heavy hydrocarbons are classified as hydrocarbon molecules with more than six carbon atoms. Much less than 1 mol% of typical natural gas is composed of heptanes (C_7), octanes (C_8), and heavier components. These components are often removed by processing, since large quantities of heavy hydrocarbons can condense to form hydrocarbon liquids in a natural gas pipeline if the stream falls below its hydrocarbon dew point temperature. Compressor oils are typically composed of hydrocarbons from C_{12} to C_{15}, but may include lighter or heavier molecules. Either of these liquids may have an adverse effect on CNG quality.

2.1.2 Diluents

Diluents are components that have no energy content, but occupy space in the gas stream that could otherwise be taken up by hydrocarbons. By diluting the natural gas, they reduce its heating value and can adversely affect its Wobbe index. The most common diluents in natural gas are nitrogen (N_2) and carbon dioxide (CO_2). Less common diluents include hydrogen (H_2), helium (He), carbon monoxide (CO), and oxygen (O_2). Processing natural gas to remove diluents must strike a balance between processing costs and the increased value of the processed gas (AGA, 2013). Because of this, natural gas supplies will often include a few mole percent of diluents.

2.1.3 Water Vapor

Water vapor is also considered a diluent, but is often treated separately for measurement purposes. Excessive amounts of water vapor can collect in fuel tanks or form hydrates that may foul NGV fuel systems. Excessive water vapor can also overload CNG station dehydration equipment or cause corrosion of high-pressure storage tanks. In most processed natural gas streams, water vapor is present in amounts much less than 1 mol%, so it may be quantified in units of parts per million by volume (ppmv). An alternate unit used by the natural gas industry is pounds mass of water vapor per million standard cubic feet of gas (lb_m/MMscf). The unit conversion is 1 lb_m/MMscf = 21.1 ppmv (Datta-Barua, 1992).

2.1.4 Sulfur and Sulfur Compounds

Sulfur can appear in pipelines in many chemical forms, including hydrogen sulfide gas (H_2S), mercaptans, elemental sulfur powder (S_8), and iron sulfide "black powder" (Fe_2S_3). Small amounts of mercaptans are added to natural gas as odorants for safety purposes. However, other forms of sulfur can foul equipment or induce corrosion in pipelines, NGVs, and refueling stations. Pipelines may quantify sulfur compounds either as "total sulfur" or by individual species, depending on their requirements for accepting gas supplies. Like water vapor, sulfur compounds are present in most processed gas streams in quantities much less than 1 mol%. Amounts are typically reported in units of grains per 100 standard cubic feet of gas, where 7,000 grains = 1 lb_m (AGA, 2013).

2.1.5 Heating Values

The heating value of a gas of known composition is the energy produced by complete stoichiometric combustion of that gas. That is, the reactants (natural gas and oxygen from the air) burn completely to form only water and CO_2, without producing soot, carbon monoxide, or oxides of nitrogen or sulfur. Heating value is typically quantified in British thermal units per standard cubic foot of gas (Btu/scf), where the standard temperature and pressure for the cubic foot of gas are 60°F and 14.696 psia.

In this report, two heating values are listed for CNG samples. The higher heating value (HHV), also called the gross heating value, is computed by assuming that the reactants and products (including nitrogen in the air, which does not participate in the reaction) are all at standard temperature and pressure, and that the water produced by the reaction is returned to the liquid state. This heating value is commonly used for pipeline custody transfer purposes, and also affects NGV performance through the Wobbe index (discussed below). The lower heating value (LHV), also known as the net heating value, differs from the HHV in that the water produced by the reaction is assumed to remain in the vapor state. Although the LHV is not often used by pipelines, it is reported here.

In this study, both the HHV and the LHV were calculated using the method of ASTM D3588 (ASTM, 2011). Property data for natural gas components were taken from GPA Standard 2145 (GPA, 2009), ASTM D3588, and GPA Technical Publication TP-17 (GPA, 1998). The latter standard was used for heating values of non-normal hydrocarbons heavier than hexane, and these data were adjusted where possible to be in harmony with normal hydrocarbon heating values from the newer GPA 2145-09 standard.

2.1.6 Specific Gravity

Specific gravity, also called relative density, is the ratio of the density of a natural gas blend of interest to the density of air, with both gases at conditions of 60°F and 14.73 psia. Note that the reference pressure for specific gravity is slightly higher than the reference pressure for heating values. For typical pipeline-quality natural gas, the specific gravity is approximately 0.6, and for "richer" gases with higher amounts of heavier hydrocarbons, the specific gravity will tend to be higher. Specific gravity values in this report were calculated using the method of ASTM D3588-11 and data from GPA 2145-09, ASTM D3588, and GPA TP-17.

2.1.7 Wobbe Index

The Wobbe index is used to assess whether different natural gas supplies are interchangeable for end-use applications. The Wobbe index was created as a measure of the rate of thermal input through a fixed orifice or nozzle to a stationary burner. As shown in Figure 2.1, the saturated hydrocarbons (alkanes) that typically make up over 95% of pipeline-quality natural gas have a unique property: the number of moles of oxygen required for complete combustion of one mole of an alkane is proportional to the HHV of the alkane. The figure also shows that the Wobbe indices of these dominant alkanes (methane through hexane) are also linearly related to the amount of oxygen needed for complete stoichiometric combustion. Since this property holds for mixtures of alkanes as well, the Wobbe index is used to guide the size of the orifices used to control both air and natural gas flow rates to stationary burners (AGA, 2013).

For NGV engines and other gas-powered engines, the Wobbe index can similarly be related to engine power and the optimum fuel-to-air ratio, and therefore can identify fuel changes that might result in poor operational and environmental performance (Natural Gas Council, 2005). As shown below, it is calculated from the HHV and the specific gravity of the gas stream. Customarily, the Wobbe index is given as a unitless number.

$$Wobbe\ index = \frac{higher\ heating\ value}{\sqrt{specific\ gravity}} \qquad [1]$$

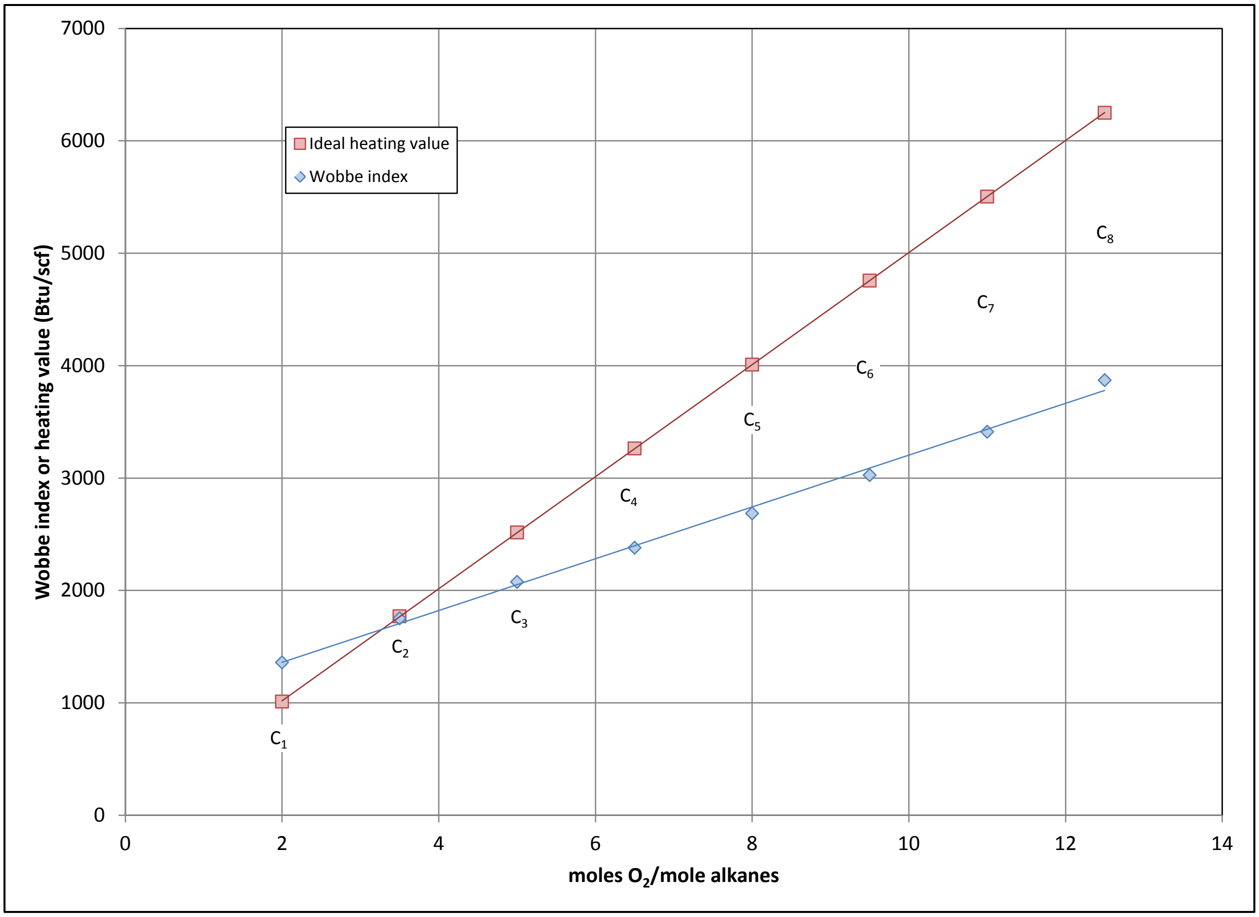

Figure 2.1. Trends in Heating Value and Wobbe Index for Alkane Hydrocarbons
The heating values and Wobbe indices for alkanes found in pipeline-quality natural gas (typically 95% methane through hexane) are linearly related to the number of oxygen atoms required for stoichiometric combustion. For this reason, the Wobbe index helps to determine the amount of air required for complete combustion and the optimum fuel-to-air ratio for CNG engines.

2.1.8 Methane Number

The methane number is a CNG property analogous to the octane number of gasoline in that it describes the ability of CNG to withstand compression before ignition. Fuels with higher methane numbers are more capable of resisting combustion knocking, while fuels with lower methane numbers may pose performance problems for NGV engines due to their higher amounts of ethane, propane, and heavier hydrocarbons that can cause combustion knocking (Natural Gas Council, 2005; AGA, 2013).

The methane number (*MN*) is a function of the hydrocarbon content of the gas stream and the motor octane number (*MON*). Several different correlations have been developed to compute the methane number from these quantities, including those reported by Ryan et al. (1993) and ISO (2013). Since this study concerns natural gas vehicle performance in the United States, methane numbers are computed here using the SAE formula (Kubesh et al., 1992; AGA, 2013).

$$MN = 1.624 \times MON - 119.1 \qquad [2]$$

Two different formulas may be used for *MON* (Kubesh et al., 1992). Equation 3, referenced by the state of California (California Air Resources Board, 2001), uses the average ratio of hydrogen atoms to carbon atoms (*H/C*) among the reactive hydrocarbons in the fuel, excluding the carbon atoms in any CO_2 present. This formula, referred to in this report as the CARB formula, is only valid for fuels with *H/C* > 2.5 and with less than 5 mol% total inerts.

$$MON = -406.14 + 508.04\left(\frac{H}{C}\right) - 173.55\left(\frac{H}{C}\right)^2 + 20.17\left(\frac{H}{C}\right)^3 \qquad [3]$$

The other formula for *MON*, known as the linear coefficient relation, is computed from the mole fractions of the most common components of natural gas (AGA, 2013). The formula, shown as Equation 4, involves the mole fractions of methane, ethane, and propane, the sum of the mole fractions of isobutane and normal butane, and the mole fractions of CO_2 and nitrogen. While no range of validity is given with the formula, it does not consider the specific contributions of hydrocarbons heavier than butane in the fuel.

$$\begin{aligned} MON = {} & 137.78\, x_{C1} + 29.948\, x_{C2} - 18.193\, x_{C3} - 167.062\, x_{C4} \\ & + 181.233\, x_{CO2} + 26.994\, x_{N2} \end{aligned} \qquad [4]$$

Because the CARB formula considers the contributions of heavy hydrocarbons, it was used to compute the motor octane number and the methane number for all gas compositions in this study. Except where noted in subsection 2.3, the limits of validity for *H/C* and inert content were not exceeded by any of the analyzed gas streams.

Notably, as the heavy hydrocarbon content of natural gas increases, the heating value and Wobbe index of the gas tend to increase, but the methane number tends to decrease. Pure methane (CH_4) has the highest *H/C* ratio of all the hydrocarbons (four) and thus the highest SAE methane number (108.4), but the lowest heating value (1,010 Btu/scf). As carbon atoms are added to the methane molecule to form ethane, propane, and heavier hydrocarbons with higher heating values, no more than two hydrogen atoms can be added with each carbon atom, so the overall *H/C* ratio of the molecule decreases from four, and the methane number decreases as well. Figure 2.2 illustrates these trends for alkane hydrocarbons. The values of these same parameters for pipeline-quality natural gas mixtures will vary with composition – particularly with the amount of non-alkane hydrocarbons and diluents – but the inverse relationship between Wobbe index and methane number still applies.

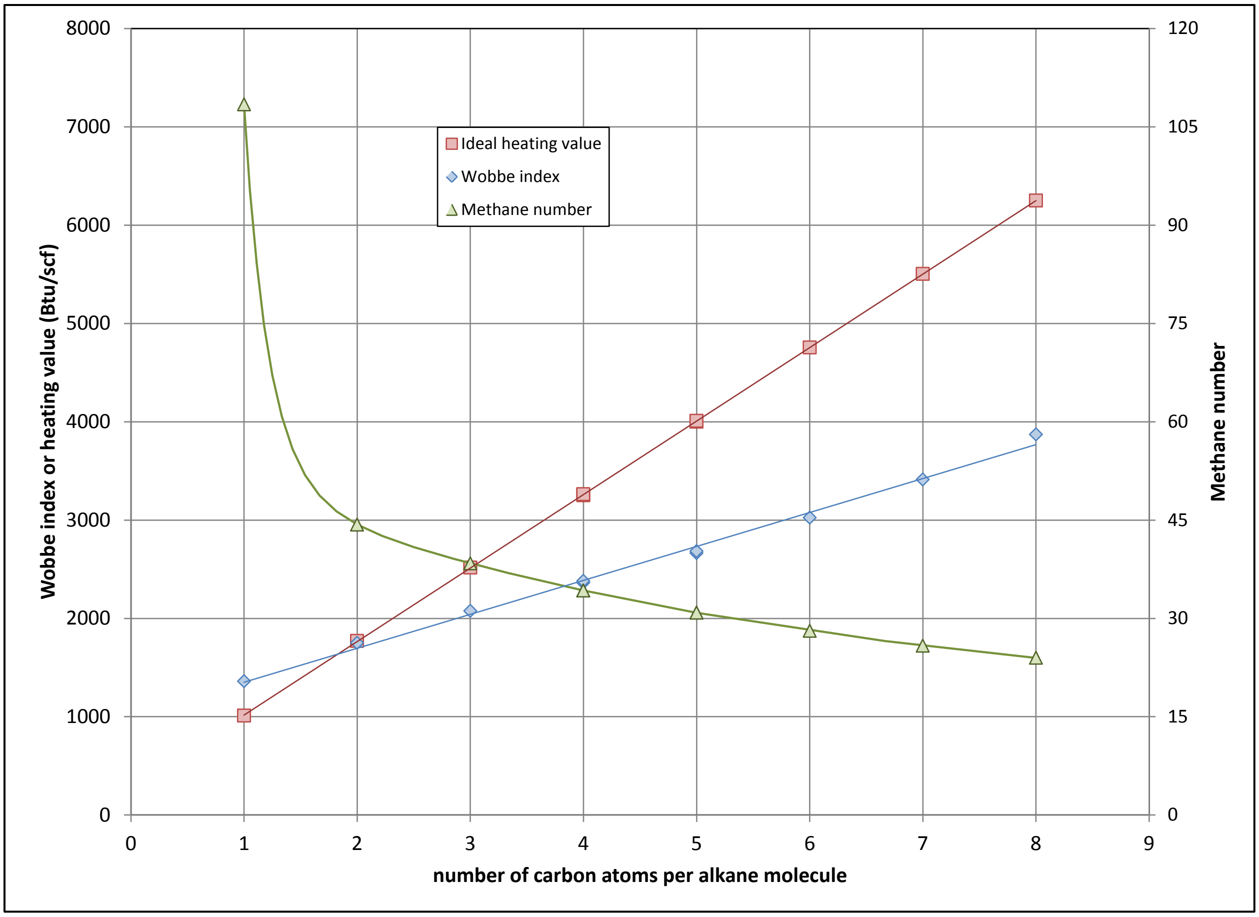

Figure 2.2. Comparison of Methane Numbers to Other Gas Quality Parameters for Alkane Hydrocarbons

The plot shows how the methane number decreases as the carbon number of the alkane increases, while heating value and Wobbe index increase with carbon number. Values of these parameters for pipeline-quality natural gases depend on the gas composition, but these opposing trends in Wobbe index and methane number also apply to natural gas mixtures.

2.1.9 Tariff Limits and Interchangeability Limits

Interstate pipeline transmission companies operate under documents known as tariffs. These documents are filed with the Federal Energy Regulatory Commission (FERC) and list a pipeline's rates for gas transportation services along with terms and conditions of service. Tariffs include gas quality specifications intended to maximize accepted gas supplies while minimizing problems with gas transportation, delivery, and end-use.

American Gas Association Report 4A (AGA, 2009) serves as a reference for gas quality and measurement provisions in pipeline tariffs. Besides explaining terms found in tariffs and describing considerations for appropriate quality specifications, the report gives examples of gas quality clauses found in North American pipeline tariffs. Table 2.1, taken from that reference, shows the ranges of contaminant limits and gas quality parameters in tariffs filed with FERC in March 2008. These data are provided to demonstrate the variations in gas quality that can exist across the country and also serve as a reference point for actual gas quality data presented later in this report. Specifications in current tariffs may differ from these 2008 values, and pipelines may accept gas supplies that exceed tariff limits under extreme circumstances, so these gas quality ranges should be taken as examples rather than as strict limits.

Another practical limit on natural gas quality is imposed by interchangeability, defined as "the ability to substitute one gaseous fuel for another in a combustion application without materially changing operational safety, efficiency, performance or materially increasing air pollutant emissions" (Natural Gas Council, 2005). Interchangeability is quantified using technical measures (such as the Wobbe index) that can be applied to many different end-use applications. Limits on these quantities may be set to guarantee the interchangeability of different gas supplies.

Table 2.1. Ranges of Pipeline Tariff Limits Posted to FERC in March 2008 (AGA, 2009)
Current tariff ranges may differ from these 2008 values.

Specification	Range of values found in tariffs
Minimum higher heating value	900 to 1,000 Btu/scf
Maximum higher heating value	1,075 to 1,200 Btu/scf
Minimum Wobbe index	1,279 to 1,340
Maximum Wobbe index	1,380 to 1,400
C_{4+} content	0.75 to 1.50 mol%
C_{5+} content	0.12 to 0.25 mol%
Maximum water vapor content	4 to 7 lb_m/MMscf (84 to 148 ppmv)
Maximum total sulfur compounds	0.5 to 20 grains/100 scf
Maximum hydrogen sulfide (H_2S)	0.25 to 1 grain/100 scf
Maximum hydrogen	400 to 1,000 ppmv
Maximum total diluent gases	3 to 6 mol%
Maximum CO_2	1 to 3 mol%
Maximum N_2	1 to 4 mol%
Maximum O_2	0.001 to 1 mol%

Gas supply compositions within interstate pipelines were relatively stable through the 1980s and early 1990s. As demand increased in the 1990s and 2000s, greater volumes of gases from non-traditional gas sources (such as coal-bed methane, LNG, and biogases) raised issues with gas quality and interchangeability. In 2004, the Natural Gas Council (NGC) convened technical experts to develop a set of interim guidelines for gas interchangeability, pending additional research and experience. These were based on interchangeability data for traditional gas appliances, but considered the lack of interchangeability data for other end-uses (such as NGVs).

The "NGC+ interim interchangeability guidelines," listed below, are subject to revision as additional research is performed (Natural Gas Council, 2005).

- Limits on Wobbe index and heating value:
    - A range of ±4% variation about the local historical gas average or target gas composition for end-use applications.
    - A maximum limit on Wobbe index of 1,400.
    - A maximum HHV of 1,110 Btu/scf.

- A maximum C_{4+} content of 1.5 mol%.
- A maximum total inert (diluent) content of 4 mol%.
- Service areas with demonstrated experience with supplies that exceed these limits may continue to use such supplies, as long as they do not cause safety or end-use problems.

After the NGC+ interim guidelines were published, FERC issued a policy statement to provide guidance for pipelines addressing gas quality and interchangeability issues (FERC, 2006). The FERC policy states that gas quality specifications must be flexible, must be based on science, and must balance safety with the ability to maximize gas supplies. Most notably, the FERC policy states that the NGC+ interim guidelines should serve as a reference for resolving gas quality issues and will carry significant weight in the resolution of any disputes brought to FERC. In light of this policy, the NGC+ interim guidelines are provided as benchmarks for pipeline gas quality data presented later in this report, similar to the example tariff limits listed in Table 2.1.

2.2 Results of Prior Gas Quality Surveys

This subsection summarizes the review of previously published natural gas quality studies. Three useful reports were found that contain data from 1991 to 2003, averaged by year and by location. The key parameters described in subsection 2.1 were compiled or computed from the data and reviewed for useful trends. The key trends are presented below, while the data are presented graphically in Appendix A.

2.2.1 Previously Published Studies

Of the three useful sources of historical data, the study covering the largest time span was performed by the Natural Gas Council while developing their Interchangeability White Paper (Natural Gas Council, 2005; AGA, 2013). These data were collected in pipeline surveys performed in 1995-96 and again in 2002-03. The data have been summarized in Appendix C of the AGA Gas Quality Measurement Manual (AGA, 2013), appearing as annual statewide averages covering 29 states. A search for the original NGC pipeline survey data was unsuccessful, but the annual statewide averages reprinted in the AGA manual have provided insight on trends in gas quality between 1995 and 2003.

The second study of interest was funded and published by the Gas Research Institute and was obtained through the GTI website. This report (Liss et al., 1992) studied regional variations in gas properties from 1990 to 1992 and considered the potential effects of these variations on natural gas engines, making it of particular interest here. The report includes annual statistics on data from gas chromatographs (GCs) used to analyze pipeline gas compositions in real time. The GC locations were identified only by state and site number, not by pipeline. However, the grouping of data by state allowed comparisons to the data from the NGC surveys.

The third study was funded by the Institute of Gas Technology (IGT) and was also obtained from the GTI website. In this study (Chao and Attari, 1995), natural gas spot samples were collected between midstream (gas processing) plants and pipeline entry points from October 1991 to June 1993. The spot samples were extensively analyzed to ppm levels for trace components and several potential pollutants. Components of interest included long-chain hydrocarbons, sulfur compounds, PCBs, water vapor, hydrogen, alcohols, arsenic, and radon. Results were listed by production region, not by pipeline or by sampling location, so these data could not be compared to the other data to analyze statewide trends. However, the study did provide historical data on components of interest to CRC and AGA.

Table 2.2 compares the components and properties to be analyzed in the field samples during this study to the components reported in the three previous studies. Only the 1995 study investigated the moisture content or the sulfur content of natural gas, and only the 1992 study reported the Wobbe index or methane number of the gases being analyzed. None of the other studies reported on carbon monoxide (CO) levels in the gas streams. Thus, the results of the current field surveys and analyses should provide new insight into these contaminants. For equitable comparisons, all gas properties from the previous studies were re-computed and reported here using the most recent standards and component property data. This will also allow direct comparisons to the results of the current study.

Table 2.2. Comparison of Gas Quality Data of Interest in the Field Survey to Data Reported in Previous Studies

Data on moisture and sulfur species were only collected in one previous study. No data on CO content were found in any of the previous reports.

Analytes of interest	**NGC+ surveys**	**Liss et al., 1992**	**Chao and Attari, 1995**
Moisture content			√
Light hydrocarbons (C_1-C_6)	√	√	√
Heavy hydrocarbons (C_{7+}, compressor oils)	C_7, C_8 only		√
N_2, CO_2	√	√	√
H_2, He, CO, O_2		O_2 only	H_2, He, O_2
Total sulfur			
Speciated sulfur			√
Computed properties			
Higher heating value		√	√
Specific gravity		√	√
Methane number		√	
Wobbe index		√	

2.2.2 Long-Term Trends by Pipeline Location

The data from the NGC survey and the 1992 GRI study were combined into a single dataset of annual average properties by state and analyzed for long-term trends. Figure 2.3 marks the states where pipeline data were gathered in these studies. As noted above, where gas composition data were sufficiently detailed, gas quality parameters were re-computed using the most recent standards to allow consistent comparisons between the datasets. Components listed in these data typically included N_2, CO_2, and hydrocarbons through octane, which were sufficient to compute higher and lower heating values, relative densities, Wobbe indices, and methane numbers.

Figure 2.4 presents the annual average Wobbe indices by state. The states are arranged on the horizontal axis by geographic region, with more eastern states on the right side of the graph. Dashed lines in the plot identify the upper limit on Wobbe index of 1,400 proposed by the 2005 NGC+ White Paper and the range of Wobbe indices observed in the FERC filings from March 2008. From 1990 to 2003, average Wobbe indices ranged from 1,310 to 1,370, within the recommended NGC+ limit and the range of indices observed in later years. The plot also shows two trends of interest.

1) In the early 1990s, the average Wobbe index in Colorado was particularly low, but by the mid-1990s, the statewide average rose to levels similar to that of other states. This may indicate that a significant change in Colorado gas supplies occurred in the 1990s that brought the gas in line with the rest of the country.
2) In many eastern states, Wobbe indices fell roughly by 20 units between 1990-92 and 2002-03, suggesting that gas supplies to these states became "leaner" (included fewer heavy hydrocarbons).

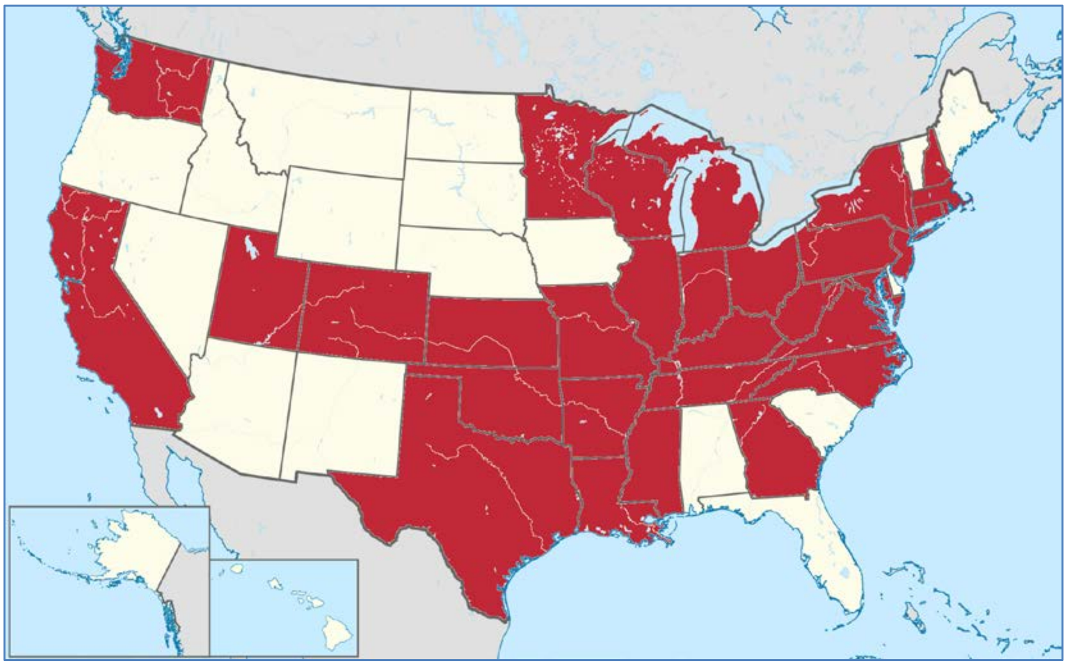

Figure 2.3. States Included in the Dataset of Annual Average Properties, 1990-2003
Data from states in red were included in the dataset.

Table 2.3 presents the statistics calculated for the Wobbe indices in the state averages dataset. The data were grouped by regions as listed on the horizontal axis of Figure 2.4, and statistics were computed for each group over all of the years in the dataset. Note that for the calculations in the table, each data point within a group is an annual average for a single measurement station, while the values in the graph represent averages over all stations in a state. The averages, standard deviations, and extreme values for each group were compared to the NGC+ recommended upper limit on the Wobbe index and the range of "typical" Wobbe indices observed in the March 2008 FERC filings. No values exceeded the NGC+ upper limit on the Wobbe index of 1,400. However, the average and minimum Wobbe indices in the Rockies region both fell below the typical range of 1,310 to 1,370, due to the low Wobbe indices seen in Colorado during the early 1990s. In the other regions, the ranges of Wobbe indices compare well to the "typical ranges" represented by the FERC tariffs from 2008.

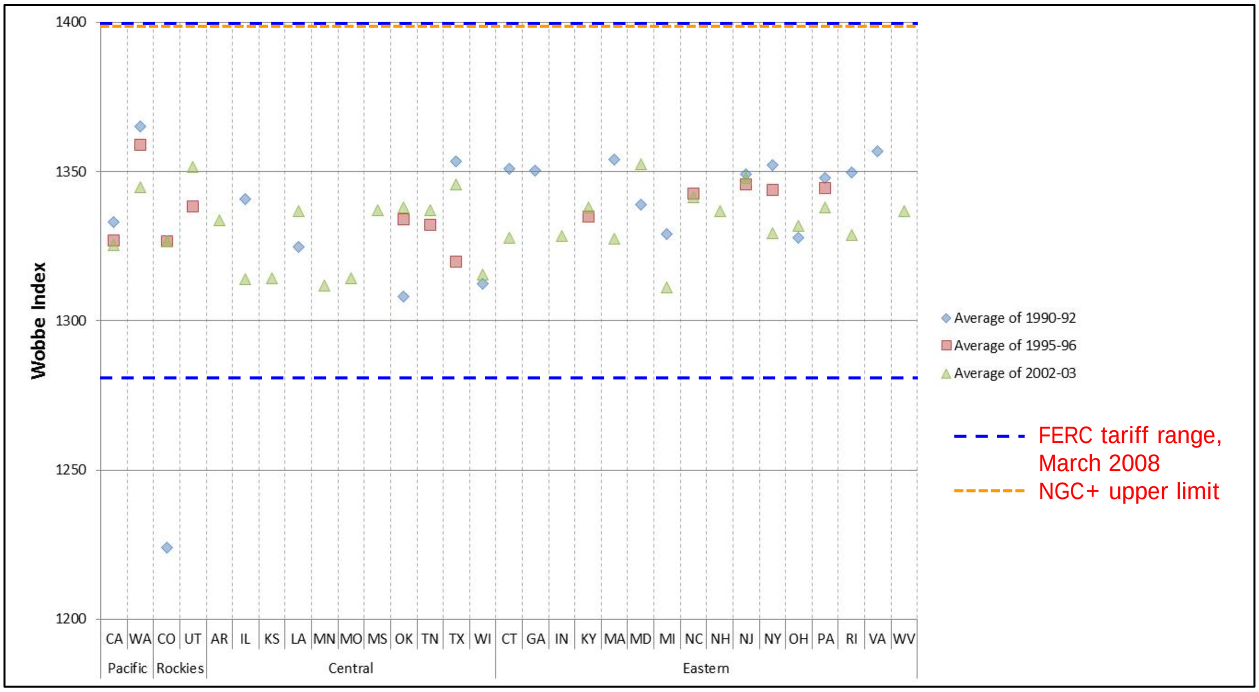

Figure 2.4. Wobbe Indices Averaged by State, 1990-2003
Many Wobbe indices in the eastern states dropped by an average of 20 units between 1990 and 2003, suggesting that gas supplies became leaner during this period.

Table 2.3. Wobbe Index Statistics by Region, 1990-2003
Minimum values in shaded cells are outside the typical range identified from the 2008 FERC data. The 95% confidence interval on the average Wobbe index for the Rockies region, computed from the standard deviation of the data, also extends outside the example FERC range. No values exceeded the upper limit recommended by the NGC+ White Paper.

Region	Data Points	Average	Standard Deviation	Maximum	Minimum
Pacific	15	1336.9	14.50	1365.3	1300.9
Rockies	7	1287.9	60.40	1351.5	1218.9
Central	22	1330.5	15.97	1366.3	1308.0
Eastern	40	1341.1	15.09	1358.5	1274.9
All regions	84	1333.1	26.04	1366.3	1218.9

Figure 2.5 presents the annual average methane numbers by state. The states are arranged in the same manner as in the previous graph. Since individual natural gas engines can have unique requirements for best performance, no acceptance criteria for the methane number are set by the NGC+ White Paper, and no "typical range" of methane numbers is drawn from the FERC filings to compare to the data.

The figure shows a general increase in methane number nationwide between the 1990-92 study and the later studies. The 1990-92 study included methane numbers for each gas composition, but did not identify the method used to calculate them. Research into the references of the 1990-92 study suggested, but could not confirm, that the methane numbers in that study were computed using earlier correlations that did not involve *MON* (Ryan and Callahan, 1991; Ryan et al., 1993). For the other studies, the methane numbers were computed directly from the gas compositions using the SAE and CARB formulas (Equations 2 and 3). These computed values are considered valid, since the H/C ratios and diluent content of the gases in these studies all fell within the valid ranges for the CARB formula. Since the formulas used in the 1990-92 study could not be verified, the increase in methane numbers between 1990-92 and later years may be due to differences in calculational methods. Table 2.4 presents statistics on the methane numbers calculated in the same fashion as the Wobbe indices in Table 2.3.

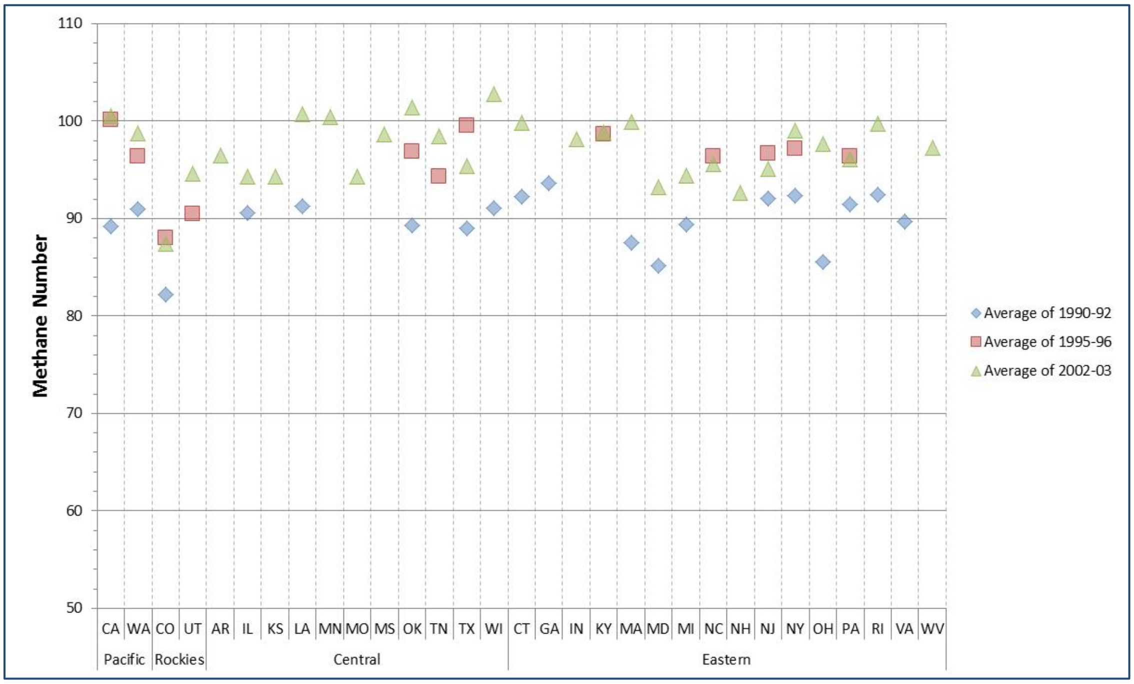

Figure 2.5. Methane Numbers Averaged by State, 1990-2003

A general increase in methane number was seen nationwide between the 1990-92 study and the later studies.

Table 2.4. Methane Number Statistics by Region, 1990-2003

Each data point within a region is an annual average for a single measurement location, not a statewide average.

Region	Data Points	Average	Standard Deviation	Maximum	Minimum
Pacific	15	92.0	4.88	100.6	86.3
Rockies	7	86.8	4.83	94.6	81.6
Central	22	94.9	4.65	102.8	85.3
Eastern	40	92.8	7.42	99.9	53.6
All regions	84	92.7	6.44	102.8	53.6

The last gas quality parameter analyzed for the state averages dataset is the higher heating value (HHV). This parameter is regularly tracked by pipelines and transmission companies and included in tariff specifications. The NGC+ White Paper also recommends an upper limit of 1,110 Btu/scf for interchangeability of gas supplies. Figure 2.6 shows that geographic variations in HHV appear to have narrowed after the 1990-92 study, with almost all subsequent gas blends falling between 1,000 Btu/scf and 1,050 Btu/scf. By comparison, the tariff values reported by FERC in March 2008 ranged from 900 Btu/scf to 1,200 Btu/scf, suggesting that pipelines may have relaxed their requirements in order to accept more varied supplies between 2003 and 2008. Table 2.5 presents statistics on the HHVs from the state averages dataset. All values, including maxima and minima, fall within both the March 2008 FERC tariff ranges and the NGC+ limit for interchangeability, suggesting that these earlier gas compositions would be acceptable today.

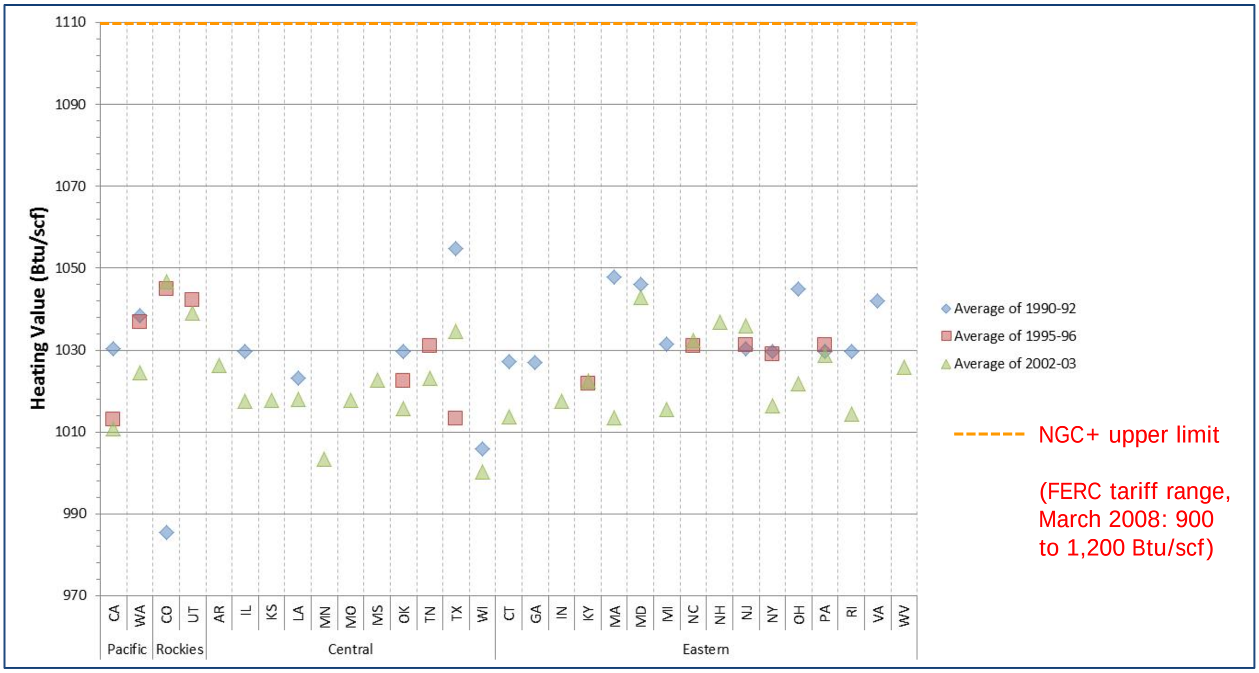

Figure 2.6. HHVs Averaged by State, 1990-2003

Variations in HHV across the country appeared to become smaller after 1990-92. By comparison, the range of acceptable HHVs included in FERC tariffs in March 2008 extends beyond the upper and lower limits of the vertical axis.

Table 2.5. HHV Statistics by Region, 1990-2003

All averages and extreme values fall within the recent FERC tariff ranges and recommended NGC+ interchangeability limits. 95% confidence intervals on the average values also fall within these ranges and limits.

Region	Data Points	Average	Standard Deviation	Maximum	Minimum
Pacific	15	1028.5	14.13	1048.4	995.3
Rockies	7	1018.5	31.15	1046.7	980.2
Central	22	1024.8	17.51	1081.2	1000.3
Eastern	40	1031.9	14.84	1102.3	1013.4
All regions	84	1028.3	17.39	1102.3	980.2

2.2.3 Analysis of Data Listed by Production Formation

In the IGT report published in 1995, gas quality data were identified by the production formations that supplied the gas to transmission networks, rather than by the locations where the samples were taken. Figure 2.7 shows the approximate locations of the formations listed in the survey.

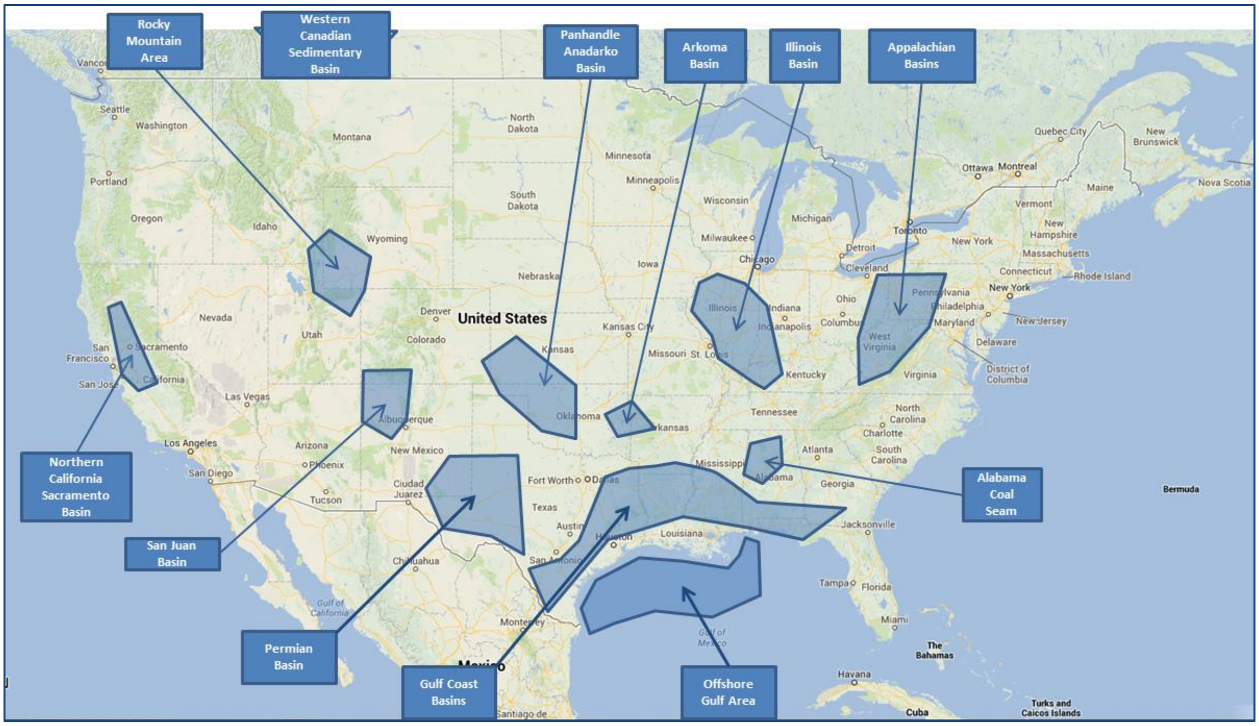

Figure 2.7. Production Formations Listed in the IGT Survey
Samples drawn at transmission network entry points were identified as coming from these formations.

Unlike the time-average values listed in the other two reports, the data from the IGT study comprise 19 individual spot samples, each taken from a different location at a single point in time. The samples were collected downstream of processing plants and analyzed for a large array of components down to ppm levels. Table 2.6 lists the components found in amounts of 0.1 mol% and above in the 19 samples. Notably, water vapor was detected at these levels at more than one location. By comparison, the typical tariff limit for water vapor is about 150 ppmv, or 0.015 mol%, so the moisture levels in some of these samples can be considered high.

Table 2.6. Significant Natural Gas Components Identified in the IGT Study (Chao and Attari, 1995)
The components listed below were found at levels of 0.1 mol% and above in at least one sample. Components in bold font were only found at these levels in the sample from the Appalachian shale formation.

methane	ethane	propane	isobutane
n-butane	**isopentane**	**n-pentane**	**total hexanes**
nitrogen	carbon dioxide	water vapor	**hydrogen**

Table 2.7 summarizes the ranges of key properties across the samples. At the time of the study, the leanest gases came from onshore Gulf Coast supplies, the Alabama coal seam reservoir, and the Sacramento Basin. The leanest gas sample (from the Sacramento Basin) had Wobbe indices below the range of tariff limits observed in the example FERC filings from 2008, suggesting that this supply would need to be blended with richer gases before being accepted. At the other end of the spectrum, the Appalachian shale formation produced the richest sample in the study. As shown in the table, the Wobbe index of the Appalachian shale formation sample exceeded the highest FERC tariff limits in March 2008, and both the HHV and the Wobbe index

exceeded the upper limits now recommended by the NGC+ White Paper for interchangeability of gases. These Appalachian shale supplies would need to be blended with leaner gas supplies or nitrogen to be acceptable by today's standards. Not unexpectedly, the Appalachian shale sample also had the lowest methane number of all the samples.

Table 2.7. Ranges of Gas Quality Parameters Observed in the IGT Study (Chao and Attari, 1995)
Values in shaded cells exceed the ranges of the example FERC tariffs. Values in bold font exceed the limits recommended by the NGC+ White Paper.

Property	**Lowest value (source formation)**	**Highest value (source formation)**
Higher heating value (Btu/scf)	982.8 (onshore Gulf Coast)	**1187.2** (Appalachian shale formation)
Specific gravity (relative density)	0.5614 (Alabama coal seam)	0.6846 (Appalachian shale formation)
Wobbe index	1276 (onshore Gulf Coast)	**1435** (Appalachian shale formation)
Methane number	66.2 (Appalachian shale formation)	108.1 (Alabama coal seam)

2.3 Daily Pipeline Gas Quality Data

Many transmission and distribution company websites post daily gas composition averages for review by interested parties. The project schedule and budget allowed daily data to be retrieved from public websites of five transmission and distribution companies covering 18 states (Figure 2.8). The five companies were Algonquin Gas Transmission, ANR Pipeline Company, Pacific Gas & Electric (PG&E), Panhandle Energy, and Southern Star Central Gas Pipeline (SSCGP). The data were collected in May of 2013, and in most cases, extended back three months.

This subsection reviews trends and observations on the daily averages from these websites. One website posted hourly gas quality data as well. No significant fluctuations from one hour to the next were observed in the hourly data, so these data are grouped with the daily data in this discussion. The FERC website was also reviewed for useful information, but the site only listed posted tariffs for acceptable gases, not actual gas composition data.

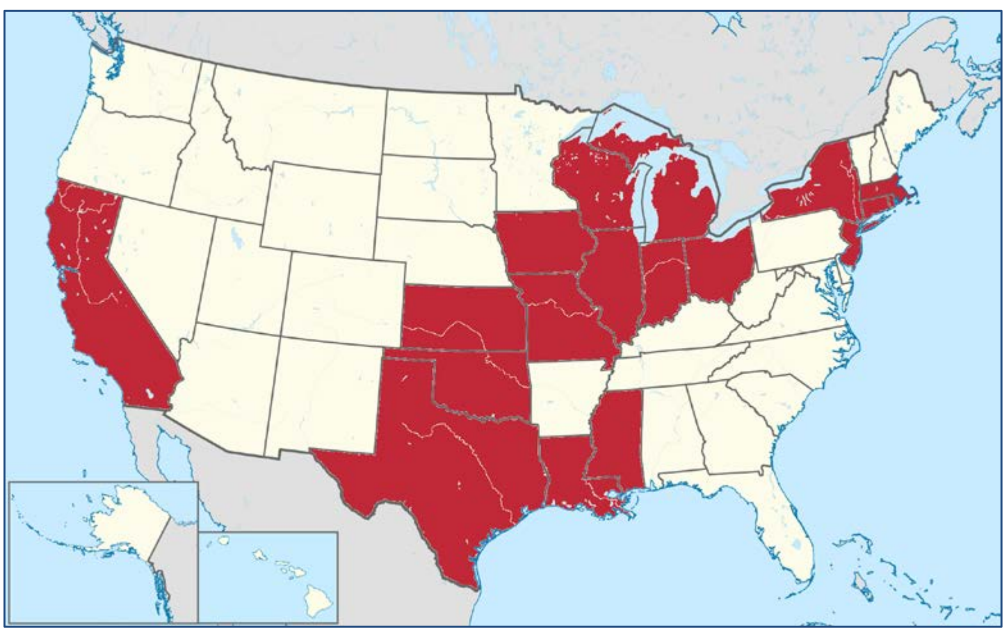

Figure 2.8. States Involved in the Analysis of Daily Property Variations
Data from states in red were included in the analysis.

Table 2.8 compares the gas quality parameters found on the pipeline websites to the quantities of interest in this survey. Data on the websites consisted mainly of composition data determined by field GCs, including N_2, CO_2, individual hydrocarbons through C_5, and combined amounts of hexane and heavier hydrocarbons (“C_{6+} fractions”). Contaminants of interest in this study, particularly moisture and sulfur, were rarely reported online. HHVs and specific gravity values were regularly reported with the composition data, and Wobbe indices were posted on many websites. However, all gas quality parameters of interest were re-computed for this report from the daily compositions using the most recent standards so that gas properties could be compared equitably to one another, to typical tariff limits, and to NGC+ recommended limits.

Table 2.8. Comparison of Gas Quality Data of Interest in the Field Survey to Data Reported on Pipeline Websites

Most daily gas quality data is posted directly from GCs. Data on moisture content, sulfur content, or parameters related to NGV engine performance were rarely or never found posted online.

Analytes of interest	**Online pipeline data**
Moisture content	One station only
Light hydrocarbons (C_1-C_6)	√
Heavy hydrocarbons (> C_6, compressor oil)	
N_2, CO_2	√
H_2, He, CO, O_2	
Total sulfur	One station only
Speciated sulfur	
Computed properties	
Higher heating value	√
Specific gravity	√
Methane number	
Wobbe index	Most but not all

2.3.1 Examples of Consistent Gas Supplies and Widely Varying Gas Supplies

The first three plots in this subsection present gas quality data from the PG&E distribution network serving most of the northern two-thirds of California. These data from April and May 2013 exhibited the smallest gas quality variations among all the daily pipeline data. Over this one-month period, Wobbe indices were relatively stable at each location, ranging from 1,320 to 1,350 across the entire service area. The largest variation in Wobbe index at a single station was roughly ±5. Methane numbers ranged from 96 to 102 across the area, and variations in methane number at a given station were typically ±2. Finally, HHVs within the PG&E network ranged from 1,000 Btu/scf to 1,030 Btu/scf, with the largest variations at one station spanning a range of ±10 Btu/scf. The Wobbe indices and HHVs all fell within the example tariff limits found on the FERC website from March 2008 and within the recommended interchangeability limits of the NGC+ White Paper.

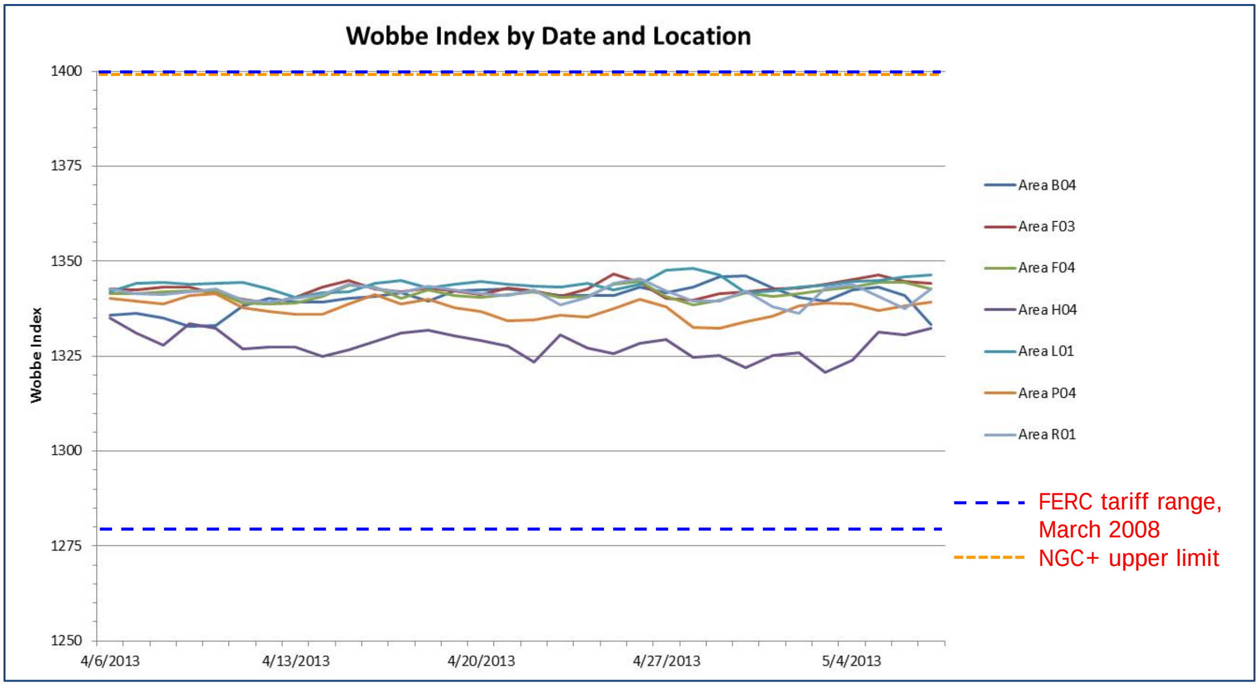

Figure 2.9. Wobbe Indices in the PG&E Service Area, April-May 2013
Wobbe indices were relatively stable at each measurement location, varying by no more than ±5 at a single location. All Wobbe indices fell within the typical FERC tariff ranges and the limits recommended by the NGC+ White Paper.

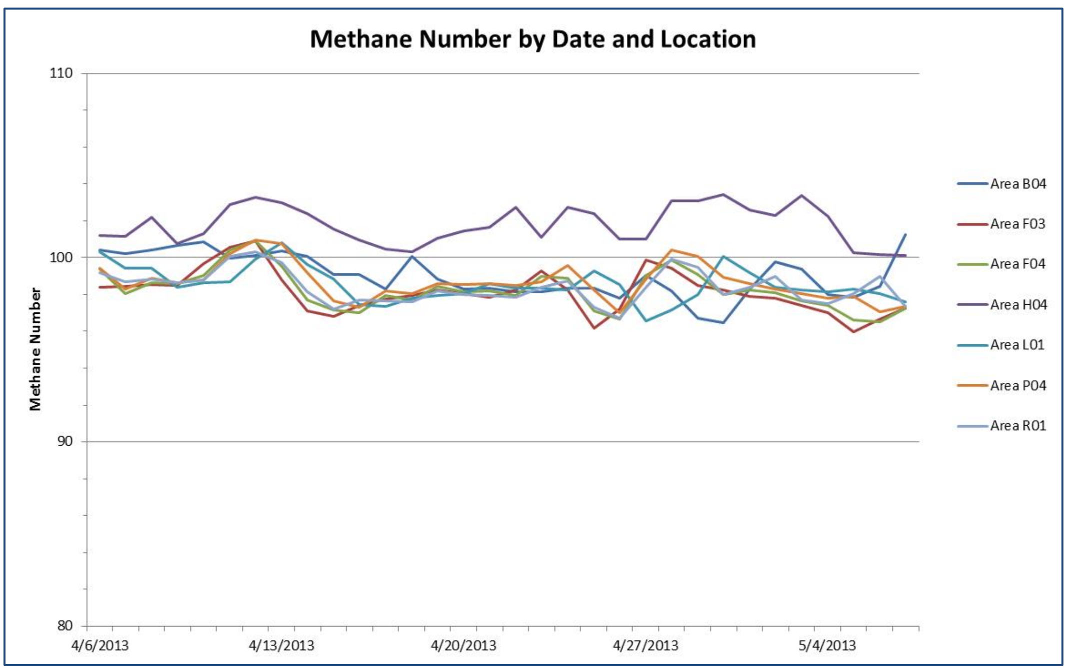

Figure 2.10. Methane Numbers in the PG&E Service Area, April-May 2013
Like the Wobbe indices, these gas quality values were stable over the course of the month, typically varying by ±2 at a given location.

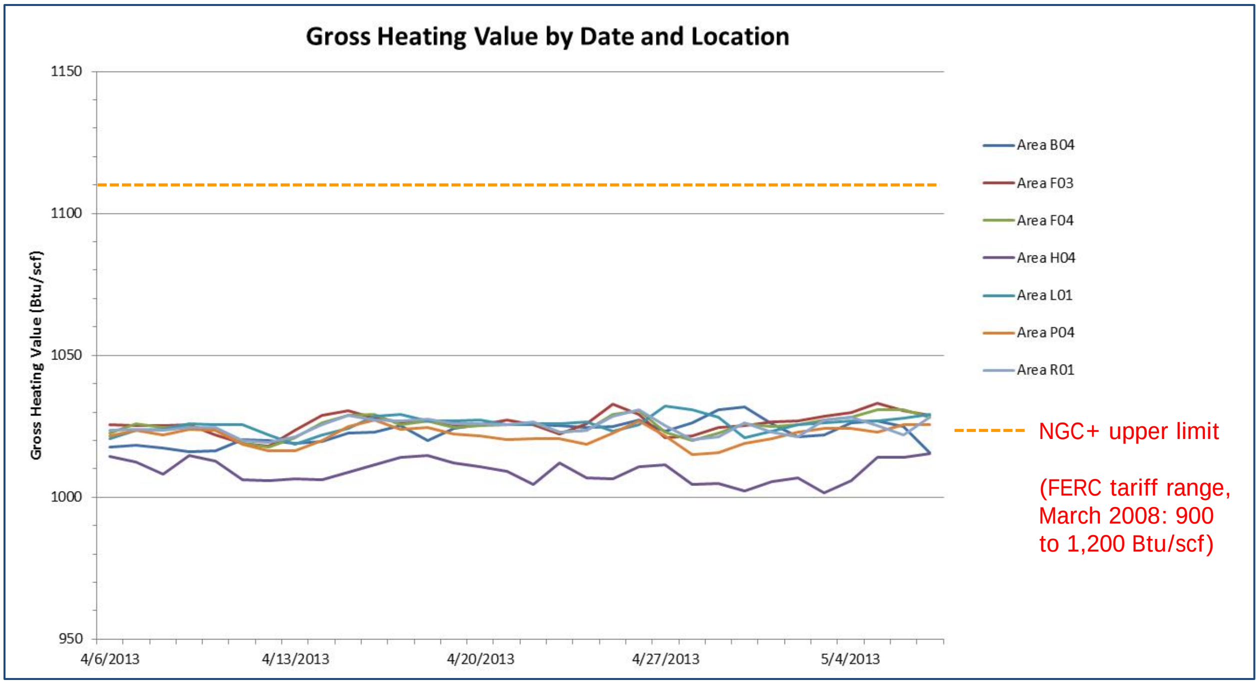

Figure 2.11. HHVs in the PG&E Service Area, April-May 2013
Heating values ranged from 1,000 Btu/scf to 1,030 Btu/scf across the service area during the month, falling well within the example FERC tariff range and the NGC+ recommended limit.

The next three graphs present gas quality data observed in the Panhandle Energy pipelines from February to May 2013. This pipeline presented the largest fluctuations in gas quality parameters of all of the daily data found online, and some gas streams fell outside the example range of tariff specifications found on the FERC website or briefly exceeded the interchangeability limits recommended by the NGC+ White Paper. Over this three-month period, changes of 50 were seen in the Wobbe index at some stations, and a temporary increase of 100 was observed at one station that lasted for two weeks. For some stations in the Panhandle system, methane numbers remained relatively stable, while at other stations, they followed similar trends as the Wobbe index. In particular, the station that experienced a brief increase of 100 units in the Wobbe index presented a corresponding decrease in the methane number of 30 units and a spike in HHV above 1,150 Btu/scf. Temporary increases in ethane, propane, and butanes were the cause of this gas quality shift. Two other stations reported gas streams with a total diluent content above 5% for the entire three-month period. Although this diluent level was beyond the valid range of the CARB formula (Equation 3), the methane numbers calculated using this method (which ranged from 85 to 90) were included in the final dataset to indicate their general levels relative to the other daily pipeline compositions. HHVs during the period generally ranged from 990 Btu/scf to 1,050 Btu/scf, excluding the station with high amounts of ethane through butanes.

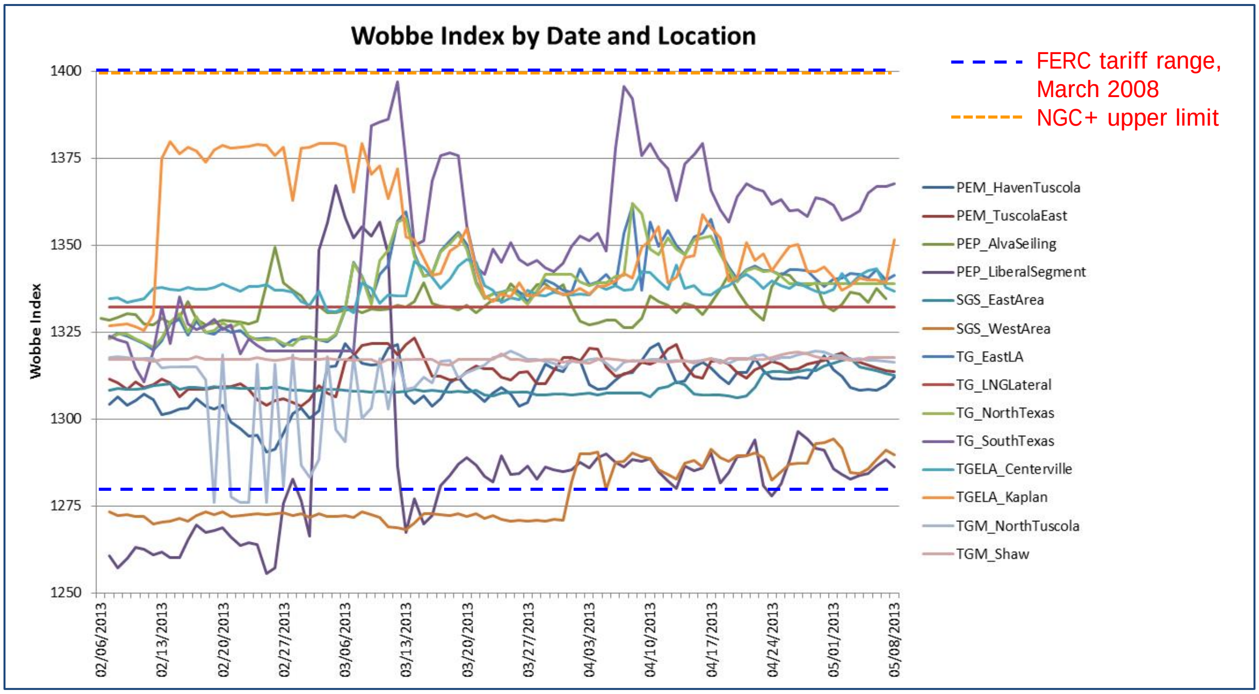

Figure 2.12. Wobbe Indices in the Panhandle Energy Service Area, February-May 2013
The range of Wobbe indices across this transmission system was the widest of all the pipelines reviewed online, spanning (and in two cases, falling outside of) the example tariff range from 2008 FERC postings.

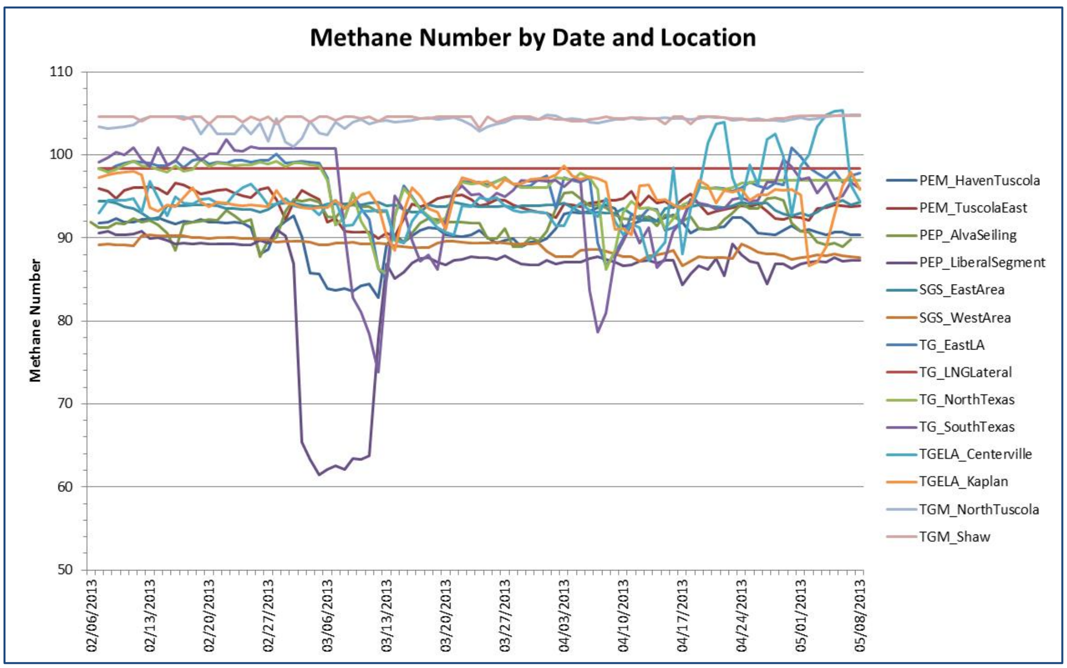

Figure 2.13. Methane Numbers in the Panhandle Energy Service Area, February-May 2013
Methane numbers measured at most locations spanned a range of 85 to 105, though one location carried rich gas with a methane number approaching 60 for a two-week period.

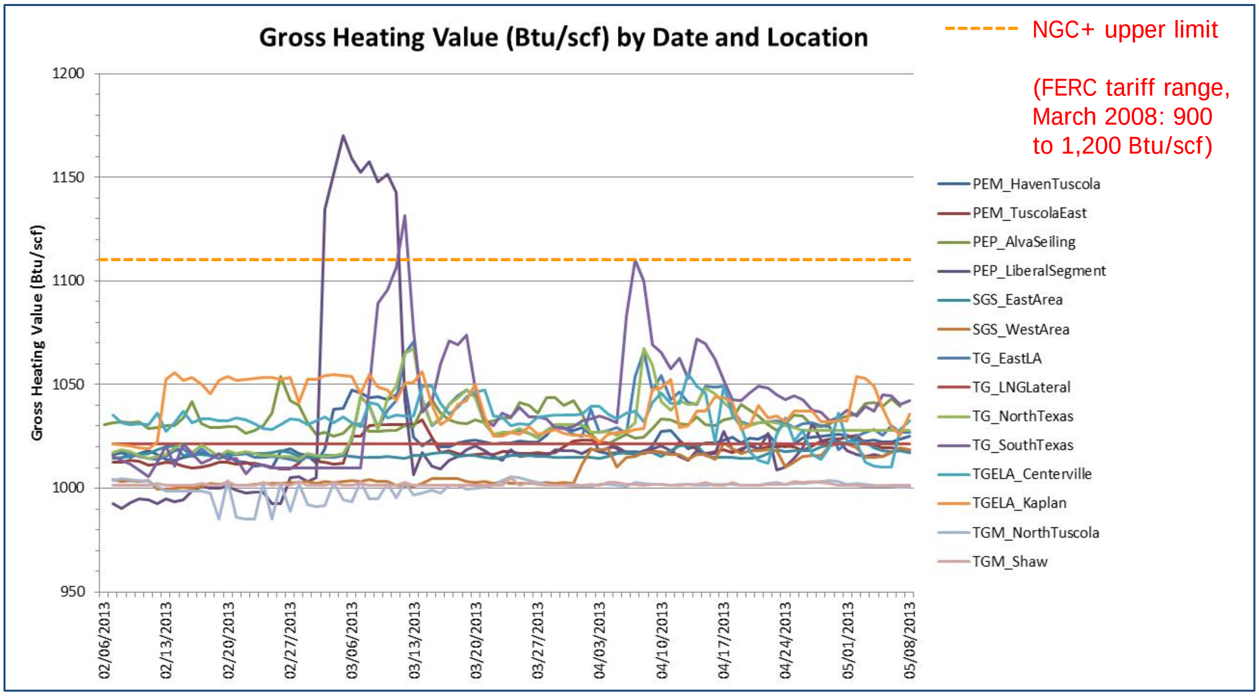

Figure 2.14. HHVs in the Panhandle Energy Service Area, February-May 2013

Heating values of gas across the system generally ranged from 990 Btu/scf to 1,050 Btu/scf, though a two-week spike above 1,150 Btu/scf at one measurement station indicated the introduction of rich gas supplies above the NGC+ limit recommended for interchangeability.

2.3.2 Analysis of All Daily Hydrocarbon Data

All of the daily gas compositions retrieved from the public websites were analyzed for trends in time and location. Statistics on the gas quality parameters were also calculated to assess the frequency at which gas quality exceeded recommended NGC+ limits. The data from different transmission pipelines show distinct differences in Wobbe indices, but the methane numbers and heating values show smaller geographic variations.

Figure 2.15 shows trends in the Wobbe index at all measurement stations across all pipelines. The data are color-coded to emphasize differences between pipelines. Over the three-month period surveyed, gas supplies in the Algonquin pipeline consistently had Wobbe indices above 1,360, supplies transported by PG&E and ANR were generally in the range of 1,320 to 1,350, and the single GC whose data were posted by SSCGP always identified the gas as having a Wobbe index below 1,320. Across all the pipelines studied, Wobbe indices ranged from 1,250 to 1,400. Except for two Panhandle Energy pipelines and the SSCGP station, the range of Wobbe indices measured over the three-month period fell within the tariff limits posted to FERC in March 2008, suggesting that gas supplies had not changed significantly between March 2008 and May 2013.

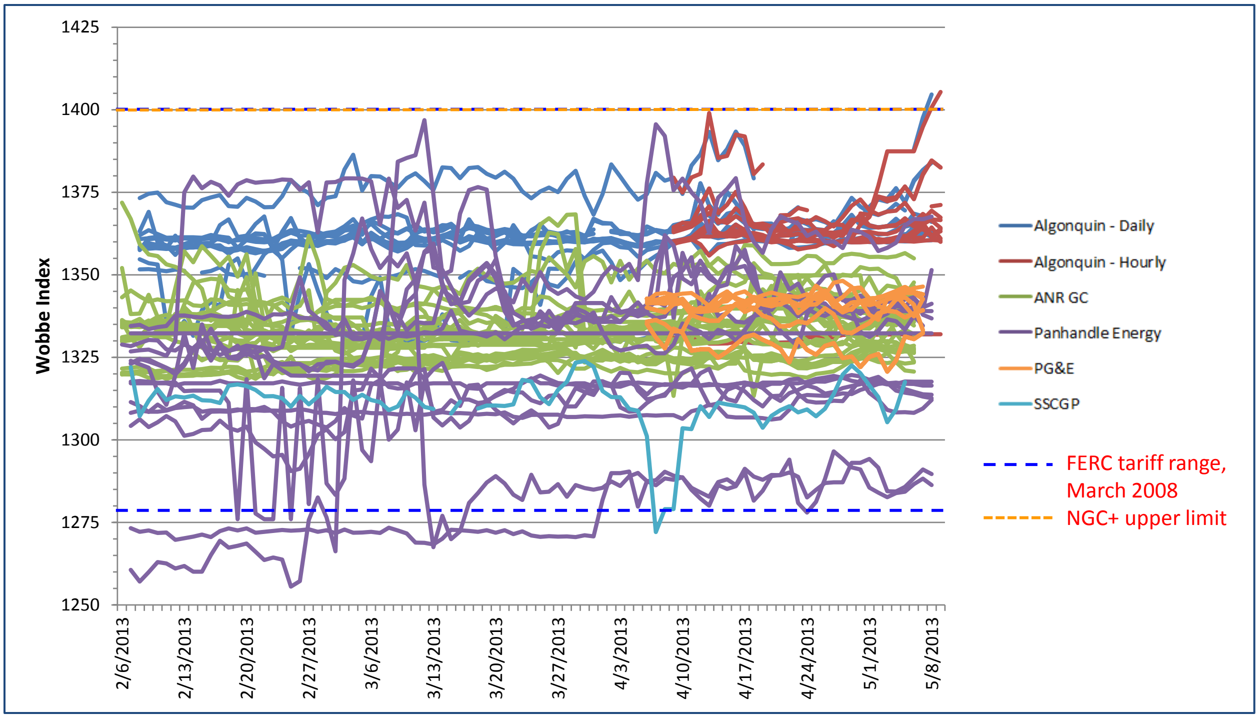

Figure 2.15. Daily Wobbe Indices Across All Pipelines, February-May 2013
Differences in the Wobbe index from one pipeline to another are fairly consistent over the three-month period. This is most likely due to different supplies for each pipeline and different processing levels on the supplies.

Table 2.9 presents a statistical analysis of the data in Figure 2.15. Each data point is a daily (or hourly) average value from a single measurement station on the listed pipeline. While the gas quality in several instances fell outside the example range of FERC-posted tariff specifications from March 2008, only extreme Wobbe indices from one pipeline (Algonquin) exceeded the NGC+ recommended upper limit for gas interchangeability.

Table 2.9. Wobbe Index Statistics Across All Pipelines, February-May 2013
Minimum values in shaded cells fall outside of the "typical" range of FERC tariff limits from March 2008. For Panhandle Energy, the 95% confidence interval on the average also extends beyond the range of FERC tariff limits. Values in bold font exceed the upper limit recommended by the NGC+ White Paper.

Pipeline	Data Points	Average	Standard Deviation	Maximum	Minimum
Algonquin - Daily	1,193	1360.6	8.81	**1404.7**	1329.2
Algonquin - Hourly	8,969	1362.7	9.91	**1407.4**	1329.1
ANR GC	2,226	1331.8	8.49	1371.8	1313.2
Panhandle Energy	1,119	1321.1	25.53	1396.8	1255.5
PG&E	224	1339.3	5.52	1348.1	1320.7
SSCGP	86	1311.1	7.94	1323.9	1272.1
All pipelines	13,817	1353.5	19.24	1407.4	1255.5

Figure 2.16 and Table 2.10 present corresponding summaries of the daily averages of methane number in the pipelines. Over the three-month period surveyed, the majority of methane numbers spanned a range from the low 80s to around 106. The notable exception was the drop in methane number for one Panhandle pipeline in the first half of March caused by gas supplies with high amounts of ethane, propane, and butanes. A key observation involves the

changes in gas composition within each pipeline. The figure shows that the variations in methane numbers in the Algonquin and PG&E pipelines were smaller than the variations observed in the ANR, Panhandle, and SSCGP pipelines over the three-month period.

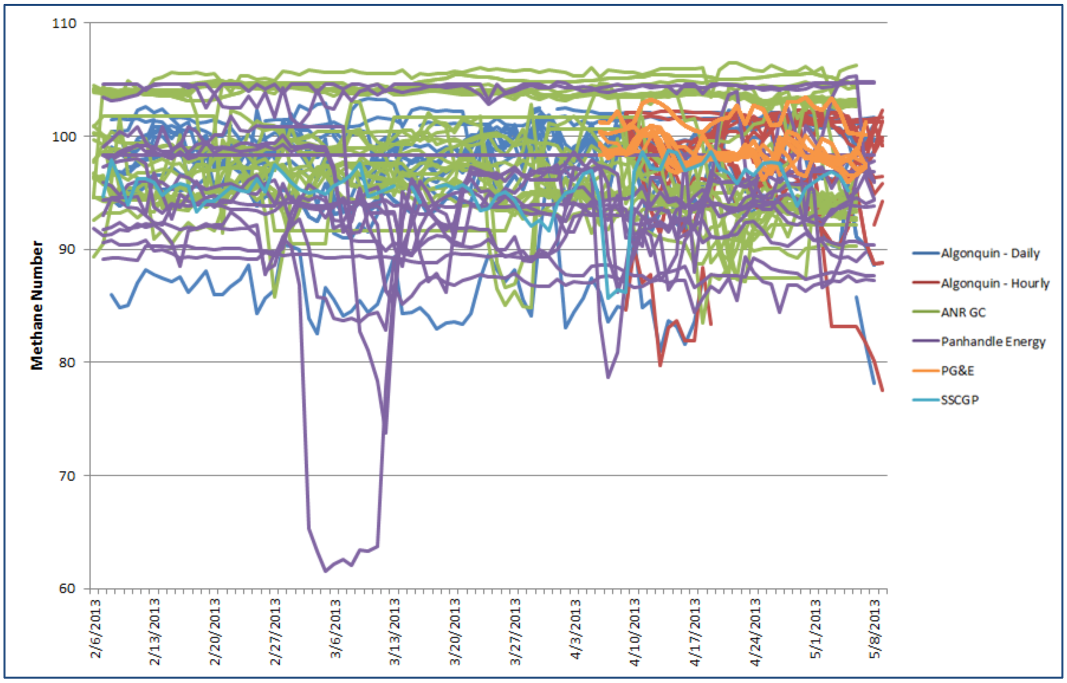

Figure 2.16. Daily Methane Numbers Across All Pipelines, February-May 2013
The majority of gas streams had methane numbers from the low 80s to 105. However, a two-week dip approaching 60 (caused by gas with high amounts of ethane, propane, and butanes) was observed at one Panhandle Energy station.

Table 2.10. Methane Number Statistics Across All Pipelines, February-May 2013
Each data point is a daily average for a single measurement location on the pipeline. While average methane numbers were between 94 and 100, excursions at various locations provided gas streams with methane numbers ranging from 61.5 to 106.5.

Pipeline	Data Points	Average	Standard Deviation	Maximum	Minimum
Algonquin - Daily	1,193	97.6	4.02	103.3	78.2
Algonquin - Hourly	8,969	98.4	4.28	102.5	71.3
ANR GC	2,226	99.2	4.65	106.5	83.5
Panhandle Energy	1,119	94.1	5.90	105.3	61.5
PG&E	224	99.0	1.57	103.4	96.0
SSCGP	86	95.4	2.28	98.8	85.7
All pipelines	13,817	98.1	4.61	106.5	61.5

Finally, Figure 2.17 and Table 2.11 present data on the higher heating values of the gas blends carried by the pipelines. The majority of gas analyses across these pipelines indicated HHVs between 1,000 Btu/scf and 1,050 Btu/scf. In nearly all instances where the gas streams moved outside this band, the HHVs still remained below the upper limit of 1,110 Btu/scf recommended by the NGC+ white paper. The notable exception was the excursion at the Panhandle Energy station when gas supplies with high amounts of ethane through butanes drove the HHV beyond 1,110 Btu/scf.

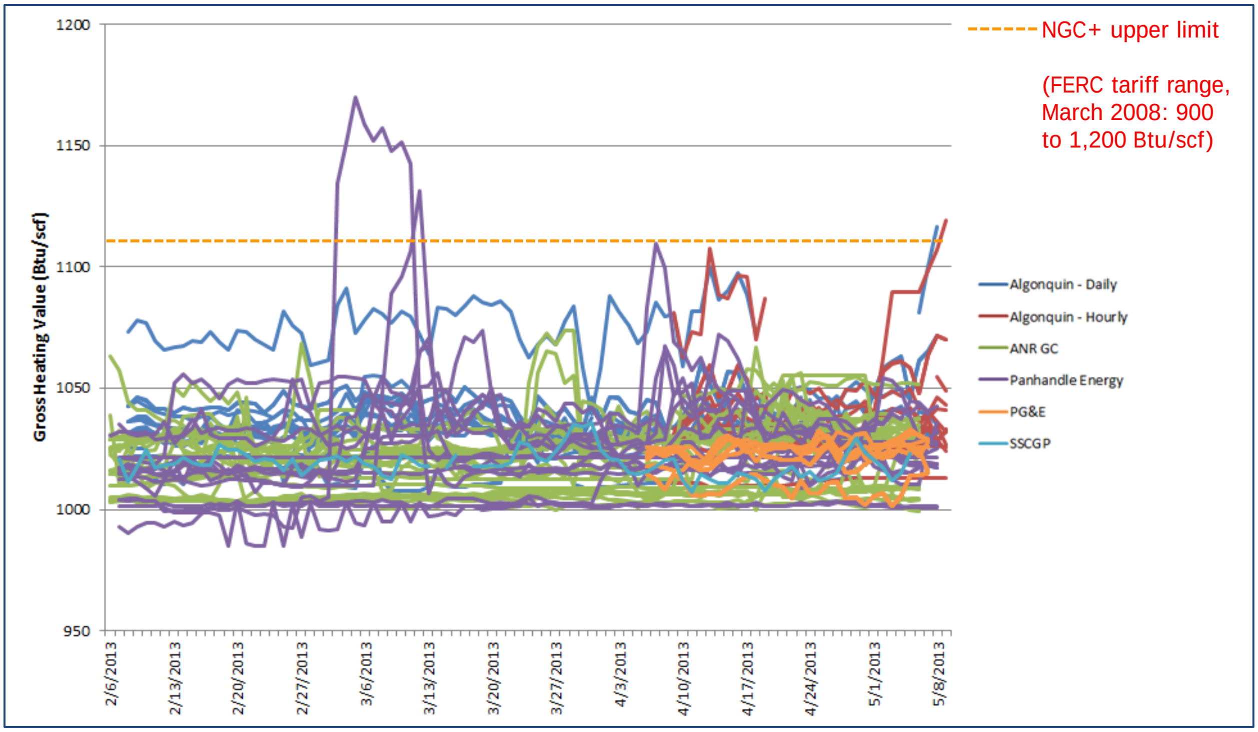

Figure 2.17. Daily Higher Heating Values Across All Pipelines, February-May 2013
Over the period studied, almost all pipelines carried natural gas with heating values between 1,000 and 1,050 Btu/scf. All HHV values of the 2013 gas streams fell within the typical tariff ranges posted to FERC in 2008, but a few exceeded the upper limit recommended by the NGC+ interchangeability guidelines.

Table 2.11. Higher Heating Value Statistics Across All Pipelines, February-May 2013
While all gas streams had heating values within the typical range of tariff limits posted to FERC in 2008, two pipelines had extreme instances (the values in bold font) of gas supplies exceeding the upper limit recommended by the NGC+ white paper.

Pipeline	Data Points	Average	Standard Deviation	Maximum	Minimum
Algonquin - Daily	1,193	1036.0	13.94	**1116.4**	1007.6
Algonquin - Hourly	8,969	1035.2	15.26	**1122.8**	1009.4
ANR GC	2,226	1018.6	12.84	1074.0	999.3
Panhandle Energy	1,119	1023.6	20.32	**1170.2**	985.2
PG&E	224	1022.3	6.50	1033.1	1001.5
SSCGP	86	1019.0	5.49	1035.5	1007.4
All pipelines	13,817	1031.3	16.54	1170.2	985.2

2.3.3 Moisture and Sulfur Data

The typical GCs used by pipeline companies only analyze natural gas streams for hydrocarbons, nitrogen, and CO_2, the major components affecting the energy content and heating value of the natural gas (ABB, 2012; Elster, 2012; Emerson, 2012 and 2013). Dedicated instruments are often installed to detect moisture levels and sulfur content (George, 2006). Before the gas is accepted for pipeline transport, moisture and sulfur are expected to be reduced below tariff limits and to have little effect on heating value. Accordingly, most of the online data were GC analyses of hydrocarbons, CO_2, and nitrogen, and very little recent moisture and sulfur data could be found online.

Of all the stations on the five pipelines for which data were posted, only one station on the Algonquin system reported hourly moisture and sulfur data from dedicated analyzers. A plot of these readings over a three-month period can be found in Figure 2.18. The moisture readings in the figure are well below the typical tariff limits on water vapor listed in Table 2.1, and the sulfur levels are well below the highest tariff limit of 20 grains per 100 scf.

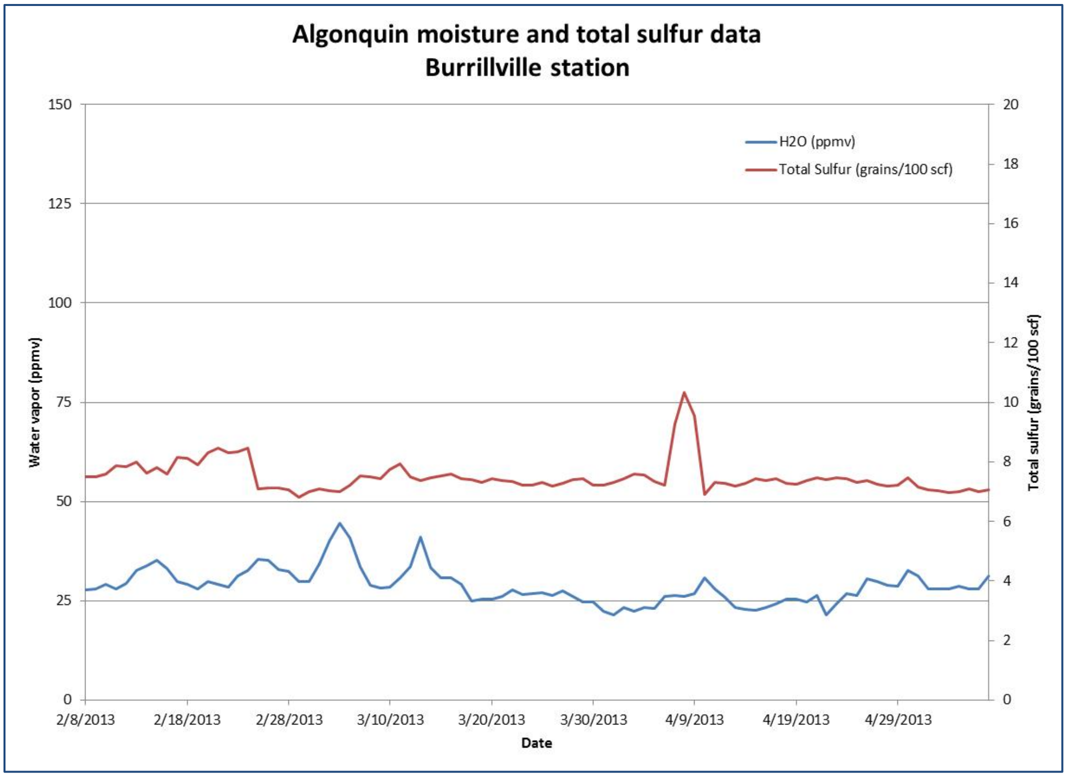

Figure 2.18. Water Vapor and Total Sulfur Measurements at Algonquin Pipeline's Burrillville Station, February-May 2013

This was the only station found in the survey that included hourly data for these contaminants. Levels of both contaminants at this station were well within typical tariff limits.

Another online source of sulfur data was found on the PG&E website. This website did not report daily data, but did include total sulfur values averaged across all stations in the system for several calendar quarters. The PG&E quarterly data are reproduced in Table 2.12. The average readings are all below the lowest tariff limit of 0.25 grains/100 scf reported by FERC, and all of the maximum readings are less than 1 grain/100 scf. Compared to the highest 2008 tariff limit of 20 grains/100 scf for total sulfur, these levels can be considered minimal. No other data on moisture and sulfur content were found during the online search, suggesting that field surveys to sample and analyze for these contaminants will provide needed information to CRC.

Table 2.12. Quarterly Averages of Total Sulfur Content Across the PG&E System, 2006-2012
Both the pipeline quarterly averages and the maximum values are low when compared to the typical tariff limits of 0.25 grains/100 scf to 20 grains/100 scf.

Date	Maximum values		Average over all sites	
	ppmv	grains/100 scf	ppmv	grains/100 scf
2012				
Fourth Quarter 2012	4.41	0.262	2.72	0.162
Third Quarter 2012	4	0.237	2.53	0.15
Second Quarter 2012	4.99	0.296	2.73	0.162
First Quarter 2012	5.82	0.346	3.04	0.18
2011				
Fourth Quarter 2011	5.19	0.308	2.8	0.166
Third Quarter 2011	5.53	0.328	3.49	0.205
Second Quarter 2011	11.11	0.659	3	0.178
First Quarter 2011	11.46	0.68	2.57	0.152
2010				
Fourth Quarter 2010	7.65	0.454	3.2	0.19
Third Quarter 2010	5.77	0.342	2.75	0.163
Second Quarter 2010		Unavailable		Unavailable
First Quarter 2010	10.03	0.595	2.55	0.151
2009				
Fourth Quarter 2009	10.03	0.595	2.77	0.164
Third Quarter 2009	12.01	0.713	3.14	0.186
Second Quarter 2009	5.5	0.326	2.79	0.166
First Quarter 2009		Unavailable		Unavailable
2008				
Fourth Quarter 2008	10.25	0.608	3.06	0.182
Third Quarter 2008	7.45	0.442	3.89	0.231
Second Quarter 2008	7.8	0.463	4.12	0.224
First Quarter 2008	8.01	0.475	3.82	0.227
2007				
Fourth Quarter 2007	7.79	0.462	3.79	0.225
Third Quarter 2007	7.1	0.421	3.44	0.204
Second Quarter 2007	5.5	0.326	3.31	0.197
First Quarter 2007	11.2	0.664	3.81	0.226
2006				
Fourth Quarter 2006	8.8	0.522	3.86	0.223
Third Quarter 2006	7.88	0.466	4.05	0.241
Second Quarter 2006	6.9	0.408	2.7	0.16
First Quarter 2006	5.37	0.318	2.45	0.145

2.4 Conclusions of the Data Survey

Published reports have been used to identify long-term trends in natural gas quality around the U.S. from 1990 to the present. Websites of natural gas transmission and distribution companies have also been used to study daily trends in natural gas quality within regional pipelines. No conclusions can be made about trends in moisture or sulfur content, since few data are available on these components in the literature or online. However, two conclusions have been made about trends in heating value, Wobbe index and methane number – key parameters affecting NGV performance.

- Long-term historical data indicate that from the early 1990s to the early 2000s, differences in heating value, Wobbe index, and methane number between gas supplies in different regions of the U.S. became smaller. In recent years, geographic variations have become broader again, as indicated by recent studies of tariff specifications and pipeline data from 2013. The diversity in gas quality is likely the result of the increasing variety of sources of natural gas, particularly shale gas supplies.
- Short-term fluctuations in gas quality at a single location are common. Changes of 50 units in the Wobbe index and 15 units in the methane number have been seen over a three-month period in a single pipeline. These may indicate seasonal or long-term changes in gas quality. Temporary swings of 100 units in the Wobbe index and 30 units in the methane number have been observed over a few days.

It should be emphasized that prior gas quality trends do not guarantee future gas quality, good or bad. Pipeline gas compositions are influenced by many factors, some of which are listed below.

- Available gas supplies nominated for purchase by producers and accepted by pipelines.
- The amount of processing performed at midstream plants.
- Gas compositions placed in storage by distribution companies in low-demand months for later withdrawal in high-demand months.
- The blending of different gas supplies by the transmission pipeline.

Consequently, the gas compositions delivered to the station may be affected by one or more of these factors. It is also possible that sudden changes in the gas delivered to CNG stations may be smoothed out by blending with older supplies in the station storage tanks. Depending on the turnover time of the station tanks, sudden jumps in gas quality may be seen quickly or gradually in the dispensed product. These considerations, along with the lack of public data on moisture and sulfur content, prompted the field study described in the next several chapters.

3. SAMPLING AND ANALYSIS PROCEDURES

This section describes the sampling equipment, sample collection procedures, and laboratory analyses used to analyze natural gas at CNG stations around the continental U.S. Except for water vapor, all liquids and CNG components of interest were determined by lab analyses of spot samples collected at the CNG dispensers. As discussed below, portable analyzers were used to directly measure moisture levels in the natural gas supplies entering the CNG stations and in the dispensed CNG.

3.1 Moisture Analyzers

Because water has an affinity for adsorbing on many surfaces, including the inside walls of sampling equipment, moisture analyses of samples collected in sample cylinders are not considered reliable. Water vapor in the initial sample will often adsorb on the cylinder walls and be lost from the sample. The water vapor cannot be detected until the sample pressure drops low enough for the moisture to desorb again, or if the cylinder is heated sufficiently to desorb the moisture from the walls. Either process makes determining the original moisture content of the sample difficult. Flow-through moisture analyzers are preferred by the natural gas industry (Barajas and George, 2006), because the moisture in the flowing stream will reach equilibrium with moisture adsorbed on the sampling hardware, and the analyzer will register the true moisture content of the stream once equilibrium is reached (George, 2011).

For this project, portable Michell MDM300-IS Dewpoint Hygrometers were used to measure moisture levels at each site. This model was chosen for its ability to analyze high-pressure gas samples, its safety certification for use on combustible gases, and its ability to use the IGT-8 industry standard correlation (Bukacek, 1955) for moisture measurements in natural gas. The analyzer, shown in Figure 3.1, uses a ceramic impedance sensor consisting of a hygroscopic (water-attracting) porous layer sandwiched between two electrodes. As the gas stream flows though the sensor, the water content of the hygroscopic layer reaches equilibrium with the flowing sample. The sensor measures the final impedance between the electrodes and converts the measurement to a water vapor dew point (WVDP) temperature or a moisture concentration, as selected by the user.

Table 3.1 lists the full specifications of the MDM300-IS. Each analyzer's calibration is traceable to the National Institute of Standards and Technology (NIST) and is certified for a period of one year. The stated accuracy of the analyzer is ±1°C in WVDP for dew points above -60°C. The unit's WVDP temperature reading is calibrated directly, while values in other units are calculated internally from the WVDP value. The corresponding uncertainty in measured moisture levels is estimated as ±1.4 lb_m/MMscf at gas distribution pressures and ±0.47 lb_m/MMscf at CNG pressures (George, 2012). The NIST-traceable calibration was accepted for this project as a practical alternative to the calibration requirements of ASTM D5454-11 (ASTM, 2011).

Figure 3.1. Michell MDM300-IS Portable Hygrometer Used in This Research
The unit uses a capacitance sensor to measure the moisture content of a flowing gas stream. Orifice fittings on the inlet and outlet allow the unit to analyze gas streams at both high pressures (such as CNG) and at low pressures (such as LDC distribution gases). The desiccant fixtures visible on the inlet and outlet were made by SwRI to maintain low moisture levels in the unit between tests.

Table 3.1. Specifications of the Michell MDM300-IS Hygrometer (Michell Instruments, 2010)
The maximum working pressure allows the device to analyze gas at all points of interest in the refueling station, including the CNG dispenser. The analyzer reports moisture content in units of mass per unit volume, avoiding the need to convert measured WVDPs to water content.

Sensor type	Ceramic impedance sensor
Gas flow rate	0.2 N l/min to 0.7 N l/min [0.42 standard cubic feet per hour (scfh) to 1.5 scfh]
Filtration	50 micron stainless steel sintered filter in the inlet port
Operating temperature	-20°C to +50°C (-4°F to +122°F)
Maximum safe working pressure	350 barg (5076 psig)
WVDP calibration range	-100°C to +20°C (-148°F to +68°F)
Measurement units	°C, °F, K for WVDP and gas temperature Parts per million by weight (ppmw) and g/kg for air, N_2, H_2, CO_2, and SF_6 ppmv, lb_m/MMscf and g/m^3 for natural gas ppmv, g/m^3 and percent relative humidity for other gases
WVDP measurement resolution	Better than 0.1°C (0.18°F)
WVDP accuracy	± 1°C from -60°C to +20°C (± 1.8°F from -76°F to +68°F) ± 2°C from -100°C to -60°C (± 3.6°F from -148°F to -76°F)
WVDP repeatability	Better than ±0.1°C (±0.18°F)
WVDP hysteresis	±0.05°C (±0.09°F)
Data logging capacity	8 MB total, log intervals of 5 to 60 seconds, up to 10,000 entries per log file

Gas port connectors with different orifice sizes are placed on the analyzer inlet and outlet to control the sample stream pressure at which the MDM300-IS measures moisture. The sample pressure itself must be input into the analyzer through an external transmitter or through the keyboard. The sample flow rate is controlled by a needle valve attached to the outlet and measured by a downstream rotameter. Orifice sizes and sample flow rates were selected with the help of Michell Instruments staff to obtain fast and accurate measurements at both distribution pressures and CNG pressures.

During startup, the MDM300-IS heats the impedance sensor to flash any residual moisture from the hygroscopic layer, so that after startup, the sensor can reach equilibrium with the flowing sample more quickly. Based on discussions with Michell Instruments staff, a second needle valve was installed upstream of the analyzer. This upstream valve and the outlet needle valve were used in tandem to improve the efficiency of the startup cycle. During startup, the downstream valve was opened completely, and the upstream valve was used to control the flow rate and reduce the inlet pressure to near-atmospheric levels. The low stream pressure at startup allowed the flowing gas to carry more moisture away from the sensor during the startup cycle. Just before the startup cycle ended, the valve settings were reversed. The downstream valve was restricted to control flow rate and increase the stream pressure, while the upstream valve was opened fully to equilibrate pressure between the gas source and the analyzer. SwRI also fabricated fixtures with desiccant capsules to place on the inlet and outlet of each analyzer. These served to dry out the gas within the analyzer between uses, which also improved the startup cycle efficiency.

Moisture measurements by the MDM300-IS can be displayed and recorded in several different units, depending upon the application. For this study, absolute moisture content was measured and recorded in units of pounds mass per million standard cubic feet of natural gas (lb_m/MMscf), the units used for gas quality tariff requirements. The option to compute moisture levels in lb_m/MMscf was introduced with the MDM300-IS model. In this mode, the analyzer converts WVDP values to lb_m/MMscf values using the IGT-8 correlation adopted by the natural gas industry for moisture determination. Each analyzer was used to log moisture values from the pipeline or CNG dispenser for approximately fifteen minutes, or until the MDM300-IS had identified a stable moisture level. Logs were downloaded to a laptop computer via Bluetooth for later analysis.

During operation, the analyzer uses an internal algorithm to assess whether the measured value is stable or equilibrating, and can display a graph of measured values over time to help the user assess moisture stability in the sample stream. A second algorithm (the Quick Response Algorithm, or QRA) introduced with the MDM300-IS model can extrapolate transient readings to display a predicted stable value before equilibrium is reached. During the shakedown tests of the MDM300-IS units at SwRI, it was found that the QRA actually delayed the final moisture reading in cases when moisture levels in the stream were decreasing. After consulting with Michell staff, it was decided to disable the QRA for these tests. Where appropriate, the logged data were extrapolated during post-processing to determine the actual moisture level of the gas streams.

3.2 CNG Sampling Manifold

A key task in this project was to create a method of collecting CNG samples for laboratory analysis while separating out any compressor oils or other liquids in the CNG stream for separate identification. There are currently no standard methods for collecting samples from CNG dispensers, which dispense fuel at pressures of 3,000 psi to 3,600 psi. Several natural gas sampling methods have been standardized by the Gas Processors Association (GPA, 2005) and incorporated into a standard by the American Petroleum Institute (API, 2006). However, these methods were created to collect samples from horizontal natural gas pipelines at distribution and transmission pressures, typically 1,500 psi and lower. The GPA methods were specifically designed to avoid any phase change of the samples during collection, since phase change and condensation preferentially separate out heavier components from the gas sample and distort its composition. For this project, a sampling manifold was designed with a similar goal, namely to separate out compressor oils and heavy fluids from the CNG stream while keeping the CNG itself intact.

Figure 3.2, adapted from the API Chapter 14.1 sampling standard (API, 2006), is a phase diagram of a typical transmission natural gas stream that illustrates the impact of poorly-controlled sampling methods on gas samples. The curve marks a phase boundary between the pure gas state (to the right of the curve) and the two-phase region where different components of the gas stream can co-exist as liquid and gas. The exact path of the phase boundary depends upon the gas composition, but the curve shown here is typical for a transmission-quality gas stream. Joule-Thomson (J-T) cooling through an unheated regulator or a partially closed valve (path 1-2) can cause heavy hydrocarbons to condense from the stream and be lost from the sample. J-T cooling can be avoided by the application of heat to the sampling system (path 1-3). If a sample in a closed cylinder is exposed to low ambient temperatures (path 4-5), the sample may become two-phase inside the cylinder. Re-heating the sample to its original temperature for several hours before opening the cylinder will re-vaporize any liquids and restore the integrity of the sample.

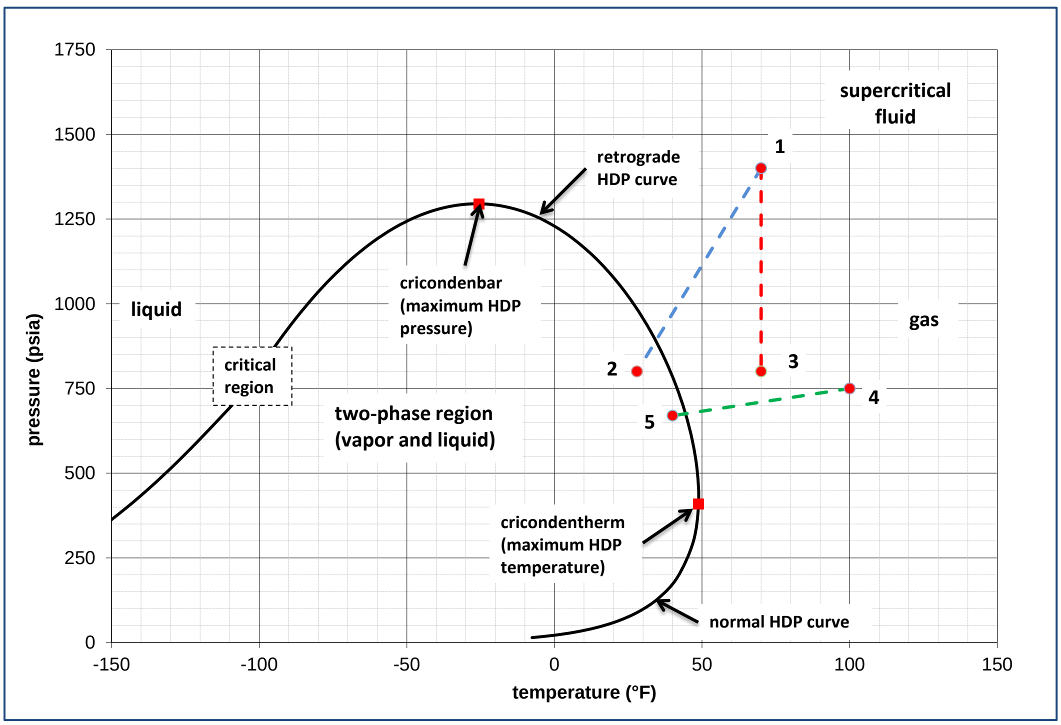

Figure 3.2. A Natural Gas Phase Diagram Showing Sampling Processes that Can Cause Condensation and Sample Distortion (adapted from API, 2006)

Path 1-2 represents retrograde condensation and sample distortion due to Joule-Thomson cooling through a regulator or throttle. Path 1-3 shows how adding heat through the flow restriction will avoid condensation of the natural gas sample. Path 4-5 demonstrates how exposing a sample to ambient temperatures below the hydrocarbon dew point will cause condensation in the sample.

By comparison, CNG is stored and dispensed at pressures of 3,000 psig to 3,600 psig. At these pressures, CNG is a supercritical fluid – a single phase with properties of both liquids and gases – and well beyond its two-phase envelope. Moderate temperature and pressure changes are less likely to cause condensation of components from the CNG than similar state changes in transmission gas samples (Figure 3.3). Specifically, at CNG pressures, the J-T coefficient is typically no more than 2°F per 100 psi, much smaller than the value of 7°F per 100 psi found at transmission pressures. As a result, throttling and ambient cooling are less likely to cause phase change of a CNG sample if the sample pressure is kept well above the cricondenbar (the maximum pressure of the curve marking the phase boundary). This principle guided the design of the sampling manifold for this project.

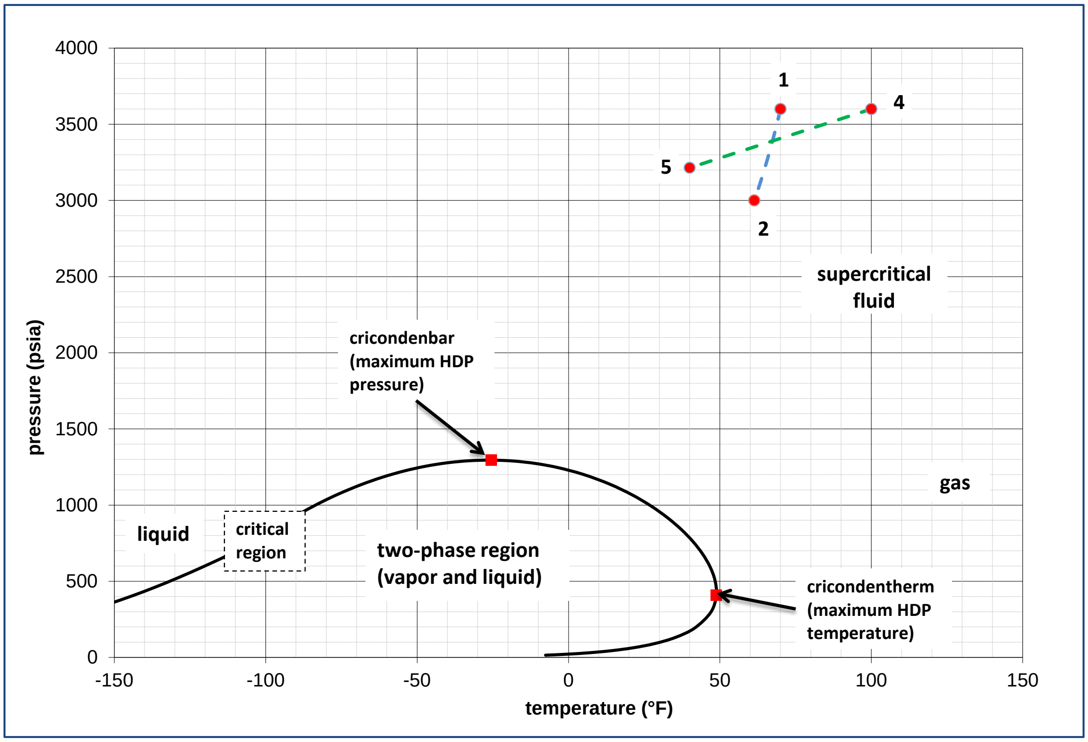

Figure 3.3. A Phase Diagram Showing how Throttling and Ambient Temperature Changes at CNG Pressures Have No Effect on CNG Sample Integrity

If the pressure reduction through any regulator or throttle (path 1-2) is small enough to keep the CNG sample supercritical, adding heat to avoid phase change should not be necessary. Ambient cooling of a supercritical CNG sample (path 4-5) is also less likely to cause phase change in the sample container than similar cooling of a gas sample at transmission pressures (see Figure 3.2).

Initially, it was planned to use a variation of a GPA sampling method to collect the CNG samples. Floating-piston sample cylinders, custom-designed for sample pressures up to 5,000 psig, were to be used to maintain the CNG samples at the dispenser pressure during sample collection. Resources were insufficient to obtain enough of these cylinders for the project, so an alternative approach was developed. To maintain the CNG at pressures above the cricondenbar during sampling, a manifold was designed using the criteria below.

- The manifold was designed to carry CNG from the dispenser, through multiple sample cylinders in parallel, and into the fuel tank of an NGV. During vehicle refueling, increasing backpressure kept the CNG in the sample cylinders in the supercritical regime.

- Valves on the sample cylinders and manifold were chosen, based on their flow coefficients and the expected CNG dispenser flow rates, so that J-T cooling through the valves would not move the CNG temperature-pressure state below the cricondenbar into the two-phase envelope.
- No regulators were used in the manifold design so that the CNG could be maintained above the cricondenbar during the sampling process.

A manifold design that met these criteria would eliminate the need for equipment heating, even in cold weather.

Another part of the manifold design addressed the need to capture any compressor oils or heavy liquids from the CNG streams for separate analysis. While API and GPA have not published standard methods for separating the phases in gas-liquid streams, a “sample conditioner” is available for use in natural gas streams suspected to contain liquids. This device, sold by Welker® as the Fluid Sentinel (Welker, 2010), is shown in Figure 3.4. The conditioner produces a centrifugal flow that separates free liquids from the gas stream and sends the liquids to a drain port. As the liquid-free gas stream is collected in one sample cylinder, any liquids can be collected in a second sample cylinder and, if desired, analyzed separately. The design of the sample conditioner allows the user to view the stream during the sampling process and identify whether free liquids are present. Since the Fluid Sentinel design requires an active flow for centrifugal action to separate the phases, the manifold was designed to collect samples during active refueling of an NGV, with the separator installed between the CNG dispenser and the NGV. The typical application for the Welker Fluid Sentinel is sampling of transmission and distribution gases, which rarely exceed 1,500 psig. For this application, two Fluid Sentinels rated for an operating pressure of 4,200 psig were custom-fabricated by Welker and purchased for the project.

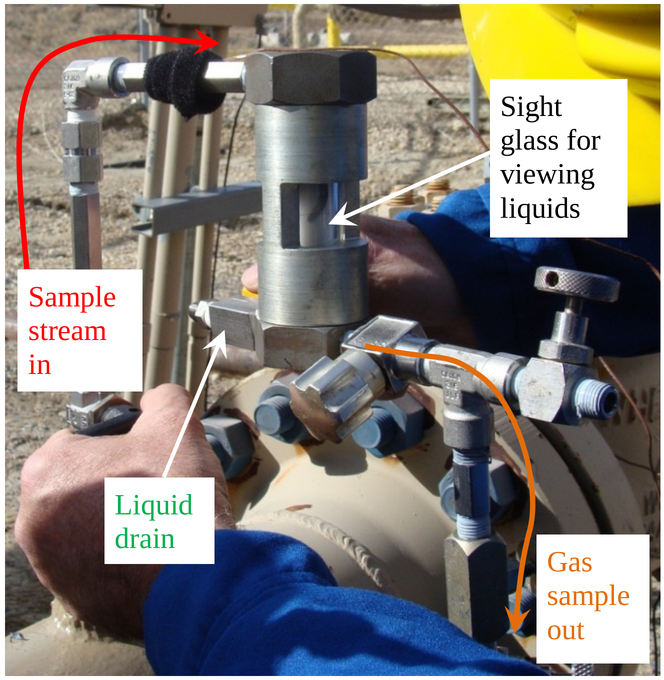

Figure 3.4. Example of a Welker Fluid Sentinel Used to Separate Liquid and Gas Phases from a Natural Gas Stream

The device includes a sight glass to view any liquids entering with the sample stream and dedicated outlets for the gas and liquid streams separated by the internal centrifugal flow.

The final manifold design is shown in Figure 3.5. CNG from the dispenser passes through an NGV-1 receptacle into a Welker Fluid Sentinel. Heavy liquids in the CNG stream, such as compressor oils, leave the separator through the liquids outlet and collect in a high-pressure sample cylinder. The CNG stream leaves the separator through the gas outlet, passes through multiple high-pressure sample cylinders, leaves the manifold through a high-pressure hose, and flows into the NGV fuel tank. Once sufficient backpressure is established in the manifold, the flow is stopped by closing the manifold outlet valve, and the valves on the sample cylinders are closed to capture the CNG and liquid samples.

The manifold includes a port for a portable hand vacuum pump, used to remove air from the manifold before CNG is introduced. This evacuation step prevents air from contaminating the CNG samples, and also prevents possible auto-ignition of a CNG-air mixture within the manifold when CNG first enters the system. After each use, the manifold is disassembled and rinsed with isopropyl alcohol. This step removes any residual liquids from the Welker Fluid Sentinel and liquids line that could contaminate samples taken later at other stations.

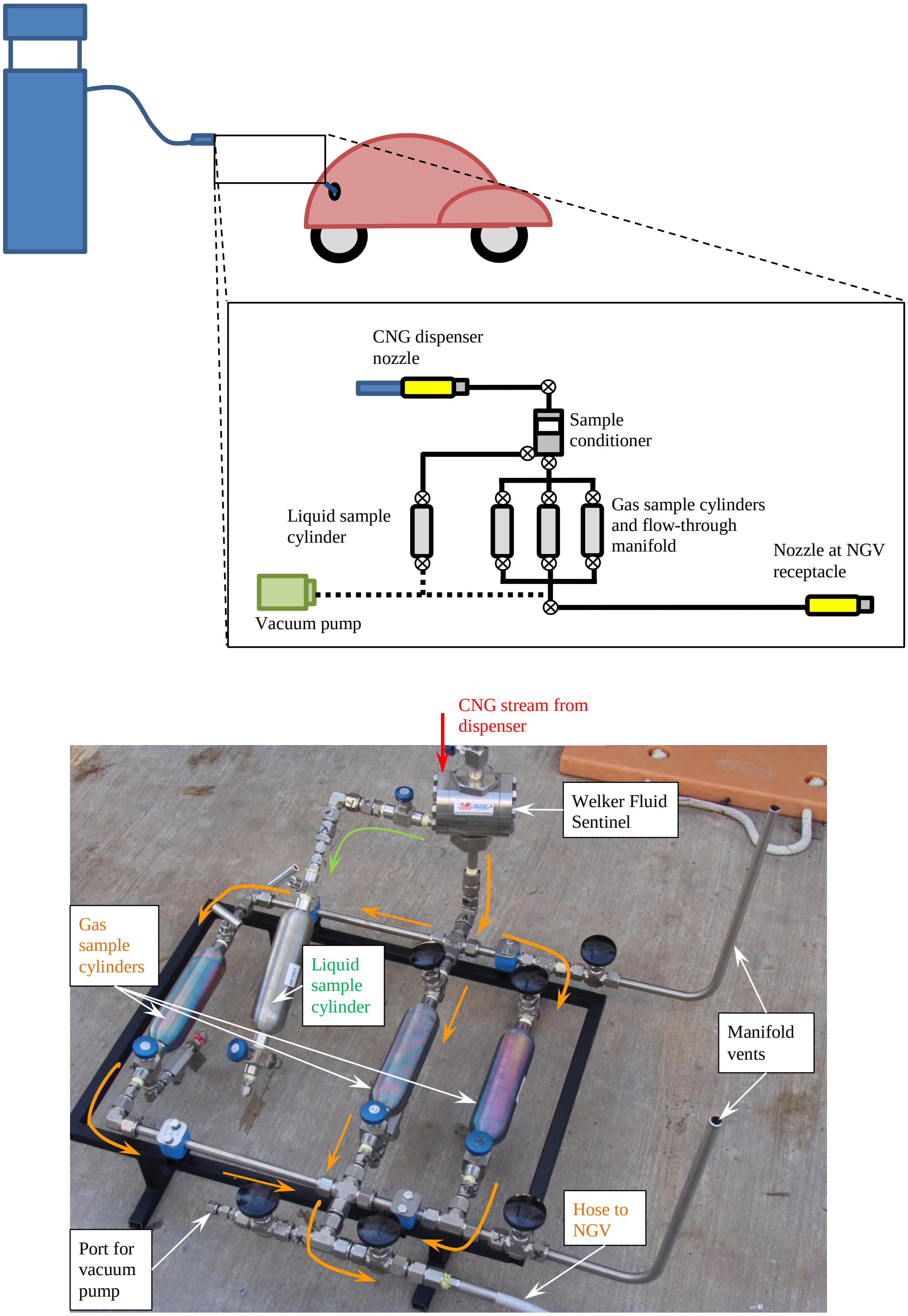

Figure 3.5. Conceptual and Final Designs of the CNG Sampling Manifold

The upper diagram shows how the manifold was designed to collect samples from a CNG stream flowing from the dispenser to an NGV during refueling. The lower photo shows the final design, with the flow path of the separated liquids marked in green and the flow paths of the gas stream marked in orange.

Two identical manifolds were built so that field staff could schedule overlapping trips to different field locations and expedite the sampling work. The tubing and valves used to build the manifolds were rated to a minimum operating pressure of 5,000 psig, providing a 40% safety factor beyond the expected CNG pressure of 3,600 psig. Both manifolds were leak-tested to a minimum of 3,600 psig and successfully held pressure for five minutes without evidence of leaks.

3.3 Sample Cylinders

The sample cylinders used with the sampling manifold were required to comply with Department of Transportation (DOT) regulations for shipment of high-pressure gas samples. These requirements include a pressure rating of 40% above the expected delivery pressure of the sample and a pressure safety mechanism to relieve pressure on the cylinder before the maximum pressure is exceeded. A total of 40 stainless steel sample cylinders were purchased that comply with DOT-3E classification guidelines (U.S. Code of Federal Regulations, 49 CFR §178.42, 2001). Each cylinder had an internal volume of 150 cc and was rated to a working pressure of 5,000 psig, 40% above the expected sample pressure of 3,600 psig.

The API natural gas sampling standard (API, 2006) and ASTM standard D5504 (ASTM, 2008) both specify the use of passivated sample cylinders to minimize the loss of sulfur components in the sample through reactions with the cylinder material. To comply with this guidance, SwRI sent 30 of the cylinders to a vendor for passivation with SilcoNert™, a silicon-based coating (SilcoTek, 2009). The passivated cylinders were reserved for collecting CNG samples, while the other ten cylinders were reserved for collecting liquid samples from the Welker Fluid Sentinel separators.

The valves chosen for use with the cylinders had pressure ratings exceeding 5,000 psig, as well as flow coefficients chosen to prevent phase change of the CNG as described above. To meet the DOT requirements for pressure relief, each cylinder was fitted with one valve with an integral rupture disc rated to burst at 5,000 psig. The valves and cylinders were assembled, and work began to leak-test the cylinders at 5,000 psig to confirm that they met the 140% pressure requirement of DOT. However, several burst discs failed at pressures well below the target pressure. Investigation identified a design flaw with the integral valve features that secured the burst discs in place. Since the valves had been tightened onto the cylinders for testing and could not be removed, the cylinders were adapted to replace the burst discs with pressure safety valves set to relieve pressure at 5,000 psig (Figure 3.6). Of the 40 cylinders, 35 passed the pressure tests and were approved for field use.

Figure 3.6. Final Configuration of Sample Cylinders Used for CNG Collection

The passivation of the cylinder against the loss of sulfur compounds produced the rainbow-like coloration on the outside surface. The pressure safety valve (PSV) was in contact with the cylinder contents, even when the valve was closed. The PSV was installed on the valve port originally used for the faulty burst discs.

3.4 Sampling and Analysis Procedure

During the manifold design work and the pressure tests, a procedure was written by SwRI staff for moisture analysis, sample collection and shipping, and surveys of station staff. The procedure included instructions for photographing key station equipment, configuring the moisture analyzer for quick startup and accurate measurements, downloading data from the moisture analyzer, correct use of the sampling manifold, and shipment of the samples to the appropriate labs. Special attention was given to accurate sampling during this time. The procedure for the CNG sampling manifold included steps to remove air from the system via a hand vacuum pump, to operate the CNG dispenser and manifold valves to capture representative samples of CNG in the gas cylinders, to vent gas from the manifold and the liquid sample cylinder, and to clean the liquid separator and liquid line with alcohol between uses.

SwRI field engineers helped to draft the procedure before their first trips to CNG stations. To evaluate the procedure and to verify equipment performance, a trial run was performed at a CNG station within driving distance of SwRI. The sampling equipment and moisture analyzer performed as intended, and the experience was used to make minor improvements to the manifold sampling procedure. The final procedure, used for the other station visits, can be found in Appendix B. Project resources did not allow the gas samples from the trial run to be analyzed, but the moisture data and the liquid sample analysis were successful, and these data have been included in the final blinded dataset in Section 5. Blinded information from the survey of this station has also been included in Appendix D.

3.5 Gas Analyses

The CNG samples were to be analyzed for a wide range of components, including moisture content, hydrocarbons, diluents (permanent gases), total sulfur content, and sulfur species. Key gas quality parameters, including heating value, methane number, and Wobbe index, were then to be computed from the analyses. The project also required that the analyses be performed according to ASTM standards for gas chromatography, in the event that the results are used to develop a future ASTM standard on CNG quality requirements.

To ensure accurate sample analyses, SwRI contracted with SPL, Incorporated (SPL) to analyze the CNG samples. SPL routinely analyzes natural gas samples for hydrocarbons and diluents according to industry chromatography standards, including ASTM standards for natural gas analysis. Table 3.2 lists the components for which each CNG sample was analyzed and the ASTM chromatography methods used to quantify the analytes. Although CRC originally requested that the samples be analyzed for argon, it was agreed that this component would be excluded from the final list of analytes. Measurement of this component would have required cryogenic equipment not available at SPL or at other labs known to SwRI, and historical databases on production gases in the United States (Springer et al., 1999) do not list argon as a component.

Table 3.2. Components Quantified in the CNG Samples by GC Analysis

All GC analyses were performed according to appropriate ASTM standards. The GC results were combined with onsite moisture measurements to obtain the complete sample composition.

CNG analytes	Chromatography method used to quantify analytes
Hydrocarbon extended analysis through C_{14} and most diluents (N_2, CO_2, O_2, H_2, and He)	ASTM D1945-03(2010)
Carbon monoxide	ASTM D1946-90(2011)
Total sulfur	ASTM D6667-10
Sulfur species, including H_2S	ASTM D5504-08

SPL was instructed to perform analyses for total sulfur content per ASTM D6667-10 before performing any sulfur speciation analyses per ASTM D5504-08. If the total sulfur content of a sample was measured at or below the typical pipeline tariff limit of 16 ppmv, SPL was instructed to perform an ASTM D5504 speciation analysis on the same sample to quantify only hydrogen sulfide (H_2S). If the total sulfur content exceeded 16 ppmv, SPL was instructed to perform a full species analysis. SPL provided the results of all analyses to SwRI for review. As discussed in Section 5, the GC analyses were combined with onsite moisture measurements to arrive at the complete CNG composition from which gas quality parameters were calculated.

3.6 Liquid Analyses

At each CNG station, a non-passivated sample cylinder was connected to the liquid outlet of the Welker Fluid Sentinel in the sampling manifold. After the high-pressure CNG samples were captured in the gas cylinders, the manifold and the liquid sample cylinder were vented of their remaining gas, and the liquid cylinder was closed and secured for shipping to SwRI. It was recognized that depressurization during this venting process could cause light hydrocarbons absorbed by the liquids to desorb and be lost. However, the heavier hydrocarbons found in compressor oils were expected to remain in the liquid sample for analysis.

Upon arrival at SwRI, each liquid sample cylinder was stored vertically for 24 hours before being opened. This storage period allowed the sample temperature to equilibrate with the room and allowed any liquids in the cylinder to collect at the bottom valve. After the 24-hour settling period, both valves were opened and any liquid contents were allowed to drain into clean sample vials. If no liquids drained from the cylinder after a few minutes, the cylinder was rinsed with acetone and emptied into a sample vial, and the acetone was allowed to evaporate before the vial was closed and sent for analysis. The volume of nearly every liquid sample collected in this manner was not measured, but was estimated at less than ten milliliters. No attempt was made to estimate the fraction of the CNG samples made up by this liquid because of the uncertainties in the liquid volume and variations in the sample collection time among stations.

The liquid samples were qualitatively analyzed by the Fuels Analysis Section of the Fuels and Lubricants Research Division of SwRI using Fourier Transform Infrared (FTIR) analysis. FTIR uses electromagnetic radiation to induce changes in the vibrational and rotational state of molecular bonds, and then detects the resulting absorption of infrared wavelengths by the affected molecules. Qualitatively, the presence or absence of absorption at specific wavelengths by the sample can be used to find if certain molecular groups are present or absent. Overlapping absorption spectra from mixtures of compounds can make identification of individual compounds in the mixture very difficult, if not impossible. However, the presence of general groups such as hydrocarbon bonds, carbon-oxygen bonds, or oxygen-hydrogen bonds may be identified. Absorption spectra from two samples can also be compared to determine general differences or similarities. If enough of the liquid sample is present, and if a selected infrared absorption band is identified that can be separated from other absorption bands in the sample, FTIR may be used in quantitative identification and measurement. In this approach, the FTIR instrument is calibrated on a series of standards with different amounts of the desired component, and absorbance is plotted versus concentration. The response of an unknown sample is then used with the absorbance curve to calculate the component concentration in the unknown sample.

It was known beforehand that the CNG streams might not contain enough condensed liquids for a quantitative FTIR analysis, and that the volume of CNG that flowed through the manifold before the CNG sample was captured could vary from one station to another. Given this, and given the potential complexity of compressor oil FTIR spectra, it was decided to perform a qualitative "fingerprint" FTIR analysis of each liquid sample to simply identify any components of interest. For reference, samples of three known compressor oils listed in Table 3.3 were analyzed by FTIR beforehand, and their spectra were compared to those of each liquid sample to potentially identify any hydrocarbons or compressor oils found by the analyses. Results of the qualitative analyses are included in Section 5, but these were not used in any calculations of CNG properties.

Table 3.3. Reference Compressor Oils Used for Comparison to Liquid Samples from CNG Stations

The three reference oils spanned a range of compressor oil viscosities that might be in use at CNG stations. Listed data were taken from manufacturer datasheets.

Product	Tellus 32	Mobil DTE 26	Summit TM-30
ISO grade	32	68	100
Equivalent SAE grade	10W	20W	30
Viscosity at listed temperature			
40°C (centistokes)	32.0	71.2	99.2
100°C (centistokes)	5.4	8.53	11.24
100°F (SUS)	165	-	524
210°F (SUS)	44.4	-	64.7
Viscosity index	95+	98	99
Flash point (°F)	420	457	520
Pour point (°F)	-25	-6	-33

4. SURVEY LOCATIONS

The work scope originally requested by CRC included visits to a total of 20 CNG stations in ten cities. As planning for the project moved forward, access could not be gained to stations in some of the proposed cities, but these were replaced by CNG stations in other cities whose owners offered to participate in the study. A proposal for additional funding was also approved to expand the size of the original station list. By the end of the project, sampling and analysis had been performed at a total of 23 stations in 12 cities. This report section presents the survey results from each station visited during this project. The survey used to collect information on each station is reproduced in Appendix C, while the results of the survey are tabulated in Appendix D. Basic layouts of each station and photographs of key equipment are reproduced in Appendix E.

As agreed upon by CRC, AGA, and SwRI, the station data have been blinded in this report. However, to allow comparisons to the earlier historical data, each station is identified by geographical region, using the same region assignments as the graphs in Section 2. Because of the small number of stations in the Rockies region visited during this project, those stations have been combined with the Pacific stations into a "Western" region. Each station is identified using a letter and number. Stations in the Western region have been assigned the letter "W," stations in the Central Region are designated by the letter "C," and Eastern stations are assigned the letter "E."

Some survey questions could not be answered by some station staff, but enough information was gathered to identify the most common station equipment arrangements, the fraction of stations aware of gas quality issues, and the types of vehicles that frequent CNG stations around the country. Trends in the survey results are discussed below.

4.1 Observations on Station Equipment Layouts

Once natural gas enters the refueling station, it undergoes three major steps: drying to remove moisture, compression, and storage. Storage is the last step before delivery at the dispenser, but depending on the station design, the first step may be either drying or compression. Of the 23 stations surveyed, 15 dry the gas before compression, and the other eight perform compression before drying the gas. A large majority of the stations surveyed (18 of 23) use desiccant stacks to remove moisture from the gas stream. Only four stations use molecular sieve driers, with these driers upstream of the compressors.

Filters and scrubbers may be placed throughout the station equipment. Staff at over one half of the stations surveyed reported that these devices are installed on inlets and outlets of compressors, driers, and storage, and in several cases, just before the dispenser. Many multi-stage compressors were reported to have filters between stages. Six of the respondents only described filters at the driers, while three station surveys only mentioned filters or scrubbers at the compressors.

All stations surveyed use multi-stage compressors, with the number of stages per compressor ranging from two to five. The most common layouts use either one or two compressors, but three stations in the Eastern region were reported to have four compressors installed. Some stations with multiple compressors use them in parallel to provide redundancy. However, the majority of stations surveyed (15 of 23) reported having only one overall compression/drying stream, suggesting that a single drying unit for an entire station is typical. Some drying units have dual beds, so that one bed can dry the supply from the LDC while the other bed is being regenerated (i.e., heated to flash away moisture when the bed is saturated).

4.2 Observations on Gas Quality

Regarding gas quality, only four of the 23 stations surveyed reported known issues with moisture in the gas taken from the LDC. Two of these stations have observed cyclical changes in the moisture content over the course of the year. Since warmer natural gas streams can hold higher amounts of water vapor, the expected trend (confirmed by one respondent) is for moisture levels to rise during the summer months and fall in colder weather. Both stations that observed cyclical changes in moisture levels have Xebec drier systems that incorporate moisture instruments to monitor drier performance.

In all, three stations in the survey reported having Xebec moisture instrumentation, and another three identified the COSA Xentaur dew point instrument as their onsite source of moisture data. On the other hand, seven of the 23 stations surveyed reported having no moisture analyzers, while another eight respondents did not know or did not respond to this question.

At five sites, WVDP temperatures from the onsite instruments were available and recorded during the sampling visit. Four of the readings were below -50°F, indicating low moisture content, and the moisture levels measured by SwRI staff with the Michell analyzer at these four sites were well below the typical limit of 7 lb_m/MMscf. The fifth station, C4, was chosen by the owner for testing because of reports of high moisture levels in the dispensed CNG. The onsite moisture analyzer presented a high WVDP of 68.0°F, and the moisture level of 11.12 lb_m/MMscf measured by SwRI was also high.

Documented intervals for drier regeneration varied greatly. Two stations reported that they have dual desiccant beds and systems that automatically switch the flow to one bed while regenerating the other. Other stations reported regeneration intervals ranging from two to twelve months; still others regenerate their driers based on weather conditions (every three months in the summer, in the fall before freezing temperatures arrive, etc.). These survey results suggest that station owners may actively monitor drier performance and schedule regeneration based on experience.

Only one station (E5) reported high amounts of heavy hydrocarbons in their incoming gas supply. This station accepts unprocessed wellhead gas rather than the processed gas normally supplied by LDCs. The same station reported that customers have observed better mileage after refueling at station E5 than after refueling at other stations in the region. Six of the 23 stations surveyed reported known problems with liquids carrying over into the dispensed CNG, with the liquids reported to be oil, water, a mixture of both, and "unknown." Notably, only four of the 23 stations surveyed regularly collect gas samples for analysis. These samples are collected at the drier before the gas enters the compressor. While samples taken at this point may not identify carryover of oil into the CNG stream, sampling downstream of the compressor may be hindered by a lack of high-pressure sampling equipment and standard methods.

4.3 Information on Station Customers and Customer Feedback

The survey also asked station operators and staff for data on station throughput, typical customers, and any feedback from customers on the fueling process. Many station staff could not provide an estimate of monthly dispensed volumes, but of those that could, their reported volumes ranged from 2,100 gasoline gallons equivalent per month (2,100 GGE/month) to 30,000 GGE/month. Station operators were also asked to estimate the amount of time for gas entering the system from the LDC to be dispensed at the pump. Ten of the 23 stations were able to estimate a “turnover time,” but the responses varied widely. Three noted that the turnover time depends upon the number and types of vehicles refueling at the station each day, particularly on the number of heavy trucks and their CNG tank volumes. The staff of one station reported that their turnover time could vary from several minutes to several days, and this reflected the range reported by other stations. The owner of station C5 reported that their station has no storage tanks, so that the gas travels directly from the LDC to the dispenser on demand.

Use of the stations appears to be evenly distributed among personal vehicles (16 of 23 stations), trucks and utility vehicles (18 of 23), and multi-passenger vehicles such as buses and vans (15 of 23). Outside these categories, garbage trucks were the most common customers. Staff also reported on positive and negative feedback from their customers. The most common compliments were for fast fill times and the ability to completely fill the CNG tanks. Staff at one station in particular received positive feedback about fast fill times after the station had been upgraded. Conversely, the most common complaints were about slow fill times (at “fast-fill” public-use stations) and low fill pressures. Two stations reported issues with oil in the vehicle. At one of these stations, independent tests found that the oil in the tank was not from the station compressors, but did not otherwise identify the source.

The final survey question on this topic was the frequency at which NGVs were towed into stations with empty tanks. Staff at eight stations could not provide an answer, while responses from other stations included “never,” “rarely/occasionally,” “about twice a year,” “about six times a year,” “once a month,” and “once a week.” At two stations in the Eastern region, the staff noted that their customers would like to have more CNG stations in the area.

5. SAMPLE ANALYSES AND REGIONAL TRENDS

Moisture data, gas samples, and liquid samples were collected from the CNG stations as described in Section 3. From the moisture data and the gas sample analyses, gas quality parameters were calculated for the CNG at each station. In this section, the sample analyses are presented, and geographical trends in gas quality are reviewed. Results are compared to the tariffs posted to FERC in 2008, to the NGC+ interim interchangeability guidelines, and (where possible) to the historical data presented in Section 2. All of the data from the CNG station visits in this project have been blinded, except for a letter in the station IDs that notes the general region of the continental United States (Western, Central, or Eastern) where each station is located.

The funded project scope included visits to 22 CNG stations across the country, plus a visit to one CNG station (station C5) for shakedown tests of the equipment and sampling methods. During this shakedown visit, SwRI staff collected the survey information reported in Appendix D, measured moisture levels at the LDC connection and the CNG dispenser, and tested the manifold for gas and liquid sampling. SwRI was unable to send the gas samples to SPL for analysis, but the moisture measurements and the liquid sample collected at C5 were considered valid and are included here.

At least two gas samples were collected at each station and sent to SPL for analysis. The extra samples provided insurance against sample leaks and loss of data. Where multiple gas samples from one station were successfully analyzed, the gas quality parameters for each sample were plotted separately in the graphs in this section. For statistical purposes, the gas quality parameters for all samples from a given station were averaged, and the average value was used to represent CNG quality at that station. This was done to avoid unfair weighting to stations from which more samples were analyzed.

Some gas quality data are unavailable for stations where samples were gathered. The contents of both gas sample cylinders from station E5 were lost before they could be analyzed by SPL. The operator of E5 noted that this station draws in unprocessed wellhead gas instead of pipeline quality gas, and that customers report better mileage using fuel from station E5 than fuel from other stations in the region. Depending upon the source of the gas, HHVs and Wobbe indices can be higher for unprocessed gas than for pipeline-quality gas, and the methane number can be lower for unprocessed gas. These trends would be consistent with customer observations of fuel mileage, but without analyses of the CNG from this station, this cannot be confirmed.

Due to an SPL laboratory error, samples from some stations in the Central and Eastern regions were not analyzed for H_2S or other sulfur species. These samples were analyzed for total sulfur content by ASTM D6667, and the highest total sulfur content of any of these samples was 8.5 parts per million by weight (8.5 ppmw), corresponding to a maximum theoretical sulfur concentration of 4.3 ppmv. However, the samples were discarded before the H_2S content could be quantified by ASTM D5504. The error was discussed with the CRC Project Monitor, and since the maximum sulfur concentration was well below the typical pipeline tariff limit of 16 ppmv, this was judged not to be a concern. To avoid this error on the remaining samples, SPL agreed to perform a full sulfur speciation on all samples regardless of total sulfur content.

In the rest of this section, plots of geographic trends and statistics are presented for CNG quality parameters including the Wobbe index, the methane number, and HHV. Other parameters of interest to CRC, including LHV, specific gravity, moisture content, and sulfur content, are graphed and reviewed for geographic trends only. The data used to create the plots and statistics are tabulated in Appendix F. The reader should bear in mind that each data point represents a "snapshot" of gas quality and properties at one location and one point in time. Gas quality at a given location can vary over time with such things as ambient temperatures and the gas supplies sent by the transmission pipeline to the local distribution company and on to the station.

5.1 CNG Properties

5.1.1 Wobbe Indices

Figure 5.1 presents the Wobbe indices computed from each sample, plotted by station ID. The station IDs have been grouped into the same geographic regions used in Figure 2.4 through Figure 2.6, but are not identified or arranged by state. Dashed lines in the plot identify the upper limit on Wobbe index of 1,400 proposed by the 2005 NGC+ White Paper and the range of Wobbe indices observed in the FERC filings from March 2008.

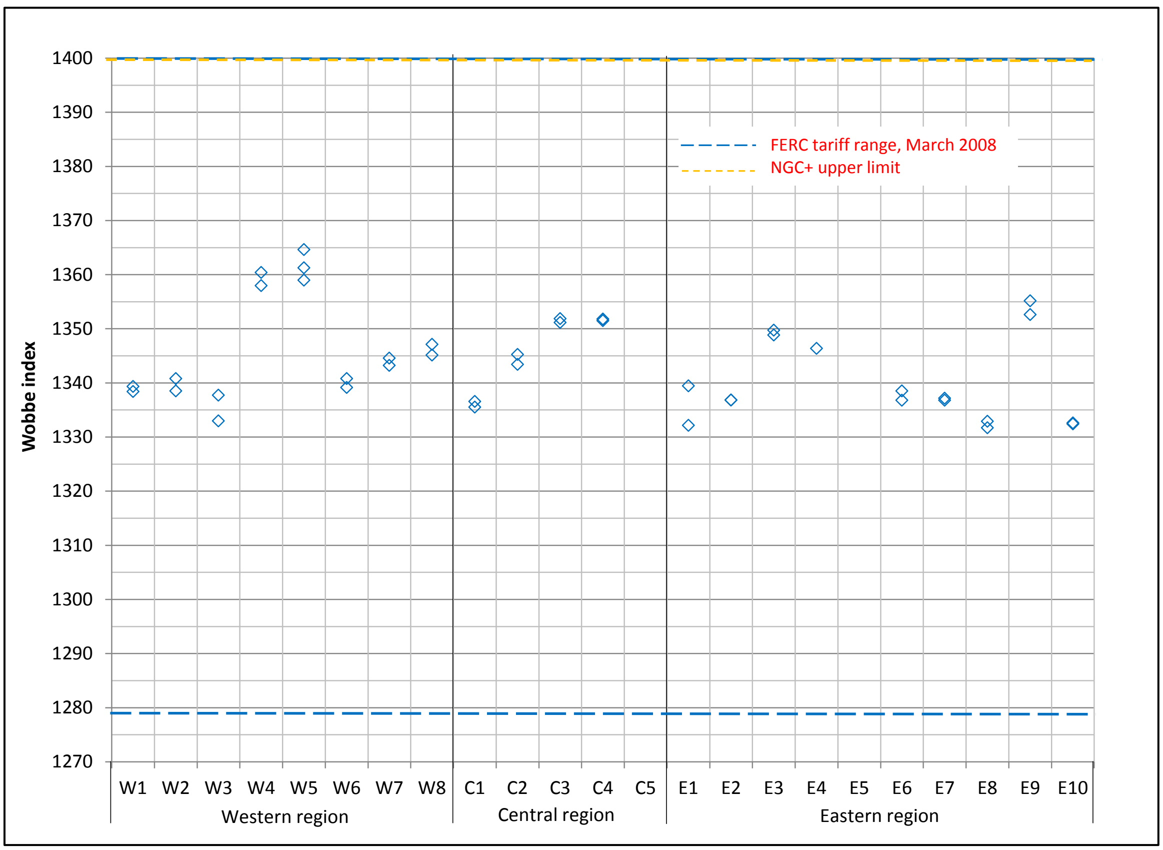

Figure 5.1. Wobbe Indices of CNG Samples Collected During this Study
Variations of 20 to 30 units within geographical regions are evident, as well as variations of 35 units across the country.

Samples were analyzed from 21 of the 23 stations (as noted above, no analyses could be performed for stations C5 and E5). CNG samples from all 21 stations during the sampling period (December 2013 to February 2014) were well within the NGC+ recommended limit on Wobbe index and within the tariff limits posted by FERC in 2008. Within each region, Wobbe index variations of 20 to 30 units are evident. In particular, the CNG samples from stations W4 and W5 had Wobbe indices roughly 20 units higher than CNG from the other stations in the Western region. Similarly, samples from stations E3, E4, and E9 were ten to 20 units higher in Wobbe index than samples from other Eastern stations.

Overall, the 21 samples presented Wobbe indices between 1,330 and 1,365, a span of 35 units. These values fall within the historical range of Wobbe indices from 1990 to 2003 presented in Figure 2.4, and also within the range of Wobbe indices observed in the daily pipeline data from early 2013 and plotted in Figure 2.15. No differences in Wobbe index are evident between the historical gas compositions and the CNG samples collected for this project, suggesting that current Wobbe indices across the country have not deviated from their historical ranges.

Table 5.1 presents the statistics on the Wobbe indices of the CNG samples collected in each region. As noted above, each data point is the average Wobbe index of all samples from a given station. This approach weighs each station equally within its geographic region. (The individual values from all samples are listed in Appendix F and plotted in Figure 5.1.) The averages, standard deviations, and extreme values for each group of Wobbe indices have been compared to the NGC+ recommended upper limit and the range of "typical" Wobbe indices observed in the March 2008 FERC filings. The 95% confidence intervals on all of the regional averages, as well as all the minimum and maximum values from the samples, fall within the NGC+ limits and the tariff requirements. Hence, none of the CNG samples would exceed the 2013 tariff limits or the NGC+ interchangeability recommendations.

Table 5.1. Wobbe Index Statistics of the CNG Samples Collected for This Study

All Wobbe indices, including the extreme values and the 95% confidence intervals on the averages computed from the standard deviations, fall within the ranges of the example FERC tariff limits and the limit recommended by the NGC+ White Paper.

Region	Data Points	Average	Standard Deviation	Maximum	Minimum
Western	8	1345.6	9.1	1361.6	1335.4
Central	4	1345.9	6.4	1351.6	1336.0
Eastern	9	1340.2	7.3	1353.9	1332.3
All regions	21	1343.3	8.3	1361.6	1332.3

5.1.2 Methane Numbers

Figure 5.2 presents the *MN* values computed from each sample, again plotted by station ID. As noted in subsection 0, *MN* is a function of the motor octane number (*MON*), and the CARB formula (Equation 3) was used to compute *MON* values in this study because that formula incorporates the contributions of heavy hydrocarbons. Inspection of the data in Appendix F will show that the valid ranges of the *H/C* ratio and inert component totals for the CARB formula were not exceeded by any of the CNG samples. Since individual NGV engines can have unique performance requirements, the NGC+ White Paper does not include *MN* acceptance criteria, and FERC tariff filings do not set limits on this parameter.

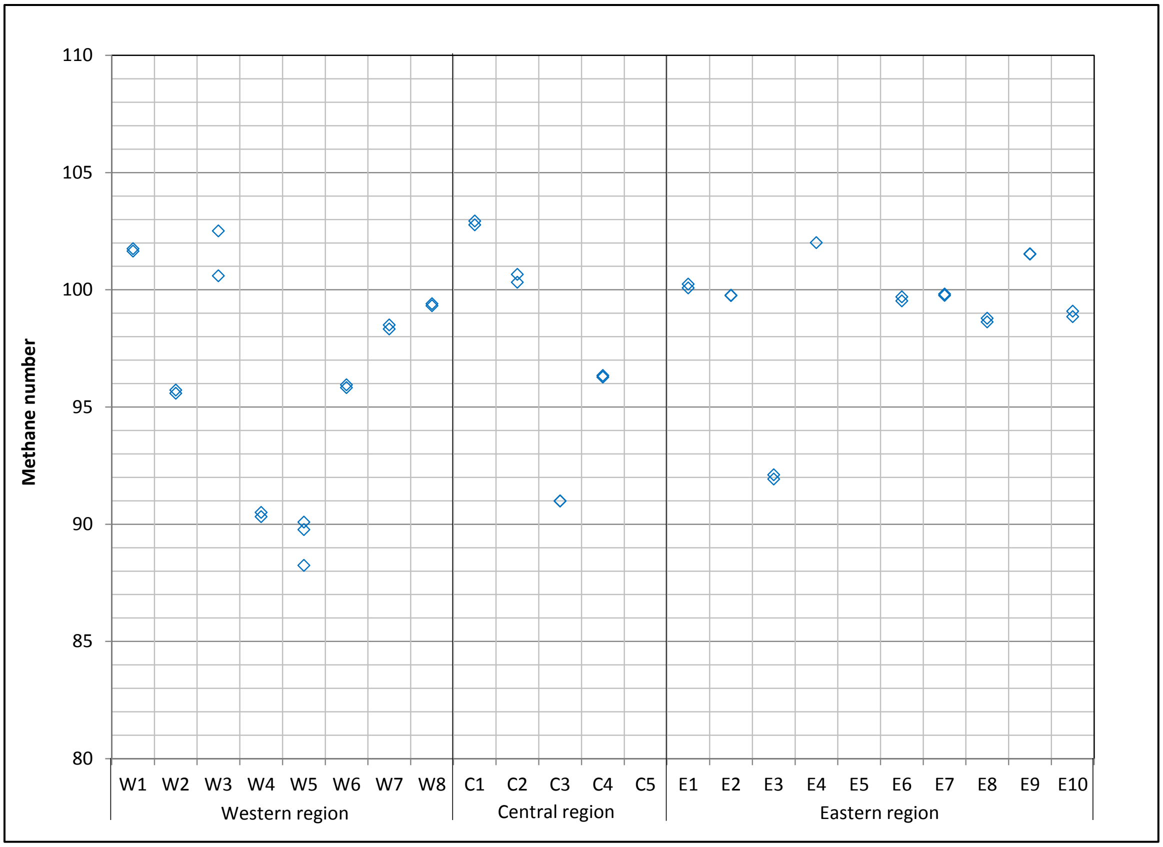

Figure 5.2. Methane Numbers of CNG Samples Collected During this Study
With the exception of CNG from station E3, stations in the Eastern region exhibit the most consistent methane numbers among their CNG supplies. In the Western and Central regions, methane numbers ranged from 88 to 103.

Of the stations visited in the Eastern region, the CNG collected from station E3 had a methane number of 92, over six units lower than the samples from the other stations. Excluding station E3, the remaining stations presented much more consistent methane numbers ranging from around 98.5 to 102. In the other two regions, *MN* values of the CNG samples ranged from approximately 88 to 103. Table 5.2 presents the statistics of the average *MN* values from each station, grouped by region, and confirms that the Eastern CNG samples were the most consistent. The average *MN* across the Eastern region was also the highest of the three.

Table 5.2. Methane Number Statistics of the CNG Samples Collected for This Study
Statistics confirm the observation from Figure 5.2 that CNG in the Eastern region has the most consistent methane numbers and the highest average methane number of the three regions.

Region	Data Points	Average	Standard Deviation	Maximum	Minimum
Western	8	96.5	4.4	101.7	89.4
Central	4	97.7	4.5	102.9	91.0
Eastern	9	99.2	2.7	102.0	92.0
All regions	21	97.9	4.0	102.9	89.4

By comparing Figure 5.1 and Figure 5.2, the reader can observe how increases in Wobbe number correspond to decreases in *MN*. As CNG becomes richer in heavy hydrocarbons, the heating value and Wobbe index of the CNG increase, but the lower *H/C* ratio of the heavier hydrocarbons lowers the *MN*. Note, however, that the distribution of the heavy hydrocarbons does not affect these two parameters in the same way, and that the relative scatter in the *MN* values is larger than the relative scatter in the Wobbe indices. Compared to the historical *MN* data in Figure 2.5, the *MN* values of the CNG samples cover the same span of values. The samples collected here also fall within the range of *MN* values seen in the daily pipeline analyses in Figure 2.16. This suggests that the methane numbers of current CNG supplies are consistent overall with historical trends from 1990 to the present.

5.1.3 Higher Heating Values

HHVs were also calculated from the compositions of each CNG sample and plotted by station ID in Figure 5.3. This parameter is regularly included in pipeline tariffs and is tracked by transmission companies to ensure that end-users receive gas compositions for which their equipment has been tuned. The HHV limits in FERC tariff postings in March 2008 ranged from 900 Btu/scf to 1,200 Btu/scf, but the NGC+ White Paper recommends an upper limit of 1,110 Btu/scf to ensure interchangeability of gas supplies. The figure shows that all CNG samples collected during this study were well within the March 2008 tariff range for HHVs and within the NGC+ upper limit. HHVs of individual samples around the country ranged from 1,013 Btu/scf to 1,063 Btu/scf, with stations W4 and W5 producing the highest HHVs. As with the methane number, the Eastern region produced samples that were the most consistent in HHV. Samples from station E3 were roughly 25 Btu/scf higher in HHV than the other samples from that region, which fell in the approximate range of 1,020 Btu/scf ± 5 Btu/scf.

While the CNG samples were all within the NGC+ interchangeability limit and the 2008 tariff limits, there were some notable outliers. When considering the Wobbe indices, the methane numbers, and the HHVs of all the samples together, stations W4, W5, and E3 appear to be providing “hotter” CNG than the other stations in their respective regions. The samples from stations W4 and W5 also had higher HHVs than many of the historical gas compositions. Comparison with Figure 2.6 shows that stations W4 and W5 were the only stations where the sample HHVs from 2013 and 2014 were higher than the range of HHVs reported in that region from 1990 to 2003. The daily pipeline data from early 2013, plotted in Figure 2.17, reveal that the large majority of gas compositions posted online had HHVs between 1,010 Btu/scf and 1,050 Btu/scf. Only a few pipeline analyses, like the CNG samples from stations W4 and W5, were above 1,050 Btu/scf.

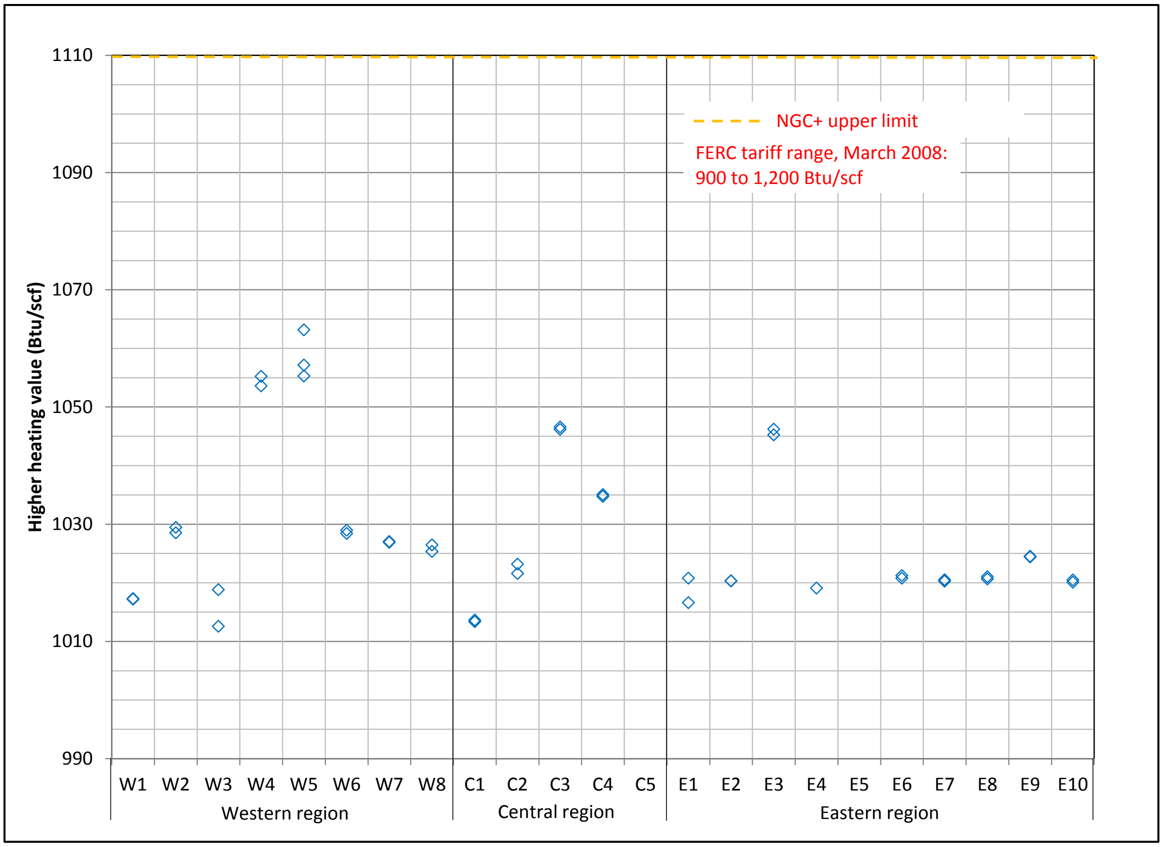

Figure 5.3. Higher Heating Values of CNG Samples Collected During this Study

HHVs of the samples were most consistent among the stations in the Eastern region. As with the Wobbe indices and methane numbers, HHVs at stations W4, W5, and E3 lie significantly outside the range of the values from the other stations in their respective regions.

Table 5.3 presents the statistics on the average HHVs from each station, grouped by region. Like the *MN*s, the Eastern CNG samples were the most consistent in HHV, though the average HHV in this region was the lowest of the three regional averages.

Table 5.3. HHV Statistics of the CNG Samples Collected for This Study

All HHVs fall within the ranges of the example FERC tariff limits and the upper limit recommended by the NGC+ White Paper. HHVs are most consistent across the Eastern region.

Region	Data Points	Average	Standard Deviation	Maximum	Minimum
Western	8	1032.0	14.9	1058.5	1015.7
Central	4	1029.3	12.5	1046.4	1013.5
Eastern	9	1023.4	8.0	1045.7	1018.7
All regions	21	1027.8	12.5	1058.5	1013.5

5.1.4 Lower Heating Values and Specific Gravities

Other CNG properties of interest included the lower heating value (LHV) and specific gravity, which are often tracked by pipelines for measurement purposes. These were both calculated for the CNG samples using the same ASTM standard and GPA component data tables that were used for the HHV calculations. Figure 5.4 compares the LHVs computed from the CNG samples taken in the three different regions. Recall that the LHV calculation assumes that all water produced by the combustion reaction remains in the vapor state, while the HHV calculation assumes that the produced water returns to a liquid state and releases its heat of vaporization as additional energy. Thus, the trends in LHV within the different regions are identical to the trends observed in the HHVs. LHVs in the CNG samples ranged from roughly 915 Btu/scf to 960 Btu/scf, with stations W4 and W5 dispensing CNG with the highest LHVs, and the Eastern region dispensing CNG with the most consistent LHVs. LHVs are not included in the example FERC tariff limits in subsection 2.1.9 or in the NGC+ interchangeability recommendations, so no comparisons can be made to the LHV data.

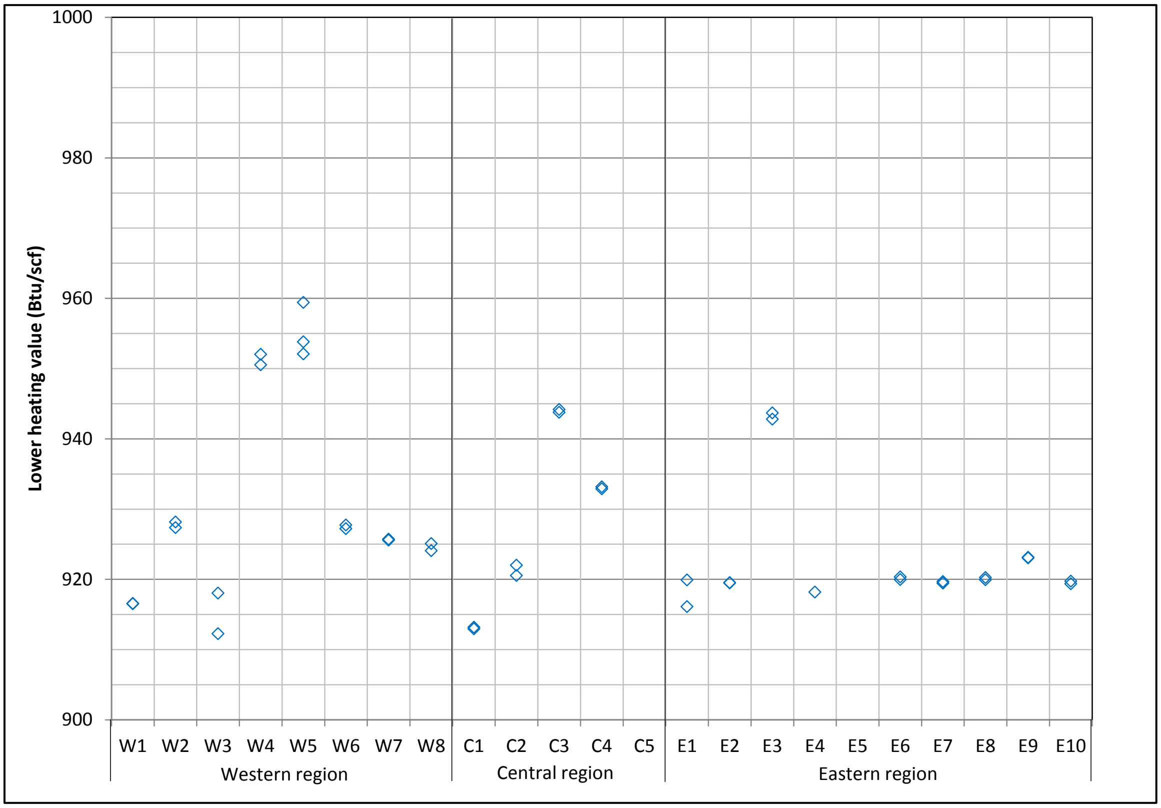

Figure 5.4. Lower Heating Values of CNG Samples Collected During this Study
The LHVs follow the same trends as the HHVs in the previous figure.

Figure 5.5 presents the specific gravity data from the analyzed CNG samples. Specific gravity is not included in the example tariff data or in the NGC+ recommendations, so no comparisons can be made to those documents. Compared to the other CNG parameters discussed above, there is less consistency and more scatter in specific gravity values within the geographic regions, possibly due to differences in the amounts of heavy hydrocarbons and diluents in the gas supplies to each station. While the specific gravity of the samples from E3 is notably higher than the other samples from the Eastern region, for example, the CNG samples from stations E4 and E9 are noticeably lower. Specific gravities of the CNG samples across the country span a range from 0.571 to 0.607.

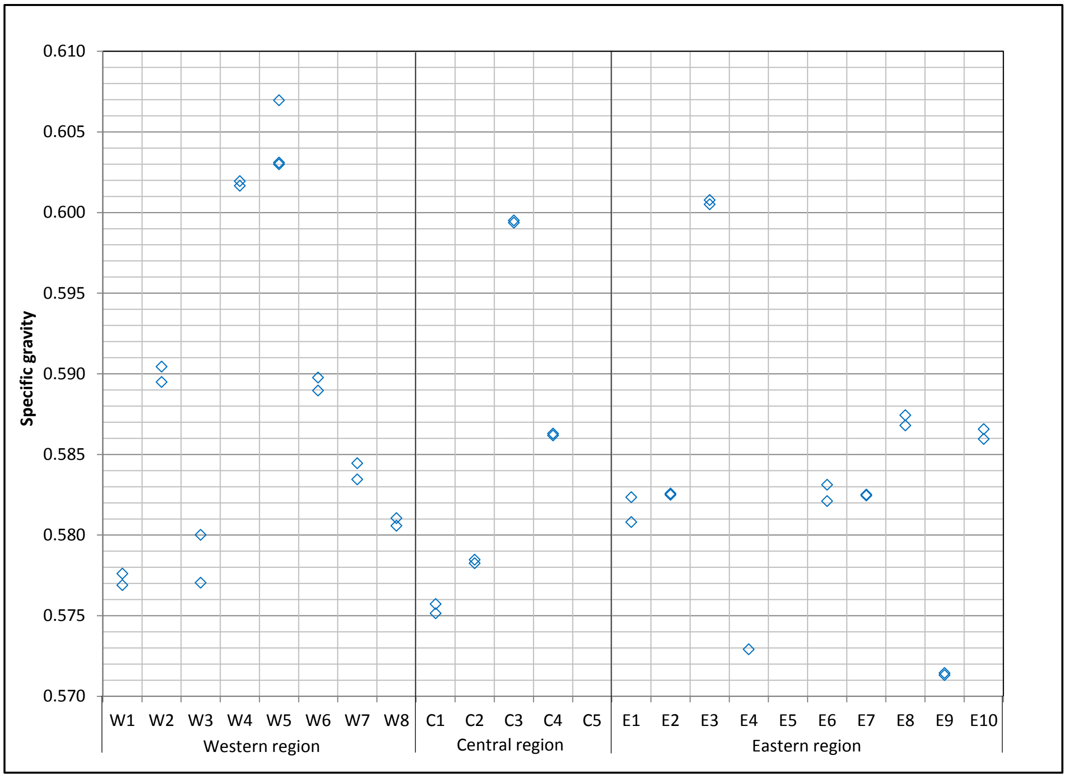

Figure 5.5. Specific Gravities of CNG Samples Collected During this Study

Specific gravity values vary across similar ranges within each geographic region, and exhibit more scatter in the Western and Eastern regions than the Wobbe indices, methane numbers, or heating values.

5.1.5 Moisture Content

Very little information was found on moisture levels in pipeline natural gas during the review of pre-existing gas quality data. It was hoped that moisture measurements during the field visits would provide useful information. A Michell MDM300-IS analyzer was used to measure the moisture content of the gas supply entering each station and the moisture content of the CNG at the dispenser nozzle. This subsection describes the data reduction of the analyzer logs, the final moisture values, and observations on dehydration at the different stations.

At each site, a Michell analyzer was used to log moisture levels at the LDC connection or dispenser nozzle over several minutes. The log files were analyzed to confirm the stability of the final readings. In some locations, analysis indicated that moisture levels of the flow through the analyzer were slowly moving toward a stable level, even though the analyzer had already flagged the value as stable. As discussed in subsection 3.1, adsorption and desorption of moisture at the internal walls of the sample line must reach equilibrium for the moisture level at the analyzer to be representative of the gas supply. In many cases where the reading was not yet stable, an exponential curve fit to the data was used to determine a final, representative moisture reading. The resulting uncertainty in measured moisture levels (at the 95% confidence level) has been estimated as ±30 ppmv (±1.4 lb_m/MMscf) at LDC pressures and ±10 ppmv (±0.47 lb_m/MMscf) at CNG pressures (George, 2012).

The next two graphs plot moisture measurements at the LDC connections and the dispenser nozzles. Figure 5.6 presents the moisture data from all 23 stations and marks the common upper moisture limit of 7 lb_m/MMscf cited in the literature. This was the highest limit on moisture reported in the FERC tariff specifications (Table 2.1) and the maximum level recommended by NGC+ for interchangeability of gas supplies. Of the 23 stations, only two (both in the Eastern region) had incoming gas streams exceeding this limit. Station E5 is known to accept unprocessed wellhead gas, and the measurement of 95.0 lb_m/MMscf at the distribution connection is consistent with gas that is saturated or nearly saturated with water vapor. By comparison, the CNG at the dispenser contains only 2.2 lb_m/MMscf of water vapor. The operator of this station regenerates the drying system much more frequently than other stations visited during this project in order to maintain this low level in the CNG. The other station to exceed the tariff limit, E3, was accepting gas with 8.46 lb_m/MMscf water vapor during the station visit.

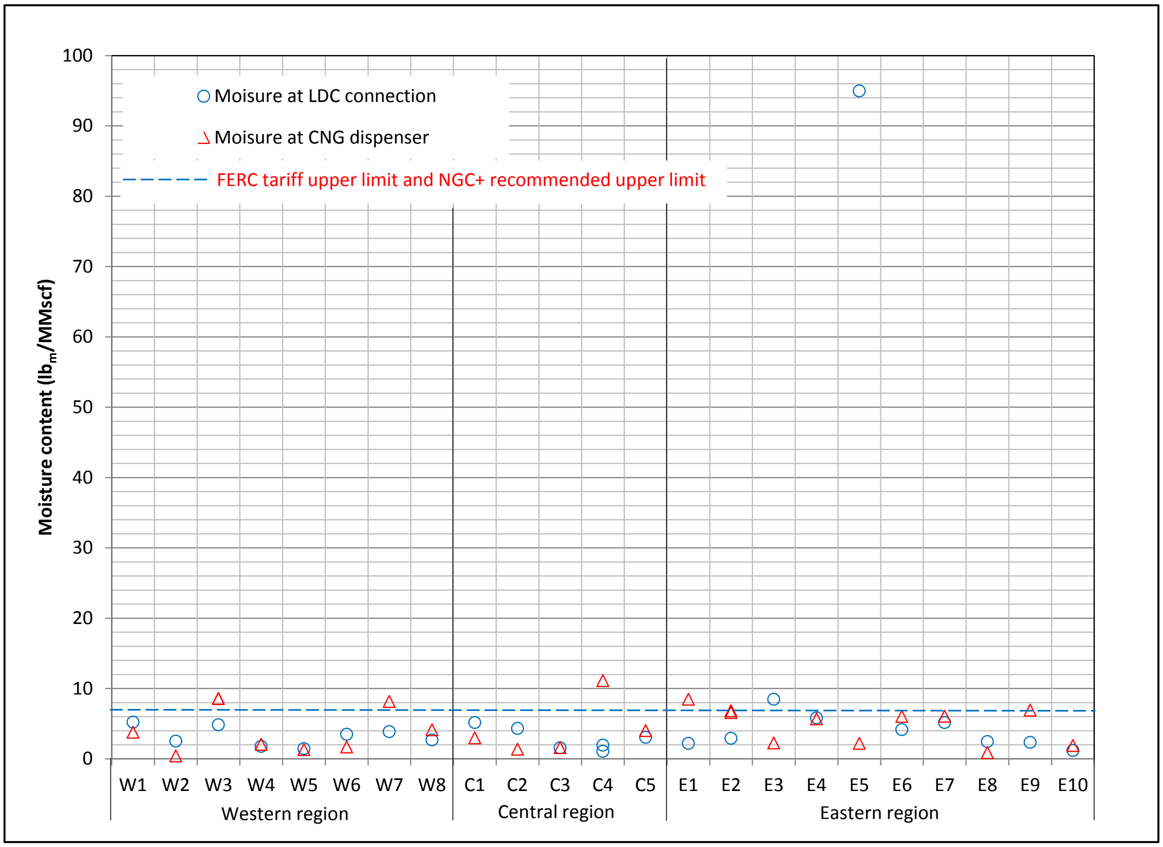

Figure 5.6. Moisture Levels of Incoming Gas and Dispensed CNG

Only stations E3 and E5 had incoming gas streams with moisture levels exceeding the common limit of 7 lb_m/MMscf (the blue dashed line). Station E5 takes in unprocessed wellhead gas with moisture levels exceeding 90 lb_m/MMscf.

However, the moisture measurements at the CNG dispenser are of strong interest. Figure 5.7 plots the same data as Figure 5.6, but with the vertical axis expanded for closer examination of the data below 20 lb_m/MMscf. The plot includes 95% confidence intervals on the data to help assess the significance of differences in the measurements. Cases in which the confidence intervals do not overlap can be considered statistically significant.

Four of the stations delivered CNG to the analyzer with moisture levels above 7 lb_m/MMscf. While the tariff limit does not strictly apply to CNG, it should be expected that a working dehydration system would lower the moisture content of the incoming gas, and the tariff limit would be an upper bound on CNG moisture content. At six stations – W3, W7, C4, E1, E2, and E9 – the moisture level at the CNG dispenser was higher than the moisture level at the LDC connection, and the differences were statistically significant. These results suggest issues with the dehydration systems at these stations, although it is unclear what mechanism would allow the gas to absorb moisture during processing.

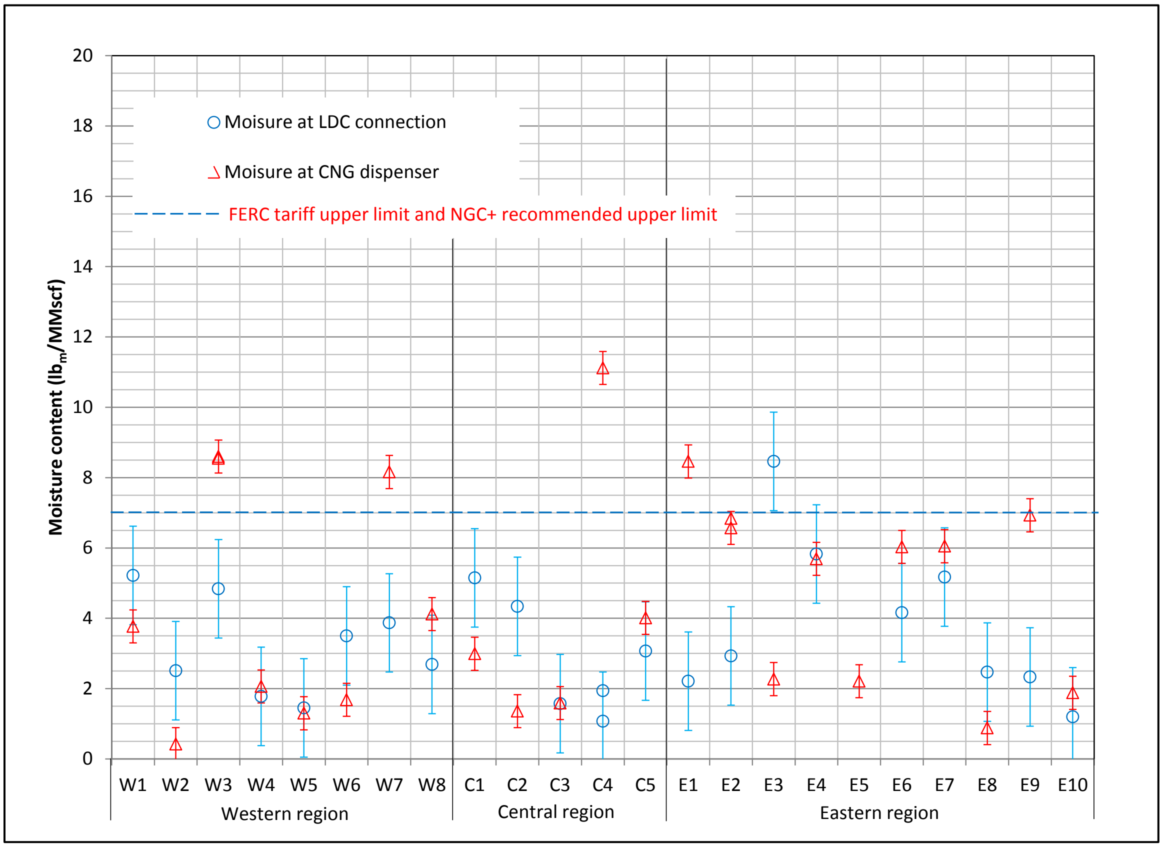

Figure 5.7. Expanded-Scale Plot of Moisture Levels of Incoming Gas and Dispensed CNG
Measured moisture levels in the CNG at seven of the 23 stations were statistically higher than moisture levels in the incoming gas, suggesting issues with the dehydration systems.

Independent data at one station supports the MDM300 reading of high CNG moisture content. Station C4 was chosen for testing by the operator to address reports of high moisture levels in the dispensed CNG. A moisture level of 11.12 lb$_m$/MMscf was measured by SwRI at the dispenser, and during the site visit, the onsite moisture monitor reported a WVDP of 68.0°F at the drier outlet. Assuming the LDC inlet pressure of 45 psig also exists at the drier outlet, the IGT-8 correlation (Bukacek, 1955) computes an extremely high moisture level of 277 lb$_m$/MMscf leaving the drier. While the IGT-8 calculation and the MDM300 reading disagree by over an order of magnitude, the onsite moisture analyzer supports the possibility of an issue with the desiccant system onsite.

Given the number of stations with measured moisture levels above 7 lb$_m$/MMscf at the dispenser, and the number of stations where moisture levels appear to be increasing through the processing chain, moisture levels may be of concern to automakers and other interested parties.

5.1.6 Total Sulfur Levels and H_2S Levels

Each CNG sample was analyzed for total sulfur content, and a majority of the samples were also analyzed for individual sulfur species. Hydrogen sulfide was of particular interest, due to its reactive nature and potential for equipment corrosion. This subsection presents the findings of the sulfur analyses.

Total sulfur amounts, analyzed according to ASTM D6667, were reported both in units of ppmw and in units of grains/100 scf. Figure 5.8 plots the total sulfur analyses in both units versus station ID. All measurements were well below the lowest tariff limit of 0.5 grains/100 scf listed in Table 2.1. All samples from stations C1, E4, and E9 had total sulfur amounts less than 0.1 ppmw, the quantification limit of the analyzer. At the other extreme, CNG samples from stations W4, W5, and E10 had total sulfur levels noticeably above the other stations in their respective regions. However, none of the total sulfur levels in the CNG samples exceeded any of the example pipeline tariff limits in Table 2.1.

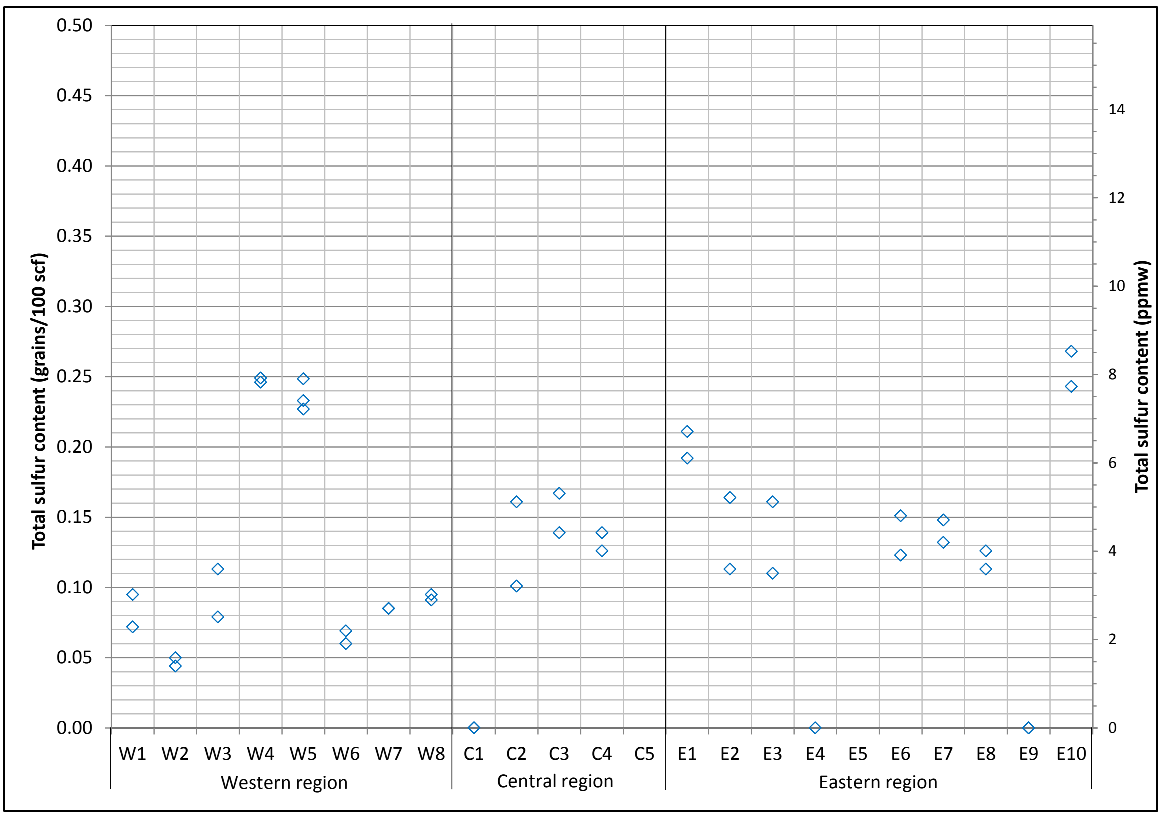

Figure 5.8. Total Sulfur Content of CNG Samples Collected During this Study
The FERC-published tariff ranges on total sulfur in Table 2.1 range from 0.5 grains/100 scf to 20 grains/100 scf. None of the CNG samples had total sulfur levels exceeding these limits.

No H_2S was found in any of the CNG samples analyzed for sulfur species by ASTM D5504, but many other sulfur species were detected. These compounds, listed in Appendix F, included carbonyl sulfide, alkane sulfides, mercaptans, and disulfides. The mercaptans were expected, since they are added to natural gas by LDCs as an odorant for leak detection. Samples from five stations – C3, C4, E3, E8, and E10 – tested positive for total sulfur but were not analyzed for individual species due to laboratory error. Of these, E10 was also the station that presented the highest total sulfur content. Under the conservative assumption that the sulfur in this CNG sample consisted entirely of H_2S, this single sample would have been the only one to exceed the lowest published tariff limit of 0.25 grains H_2S/100 scf listed in Table 2.1.

Other than H_2S, only a few of the sulfur compounds found in the speciation analyses have published data that can be used in calculating heating values or gas quality parameters by ASTM D3588. To decide whether to neglect these other sulfur compounds in the gas quality calculations, a worst-case calculation was performed on the sample with the most total sulfur. The highest total sulfur content in all of the CNG samples was 0.268 grains/100 scf (8.5 ppmw) in a sample from station E10. Since H_2S is the lightest of the sulfur species, assuming that all of the total sulfur measured by weight was H_2S would lead to the largest possible mole percentage of sulfur species in the sample. This conservative assumption produced an H_2S concentration of only 4.3 ppmv (0.00043 mol%) in the worst-case E10 CNG sample. Based on this low value for the worst possible case, the sulfur compounds were neglected in the calculations of heating value, specific gravity, Wobbe index, and methane number.

5.1.7 Other CNG Components of Interest

Besides the gas quality parameters and components listed above, the NGC+ Interchangeability White Paper and the example pipeline tariff data in Table 2.1 list limits on other natural gas components: hydrogen, CO_2, N_2, O_2, C_{4+}, C_{5+}, and total diluents. Table 5.4 compares the ranges of these components found in the CNG samples to the upper limits found in the March 2008 pipeline tariffs and the NGC+ recommended upper limits. The diluent and C_{4+} amounts in the CNG samples were well within the NGC+ recommended upper limits, and all of the components and totals of interest were well within the highest FERC-posted tariff limit listed in Table 2.1. One point of interest is that none of the CNG samples were found to contain any hydrogen above the detection limit of 0.001 mol%. In summary, the CNG samples collected here would be in good compliance with most tariff limits and the NGC+ interchangeability limits.

Table 5.4. Ranges of Other Components of Interest in the CNG Samples Collected in This Study
All samples collected for this study complied with the interchangeability limits recommended by NGC+ and would be accepted under nearly all the example tariff limits described in Table 2.1.

Specification	Range of upper limits in FERC tariffs, March 2008	NGC+ upper limits for interchangeability	Range of content in CNG samples in this study
C_{4+} content	0.75 to 1.50 mol%	1.5 mol%	0.01 mol% to 0.52 mol%
C_{5+} content	0.12 to 0.25 mol%	-	< 0.003 mol% to 0.14 mol%
Maximum hydrogen	400 to 1,000 ppmv	-	None found
Maximum CO_2	1 to 3 mol%	-	0.21 mol% to 1.19 mol%
Maximum N_2	1 to 4 mol%	-	0.41 mol% to 1.74 mol%
Maximum O_2	0.001 to 1 mol%	-	0 to 0.08 mol%
Maximum total diluents	3 to 6 mol%	4 mol%	0.71 mol% to 2.13 mol%

5.2 FTIR Analyses of Liquid Samples

During CNG sample collection at the dispensers, any liquids separated from the stream by the Welker WFS-3 separators and the sampling manifold were collected in a separate sample cylinder. The intent was to collect compressor oils or other liquids in the dispensed CNG for separate analysis. Once the samples had been collected and the gas cylinders had been isolated, any gas in the liquid sample cylinder was vented along with the gas in the manifold. This step would flash off any gas components dissolved in the liquids, but would leave the heavier hydrocarbons from the compressor oils (typically C_{12+}) in the sample cylinder. The liquid sample cylinders were then closed, removed from the sampling manifold, and returned to SwRI for analysis.

Once at SwRI, each liquid sample cylinder was placed vertically in a clamp stand for at least 24 hours. This resting period allowed the cylinder contents to equilibrate with room temperature and allowed any liquids in the cylinder to drain toward the valve at the bottom. After the resting period, the bottom valve was opened, and any free liquids were collected in a sample vial for FTIR analysis. For many liquid samples, an insignificant amount of liquid (less than one to two milliliters) drained from the cylinder. In these cases, an acetone rinse was used to collect any residue from the cylinder walls, and the acetone was allowed to vaporize from the sample before the residue was analyzed by FTIR. These samples were still noted as not having significant amounts of liquid.

The FTIR analyses qualitatively determined whether water and hydrocarbon liquids were present in the liquid samples. The hydrocarbon signatures were also compared to the FTIR signatures of the reference compressor oils listed in Table 3.3 to potentially identify any hydrocarbon residue in the liquids. Table 5.5 summarizes the results of the FTIR analyses, along with the CNG moisture levels measured by the Michell MDM300-IS. Significant amounts of liquid were drained from nine of the liquid cylinders. FTIR analysis of all nine of these samples identified both water and hydrocarbons in the liquid. Of the 13 cylinders that did not produce significant amounts of liquids without rinsing, only four samples showed evidence of water in the residue. Every FTIR analysis of collected liquids or residue found indications of hydrocarbons in the sample, but only four of the samples (all from the Western region) had infrared spectra similar to one of the three reference compressor oils. Because of the wide variety of compressor oils in use, work to identify the hydrocarbons in the other samples was impractical.

Although every liquid sample that involved more than a few milliliters of liquid was found to contain water, no correlation was found in the data between the presence of water in the liquid sample and the CNG moisture levels measured by the Michell analyzer. This is not unexpected and should not reflect poorly on either the liquid sample analyses or the moisture measurements. To capture the liquid samples, the liquid drain from the Welker separator was routed to a single cylinder closed at the other end. The amount of time needed to create a stable CNG flow through the sampling manifold varied between stations, so the total CNG flow through the separator (and the potential volume of collected liquids) varied as well. The intent of the liquid sample analysis was to qualitatively identify the liquids present as water, compressor oils, or other hydrocarbons, rather than to quantitatively measure the dispensed liquids, and the samples achieved this goal.

Table 5.5. Results of Liquid Sampling from CNG Stations
Every sample consisting of more than a few milliliters of liquid was found to contain water. However, no correlation was found between the presence or the amount of water in the liquid and the CNG moisture content measured by the portable analyzer.

Site code	Significant liquids drained from cylinder?	Water identified by FTIR?	CNG moisture measurement (lb_m/MMscf)	Hydrocarbons identified by FTIR?	Known compressor oil identified?
W1	no	no	3.77	yes	no
W2	no	no	0.42	yes	Similar to Summit TM-30 (SAE-30)
W3	no	no	8.6	yes	no
W4	yes	yes	2.06	yes	no
W5	yes	yes	1.3	yes	no
W6	no	no	1.68	yes	Similar to Summit TM-30 (SAE-30)
W7	no	no	8.16	yes	Similar to Summit TM-30 (SAE-30)
W8	no	no	4.12	yes	Similar to Summit TM-30 (SAE-30)
C1	no	no	2.99	yes	no
C2	no	no	1.36	yes	no
C3	yes	yes	1.59	yes	no
C4	yes	yes	11.12	yes	no
C5	yes	yes	4.01	yes	no
E1	no	yes	8.46	yes	no
E2	yes	yes	6.57	yes	no
E3	no	yes	2.27	yes	no
E4	yes	yes	5.69	yes	no
E5	yes	yes	2.21	yes	no
E6	yes	yes	6.03	yes	no
E7	no	no	6.05	yes	no
E8	no	yes	0.88	yes	no
E9	no (no rinse performed)				
E10	no	yes	1.88	yes	no

6. CONCLUSIONS

One goal of this project was to provide CRC with data on natural gas quality at three different points within the U.S. natural gas infrastructure: transmission pipelines, LDC pipelines, and CNG stations (specifically, the CNG dispenser). A second goal of the project was to provide CRC with an understanding of geographic variations in natural gas compositions. A literature review obtained data on average transmission and distribution gas compositions in the period from 1990 to 2003 and helped to document long-term variations in natural gas quality. A recent search of transmission and distribution company websites provided insight into the daily variations in gas composition and gas quality. For data on gas quality at CNG stations, a total of 23 stations around the continental U.S. were visited to collect CNG samples and to measure moisture levels at the LDC/station connection and at the CNG dispenser. The station data are "snapshots" of gas quality at each station at the time of the visit, rather than indicators of year-round CNG quality. However, the station data have provided useful information on variations in the quality of dispensed CNG across the nation. The data gathered from this study have been included in the appendices, and statistics on key gas quality and interchangeability parameters have been included in the body of the report.

Several useful conclusions have been drawn from the data. These conclusions focus on natural gas interchangeability parameters such as heating value, Wobbe index, and methane number, and contaminants that can affect NGV systems such as moisture content and sulfur compounds.

- From the early 1990s to the early 2000s, differences in HHV, Wobbe index, and methane number among gas supplies in different regions of the U.S. became smaller. Geographic variations in these parameters, and in the tariff specifications that set limits on pipeline natural gas compositions, have become broader again across the U.S. since the early 2000s. This diversity in gas quality is attributed to the increasing variety of sources of natural gas, particularly shale gas supplies.

- Within each geographic region defined for this study (Pacific, Rockies, Central, and Eastern regions), CNG samples from some stations were distinctly higher in HHV and Wobbe index than other stations in the same region. Overall, however, the average HHVs, Wobbe indices, and methane numbers for each region were not statistically different from one another.

- Fluctuations in gas quality at a single location have been observed over periods of months, weeks, and days. Temporary swings of 100 units in the Wobbe index and 30 units in the methane number have been observed over the course of a few days. Changes of 50 units in the Wobbe index and 15 units in the methane number have been seen over a three-month period in a single pipeline.

- The NGC+ Interchangeability White Paper recommends limits on HHVs and Wobbe indices for pipeline natural gas so that gas supplies from different sources are interchangeable with one another at the point of use. A 2008 survey also listed the ranges of interchangeability parameters and gas quality parameters that pipelines would accept in the gas supplies that they purchased from producers and processors. The gas samples collected from CNG stations for this project complied with all these interchangeability limits and example tariff limits, except for the moisture content at a few stations. However, the daily gas quality data from the literature review show that the limits and tariffs on HHV, Wobbe index, and methane number can be exceeded for several days at a time.

- A significant finding of the CNG station surveys involved the moisture content of the dispensed CNG. Only two of the 23 stations visited had natural gas entering at the LDC connection with moisture levels exceeding the recommended limit of 7 lb_m/MMscf. Both stations dispensed CNG with moisture levels below this limit. However, at four other stations, the dispensed CNG contained moisture in excess of 7 lb_m/MMscf. At six of the 23 stations, the measured moisture content of the dispensed CNG exceeded the measured moisture content of the gas entering at the LDC connection, and the differences were statistically significant. These findings were supported by a number of liquid samples found to contain water and (at one station) by data from onsite equipment. The cause of these high moisture levels is unknown at this time, and may require examination of the station dispensers for poorly maintained drying equipment or locations downstream of the drier where water may collect and saturate the CNG.
- All of the liquid samples collected from the CNG stations were found to contain trace amounts of heavy hydrocarbons left behind after the lighter CNG components flashed off from the liquid sample cylinders. Only four of the 22 liquid samples produced heavy hydrocarbons resembling known compressor oils, but the others contained hydrocarbons with similar carbon numbers to compressor oils. The small liquid amounts prevented quantitative estimates of the relative fractions of heavy components in the CNG.

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APPENDIX A
SUMMARIES OF HISTORICAL AND ONLINE GAS QUALITY DATA

Summary of Tables and Figures in Appendix A

A-3. Summarized Current Gas Quality Data for Each Provider Studied

A-3-1. Algonquin Summary

A-3-2. ANR Pipeline Summary

A-3-3. PG&E Service Area Pipeline Summary

A-3-4. Panhandle Energy Pipeline Summary

A-3-5. Southern Star Central Gas Pipeline (SSCGP) Summary

A-1. Summarized Historical Gas Quality Data

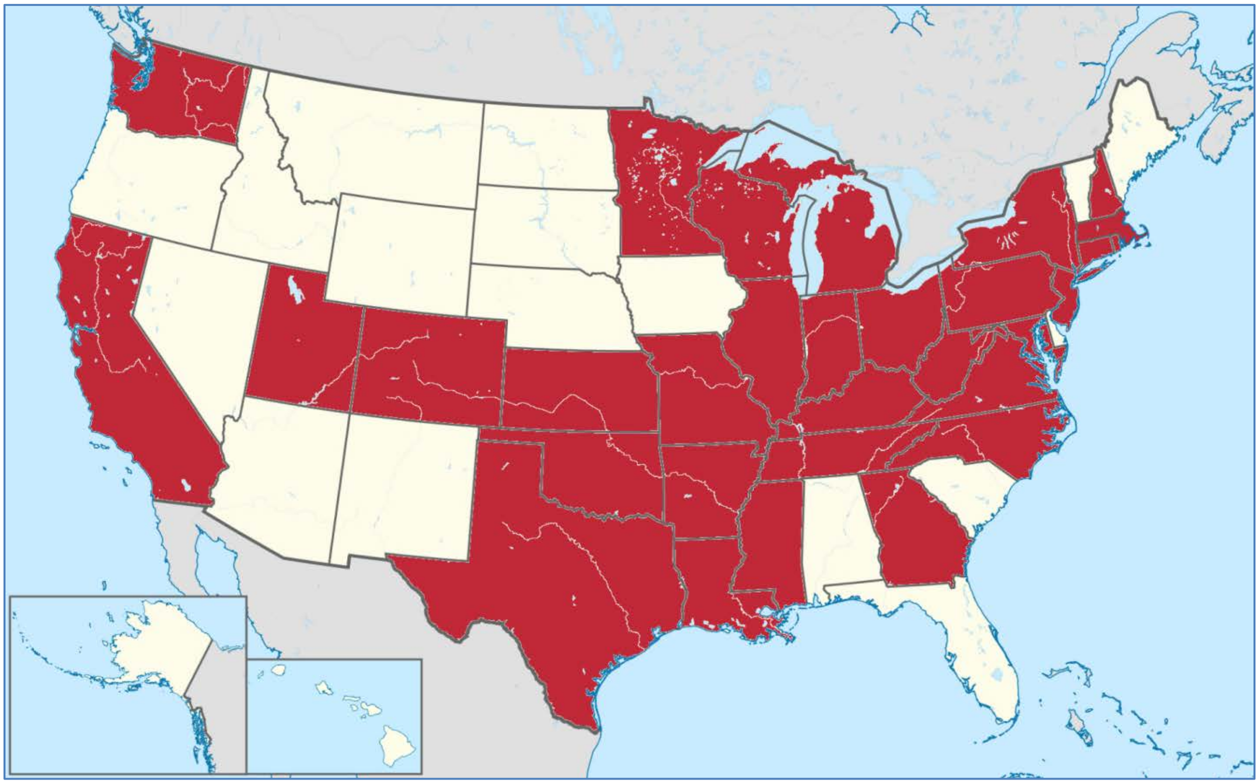

Figure A.1. States Included in the Annual Averages Dataset, 1990-2003
The states highlighted in red were included in the GRI-92/0123 report and the NGC surveys conducted in 1995-96 and 2002-03.

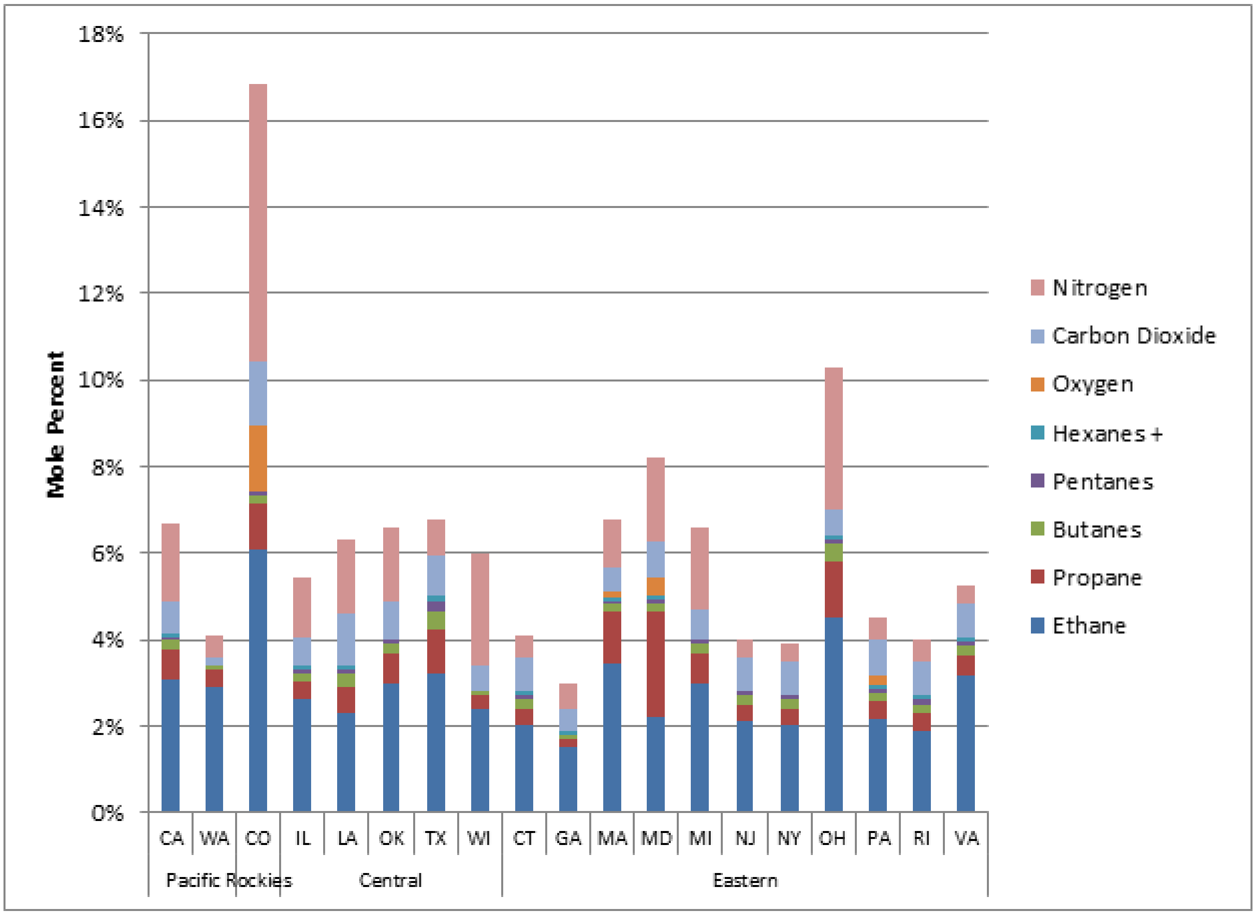

Figure A.2. Gas Components Reported in the GRI-92/0123 Report

All gas components' molar percentages are shown as averages per state. The remaining percentage of gas not shown is methane, which was excluded for clarity.

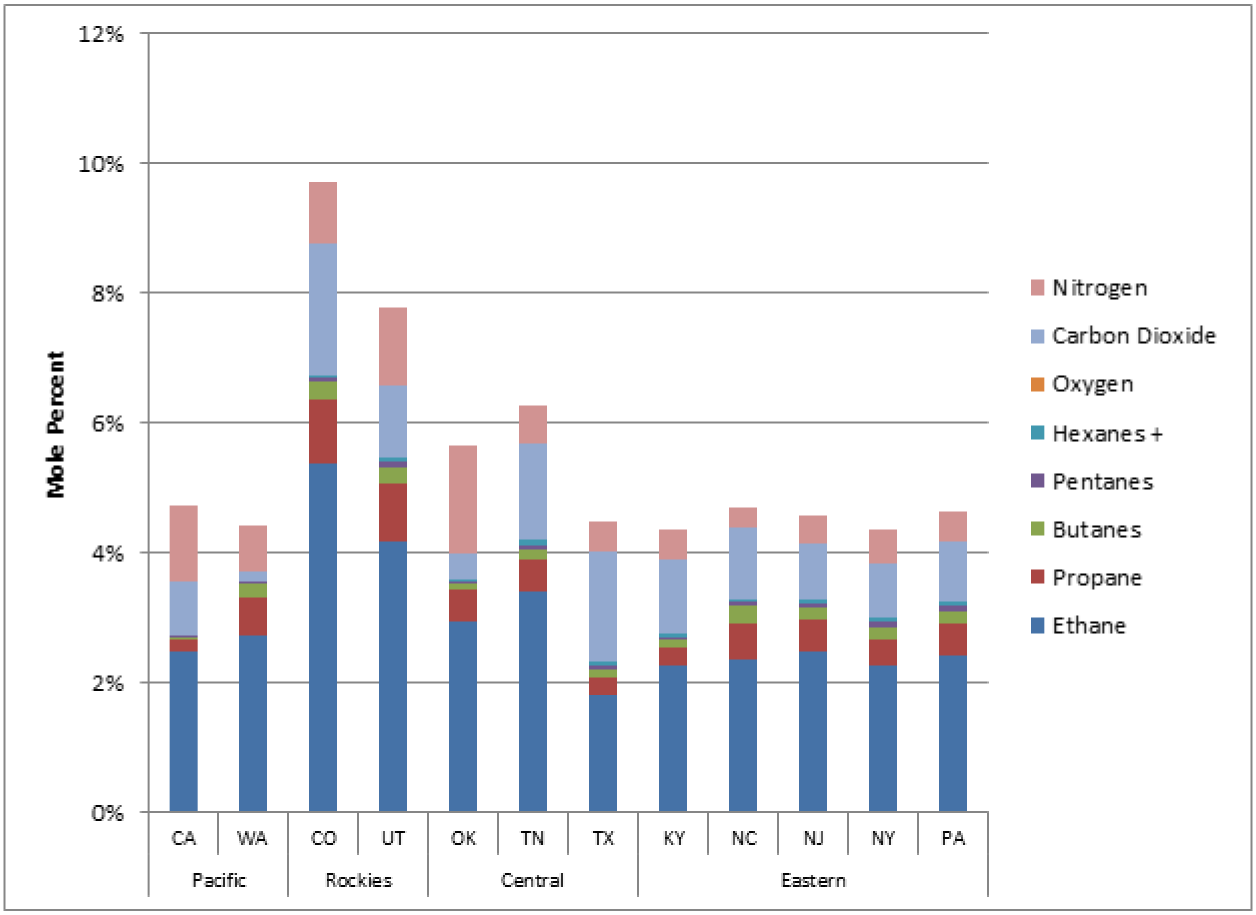

Figure A.3. Gas Components Reported in the 1995-96 NGC survey

All gas components' molar percentages are shown as averages per state. The remaining percentage of gas not shown is methane, which was excluded for clarity.

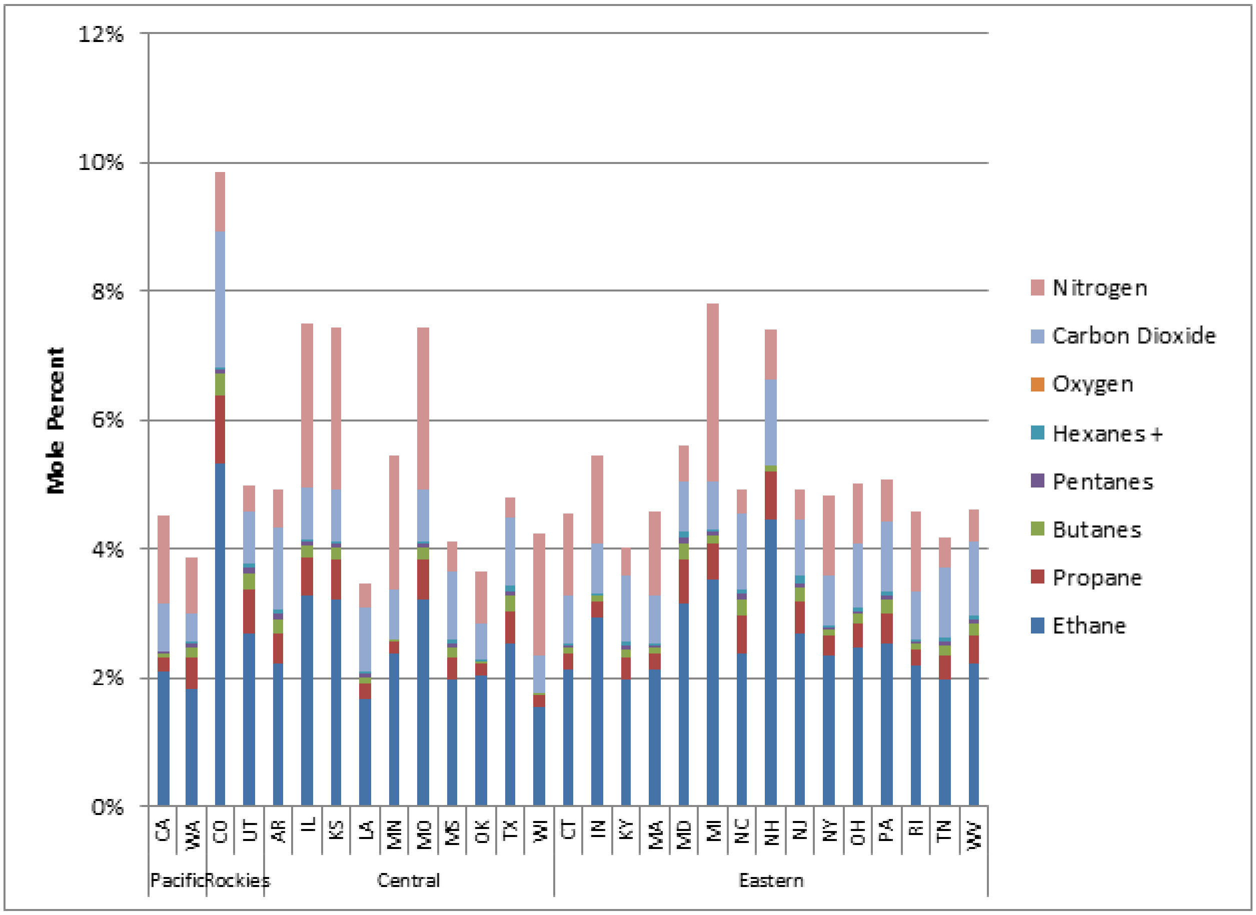

Figure A.4. Gas Components Reported in the 2002-03 NGC survey
All gas components' molar percentages are shown as averages per state. The remaining percentage of gas not shown is methane, which was excluded for clarity.

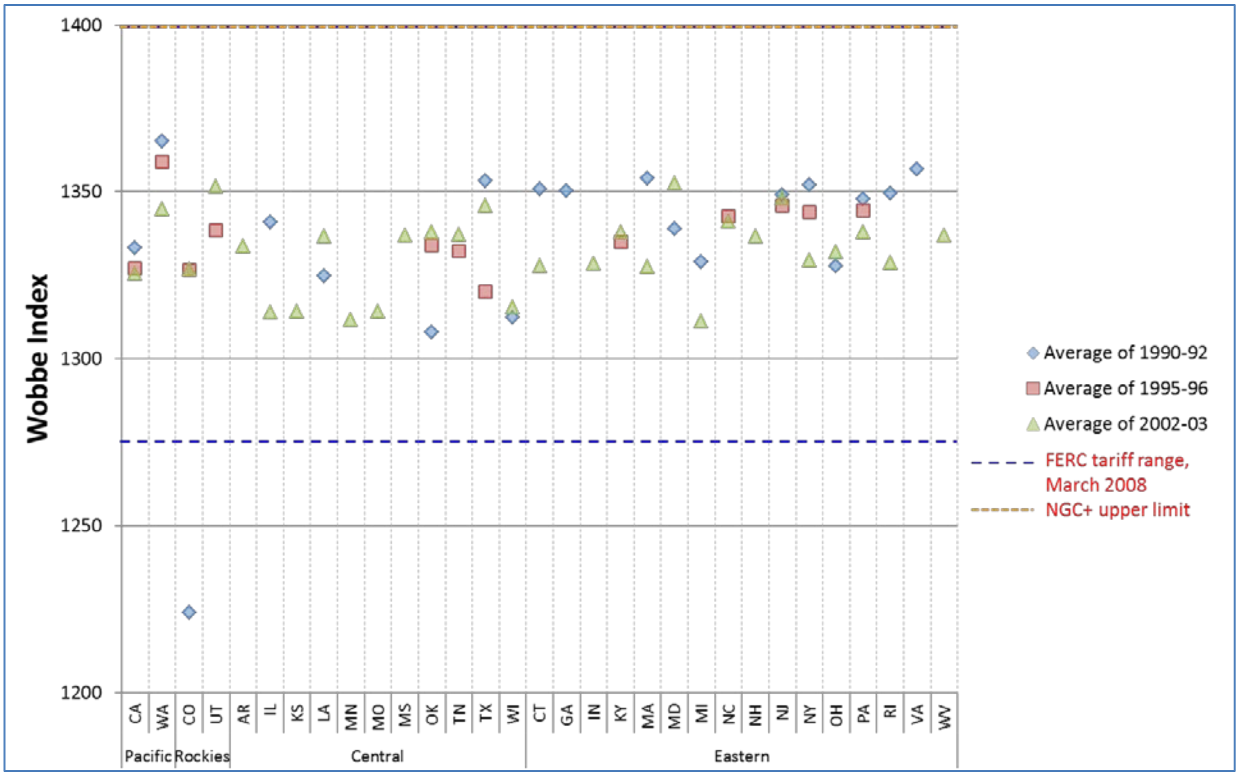

Figure A.5. Wobbe Index Averaged by State, 1990-2003

These numbers are averaged over several stations from each state from the GRI-92/0123 report and the NGC surveys. In the early '90s, the average Wobbe index in Colorado was particularly low. Many Wobbe indices in the east fell about 20 Btu/scf between 1990-92 and 2002-03. Typical Wobbe indices ranged from 1,310 to 1,370.

Table A.1. Wobbe Index Statistics by Region, 1990-2003

Each data point in this table is an annual average for a single measurement station, not a statewide average as in the preceding graph. Circled items are extreme values with a 95% confidence interval average outside of the FERC tariff range as of March 2008.

Region	Data Points	Average	Standard Deviation	Maximum	Minimum
Pacific	15	1336.9	14.50	1365.3	1300.9
Rockies	7	1287.9	60.40	1351.5	1218.9
Central	22	1330.5	15.97	1366.3	1308.0
Eastern	40	1341.1	15.09	1358.5	1274.9
All regions	84	1333.1	26.04	1366.3	1218.9

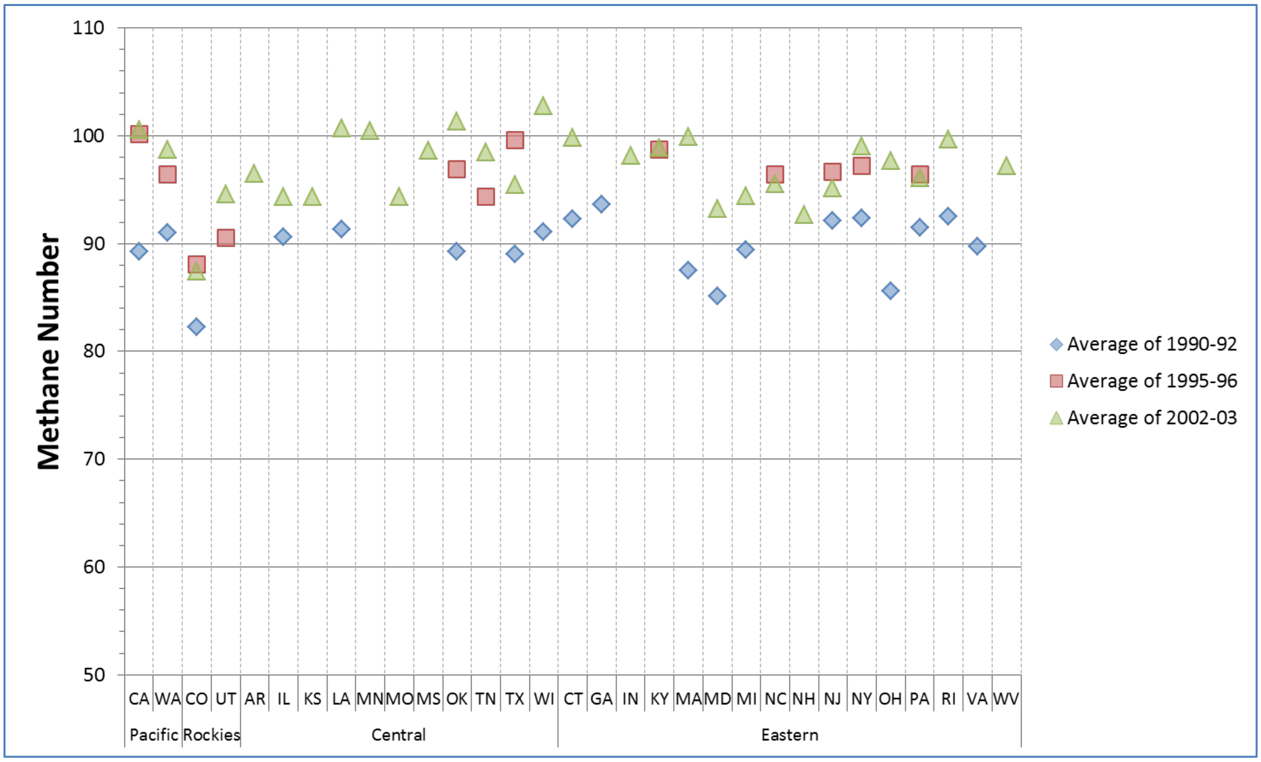

Figure A.6. Methane Number Averaged by State, 1990-2003

These numbers are averaged over several stations from each state from the GRI-92/0123 report and the NGC surveys. A general increase in methane number was seen nationwide between the 1990-92 study and the later surveys. This could be due to differences in calculations between the studies.

Table A.2. Methane Number Statistics by Region, 1990-2003

Each data point in this table is an annual average for a single measurement station, not a statewide average as in the preceding graph.

Region	Data Points	Average	Standard Deviation	Maximum	Minimum
Pacific	15	92.0	4.88	100.6	86.3
Rockies	7	86.8	4.83	94.6	81.6
Central	22	94.9	4.65	102.8	85.3
Eastern	40	92.8	7.42	99.9	53.6
All regions	84	92.7	6.44	102.8	53.6

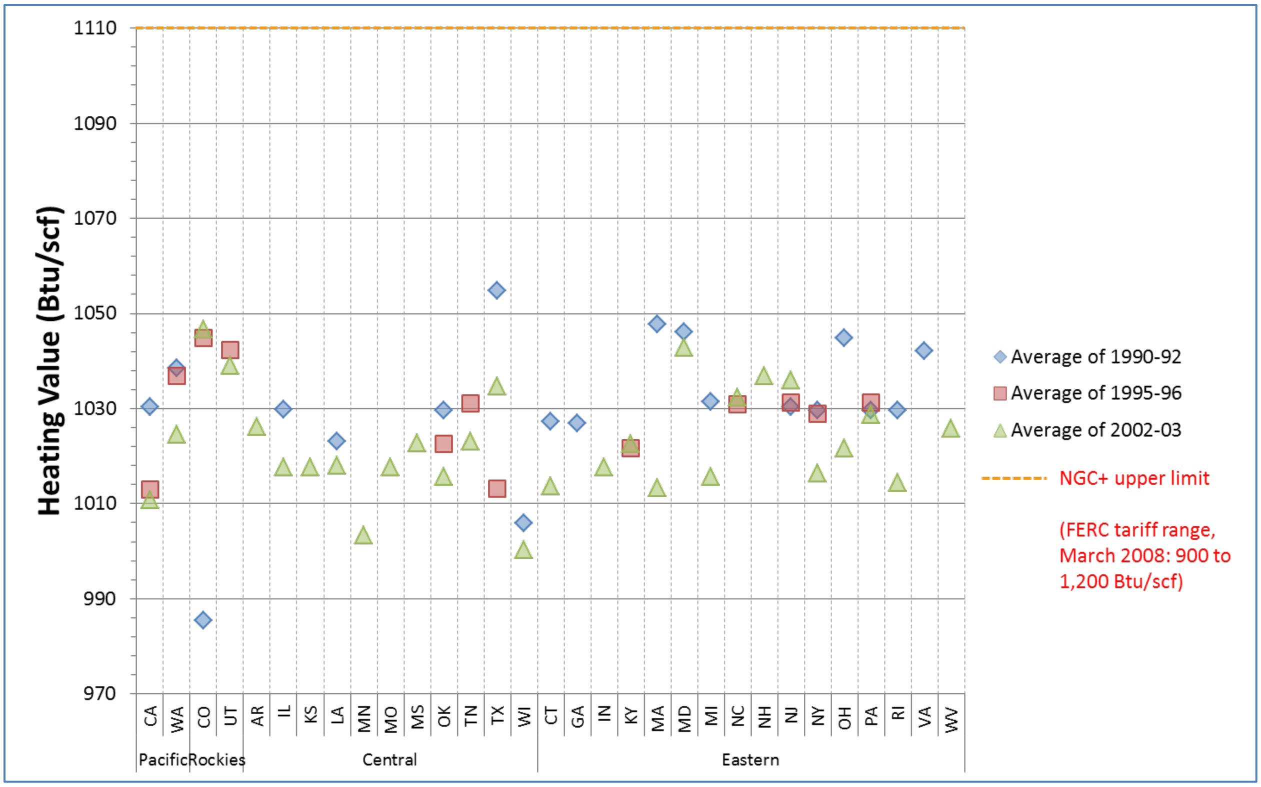

Figure A.7. Higher Heating Value Averaged by State, 1990-2003

These numbers are averaged over several stations from each state from the GRI-92/0123 report and the NGC surveys. Geographic variations in heating value appear to have narrowed after the 1990-92 study, with almost all subsequent gases falling between 1,000 and 1,050 Btu/scf.

Table A.3. Higher Heating Value Statistics by Region, 1990-2003

Each data point in this table is an annual average for a single measurement station, not a statewide average as in the preceding graph. No values fell outside of the FERC March 2008 tariff ranges or NGC+ guidelines.

Region	Data Points	Average	Standard Deviation	Maximum	Minimum
Pacific	15	1028.5	14.13	1048.4	995.3
Rockies	7	1018.5	31.15	1046.7	980.2
Central	22	1024.8	17.51	1081.2	1000.3
Eastern	40	1031.9	14.84	1102.3	1013.4
All regions	84	1028.3	17.39	1102.3	980.2

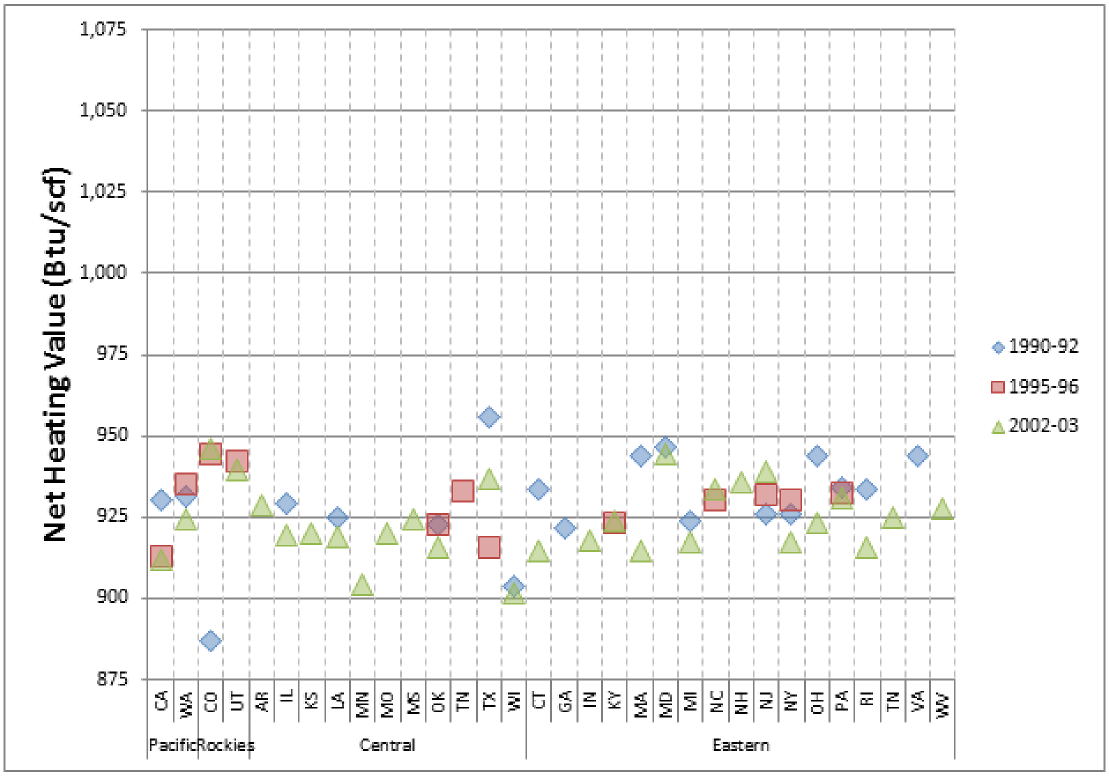

Figure A.8. Lower Heating Value Averaged by State, 1990-2003
These numbers are averaged over several stations from each state from the GRI-92/0123 report and the NGC surveys. Geographic variations in heating value appear to have narrowed after the 1990-92 study.

Table A.4. Lower Heating Value Statistics by Region, 1990-2003
Each data point in this table is an annual average for a single measurement station, not a statewide average as in the preceding graph.

Region	Data Points	Average	Standard Deviation	Maximum	Minimum
Pacific	15	927.8	12.88	946.1	900.1
Rockies	7	919.2	30.23	946.2	883.1
Central	21	925.7	18.87	985.1	901.5
Eastern	41	932.4	13.86	998.3	914.5
All regions	84	928.8	17.01	998.3	883.1

0

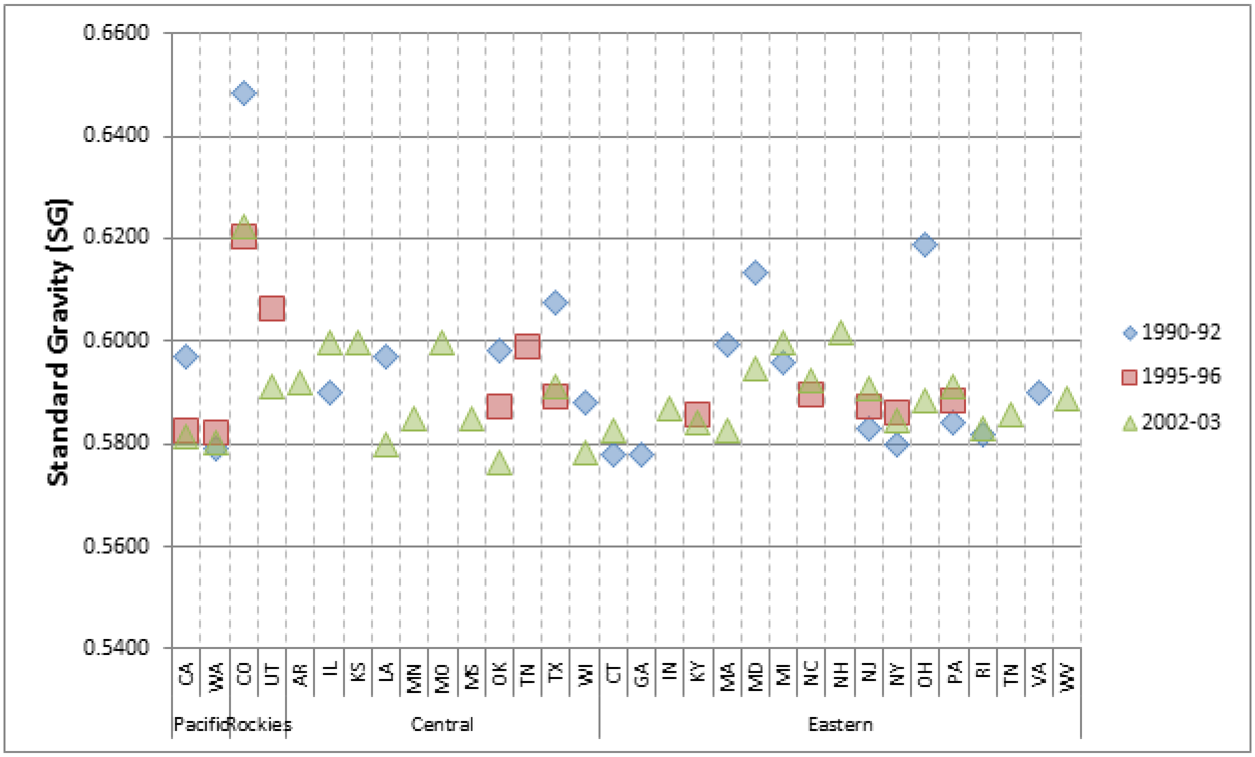

Figure A.9. Specific Gravity Value Averaged by State, 1990-2003
These numbers are averaged over several stations from each state from the GRI-92/0123 report and the NGC surveys. Geographic variations in heating value appear to have narrowed after the 1990-92 study.

Table A.5. Specific Gravity Statistics by Region, 1990-2003
Each data point in this table is an annual average for a single measurement station, not a statewide average as in the preceding graph.

Region	Data Points	Average	Standard Deviation	Maximum	Minimum
Pacific	15	0.5919	0.0111	0.6150	0.5790
Rockies	7	0.6265	0.0229	0.6510	0.5911
Central	22	0.5928	0.0123	0.6330	0.5764
Eastern	40	0.5923	0.0265	0.7500	0.5780
All regions	84	0.5952	0.0229	0.7500	0.5764

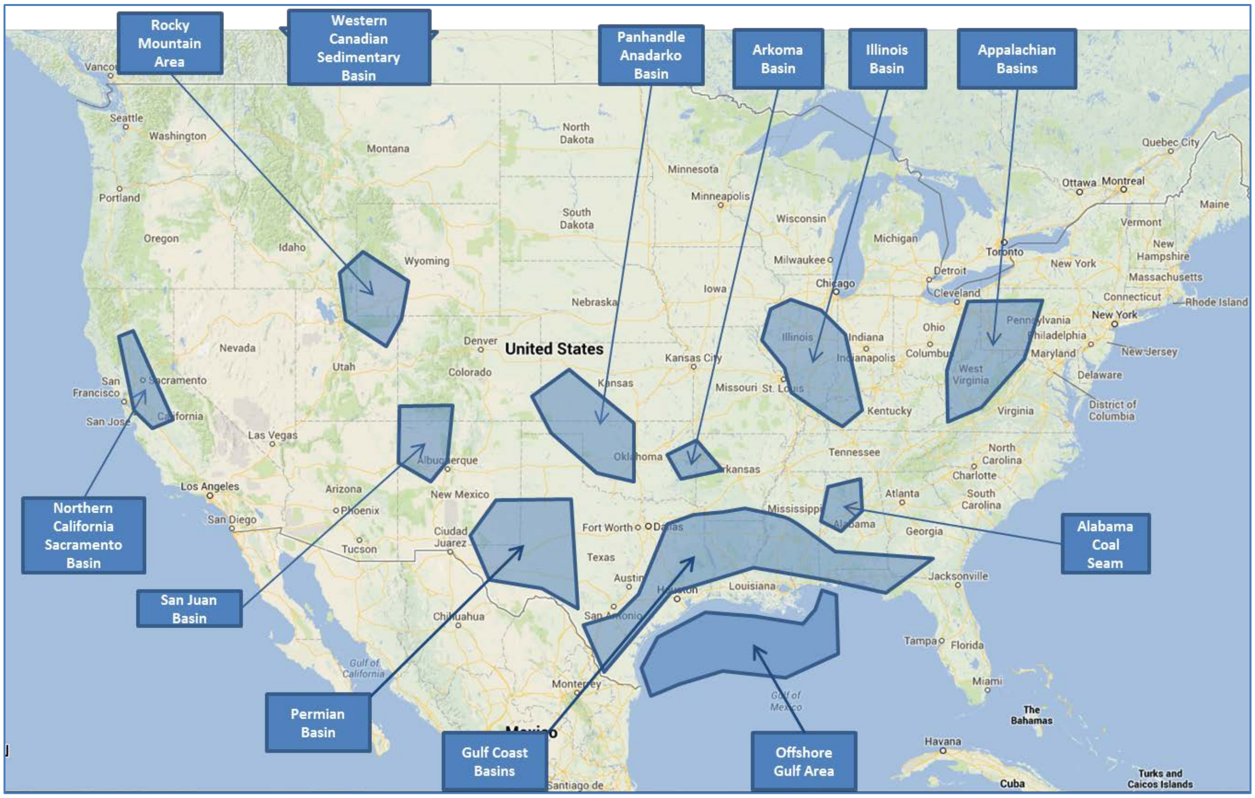

Figure A.10. Production Formations Listed in 1991-93 Sampling Survey
These are the natural gas formations that are the original sources for all natural gas analyzed in the GRI-94/0243.2 Report. Samples themselves were taken downstream from processing plants not located at the production gas formations.

Table A.6. Natural Gas Data by Production Formation
These data include 19 individual samples taken from 19 different pipelines. Blue, solid circles indicate an extreme value outside of the FERC tariff range as of March 2008. Red, dashed circles indicate values that exceed the NGC+ upper limit. At the time of t0he study, the leanest gases were found from the onshore Gulf Coast supplies, the Alabama coal seam reservoir, and the Sacramento basin. The Appalachian shale formation consistently produced the richest gases studied.

Property	Lowest value (source)	Highest value (source)
Gross heating value (Btu/scf)	982.8 (onshore Gulf Coast)	1187.2 (Appalachian shale formation)
Specific gravity (relative density)	0.5614 (Alabama coal seam)	0.6846 (Appalachian shale formation)
Wobbe index	1276 (onshore Gulf Coast)	1435 (Appalachian shale formation)
Methane number	66.2 (Appalachian shale formation)	108.1 (Alabama coal seam)

A-2. Summarized Online Gas Quality Data for All Providers

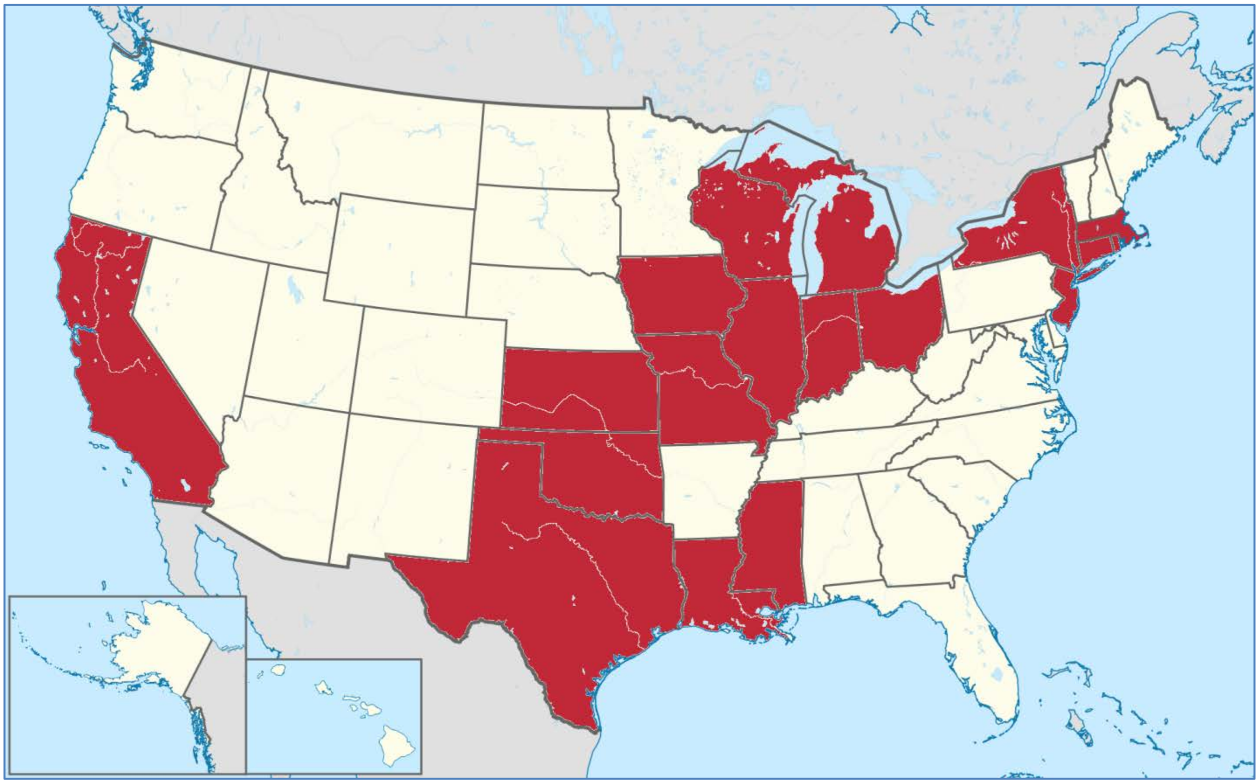

Figure A.11. States Included in the Online Daily Gas Quality Dataset, February – May 2013
The states highlighted in red were included in the daily online data collected from various suppliers between February and May of 2013.

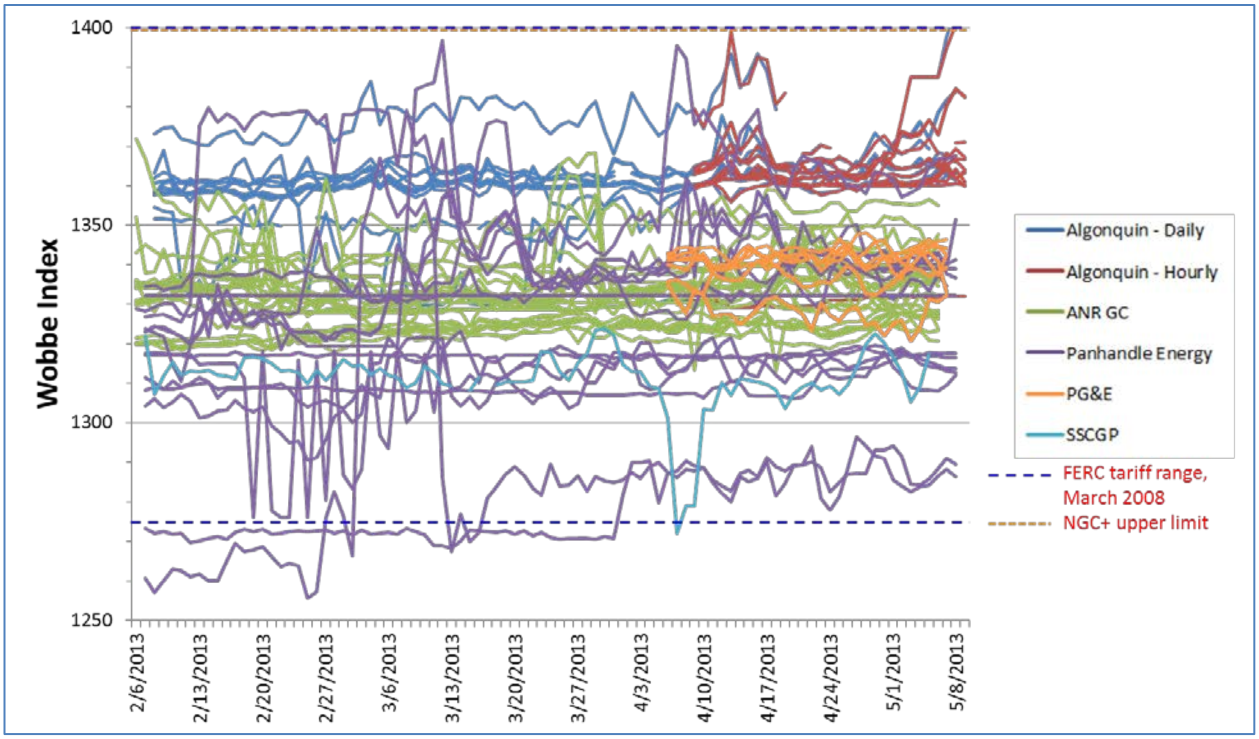

Figure A.12. Daily Wobbe Indices Among All Pipelines, February – May 2013
The Wobbe indices from all online sources are plotted above with the FERC and NGC+ guidelines for reference. Note the geographical differences in Wobbe indices between pipelines (Algonquin versus ANR, for example). Across all pipelines studied, Wobbe indices ranged from 1,250 to 1,400.

Table A.7. Wobbe Index Statistics by Pipeline, February – May 2013
Each data point in this table is a daily average for a single measurement station on the pipeline. Blue, solid circles indicate items that are extreme values with a 95% confidence interval average outside of the FERC tariff range as of March 2008. Red, dashed circles indicate items that exceed the NGC+ upper limit.

Pipeline	Data Points	Average	Standard Deviation	Maximum	Minimum
Algonquin - Daily	1,193	1360.6	8.81	1404.7	1329.2
Algonquin - Hourly	8,969	1362.7	9.91	1407.4	1329.1
ANR GC	2,226	1331.8	8.49	1371.8	1313.2
Panhandle Energy	1,119	1321.1	25.53	1396.8	1255.5
PG&E	224	1339.3	5.52	1348.1	1320.7
SSCGP	86	1311.1	7.94	1323.9	1272.1
All pipelines	13,817	1353.5	19.24	1407.4	1255.5

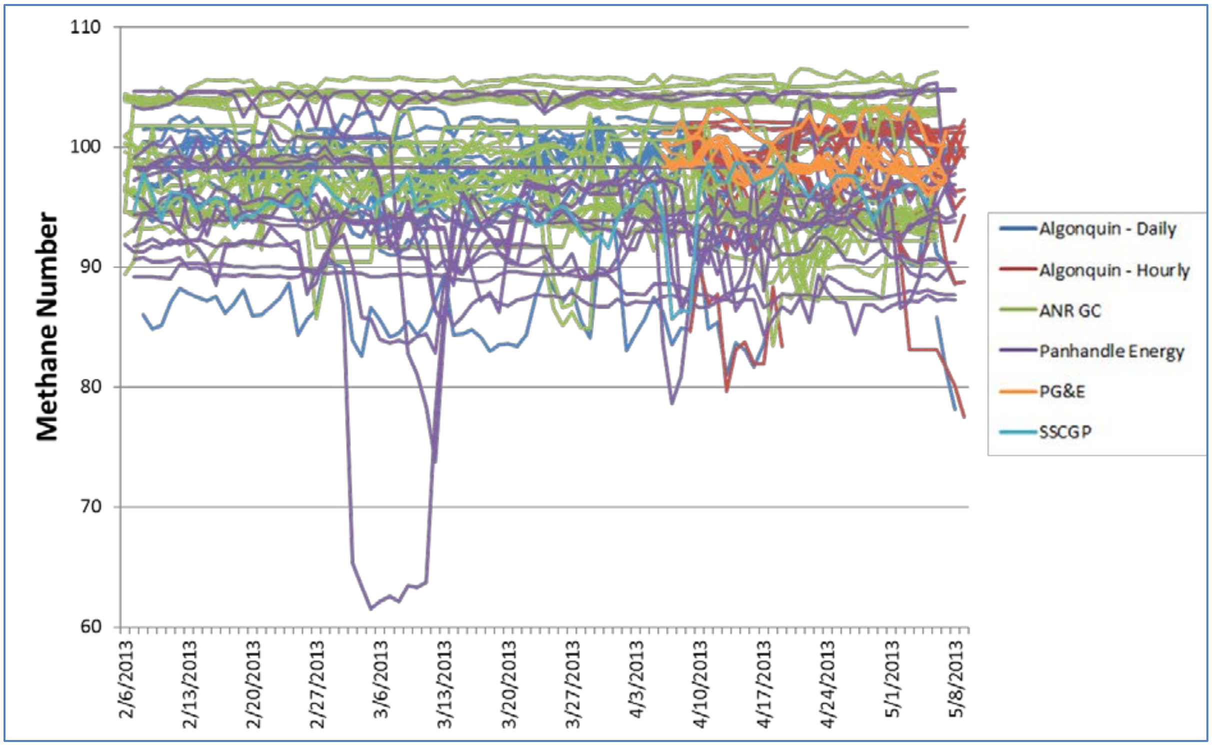

Figure A.13. Daily Methane Numbers Among All Pipelines, February – May 2013
The Wobbe indices from all online sources are plotted above. The majority of methane numbers span a range from the low 80s to approximately 105. However, a few values below 80 were witnessed in the Panhandle Energy dataset.

Table A.8. Methane Number Statistics by Pipeline, February – May 2013
Each data point in this table is an average for a single measurement station on the pipeline.

Pipeline	Data Points	Average	Standard Deviation	Maximum	Minimum
Algonquin - Daily	1,193	97.6	4.02	103.3	78.2
Algonquin - Hourly	8,969	98.4	4.28	102.5	71.3
ANR GC	2,226	99.2	4.65	106.5	83.5
Panhandle Energy	1,119	94.1	5.90	105.3	61.5
PG&E	224	99.0	1.57	103.4	96.0
SSCGP	86	95.4	2.28	98.8	85.7
All pipelines	13,817	98.1	4.61	106.5	61.5

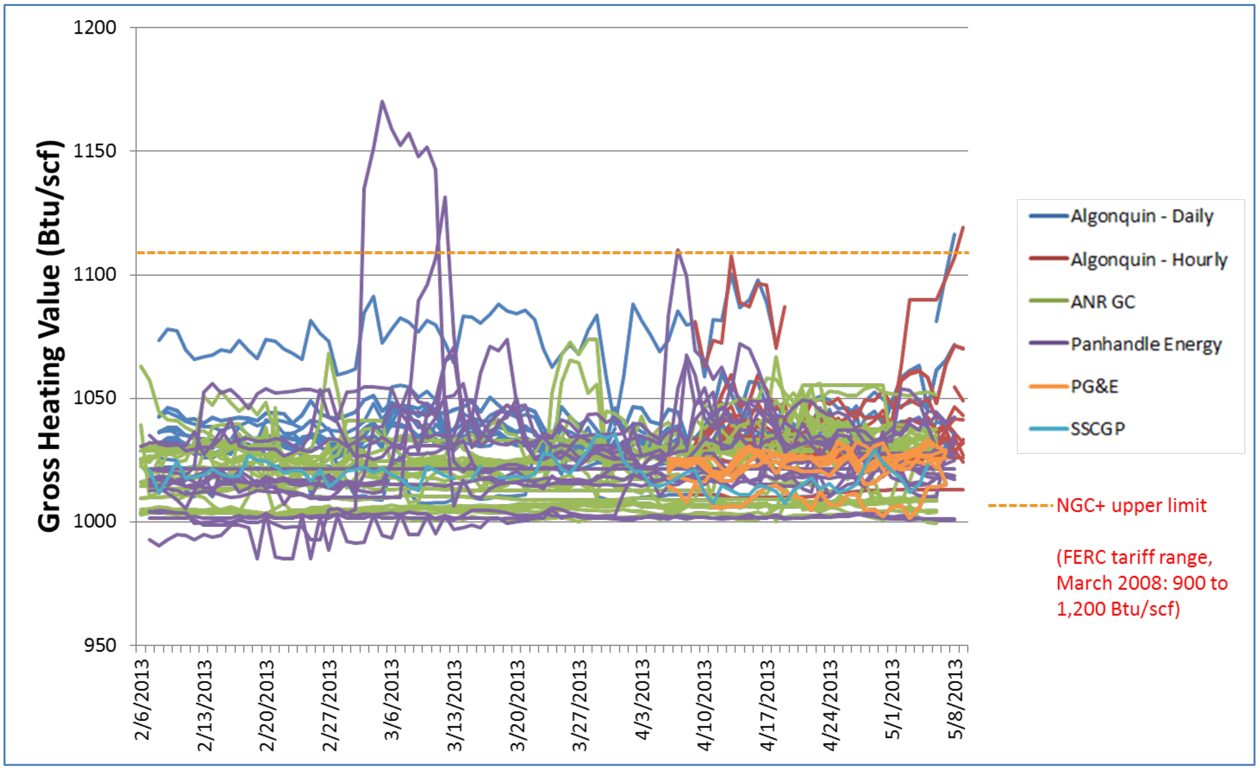

Figure A.14. Daily Higher Heating Values (Btu/scf) Among All Pipelines, February – May 2013
The gross heating values in Btu/scf from all online sources are plotted above. Note that all data points fell well within the FERC tariff range, but a few exceeded the NGC+ upper limit.

Table A.9. Higher Heating Value Statistics by Pipeline, February – May 2013
Each data point in this table is an average for a single measurement station on the pipeline. Red, dashed circles indicate items that exceed the NGC+ upper limit.

Pipeline	Data Points	Average	Standard Deviation	Maximum	Minimum
Algonquin - Daily	1,193	1036.0	13.94	1116.4	1007.6
Algonquin - Hourly	8,969	1035.2	15.26	1122.8	1009.4
ANR GC	2,226	1018.6	12.84	1074.0	999.3
Panhandle Energy	1,119	1023.6	20.32	1170.2	985.2
PG&E	224	1022.3	6.50	1033.1	1001.5
SSCGP	86	1019.0	5.49	1035.5	1007.4
All pipelines	13,817	1031.3	16.54	1170.2	985.2

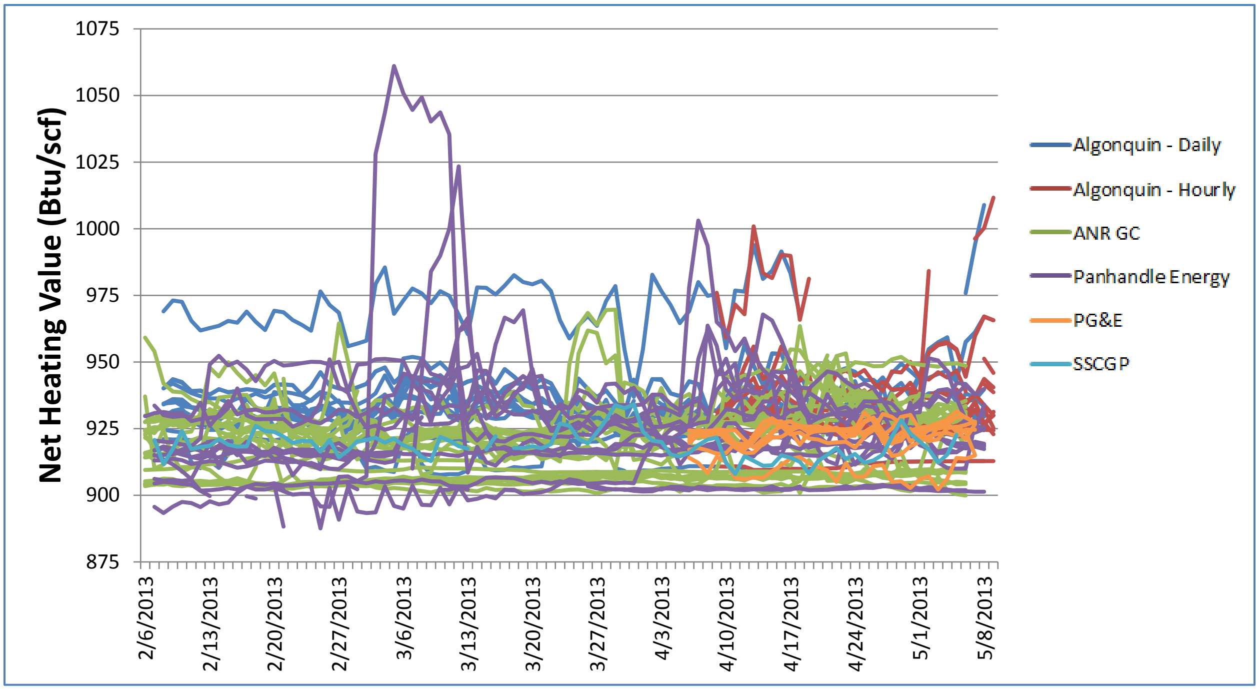

Figure A.15. Daily Lower Heating Values Among All Pipelines, February – May 2013

The net heating values in Btu/scf from all online sources are plotted above. The spikes in gross heating value are reflected in corresponding spikes in net heating value, as would be expected.

Table A.10. Lower Heating Value Statistics by Pipeline, February – May 2013

Each data point in this table is an average for a single measurement station on the pipeline. Panhandle Energy had the largest variation, encompassing the maximum and minimum values of the dataset. Algonquin had the highest average net heating value at approximately 930 Btu/scf.

Pipeline	Data Points	Average	Standard Deviation	Maximum	Minimum
Algonquin - Daily	1,193	933.7	13.10	1008.9	907.7
Algonquin - Hourly	8,969	933.2	14.19	1016.0	909.4
ANR GC	2,226	918.0	12.04	969.7	899.9
Panhandle Energy	1,119	923.1	18.82	1061.1	887.6
PG&E	224	921.4	6.01	931.5	902.2
SSCGP	86	918.8	5.10	934.1	908.0
All pipelines	13,817	929.7	15.33	1061.1	887.6

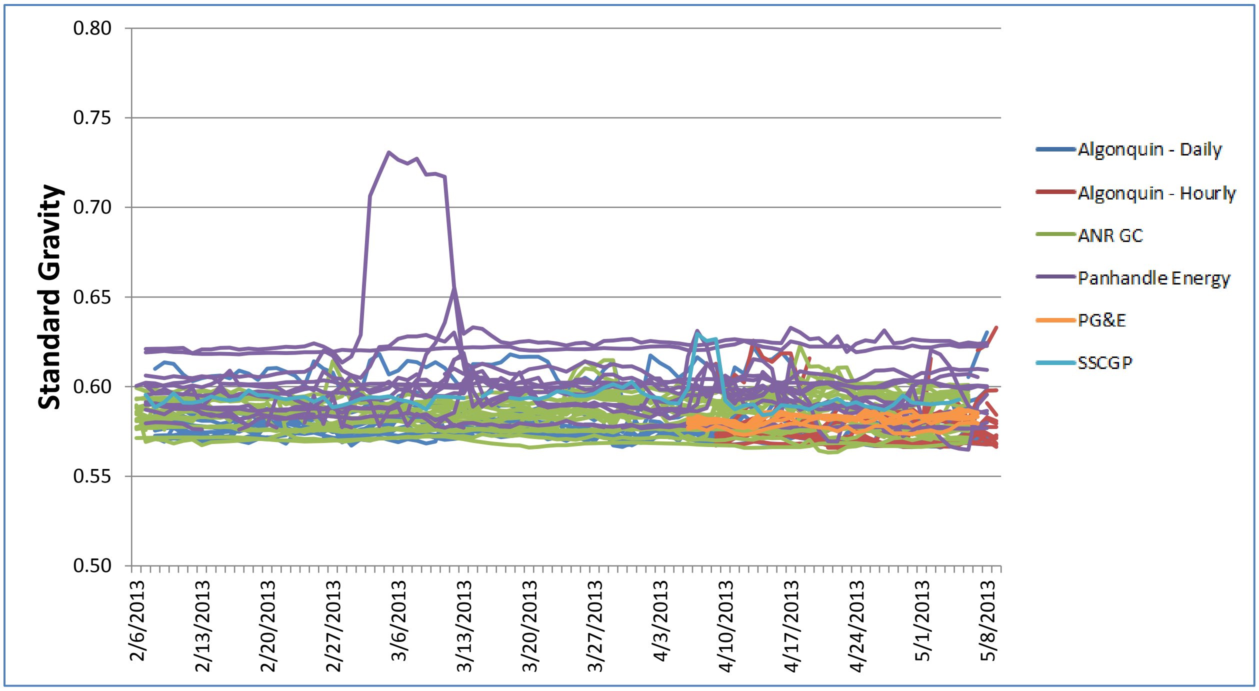

Figure A.16. Daily Specific Gravity Values Among All Pipelines, February – May 2013
The standard gravity values from all online sources are plotted above. Standard gravity is generally steady amongst all pipelines; however, the spikes in other properties are reflected here as well.

Table A.11. Specific Gravity Statistics by Pipeline, February – May 2013
Each data point in this table is an average for a single measurement station on the pipeline. Panhandle Energy had the largest variation, and had the highest average value. Algonquin had the lowest average gravity at approximately 0.577.

Pipeline	Data Points	Average	Standard Deviation	Maximum	Minimum
Algonquin - Daily	1,193	0.5798	0.0101	0.6317	0.5669
Algonquin - Hourly	8,969	0.5771	0.0107	0.6682	0.5661
ANR GC	2,226	0.5849	0.0092	0.6240	0.5641
Panhandle Energy	1,119	0.6006	0.0183	0.7327	0.5658
PG&E	224	0.5826	0.0031	0.5888	0.5740
SSCGP	86	0.6042	0.0074	0.6402	0.5943
All pipelines	13,817	0.5808	0.0131	0.7327	0.5641

A-3. Summarized Current Gas Quality Data for Each Provider Studied

A-3-1. Algonquin Summary

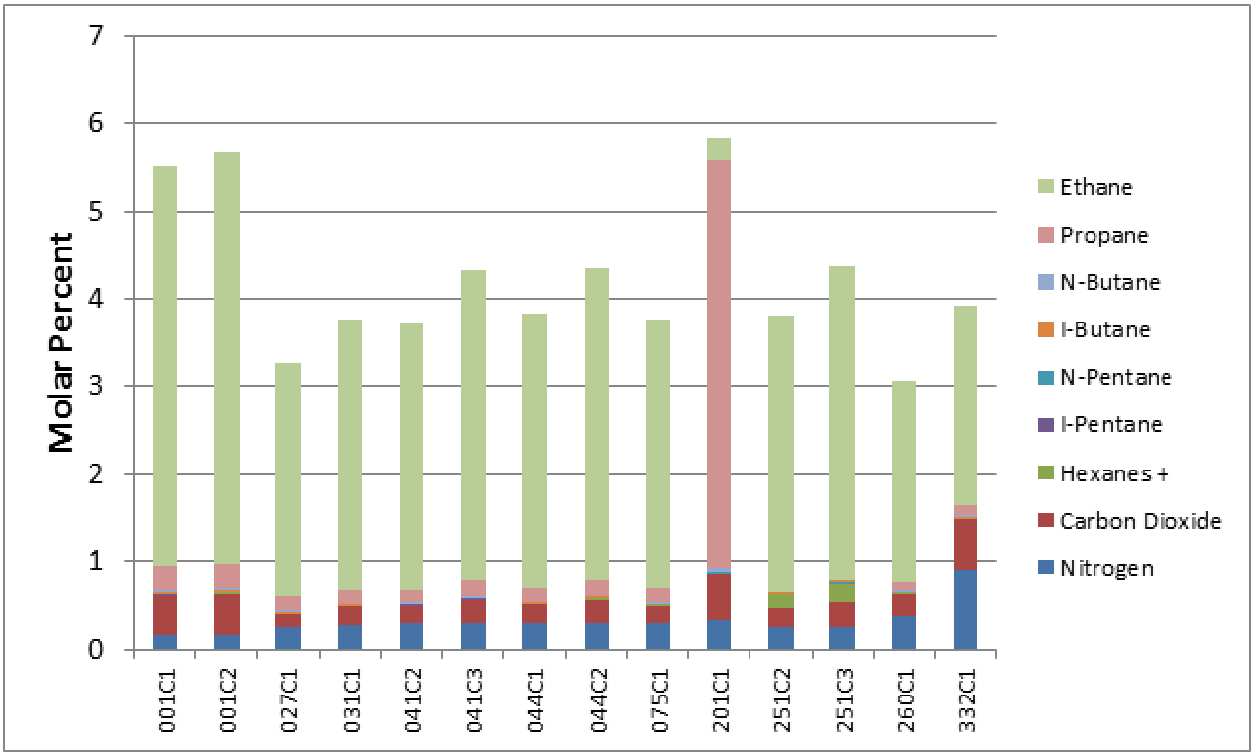

Figure A.17. Average Gas Components Reported in Algonquin Online Daily Postings
All gas components' molar percentages are shown as averages per location over the entire period of February – May 2013. The remaining percentage of gas not shown is methane, which was excluded for clarity.

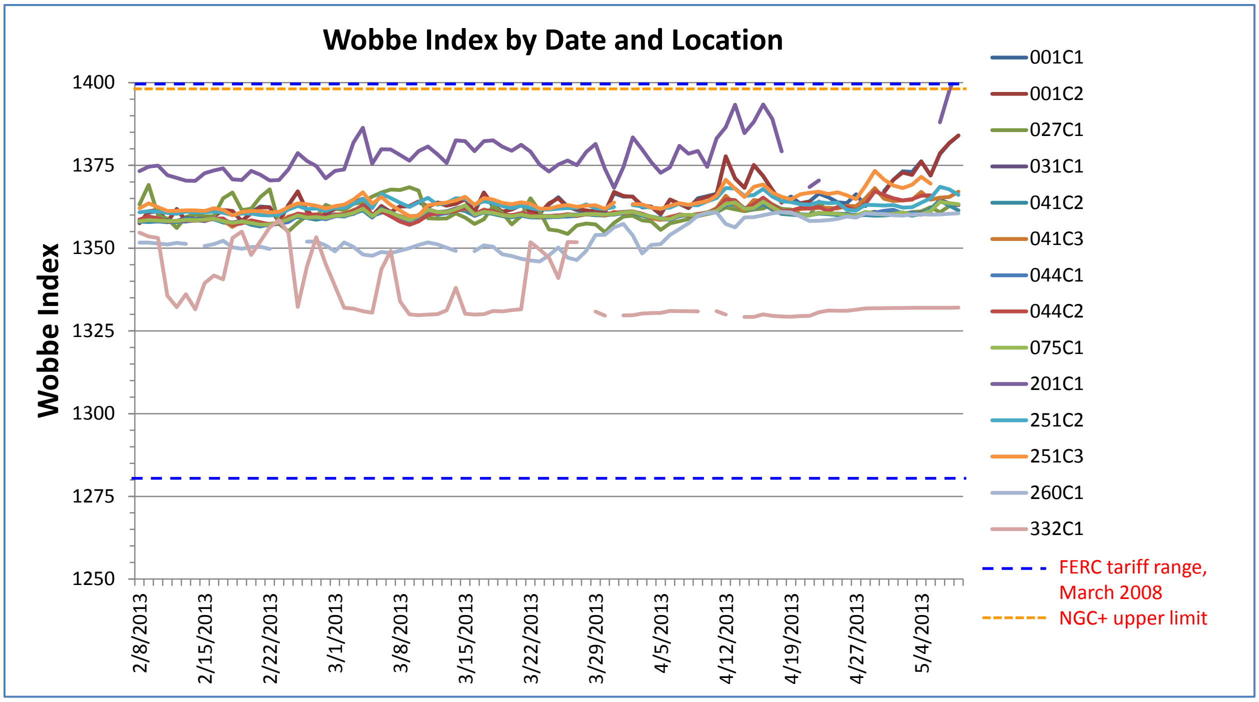

Figure A.18. Wobbe Indices in Algonquin Gas Transmission Daily Postings
This illustrates the Wobbe indices at various locations as per daily averages. Locations are in New Jersey, New York, Connecticut, Rhode Island, and Maryland. FERC and NGC+ limits are shown for reference.

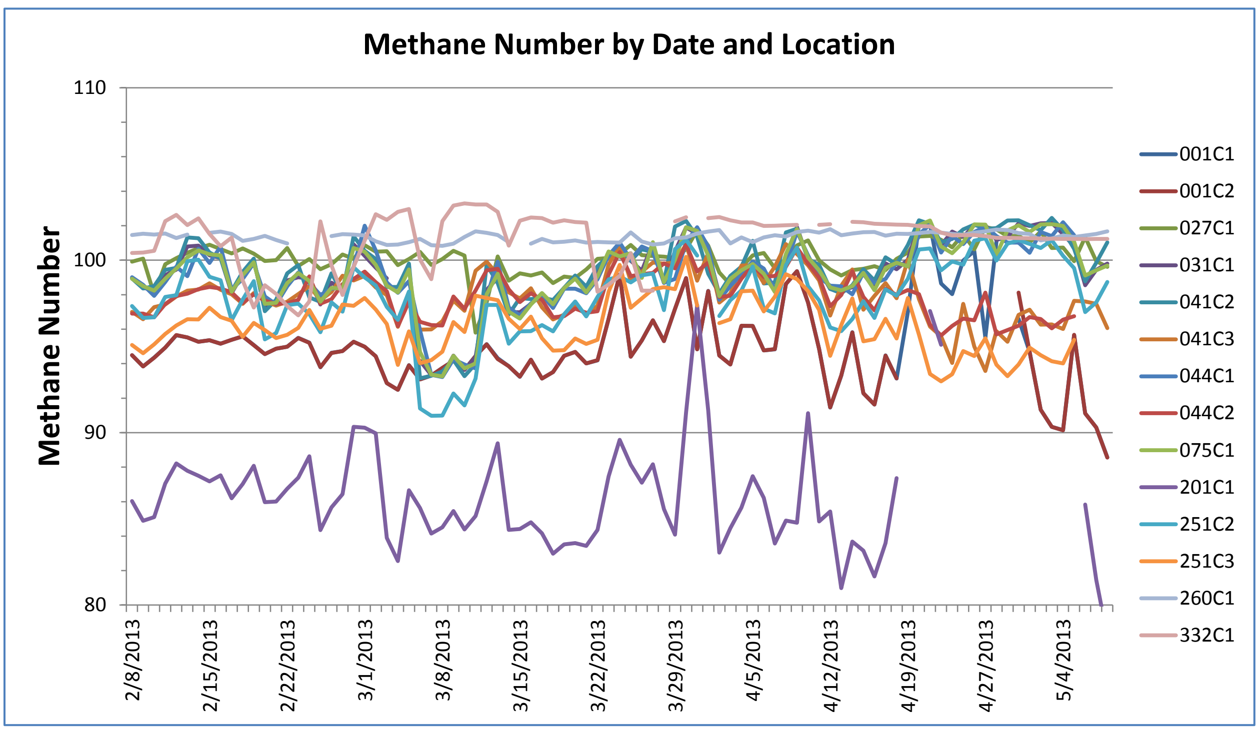

Figure A.19. Methane Numbers in Algonquin Gas Transmission Daily Postings
This illustrates the methane numbers at various locations as per daily averages. Locations are in New Jersey, New York, Connecticut, Rhode Island, and Maryland.

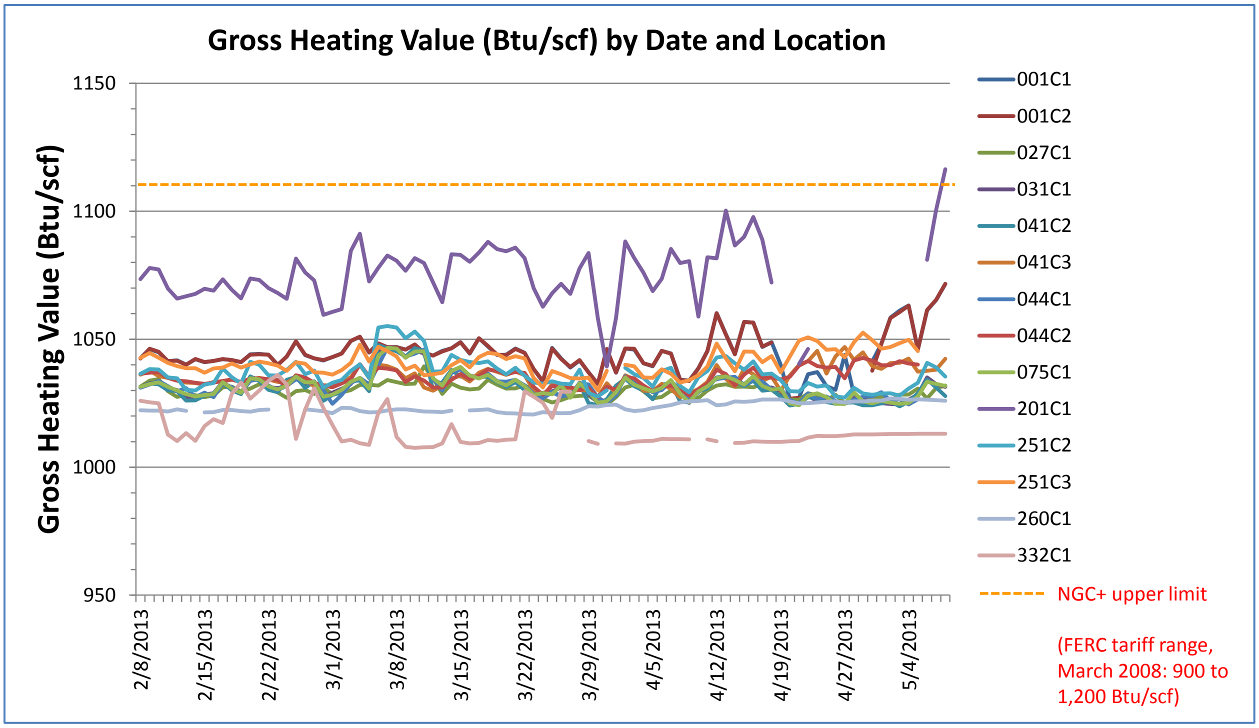

Figure A.20. Higher Heating Values in Algonquin Gas Transmission Daily Postings
This illustrates the gross heating values in Btu/scf at various locations as per daily averages. Locations are in New Jersey, New York, Connecticut, Rhode Island, and Maryland.

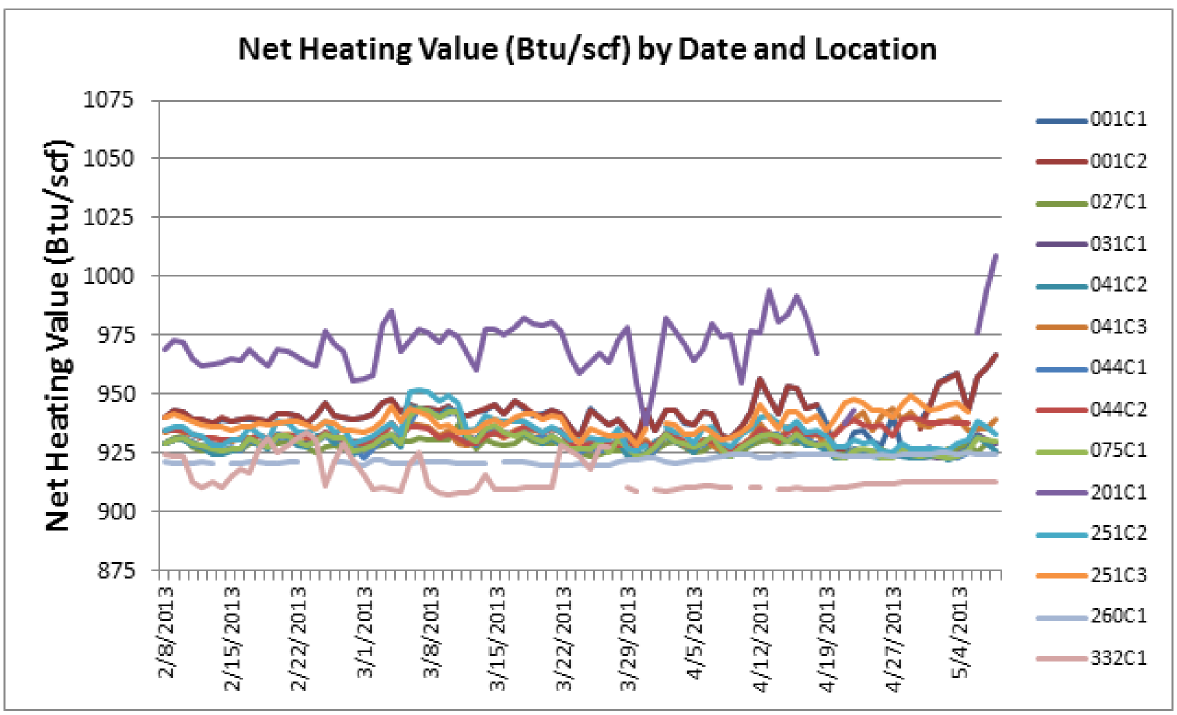

Figure A.21. Higher Heating Values in Algonquin Gas Transmission Daily Postings
This illustrates the net heating value, also known as the lower heating value (LHV). The sharp increase near the end of the gross heating value plot is reflected here as well.

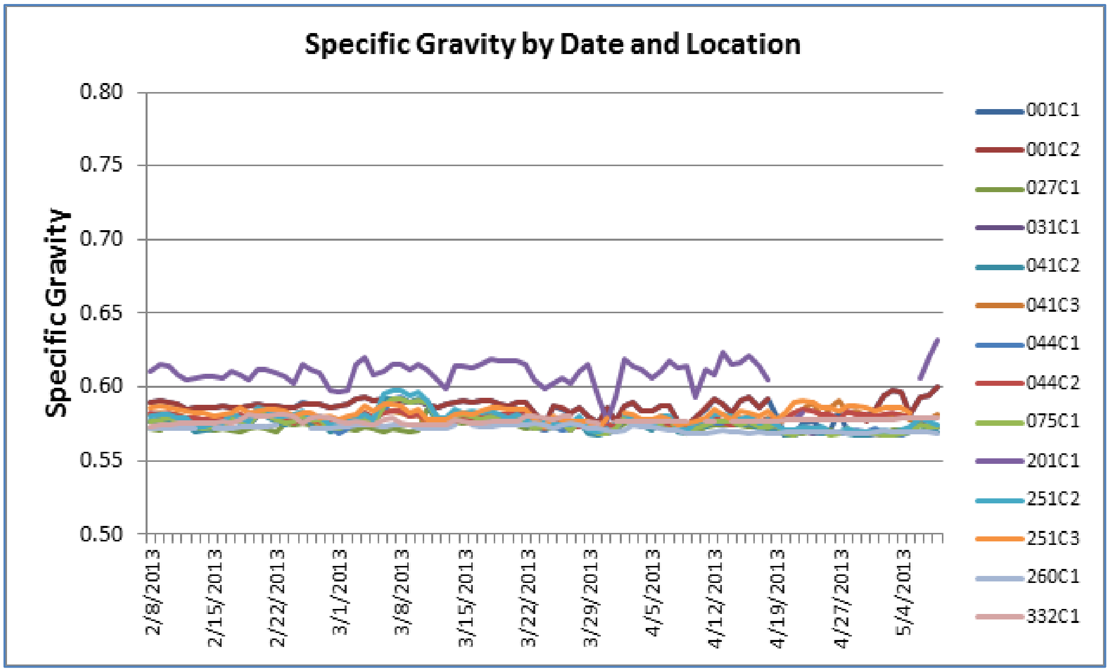

Figure A.22. Specific Gravity Values in Algonquin Gas Transmission Daily Postings
This illustrates the standard gravity of the Algonquin data. Station 201C1 consistently had higher specific gravity values than all other stations.

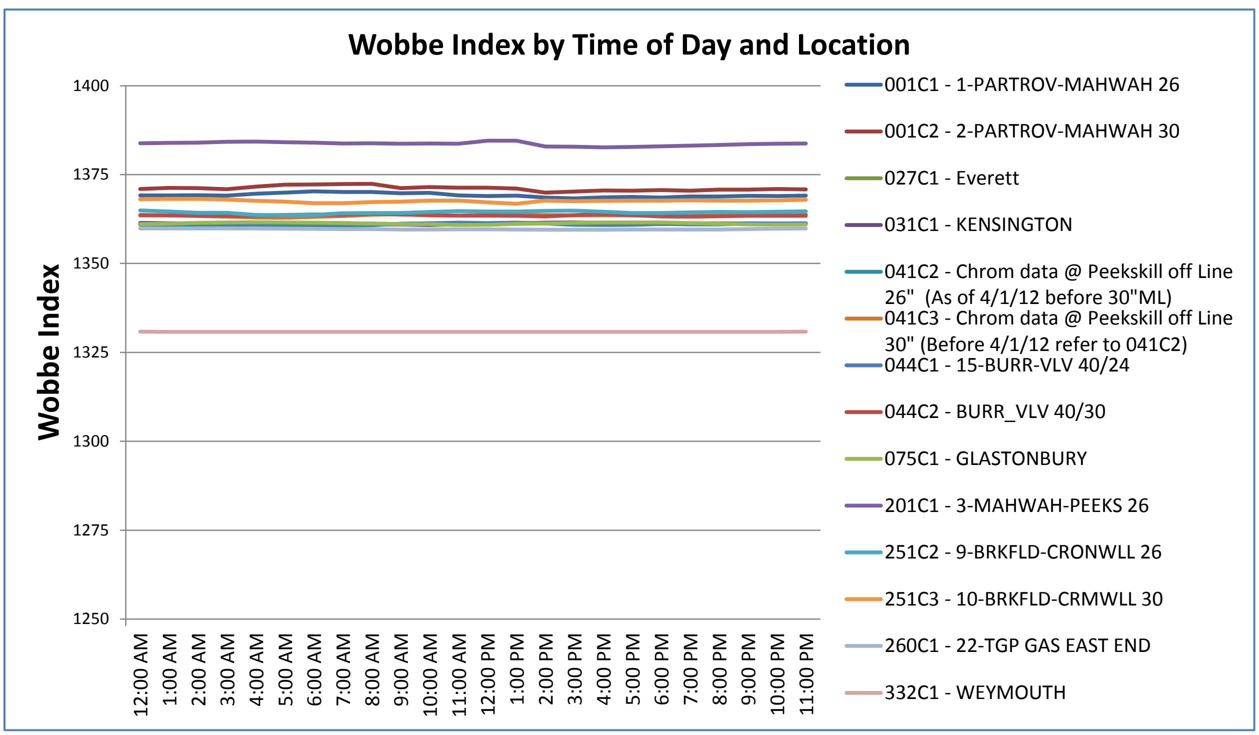

Figure A.23. Wobbe Indices in Algonquin Hourly Transmission Postings
This is the average of all of the hourly postings from April 6 to May 16, averaged by time of day. It illustrates that there is no detectable trend based on time of day, based on the data collected. Methane numbers and gross heating values also did not show any noticeable trends.

A-3-2. ANR Pipeline Summary

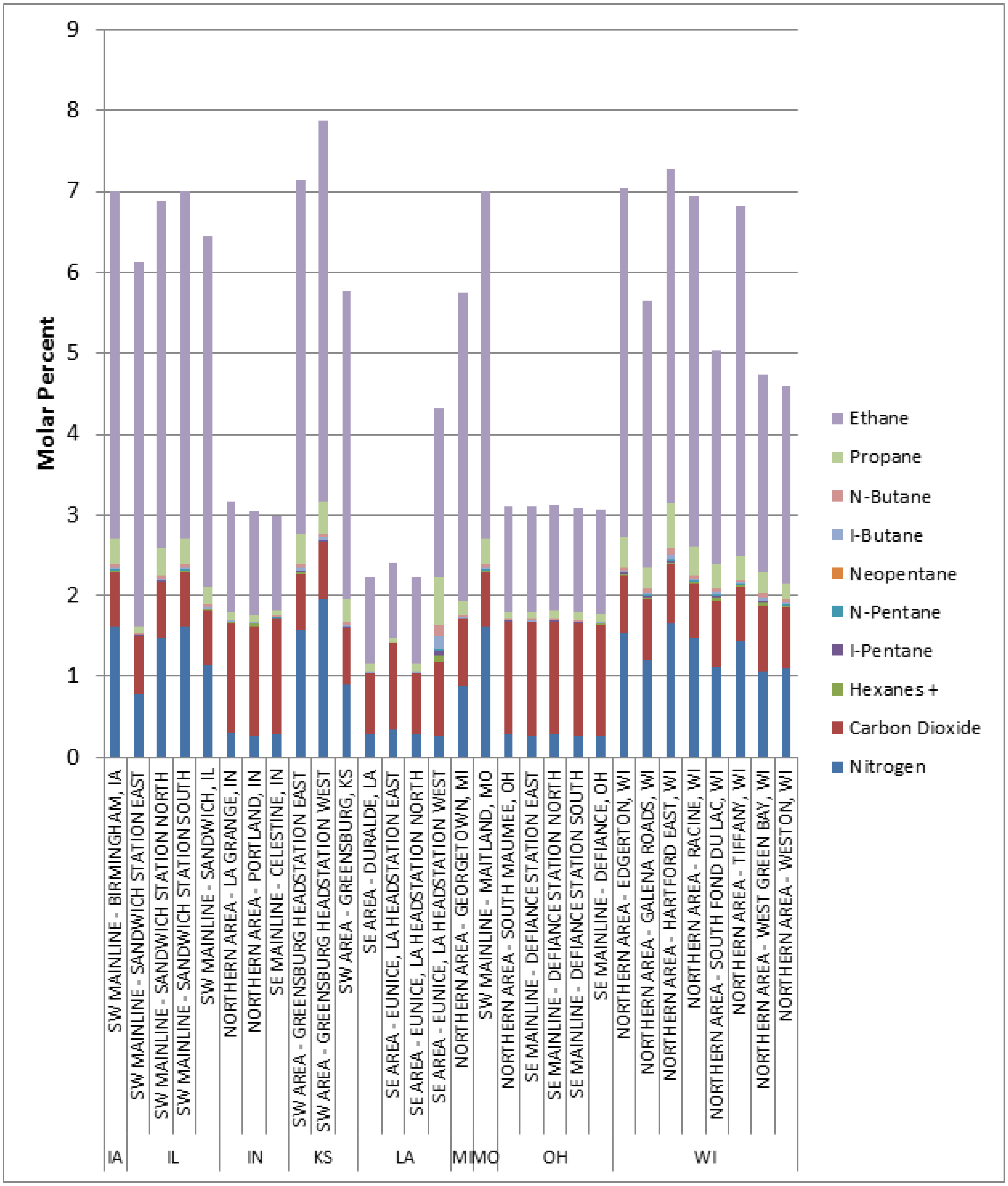

Figure A.24. Average Gas Components Reported in ANR Online Daily Postings

All gas components' molar percentages are shown as averages per location over the entire period of February – May 2013. The remaining percentage of gas not shown is methane, which was excluded for clarity.

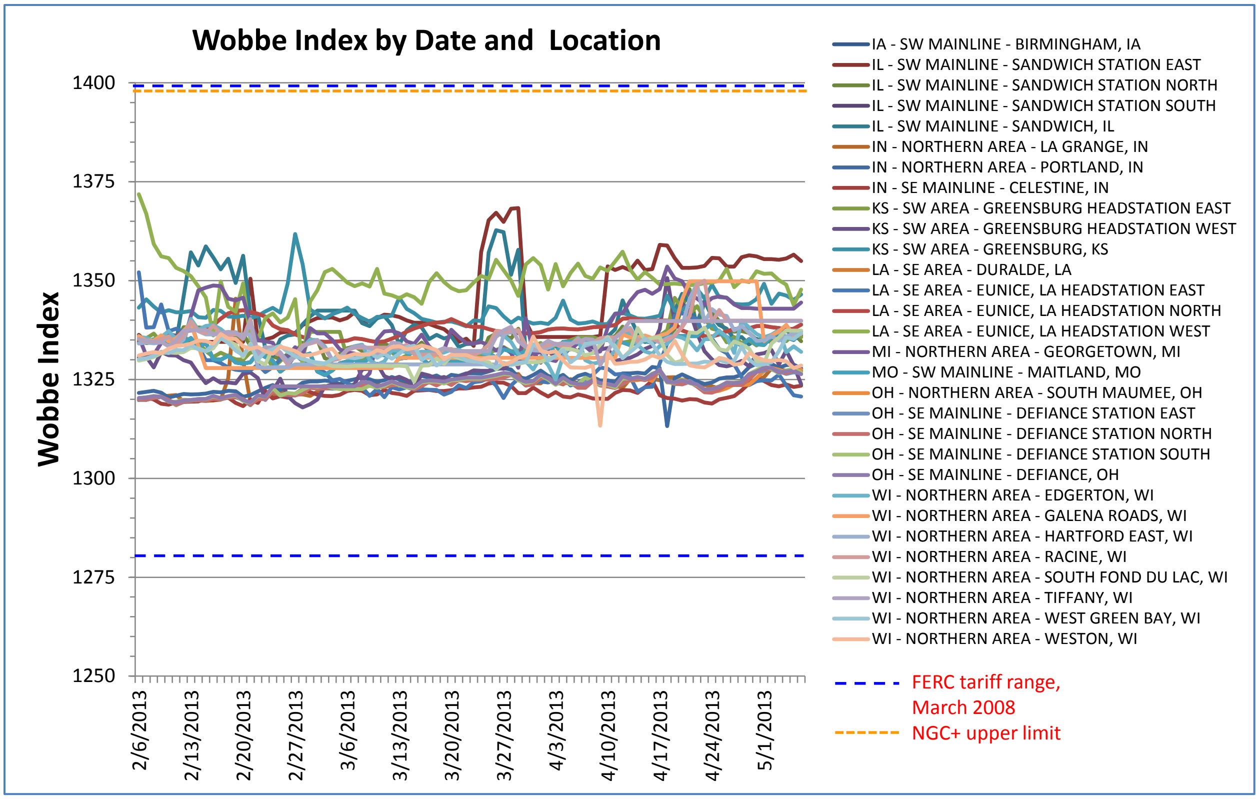

Figure A.25. Wobbe Indices in ANR Pipelines

This illustrates the Wobbe indices at various locations as per day averages. Locations are in Iowa, Illinois, Indiana, Kansas, Louisiana, Mississippi, Missouri, Ohio, and Wisconsin. FERC and NGC+ limits are shown for reference.

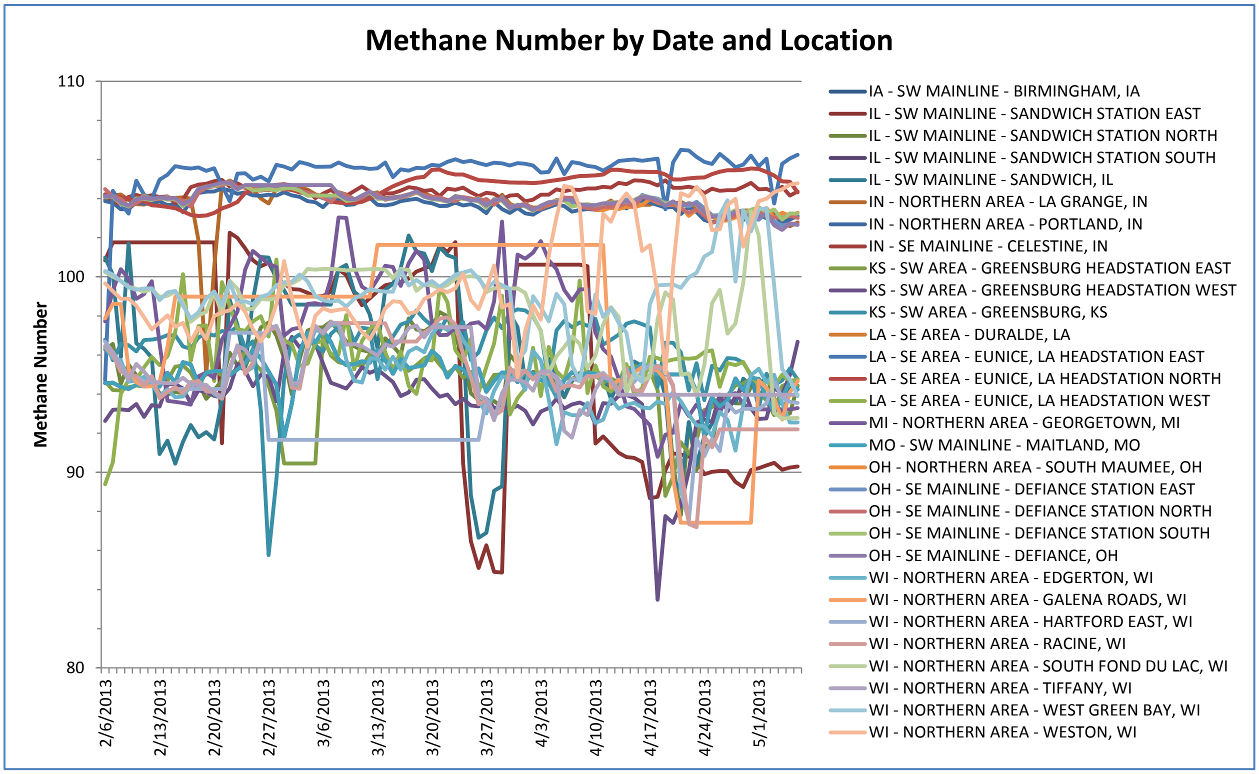

Figure A.26. Methane Numbers in ANR Pipelines

This illustrates the methane numbers measured at various locations as per day averages. Locations are in Iowa, Illinois, Indiana, Kansas, Louisiana, Mississippi, Missouri, Ohio, and Wisconsin.

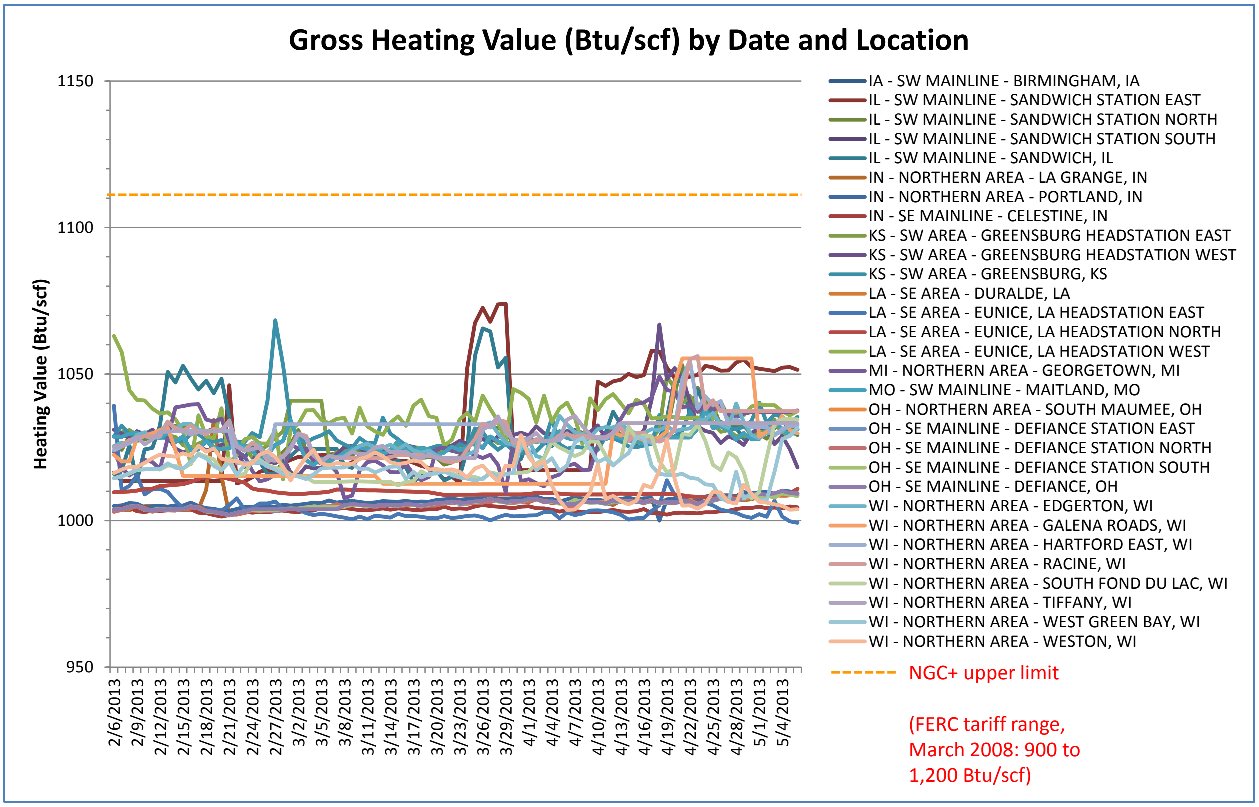

Figure A.27. Gross Heating Values in ANR Pipelines

This illustrates the gross heating values in Btu/scf at various locations as per day averages. Locations are in Iowa, Illinois, Indiana, Kansas, Louisiana, Mississippi, Missouri, Ohio, and Wisconsin. The NGC+ upper limit is shown for reference.

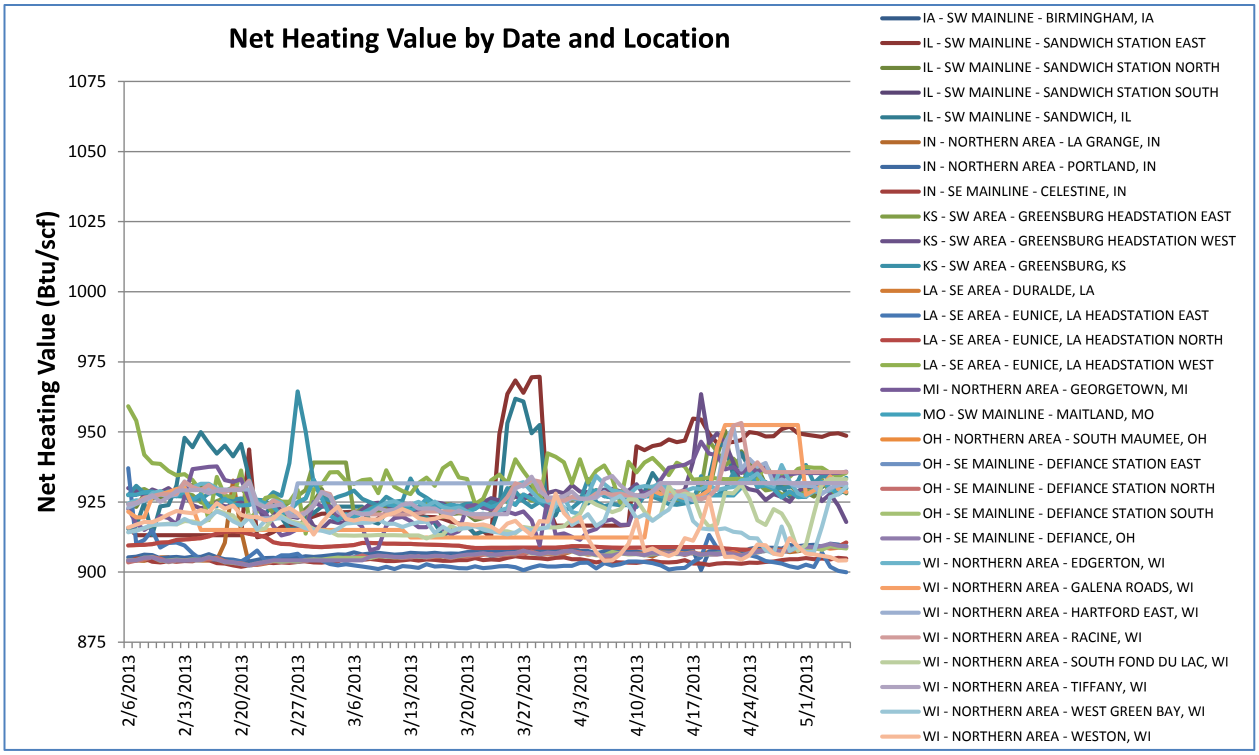

Figure A.28. Net Heating Values in ANR Pipelines

This illustrates the net, or lower, heating values in the ANR online postings. The spikes visible in the Sandwich, IL stations are again reflected in these postings. Locations are in Iowa, Illinois, Indiana, Kansas, Louisiana, Mississippi, Missouri, Ohio, and Wisconsin.

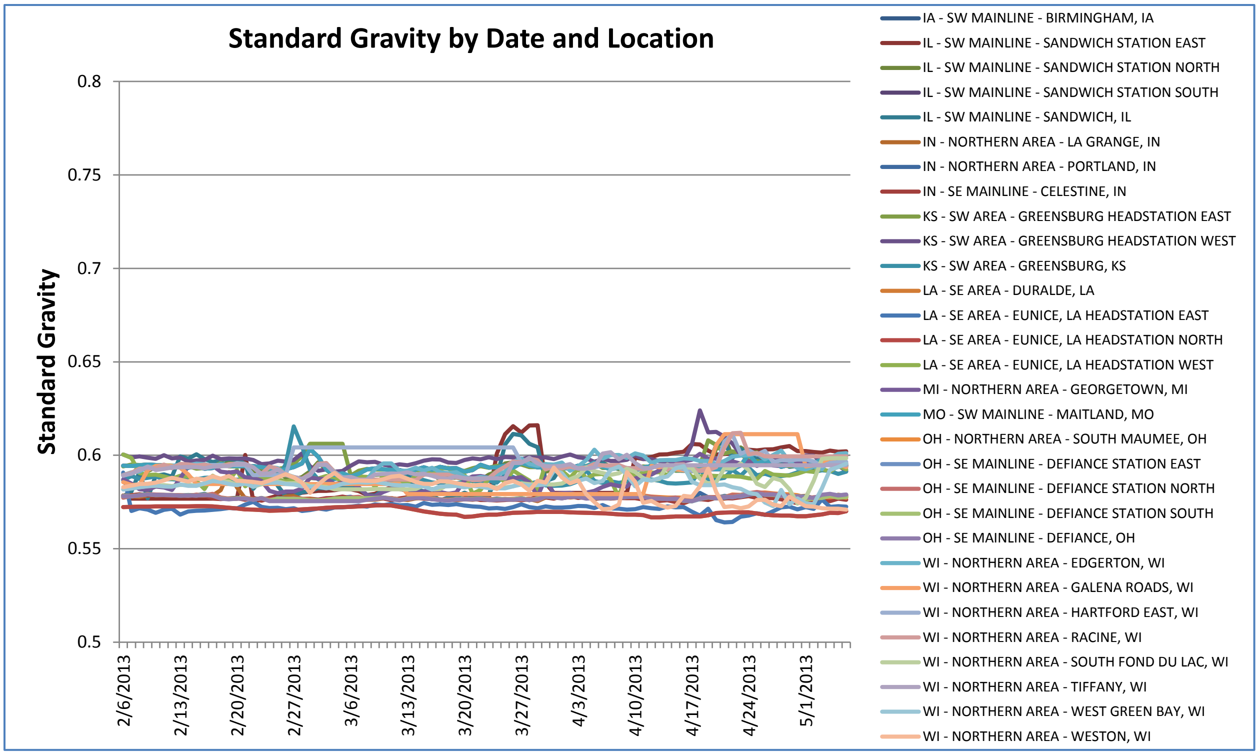

Figure A.29. Standard Gravity Values in ANR Pipelines

This illustrates the standard gravity values calculated from data in the ANR online postings. The spikes visible in the Sandwich, IL stations are again reflected in these postings. Locations are in Iowa, Illinois, Indiana, Kansas, Louisiana, Mississippi, Missouri, Ohio, and Wisconsin.

A-3-3. PG&E Service Area Pipeline Summary

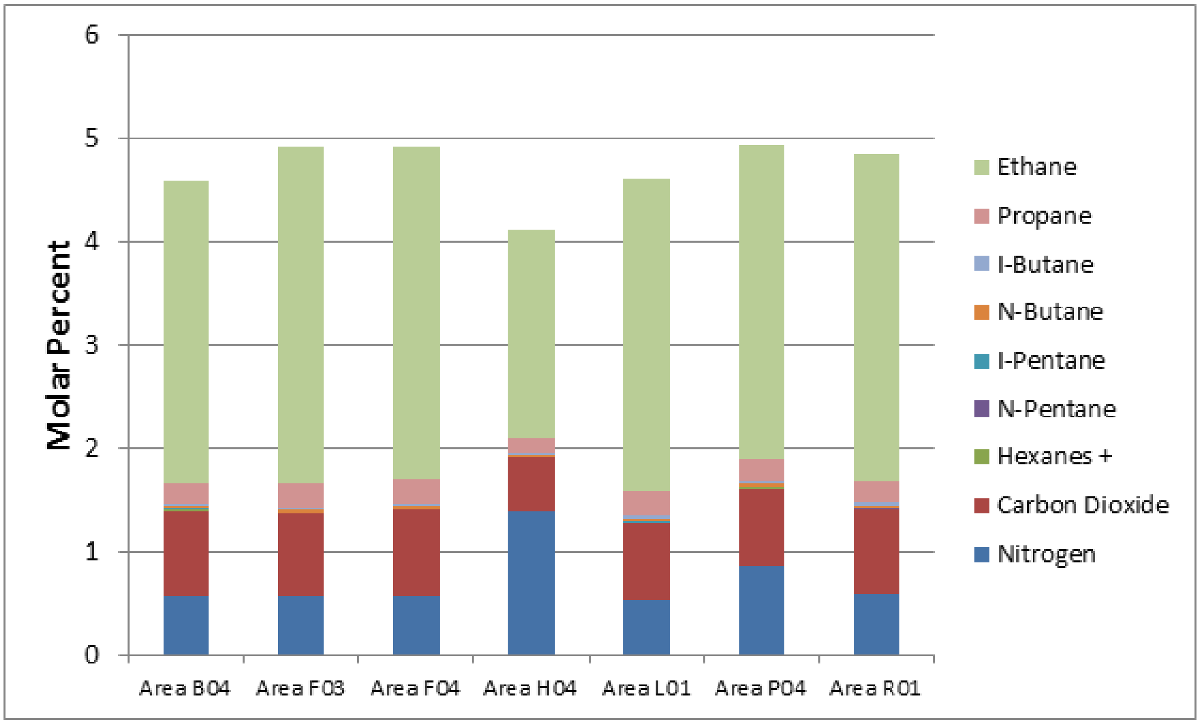

Figure A.30. Average Gas Components Reported in PG&E Service Area Online Postings
All gas components' molar percentages are shown as averages per location over the entire period of April – May 2013. Several stations consistently reported identical data, and for this chart those duplicates were removed for clarity. Other charts below will include all of the stations' data. The remaining percentage of gas not shown is methane, which was excluded for clarity.

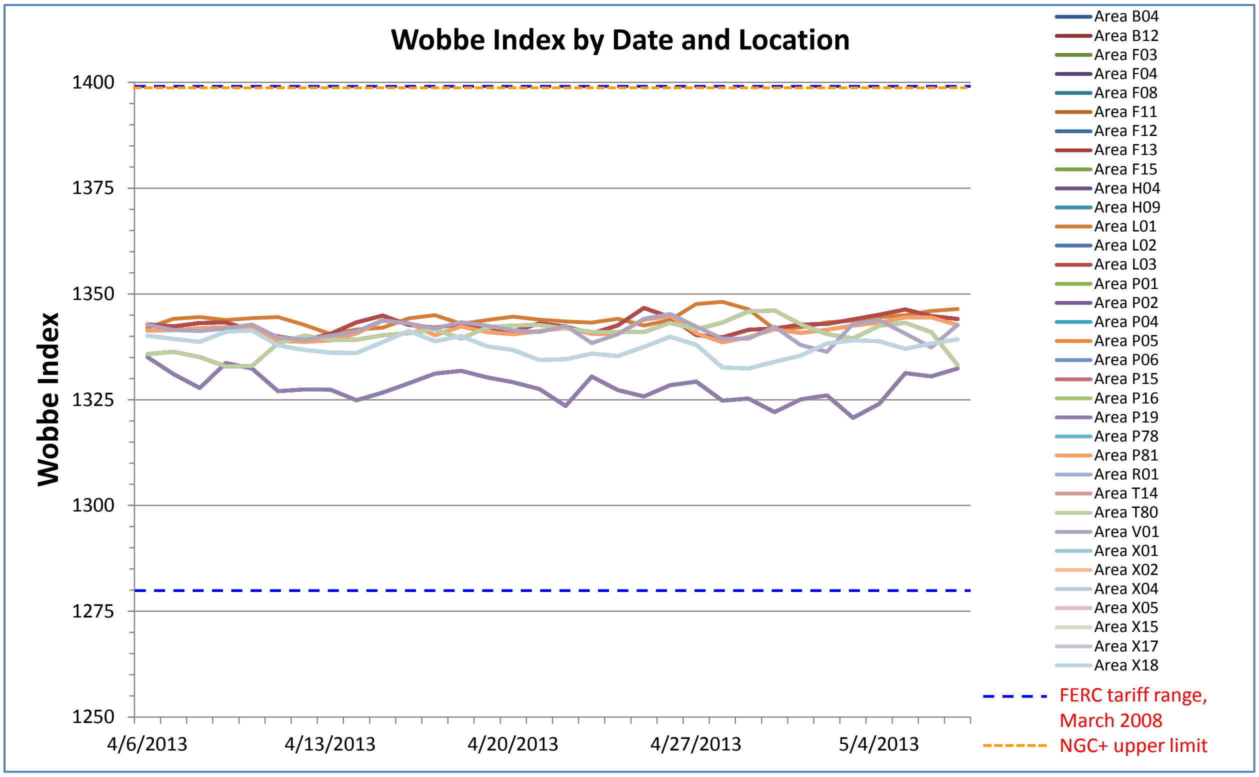

Figure A.31. Wobbe Indices in the PG&E Service Area
This illustrates the Wobbe indices at various locations as per day averages. All locations are in California. FERC and NGC+ limits are shown for reference.

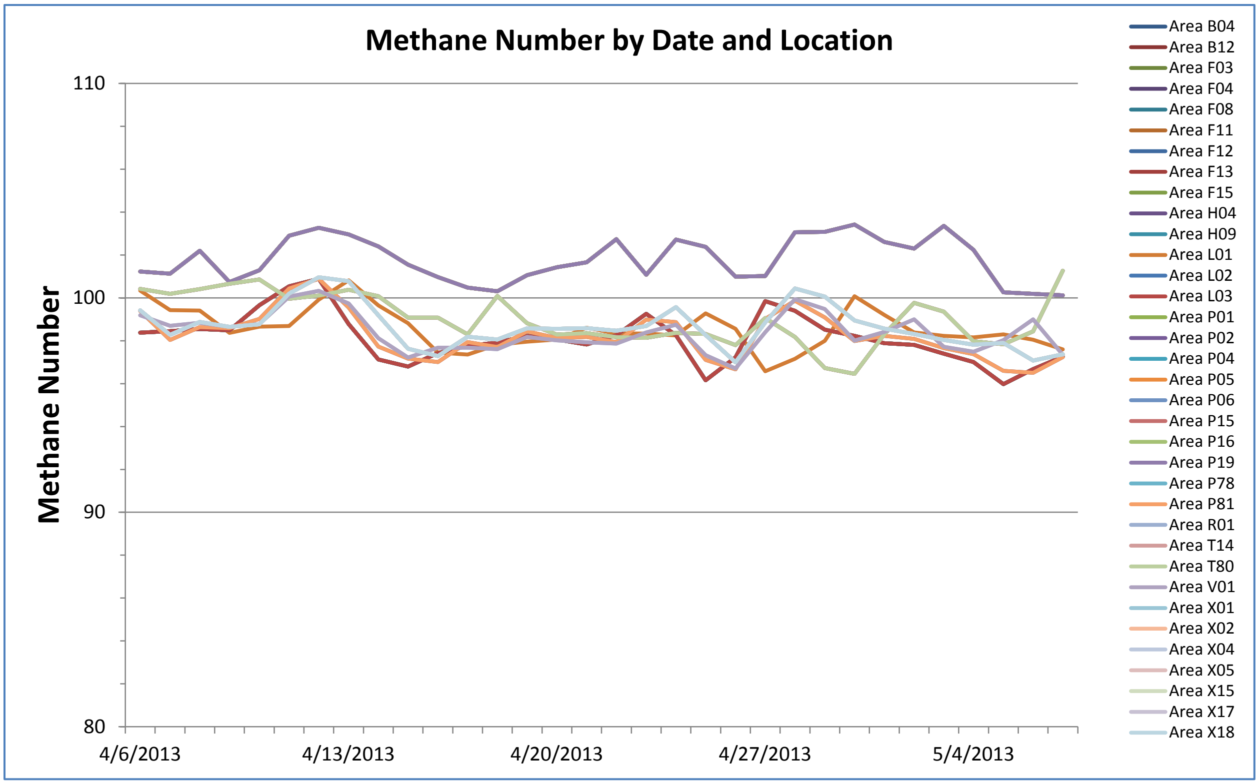

Figure A.32. Methane Numbers in the PG&E Service Area

This illustrates the methane numbers at various locations as per day averages. All locations are in California.

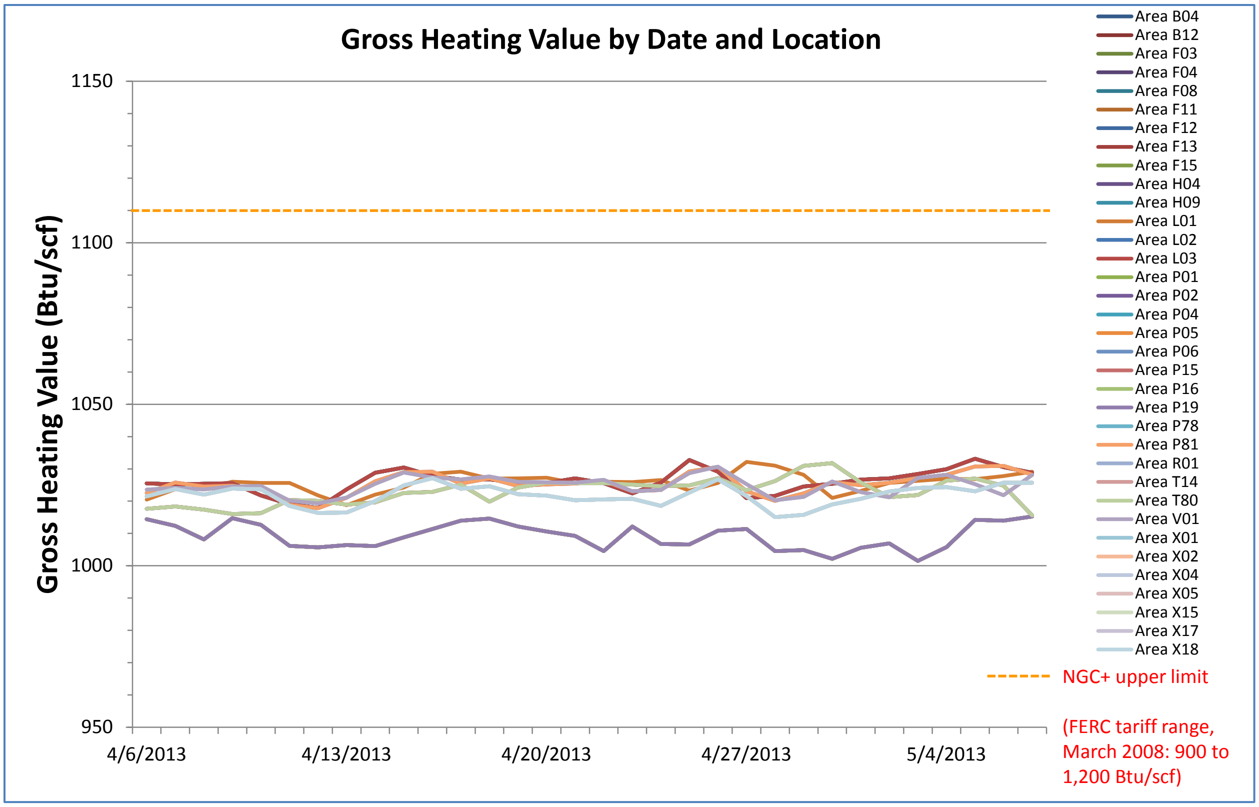

Figure A.33. Gross Heating Values in the PG&E Service Area

This illustrates the gross heating values in Btu/scf at various locations as per day averages. All locations are in California. The NGC+ upper limit is shown for reference.

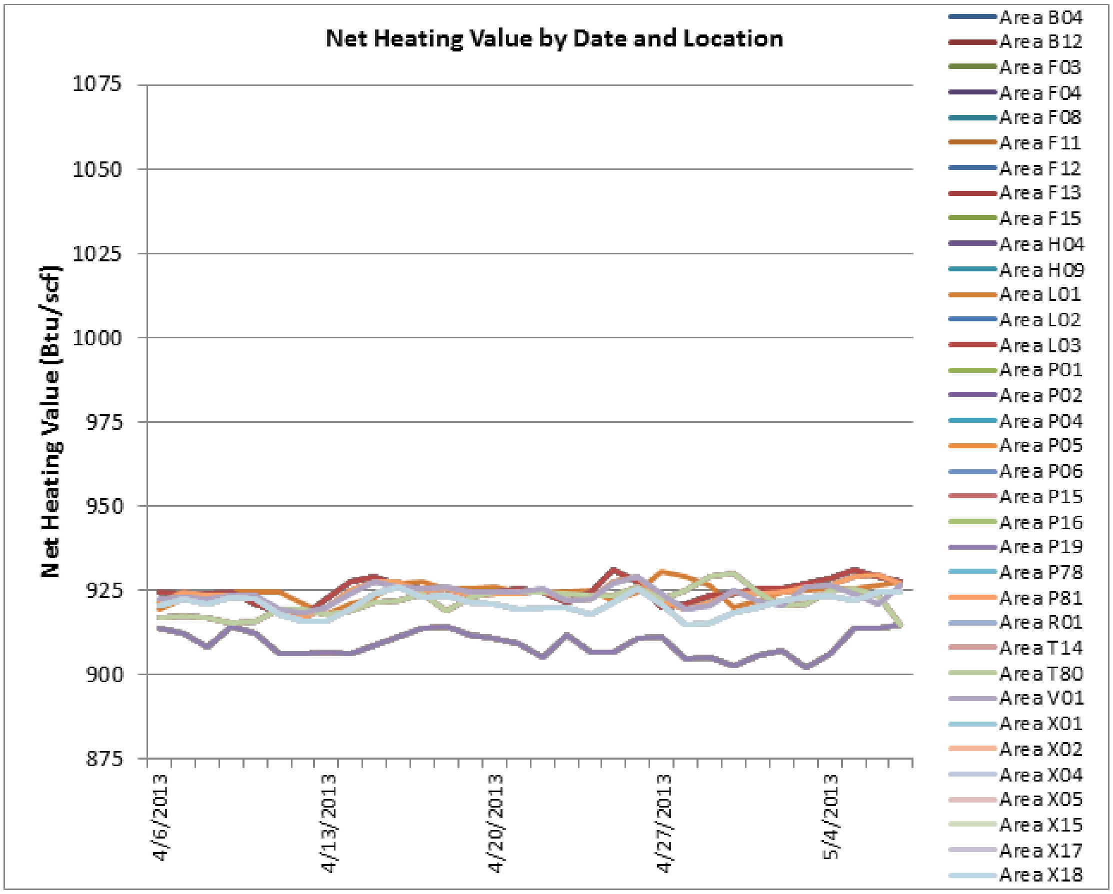

Figure A.34. Net Heating Values in the PG&E Service Area

This illustrates the net, or lower, heating values in the PG&E online postings. Area H04 had a consistently lower value, reflecting the trend in the gross heating value plot above. All locations are in California.

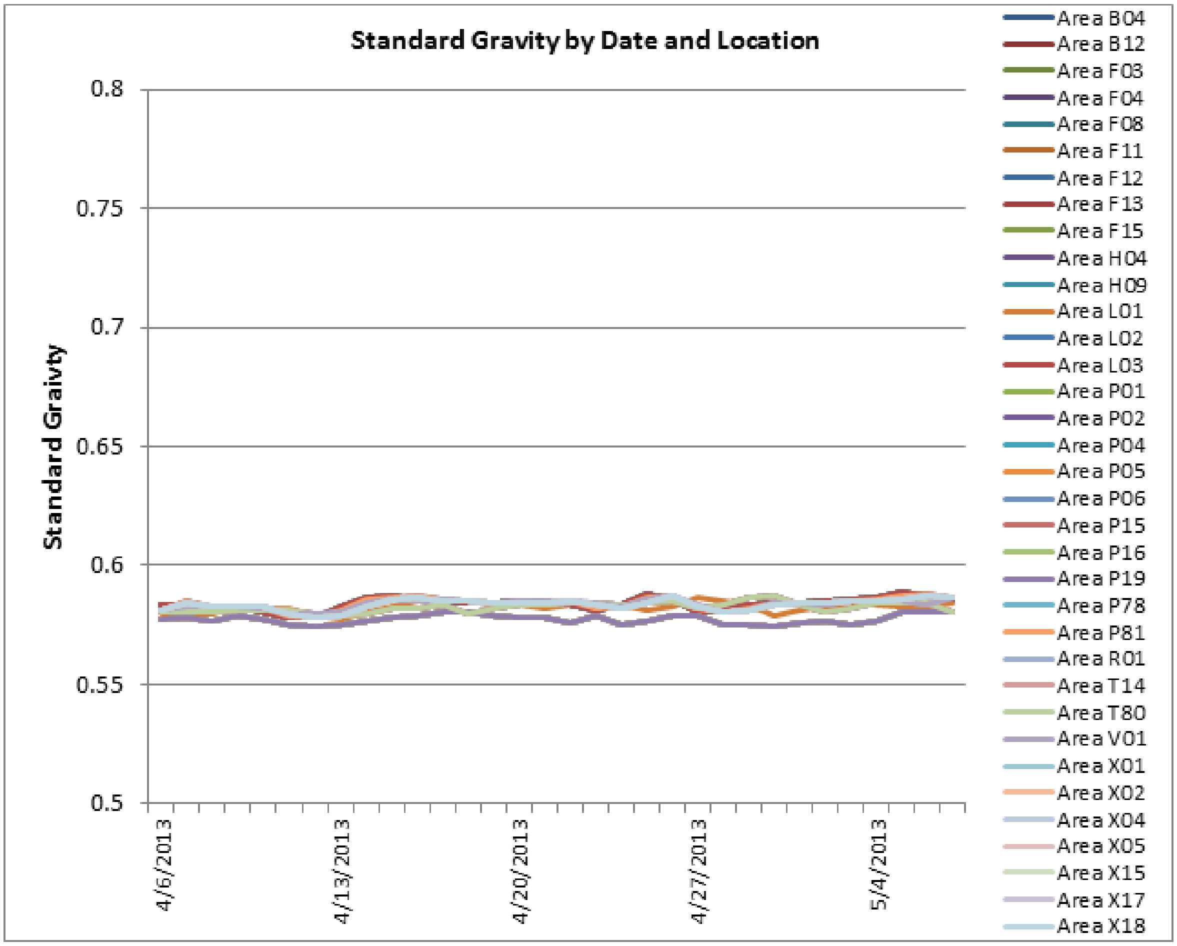

Figure A.35. Standard Gravity Values in the PG&E Service Area
This illustrates the standard gravity values calculated from data in the PG&E online postings. All locations are in California.

A-34. Panhandle Energy Pipeline Summary

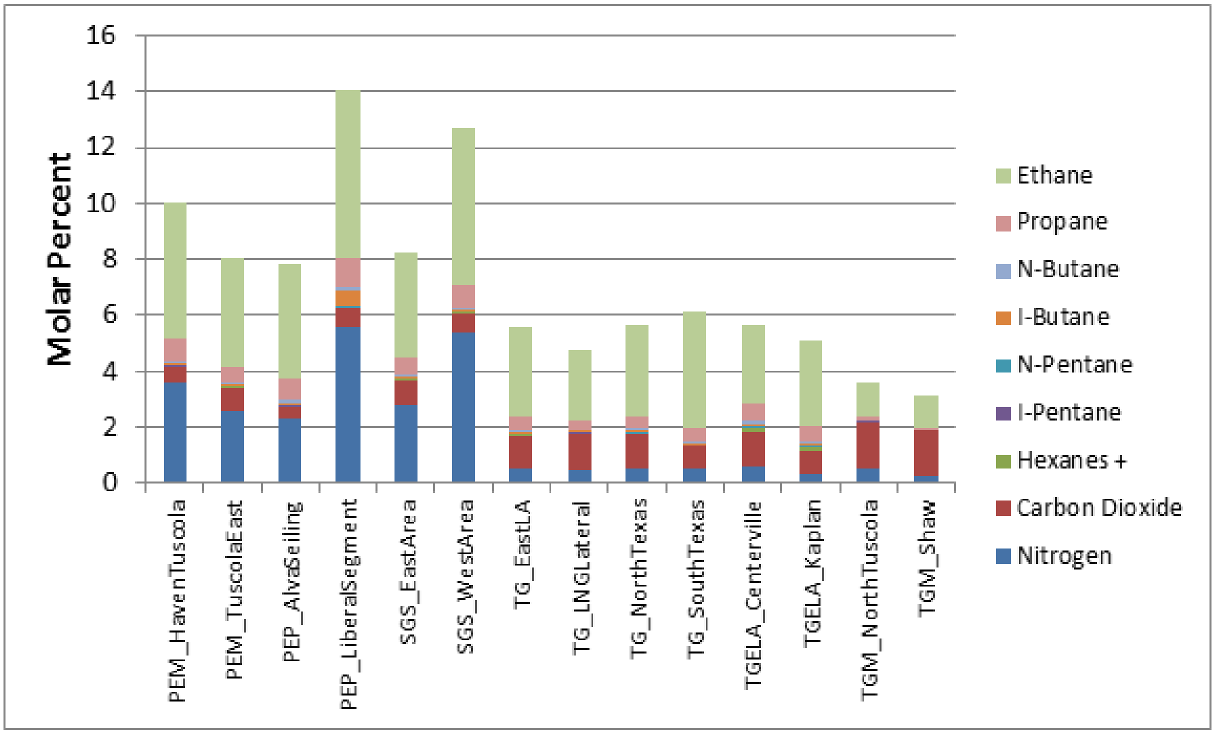

Figure A.36. Average Gas Components Reported in Panhandle Energy Online Postings
All gas components' molar percentages are shown as averages per location over the entire period of February – May 2013. The remaining percentage of gas not shown is methane, which was excluded for clarity.

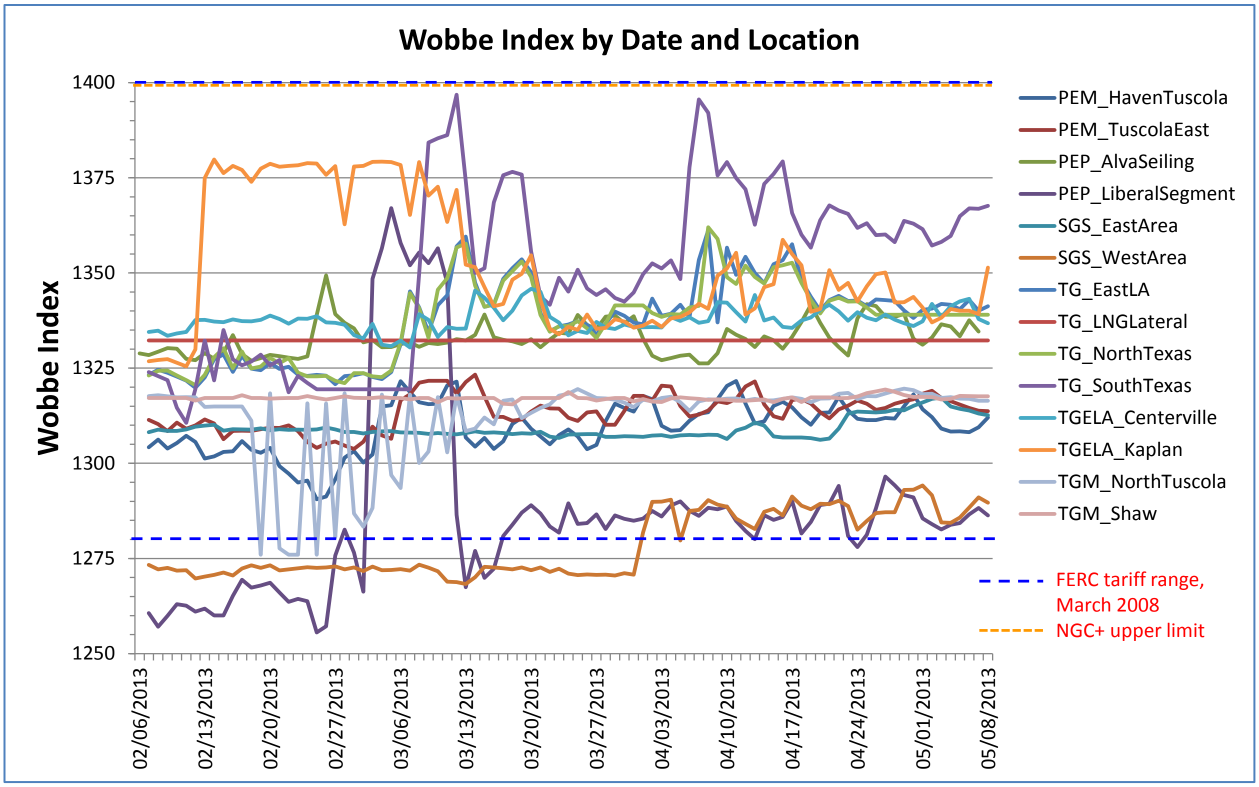

Figure A.37. Wobbe Indices in Panhandle Energy Pipelines

This illustrates the Wobbe indices at various locations as per day averages. Locations are in Kansas, Oklahoma, Texas, Missouri, Louisiana, Ohio, Illinois, and Michigan. FERC and NGC+ limits are shown for reference.

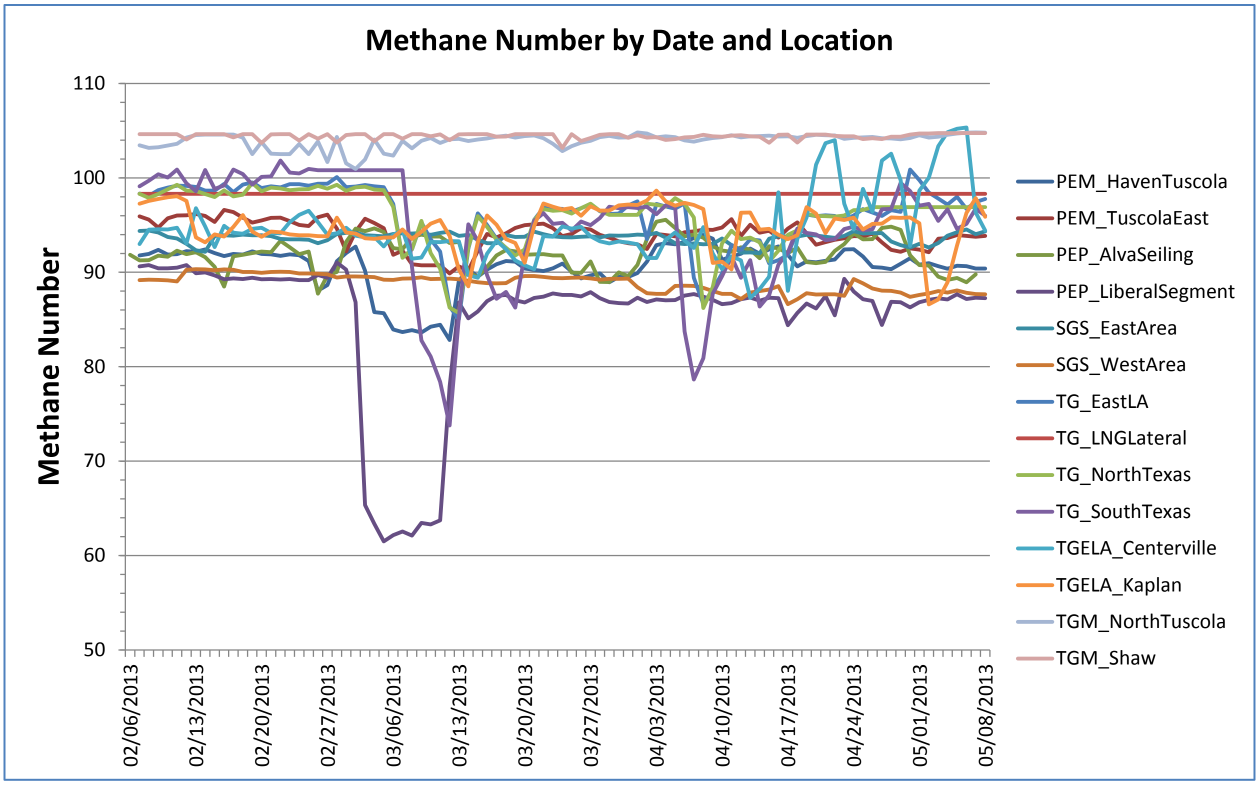

Figure A.38. Methane Numbers in Panhandle Energy Pipelines

This illustrates the methane numbers at various locations as per day averages. Locations are in Kansas, Oklahoma, Texas, Missouri, Louisiana, Ohio, Illinois, and Michigan.

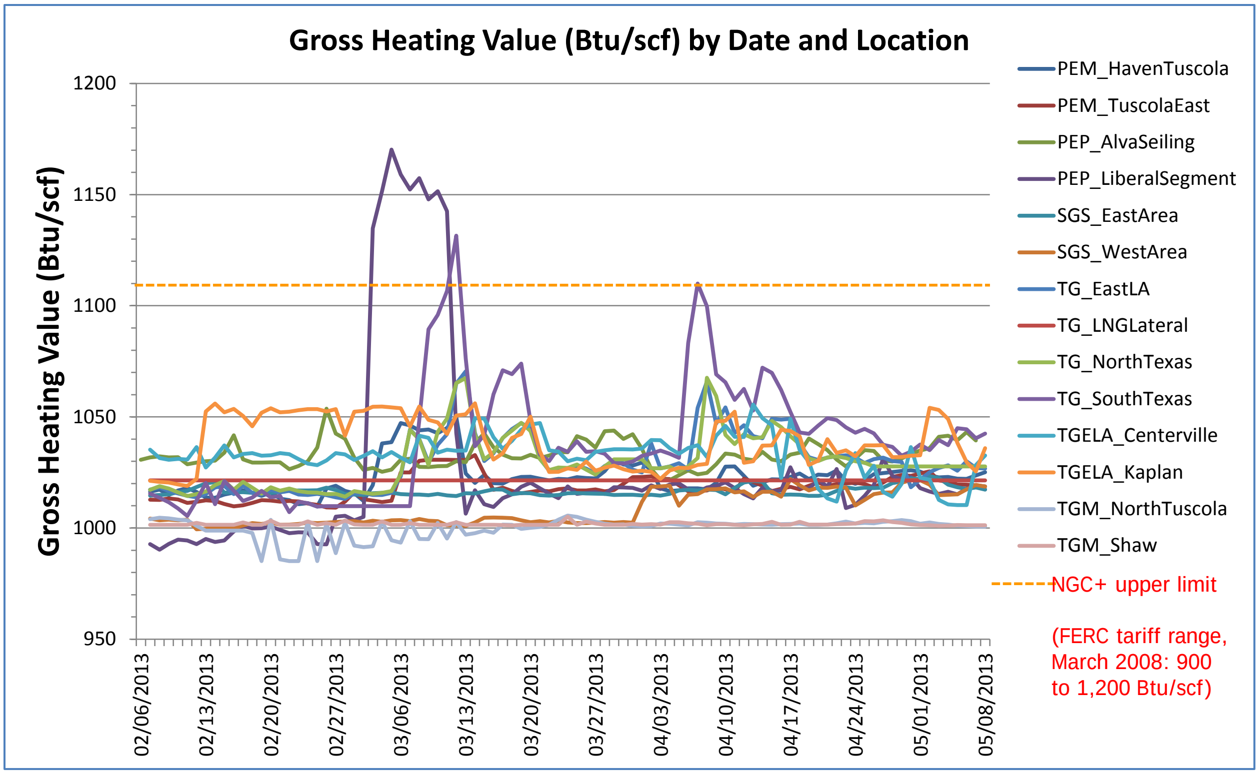

Figure A.39. Gross Heating Values in Panhandle Energy Pipelines

This illustrates the gross heating values in Btu/scf at various locations as per day averages. Locations are in Kansas, Oklahoma, Texas, Missouri, Louisiana, Ohio, Illinois, and Michigan. The NGC+ upper limit is shown for reference.

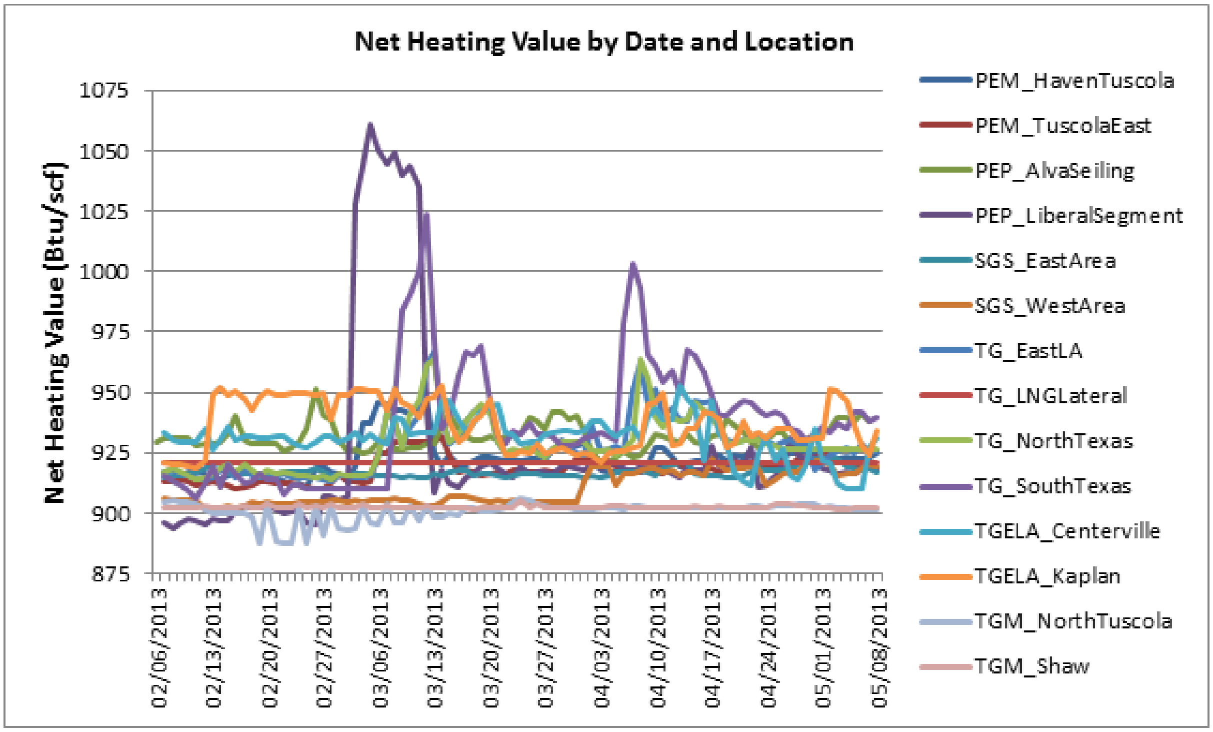

Figure A.40. Net Heating Values in Panhandle Energy Pipelines
This illustrates the net, or lower, heating values in Btu/scf at various locations as per day averages. Locations are in Kansas, Oklahoma, Texas, Missouri, Louisiana, Ohio, Illinois, and Michigan.

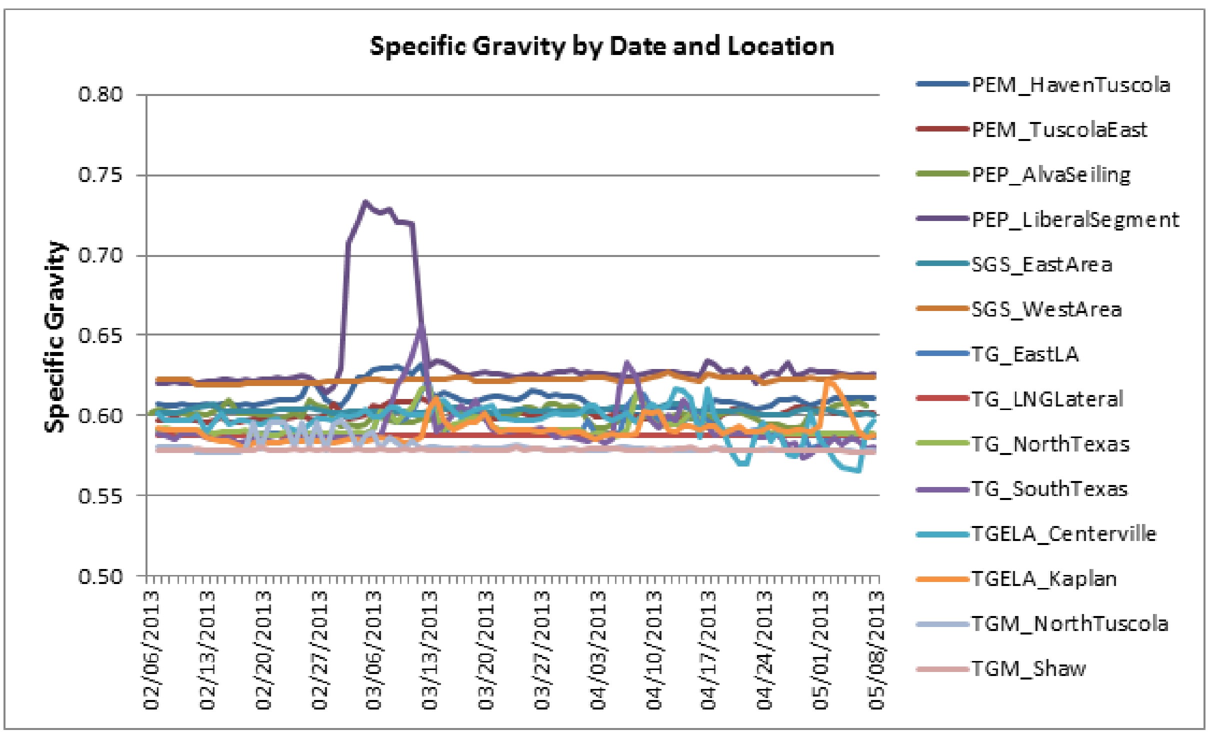

Figure A.41. Specific Gravity Values in Panhandle Energy Pipelines
This illustrates the specific gravity values calculated at various locations as per day averages. Locations are in Kansas, Oklahoma, Texas, Missouri, Louisiana, Ohio, Illinois, and Michigan.

A-3-5. Southern Star Central Gas Pipeline (SSCGP) Summary

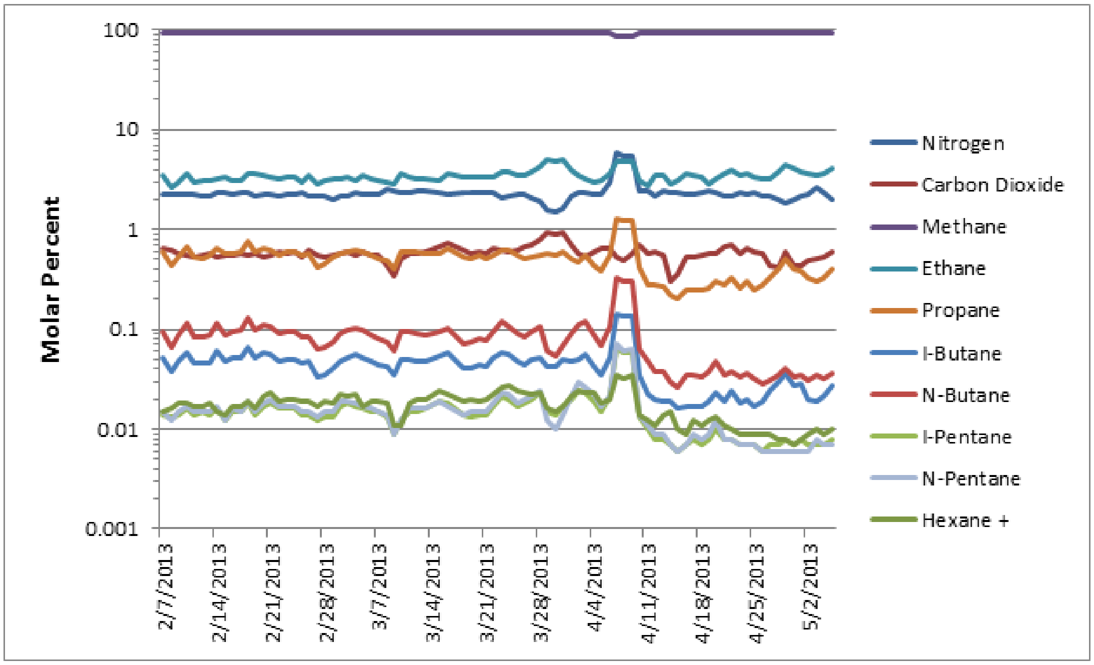

Figure A.42. Average Gas Components Reported in One SSCGP Pipeline
Data was only available in SSCGP's Glavin to Kansas City pipeline and is shown above as daily averages. The remaining percentage of gas not shown is methane, which was excluded for clarity.

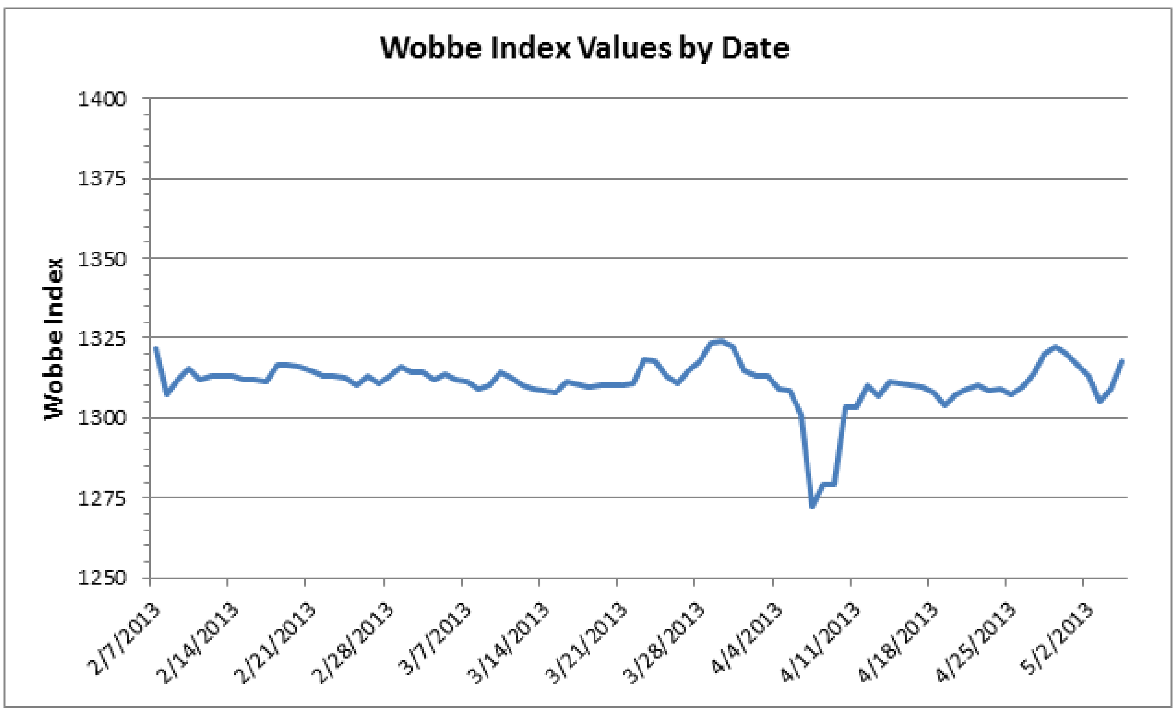

Figure A.43. Wobbe Indices in SSCGP Pipeline from Glavin to Kansas City
This illustrates the Wobbe indices in one pipeline controlled by SSCGP as reported in the available online data. The large drop during the week of April 4th aligns with a corresponding drop in methane content.

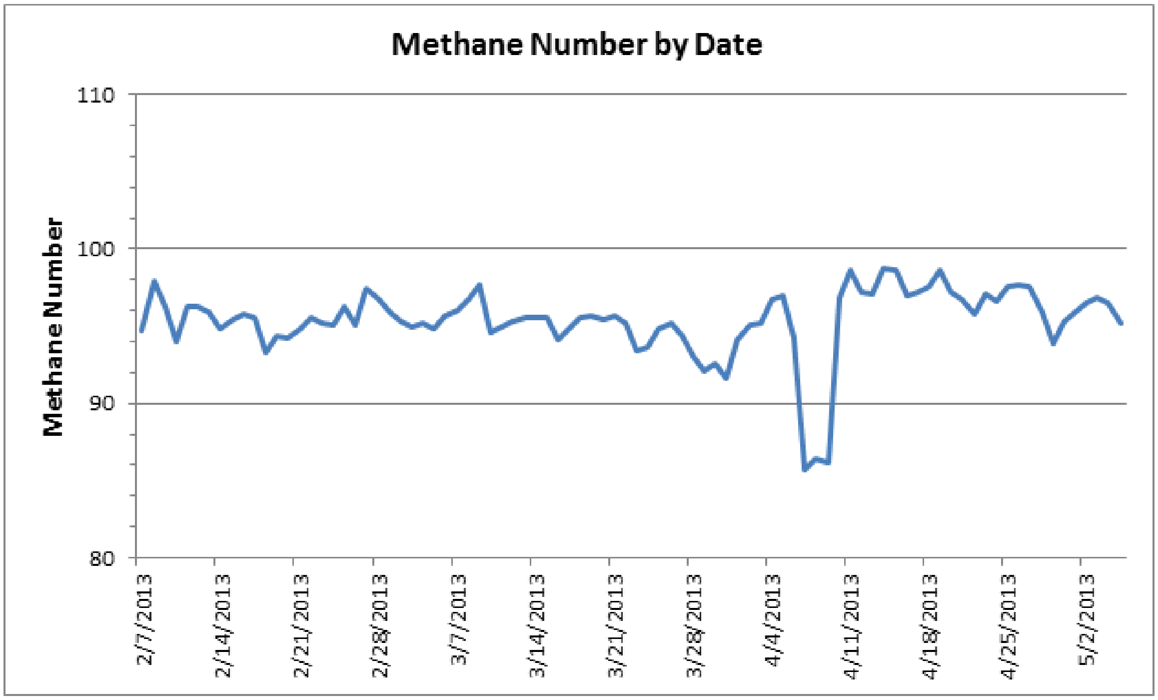

Figure A.44. Methane Numbers in SSCGP Pipeline from Glavin to Kansas City
This illustrates the methane numbers calculated in one pipeline controlled by SSCGP from data reported online. The large drop during the week of April 4th aligns with a corresponding drop in methane content.

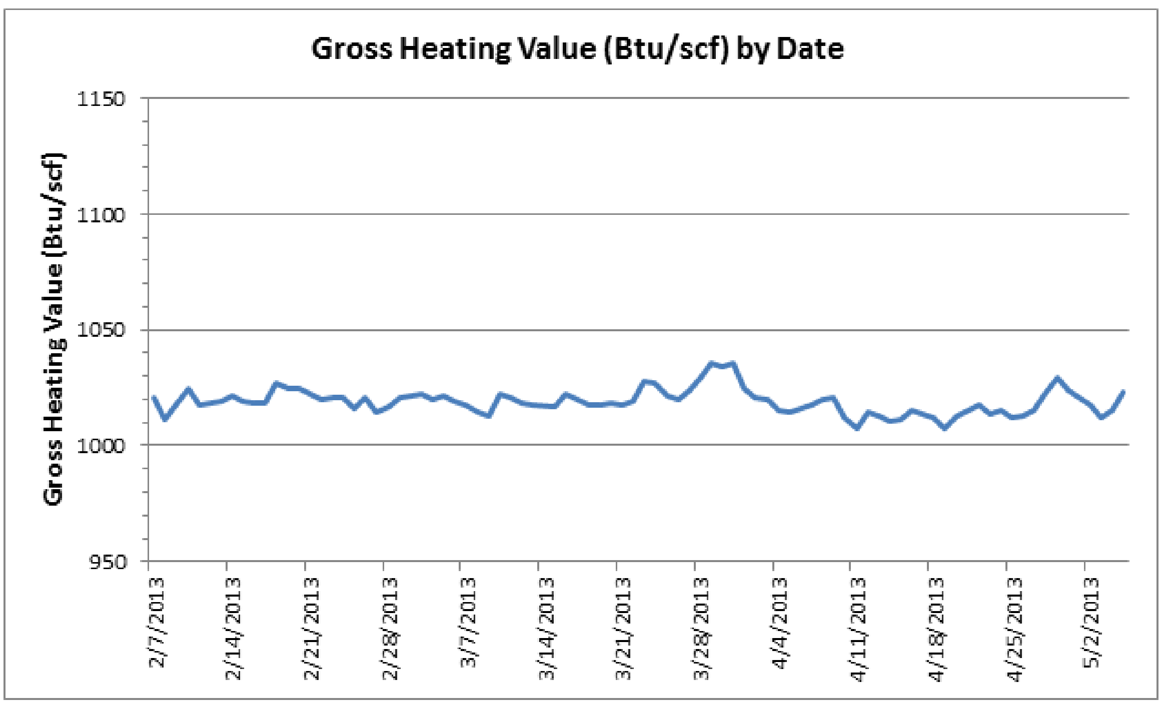

Figure A.45. Gross Heating Value in SSCGP Pipeline from Glavin to Kansas City
This illustrates the gross heating values in Btu/scf calculated in one pipeline controlled by SSCGP from data reported online. The large drop in methane content during the week of April 4th does not produce an especially pronounced spike in gross heating value.

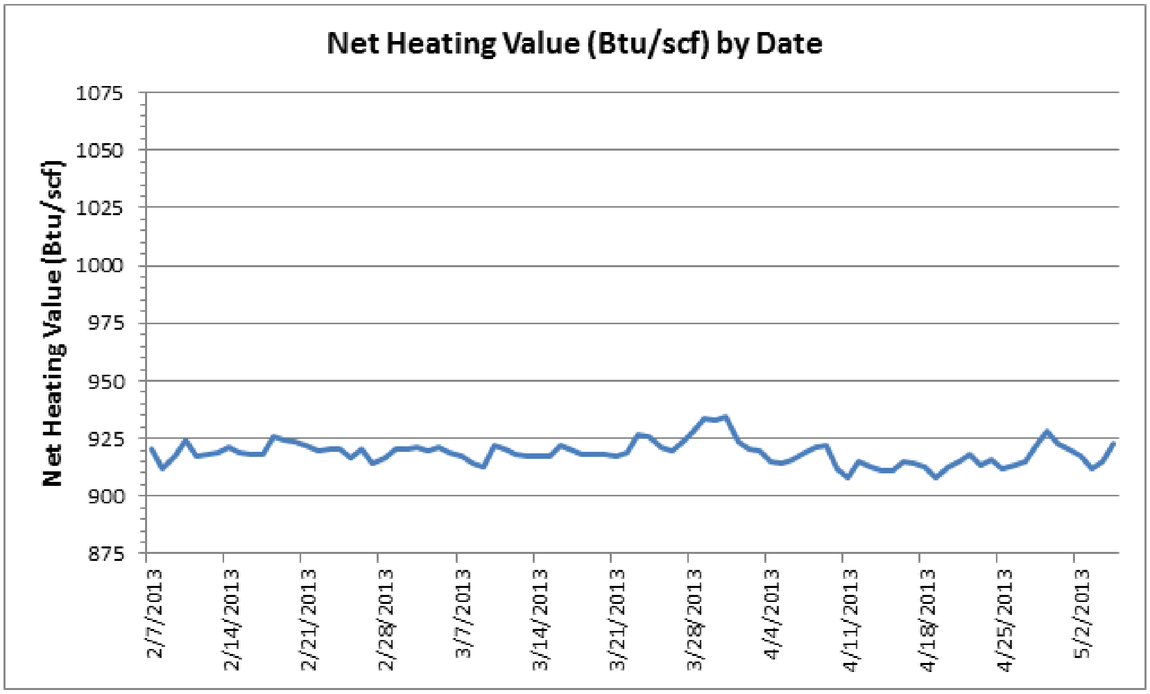

Figure A.46. Net Heating Value in SSCGP Pipeline from Glavin to Kansas City
This illustrates the net, or lower, heating values in Btu/scf calculated in one pipeline controlled by SSCGP from data reported online. The large drop in methane content during the week of April 4th does not produce an especially pronounced spike in gross heating value.

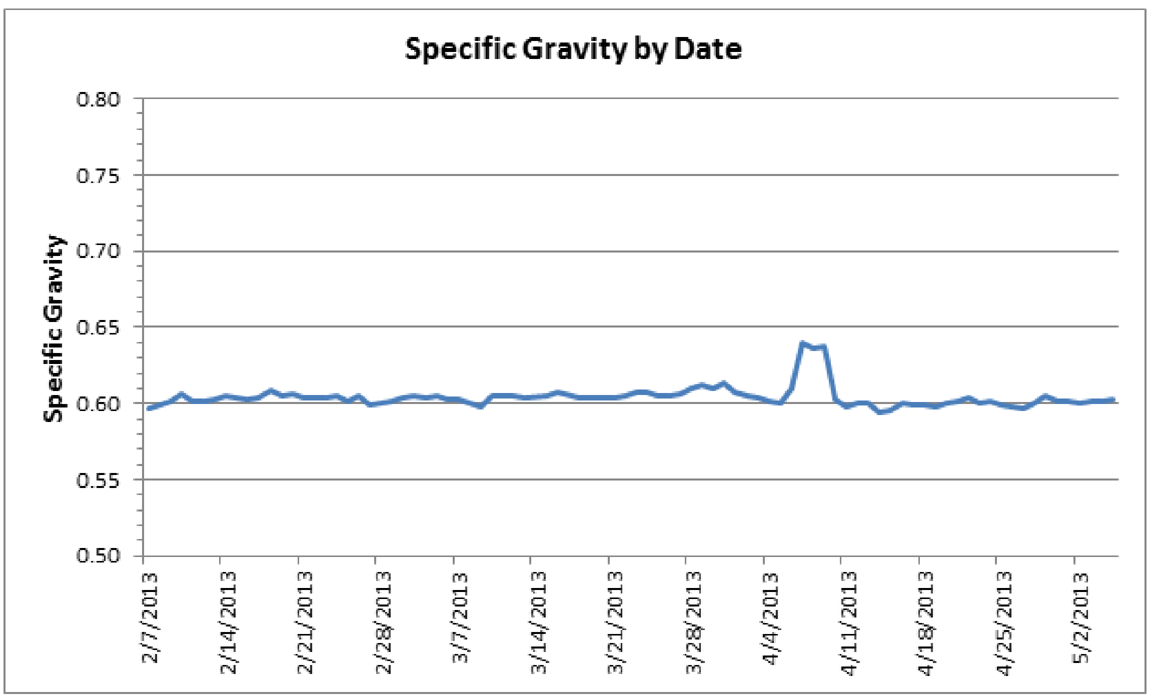

Figure A.47. Specific Gravity Values in SSCGP Pipeline from Glavin to Kansas City
This illustrates the specific gravity values calculated in one pipeline controlled by SSCGP from data reported online. The large drop in methane content during the week of April 4th produces a large spike in specific gravity.

APPENDIX B

CNG STATION DATA COLLECTION AND SAMPLING PROCEDURE

CNG Station Data Collection and Sampling Procedure

Project 18.19236 for CRC and AGA, November 18, 2013

Information Survey

Complete the survey (on the separate form) with the maintenance staff. This can be done while the moisture analyzer is stabilizing on the LDC moisture measurement.

Photographs

Take photos of the locations listed below. This can also be done while the moisture analyzer is stabilizing on the LDC moisture measurement.

- The sample port used to measure the moisture content of the gas entering the station from the LDC. This will be upstream of the compression and dehydration equipment.
- Dehydration unit (desiccant stack, mol sieve, deliquescent salt tank, etc.).
- Compression equipment.
- Storage tanks.
- Moisture analyzer connected to dispenser during CNG moisture analysis.
- Manifold and sample cylinders connected between dispenser and NGV during spot sample collection.

Procedure for Moisture Measurements at LDC Connection

Do not use Snoop to check for leaks during this procedure. A port connector (¼” NPT to Swagelok) will be installed at the sample port valve. All other connections should be made using Swagelok fittings and ¼” tubing.

1. Record the LDC line pressure in the data table at the bottom of the station survey. This will be input to the analyzer later. If known, also record the gas temperature.
2. Blow out any accumulated dirt or contaminants from the LDC sample valve by briefly opening the sample port valve. Close the LDC sample valve.
3. Remove the desiccant assembly from the analyzer inlet, and plug the open end to keep ambient moisture out of the desiccant.
4. Connect the LDC sample valve to the analyzer inlet using a tube connector with Swagelok fittings.
5. Remove the desiccant assembly from the analyzer outlet, and plug the open end to keep ambient moisture out of the desiccant.
6. Connect the rotameter and valve to the analyzer outlet. Uncap the rotameter outlet (if capped). The rotameter should vent straight up.
7. Completely open the valve at the rotameter inlet. Crack open the sample port valve until the flow rate is 0.6 scfh. The gas flowing through the unit will be at atmospheric pressure so that it can flush as much moisture from the sensor as possible.

8. Turn on the moisture analyzer. The analyzer will begin a warm-up cycle and heat the sensor to flush away existing moisture.
9. With one minute remaining on the warm-up cycle, completely close the valve at the rotameter inlet, and then slowly open the LDC sample valve to its full-open position. This will bring the gas in the analyzer to line pressure.
10. Slowly open the rotameter valve until the flow rate is approximately 1.5 scfh. Record the actual flow rate in the data table.
11. Once the warm-up cycle is complete, confirm that the analyzer clock is synchronized to the time zone where it is being used. Usually, only the HOUR value will need to be adjusted.

CLOCK menu -> YEAR

MONTH

DAY

HOUR (adjust for current time zone)

MIN

12. Configure the analyzer to measure the moisture in the natural gas at line pressure.

SETTINGS menu -> PRIMARY DP AT PRESS

DP/TEMP UNIT °F

PRESSURE UNIT **PSIA or PSIG as appropriate**

GAS TYPE USER

MOL WEIGHT 16

CHART INTERVAL 5 s

EXTERNAL menu ->EXTERNAL TYPE NONE

EXTERNAL ZERO N/A

EXTERNAL SPAN N/A

USER PRESSURE (line pressure from the data table **with the correct units**)

13. Enter a unique filename for the new log and start the logging process. Record the filename and the start time in the data table.

LOGGING menu -> FILENAME (unique filename)

PARAMETER LBMMSCF(NG)

LOG INTERVAL 5 s

START? STARTED

14. Continue to log data for at least 15 minutes. If the message “Measurement in Progress” is still flashing on the screen after 15 minutes, continue to log until 30 minutes total have elapsed.

15. Stop the log and record the final moisture reading and the stop time in the data table.

    LOGGING menu -> START? STOPPED

16. Return the analyzer to the home screen and turn off the analyzer.
17. Close the LDC sample valve and allow the remaining gas to vent from the analyzer until the flow rate is zero.
18. Disconnect the analyzer from the LDC sample valve. Attach a desiccant assembly to the analyzer inlet and cap the rotameter outlet (if possible).
19. Remove any tubing from the LDC sample port. Leave the rotameter attached to the analyzer outlet.

PROCEDURE FOR MOISTURE MEASUREMENT AT THE CNG DISPENSER

Do not use Snoop to check for leaks during this procedure. An NGV-1 receptacle with a port connector (¼" NPT to Swagelok) will be installed at the dispenser nozzle. All other connections should be made using Swagelok fittings and ¼" tubing.

1. Record the dispenser pressure in the data table at the bottom of the station survey. This will be input to the analyzer later. If known, also record the gas temperature.
2. Connect the appropriate NGV-1 receptacle to the CNG dispenser nozzle. Connect a multi-turn needle valve to the NGV-1 receptacle.
3. Remove the desiccant assembly from the analyzer inlet, and plug the open end to keep ambient moisture out of the desiccant.
4. Connect the outlet of the multi-turn needle valve to the analyzer inlet.
5. Uncap the rotameter outlet (if capped). Place the analyzer in a stable position (on the ground or on the Pelican case) so that the rotameter vents straight up.
6. Completely open the valve at the rotameter inlet. Crack open the multi-turn needle valve at the NGV-1 receptacle until the flow rate is 0.6 scfh. The gas flowing through the unit will be at atmospheric pressure so that it can flush as much moisture from the sensor as possible.
7. Turn on the moisture analyzer. The analyzer will begin a warm-up cycle and heat the sensor to flush away existing moisture.
8. With one minute remaining on the warm-up cycle, completely close the valve at the rotameter inlet.
9. Slowly open the multi-turn needle valve upstream of the analyzer to its full-open position. This will bring the gas in the analyzer to CNG pressure.
10. Slowly open the rotameter valve until the flow rate is approximately 1.5 scfh. Record the actual flow rate in the data table.
11. Configure the analyzer to measure moisture at CNG pressure.

    SETTINGS menu -> PRIMARY DP AT PRESS

    DP/TEMP UNIT °F

PRESSURE UNIT **PSIA or PSIG as appropriate**

GAS TYPE USER

MOL WEIGHT 16

CHART INTERVAL 5 s

EXTERNAL menu ->EXTERNAL TYPE NONE

EXTERNAL ZERO N/A

EXTERNAL SPAN N/A

USER PRESSURE (CNG pressure from the data table **with the correct units**)

12. Enter a unique filename for the new log and start the logging process. Record the filename and the start time in the data table.

    LOGGING menu -> FILENAME (unique filename)

    PARAMETER LBMMSCF(NG)

    LOG INTERVAL 5 s

    START? STARTED

13. Continue to log data for at least 15 minutes. If the message “Measurement in Progress” is still flashing on the screen after 15 minutes, continue to log until 30 minutes total have elapsed.
14. Stop the log and record the final moisture reading and the stop time in the data table.

    LOGGING menu -> START? STOPPED

15. Return the analyzer to the home screen and turn off the analyzer.
16. Close the needle valve upstream of the analyzer and allow the remaining gas to vent from the analyzer until the flow rate is zero. Do not open the rotameter valve to increase the flow rate through the analyzer at this point, since the rotameter is not rated for high pressures.
17. Disconnect the analyzer and the needle valve from the CNG nozzle, but leave the NGV-1 receptacle on the nozzle. Remove the rotameter assembly from the analyzer outlet.
18. Attach the desiccant assemblies to the analyzer inlet and outlet. Store the plugs used to isolate the desiccant assemblies for later use.

PROCEDURE FOR SPOT SAMPLE COLLECTION AT THE CNG DISPENSER

Snoop can be used to check for leaks during this procedure.

1. Fasten the upper half of the manifold (the half with the Welker separator) to one side of the stand using the blue brackets.

2. Connect three <u>passivated</u> (rainbow-colored) cylinders to the ports coming from the gas outlet of the separator. The Swagelok cylinder valves (without rupture discs) should be connected to this side of the manifold.
3. Connect a non-passivated (silver) liquid sample cylinder to the port coming from the liquid outlet of the separator. The Swagelok cylinder valve (without a rupture disc) should be connected to this side of the manifold.
4. Connect the lower half of the manifold to the three passivated gas sample cylinders. These connections should be made to the Phoenix cylinder valves (with the pressure safety valves).
5. Fasten the lower half of the manifold to the other side of the stand using the blue brackets.
6. Connect the vent lines to the vent valves on each half of the manifold so that the vents point straight up.
7. Connect the NGV-1 receptacle rated for 3,600 psig to the inlet on the upper half of the manifold (the half with the Welker separator).
8. Connect the hand vacuum pump to the vacuum line on the lower half of the manifold.
9. Connect the high-pressure hose to the other side of the lower half of the manifold.
10. Connect the CNG nozzle rated for the pump pressure (3,000 psig or 3,600 psig) to the high-pressure hose.
11. Connect the CNG nozzle on the high-pressure hose to the NGV to be refueled.
12. Connect the dispenser nozzle to the NGV-1 receptacle on the upper manifold.
13. Open the valve between the manifold and the high-pressure hose.
14. Open all valves on the gas sample cylinders.
15. Open the upstream valve on the liquid cylinder. Ensure that the outlet valve (unconnected to the manifold) is closed and capped.
16. Open both valves on the Welker separator.
17. Close the vent valves on both halves of the manifold.
18. Open the valve between the vacuum pump and the manifold. Use the vacuum pump to remove as much air as practical from the manifold and cylinders. Try to get ~20 in Hg.
19. Close the vacuum pump valve and disconnect the vacuum pump.
20. Activate the dispenser to flow CNG through the separator and sample cylinders. Watch the separator windows for any evidence of liquids.
21. Once the flow is established, slowly close the valve between the manifold and the high-pressure hose to capture the sample.
22. Close both valves on each gas sample cylinder to capture the gas samples. Leave the valve on the upper end of the liquid cylinder open.

23. Turn off the dispenser valve and remove the dispenser from the receptacle.
24. Open the valve between the manifold and the high-pressure hose to allow venting from the hose up to the nozzle.
25. Slowly open both vent valves to bleed pressure from both sides of the manifold.
26. Once venting is complete, disconnect the nozzle from the vehicle.
27. Close the liquid bottle upstream valve once venting is complete.
28. Disconnect the liquid sample cylinder from the manifold. Plug both valves.
29. Disconnect the lower half of the manifold from the stand so that the cylinders can be removed.
30. Disconnect the three gas sample cylinders from the manifold and plug each end. Check the connections for leaks, carefully tighten if needed to eliminate leaks, and store for shipping.
31. Disconnect the liquid sample cylinder from the manifold, plug both ends, and store for shipping.
32. Disconnect the NGV-1 receptacle from the upper manifold and store the receptacle in the Pelican case.
33. Disconnect the nozzle from the hose and store the nozzle in the Pelican case.
34. Disassemble all remaining equipment and place all parts (except the liquid sample cylinder) in the Pelican case.
35. Rinse the liquid drain line and Welker separator with isopropyl alcohol before storing the manifold.

Preparing the Spot Samples for Shipment

1. Ensure that the cylinder valves are closed and capped. If not already done, use Snoop to check the gas sample cylinders for leaks.
2. Complete an SPL Chain of Custody form for the gas cylinders. Mark which cylinders are to be analyzed and which cylinders are being sent as backup samples.
3. Build up a large hazmat shipping box for the gas sample cylinders.
4. Pack six gas cylinders in the large box, padding the cylinders with bubble wrap and ensuring that the valves do not make contact with one another.
5. Include the Chain of Custody form and a natural gas MSDS in the box with the cylinders.
6. Prepare a small hazmat shipping box for the liquid sample cylinders.
7. Pack two liquid cylinders in the small box, padding the cylinders with bubble wrap and ensuring that the valves do not make contact with one another.
8. Include an MSDS for compressor oil in the box with the cylinders.

9. Seal each box. Attach a shipping label to SPL on the large box with the gas cylinders and a shipping label to SwRI on the small box with the liquid cylinders.
10. Ensure that a bill of lading is present in your vehicle.
11. Meet with the shipper (to be determined before the trips begin), complete the shipping ticket, and transfer the samples for shipment to the labs.

Procedure for Downloading Data from the Moisture Analyzer

Moisture logs are downloaded from the analyzers using a Bluetooth-enabled laptop. A laptop running Windows XP will be sent with each analyzer. This procedure assumes that the laptop is running and has Bluetooth wireless enabled, and that the analyzer has been turned on. Each laptop is paired with one analyzer.

- The Latitude D620 (silver case) is paired with Michell S/N 139723 on COM port 40. The Bluetooth can be enabled with the switch on the left edge of the laptop. The Bluetooth transmitter is on when the switch is pushed toward the user and the Bluetooth icon in the lower-right corner of the screen is white-on-blue. (Red-on-blue means the Bluetooth antenna is off.)
- The Latitude C640 (black case) is paired with Michell S/N 139725 on COM port 5. This laptop uses a RocketFish micro-Bluetooth adapter that must be plugged into the USB port. Once the adapter is plugged in, it can be activated using the following steps:
    - Right-click on the Bluetooth icon in the tray on the lower right corner of the desktop.
    - Click on "Explore My Bluetooth Places."
    - A window will appear showing one Bluetooth connection, "MDM300 AT Serial, not connected." Right-click on the icon, and click "Connect."

1. On the Michell analyzer, activate the Bluetooth mode.

   BLUETOOTH menu -> ENABLE <u>YES</u>

2. Activate the Bluetooth function on the laptop.
3. On the XP desktop, click the Start button, and then click "MDM Application Software." A window labeled "Connection console" will appear.
4. In the "Connection console" window, select the correct COM port for the analyzer and the laptop. If the "Drive letter" setting is listed as "automatic," leave it as is; otherwise, select an unused drive letter such as "Z." Click "Connect." The Michell software should find the MDM and assign a drive letter to it. Once the connection process is finished, click "OK." (If the software does not find the analyzer, quit the Michell software and restart it, disable and re-enable the Bluetooth mode on the analyzer, and try again.)
5. Once the laptop and analyzer are connected, the main MDM window will appear with the current analyzer settings. On the right side, find the window labeled "File System" showing the log files saved on the analyzer.

6. Each log file must be downloaded individually to the laptop (the Michell software will not allow you to select multiple files for download). In the MDM window, right-click on the log file to be downloaded, and then select the destination ("To desktop" or "To folder…"). A dialog box will ask if you are sure you want to download the log file; click "Yes."
7. The memory on the analyzer is limited. At the end of each day, after the logs have been downloaded to the laptop, delete the files from the analyzer. In the MDM window, select one or more files to be deleted, then right-click and select "Delete." A dialog box will ask if you are sure you want to delete the selected files; click "Yes."
8. Once all log files have been downloaded, close the MDM software by clicking the "Quit" button on the upper right of the window.
9. On the Michell analyzer, deactivate the Bluetooth mode.

   BLUETOOTH menu -> ENABLE <u>NO</u>

10. Use the left arrow button on the Michell analyzer to return to the main menu, then turn the analyzer off.

APPENDIX C

STATION SURVEY AND DATA COLLECTION FORMS

CNG Station Operation Survey for CRC and AGA

Collect the following information on each CNG station from the operators during the site visits.

Station name/location ______________________________________

Station layout

Take photos of key station components (compressor, drier, filtration, storage tanks) ___

Processing order: Compression before drying ___ Drying before compression ___

Moisture drying method: Desiccant ___ Molecular sieve ___ Deliquescent salt tank ___

Other (describe) ______________________________

Locations of any filters and scrubbers (before or after drier, after compression, etc.)

____

____

Number and type(s) of compressors, number of compression stages

____

____

Number of parallel compression/drying streams ___

Ability to bypass storage and draw directly from the compressor/drier (Y/N) ___

LDC information

Name of LDC providing gas to the CNG station.

____

Delivery pressure from LDC __________.

Describe any known changes in incoming gas quality, sulfur, or moisture levels on a daily, monthly, or seasonal basis.

____

____

Describe any known problems resulting from changes in incoming gas quality (freeze-ups, liquids, etc.).

____

____

Station throughput

Approximate monthly dispensed volumes ____________________

Estimated turnaround time (time for gas entering the system to be dispensed) __________

CUSTOMER INFORMATION

Typical customers (check all that apply): Personal vehicles ___ Trucks/utility vehicles ___

Buses/multi-passenger vehicles ___ Other (describe) ___________________

Any customer feedback on NGV performance after refueling (improved, runs rough, etc.)

____

____

Any customer feedback on fueling process? (struggling with the nozzle, slow fill times, long lines, etc.)

____

____

How often are NGVs towed in with empty tanks? ___________________

GAS QUALITY AT THE STATION

Brand and model of any moisture instrumentation onsite.__________________

Location of moisture instrumentation in station layout. ___________________

Reading at the time of the visit. _________

How often is drier regeneration needed? ___________________

Date of last regeneration? _________

Any known carryover of liquids (compressor oil, water) into dispensed CNG? Describe liquids.

____

____

Does the operator regularly collect samples for analysis? (Y/N) ___

Sampling frequency. _________

Components analyzed.

____

____

Data from operator sample analyses not required.

CNG Station Data

Record the following data for use with the MDM-300 moisture analyzers.

Station name/location			
Moisture analysis point	LDC connection	CNG dispenser	
Source pressure			
Gas temperature (if known)			
Analyzer flow rate			
Log filename			
Log start time			
Final moisture reading			
Log stop time			

Record the cylinder numbers for the samples taken at the station.

Gas sample cylinders			
Liquid sample cylinder			

Sketch the basic station layout below and mark moisture sampling points.

APPENDIX D

STATION SURVEY RESULTS

Table D.1. Survey Results from CNG Stations in Pacific and Rockies States

Of the eight stations in the Western region, one half have moisture instruments onsite, and only one has noted changes in moisture content coming from the LDC. Two stations reported issues with liquid carryover into the dispensed CNG.

Station ID	**W1**	**W2**	**W3**	**W4**	**W5**
Station layout					
Processing order:					
Compression before drying					
Drying before compression	√	√	√	√	√
Moisture drying method:					
Desiccant	√	√	√	√	√
Molecular sieve					
Deliquescent salt tank					
Other					
Locations of any filters and scrubbers	Before and after drier, filter on each compression stage, two on compressor discharge, one at dispenser	Filter at each stage of compression, one at the drier inlet, two filters after compression, filter at dispenser	Filters within each compression stage, before and after the drier, and before and after storage	Before and after the drier, at each stage of compression, and before the dispenser	Before the drier, in the drier, at each compression stage
Number and types of compressors, number of compression stages	One reciprocating Greenfield compressor with five stages	Two compressors in series, four stages each	One reciprocating compressor, five stages	One reciprocating compressor, four stages	One Ariel reciprocating compressor, three stages
Number of parallel compression/drying streams	One	Two (only one active at a time)	One	One	One
Ability to bypass storage and draw directly from the compressor or the drier	Yes	Yes	Yes	Yes	Yes

Table D.1. Survey Results from CNG Stations in Pacific and Rockies States (Continued)

Station ID	**W1**	**W2**	**W3**	**W4**	**W5**
LDC information					
Delivery pressure from LDC	15 psig	60 psig	40 psig	38 psig	245 psig
Known changes in incoming gas quality on a periodic basis	None	None	None	None	Quality has been good lately, moisture level drops when colder
Known problems resulting from changes in incoming gas quality	None	None	None	None	None
Station throughput					
Approximate monthly dispensed volumes	30,000 GGE	Unknown	25,000 GGE	Unknown	Unknown
Estimated time for gas entering the system to be dispensed	Typically five minutes, depending on how busy the station is	Five minutes	Five minutes	Unknown	Unknown
Customer information					
Typical customers:					
Personal vehicles		√	√	√	√
Trucks/utility vehicles	√	√	Semis	√	√
Buses/multi-passenger vehicles	√	√		√	√
Other	AT&T vehicles, school buses, cabs	Military base vehicles, AT&T, Allied Waste, public, airport shuttles	Trash trucks, cabs, local air quality district vehicles, van pools	Trash trucks, a few transit buses	Trash trucks and transit buses
Customer feedback on NGV performance after refueling	Good performance, complete fulls	Happy with recent upgrade, new compressor, drier and dispenser	None	Customers have been happy	Complaints about being unable to fill tank as full in cold weather

Table D.1. Survey Results from CNG Stations in Pacific and Rockies States (Continued)

Station ID	**W1**	**W2**	**W3**	**W4**	**W5**
Customer feedback on fueling process	Occasionally bad, but many customers like the station because of complete fills	Fueling process quicker after upgrade	Fast fueling	None	None
How often are NGVs towed in with empty tanks?	About six times a year ("auction people," cabs)	Occasionally (AT&T vehicles and small cars)	Unknown	Once a week	Once a week
Gas quality at the station					
Brand and model of any onsite moisture instrumentation	Dew point analyzer after drier	None	None	Xebec drier	Xebec drier
Location of moisture instrumentation in the station layout	After drier			Within drier	Within drier
Reading at the time of the visit	-123.7°F			-66°F	-63°F
How often is drier regeneration needed?	Any time dew point falls below -40°F	Unknown	Internal drier, no regeneration cycle	Twice a year; one is every fall before freezing temperatures	Not needed in winter; every three months in summer
Date of last regeneration?	October/November 2013	Unknown		Fall 2013	October 2013
Any known carryover of liquids into dispensed CNG?	None	None known	None	None	None
Does the operator regularly collect samples for analysis?	No	Unknown	No	No (LDC might collect samples)	Only at drier
Sampling frequency					Unknown
Components analyzed					Unknown

Table D.1. Survey Results from CNG Stations in Pacific and Rockies States (Continued)

Station ID	W6	W7	W8
Station layout			
Processing order:			
Compression before drying	√	√	√
Drying before compression			
Moisture drying method:			
Desiccant	√	√	√
Molecular sieve			
Deliquescent salt tank			
Other			
Locations of any filters and scrubbers	One filter each before and after compression, two filters after drier	One filter per compression stage, two filters per drier. Filters changed very regularly (every 500 hours).	Filter on drier, main filter between drier and storage
Number and types of compressors, number of compression stages	Two parallel compressors, four stages each	Slow fill and fast (public) fill systems each have one compressor with four stages	Two compressors in series, each with two stages
Number of parallel compression/drying streams	Two parallel compressors, one drying stream	One per system	Two
Ability to bypass storage and draw directly from compressor or drier	No	Yes (can also bypass drier)	Yes

Table D.1. Survey Results from CNG Stations in Pacific and Rockies States (Continued)

Station ID	W6	W7	W8
LDC information			
Delivery pressure from LDC	455 psig	175 psig	375 psig
Known changes in incoming gas quality on a periodic basis	None	None	None
Known problems resulting from changes in incoming gas quality	None	None	None
Station throughput			
Approximate monthly dispensed volumes	Unknown	Unknown	Unknown
Estimated time for gas entering the system to be dispensed	30 minutes	Seconds (#1 highest volume public station)	Seconds
Customer information			
Typical customers:			
Personal vehicles	√		
Trucks/utility vehicles	√		√
Buses/multi-passenger vehicles	√	√	√
Other	Military base vehicles, AT&T, Allied Waste, public, airport shuttles	AT&T, transit vehicles, utility vehicles	AT&T, school buses
Customer feedback on NGV performance after refueling	None	Customers happy	One incident with oil present in a large semi-truck fuel tank. No problems with buses.

Table D.1. Survey Results from CNG Stations in Pacific and Rockies States (Continued)

Station ID	W6	W7	W8
Customer feedback on fueling process	Customers surveyed, complaints about low filling pressure	None	Comments on longer fueling times, smaller storage
How often are NGVs towed in with empty tanks?	Once a month, typically Honda Civics	N/A	None known
Gas quality at the station			
Brand and model of any onsite moisture instrumentation	Panametrics	None	Unknown
Location of moisture instrumentation in the station layout	After drier		
Reading at the time of the visit	None available		
How often is drier regeneration needed?	Once every six months	Unknown	Checked every month, regeneration interval slightly longer than three months
Date of last regeneration?	January 2014		2 ½ months before site visit
Any known carryover of liquids into dispensed CNG?	Occasional compressor oil carryover	None	One case known; liquids unknown
Does the operator regularly collect samples for analysis?	No	No	No
Sampling frequency			Last sample collected in early 2013
Components analyzed			

Table D.2. Survey Results from CNG Stations in Central States

Four of five stations in the Central region have moisture instruments onsite, and one of these (station C4) confirmed SwRI measurements of high moisture content in the CNG stream. This was also the only station to report significant liquid carryover into the dispensed CNG.

Station ID	**C1**	**C2**	**C3**	**C4**	**C5**
Station layout					
Processing order:					
Compression before drying					√
Drying before compression	√	√	√	√	
Moisture drying method:					Unknown
Desiccant	√	√	√	√	
Molecular sieve					
Deliquescent salt tank					
Other					
Locations of any filters and scrubbers	Before and after the drier; at the compressor inlet, between stages, and before discharge (10 μm and 4 μm coalescing filters); large coalescing filter before the input to the priority panel; filters from low, mid, and high bank inputs to the dispensers	Before and after the drier; at the compressor inlet, between stages, and before discharge (10 μm and 4 μm coalescing filters); large coalescing filter before the input to the priority panel; filters from low, mid, and high bank inputs to the dispensers	Before and after the drier	Before and after the drier	One scrubber and four filters after the compressor
Number and types of compressors, number of compression stages	Two ANGI-packaged Ariel JGP/2 compressors with four stages each	Two ANGI-packaged Ariel JGQ/2 compressors with three stages each	One Greenfield compressor with five stages	Two parallel compressors, four stages each, supplying storage vessels	Unknown
Number of parallel compression/drying streams	One	One	One	One	One

Table D.2. Survey Results from CNG Stations in Central States (Continued)

Station ID	**C1**	**C2**	**C3**	**C4**	**C5**
LDC information					
Ability to bypass storage and draw directly from the compressor or the drier	Yes	Yes	No	No	No
Delivery pressure from LDC	25 psi	300 psi	50 psi	45 psi	63 psi
Known changes in incoming gas quality on a periodic basis	None	None	Changes in moisture content over the course of the year	Station just opened, high moisture levels coming from one dispenser	No real issues known. System will shut down if delivery pressure is less than 20 psi, but this has never happened
Known problems resulting from changes in incoming gas quality	None	None	None	Liquids cause freeze-ups of one pump in cold weather (solenoid valve sticking)	None
Station throughput					
Approximate monthly dispensed volumes	Unknown – new station	20,000 GGE	Unknown	~3,000 GGE	Unknown
Estimated time for gas entering the system to be dispensed	Three hours	½ hour	Eight minutes	30 minutes to one hour	Straight through from LDC to dispenser (no storage tanks)
Customer information					
Typical customers:					
Personal vehicles	√	√	√	√	
Trucks/utility vehicles	√	√	√	√	
Buses/multi-passenger vehicles				√	√
Other			Government vehicles	Tow trucks, AAA	

Table D.2. Survey Results from CNG Stations in Central States (Continued)

Station ID	C1	C2	C3	C4	C5
Customer feedback on NGV performance after refueling	Nothing negative	Nothing negative	"They love it."	None	Issues with engines, may not be fuel-related; was getting some oil in secondary filters; sent to lab for analysis, but did not match compressor oil used at station
Customer feedback on fueling process	Different nozzles, but customers like them	Good fills, fast	Some complaints about nozzles, slow fills at high-use locations	"Fastest fueling in the state"	Dispensers work smoothly
How often are NGVs towed in with empty tanks?	Do not know, haven't seen any yet	Rarely	None at this station; twice at another station in the same city	About twice a year	Never (vehicles refueled nightly)
Gas quality at the station					
Brand and model of any onsite moisture instrumentation	Xentaur XDT	Xentaur XDT	Xebec STR	Xentaur series	None
Location of moisture instrumentation in the station layout	Drier output	Drier output	Not reported	After drier	
Reading at the time of the visit			-55°F	WVDP = 68.0°F	
How often is drier regeneration needed?	Don't know yet	Approximately every nine months	Never done at this location	Once every two to six months	Don't know
Date of last regeneration?				Unknown	
Any known carryover of liquids into dispensed CNG?	None	None	Minimal	Yes – water and oil mixture	None
Does the operator regularly collect samples for analysis?	No	No	No	No	No
Sampling frequency			This is the first sample in over three years		
Components analyzed					

Table D.3. Survey Results from CNG Stations in Eastern States

Only one station (E5) reported receiving gas from the local utility with noticeable amounts of hydrocarbon liquids and moisture. This station receives unprocessed wellhead gas instead of distribution-quality gas. Three of the ten stations, including E5, have experienced liquid carryover into delivered CNG. However, the survey respondents in this area either reported that no moisture analyzer was installed, or did not respond to the survey question about onsite moisture measurements.

Station ID	**E1**	**E2**	**E3**	**E4**	**E5**
Station layout					
Processing order:					
Compression before drying					
Drying before compression	√	√	√	√	√
Moisture drying method:					
Desiccant	√	√		√	
Molecular sieve			√		√
Deliquescent salt tank					
Other					
Locations of any filters and scrubbers	Before and after all processes (compression, drying…)	"All throughout system"	Filter upstream of drier	Before and after drier	Coalescing filter at inlet to molecular sieve drier, particulate filter at drier outlet
Number and types of compressors, number of compression stages	Four reciprocating compressors, all three-stage	Four reciprocating compressors, all three-stage, driven by natural gas engine	Single Ariel reciprocating compressor, four-stage	Four small reciprocating compressors, three-stage	Two Ingersoll-Rand three-stage compressors; one serves as a backup for the other
Number of parallel compression/drying streams	Four parallel compressors, one drying stream	?	One	Two	One
Ability to bypass storage and draw directly from the compressor or the drier	Yes	Unknown	Unknown	Unknown	Unknown

Table D.3. Survey Results from CNG Stations in Eastern States (Continued)

Station ID	E1	E2	E3	E4	E5
LDC information					
Delivery pressure from LDC	300 psi	175 psi	40 psig	21 psig	40 psig to 50 psig, regulated down to 25 psig
Known changes in incoming gas quality on a periodic basis	None known	None known	None known	None known	Lots of heavy hydrocarbons and moisture on a regular basis
Known problems resulting from changes in incoming gas quality	None known	None known	None known	None known	None
Station throughput					
Approximate monthly dispensed volumes	Unknown	70 to 80 GGE/night (~2,100 to 2,500 GGE/month)	~3000 GGE	Unknown	~3000 GGE
Estimated time for gas entering the system to be dispensed	Unknown	Unknown	Unknown	Unknown (depends on storage capacity of heavy trucks that use the station)	Unknown
Customer information					
Typical customers:					
Personal vehicles			√	√	√
Trucks/utility vehicles			√	√	
Buses/multi-passenger vehicles	√	√	√		√
Other			Some semi-trucks; not regular, but go in batches		Private vehicles, some company vehicles
Customer feedback on NGV performance after refueling	None	None	None	None	Higher mileage due to higher Btu gas

Table D.3. Survey Results from CNG Stations in Eastern States (Continued)

Station ID	E1	E2	E3	E4	E5
Customer feedback on fueling process	None	None; sometimes stiff nozzles	Complaints that station does not accept credit cards	None	Have manual control of filling banks
How often are NGVs towed in with empty tanks?	Unknown	Occurred early in station implementation, but not now	Unknown	Unknown	Unknown
Gas quality at the station					
Brand and model of any onsite moisture instrumentation	Unknown	Unknown	None	None	None
Location of moisture instrumentation in station layout					
Reading at the time of the visit					
How often is drier regeneration needed?	Dual-bed system regenerates automatically	Dual-bed system regenerates automatically	Approximately once a year	Unknown	Every 2.5 months
Date of last regeneration?			May 2013 (sampled in December 2013)	Unknown	Nov. 9, 2013 (sampled on Dec. 11, 2013)
Any known carryover of liquids into dispensed CNG?	None known	Filters all through the system, but still have some liquid carryover; not as much of an issue since upgrade	None known	None known	Moisture (water)
Does the operator regularly collect samples for analysis?	No	No	No	Yes	No
Sampling frequency				Annually	
Components analyzed				Not indicated	

APPENDIX E
STATION LAYOUTS AND PHOTOGRAPHS

This appendix includes drawings of the equipment layouts at each CNG station where samples were collected. Layouts indicate the number of parallel processing paths at each station and the locations in the processing chains of key components such as driers, compressors, filters, and storage tanks. Station layouts are blinded and listed only by station ID.

During each visit, LDC connections, arrangements of compression and dehydration equipment, and dispensing pumps were photographed. Sampling equipment connections used to analyze moisture content and collect samples were also photographed where possible. To reduce the final size of the appendix, example photographs of key equipment have been included for four of the stations. The complete set of photographs has been provided to CRC electronically. The photographs have been edited to blind the station locations.

Station W1 Layout and Photographs

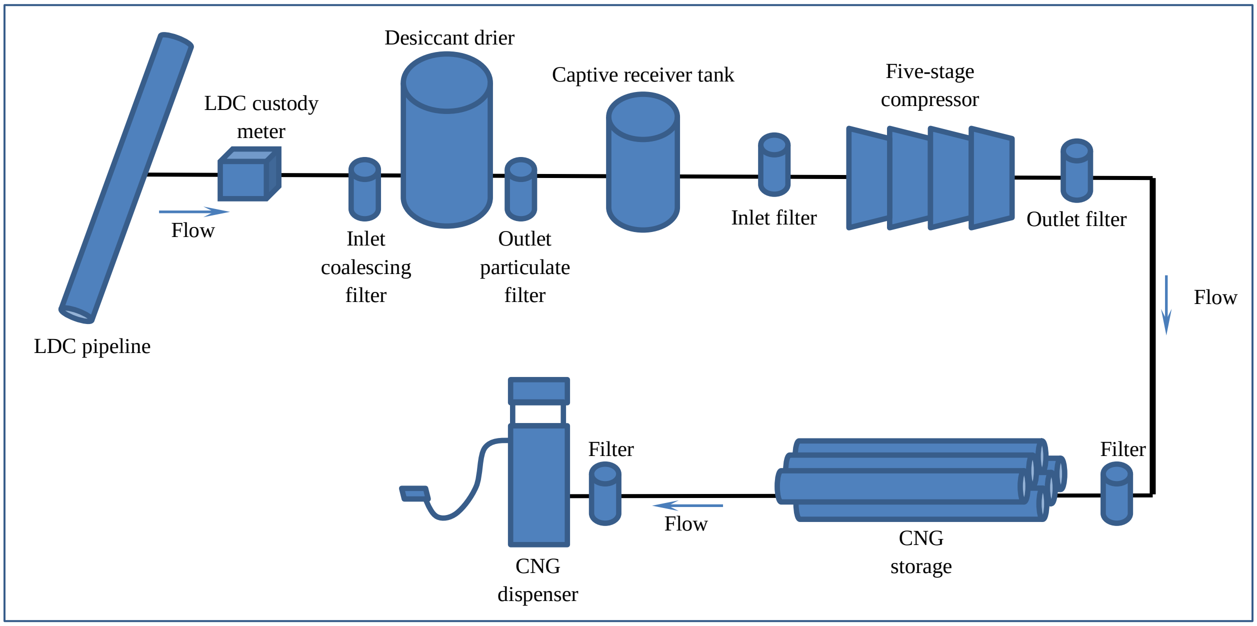

Figure E.1. Equipment Arrangement at Station W1
Filters are located at the inlets of each major piece of equipment and at the drier and compressor outlets. The captive receiver tank downstream of the drier is unique to this station.

Figure E.2. LDC Custody Transfer Meter Run at Station W1
The circle marks the rotary meter used to measured gas volumes entering the CNG station. The white box is a volume corrector that adjusts meter output for variations in gas temperature.

Figure E.3. Moisture Measurement Location at the W1 LDC Connection
The tap and valve at the rotary meter inlet (circled at left) were used to measure the moisture levels in the gas entering the CNG station (as shown at right).

Figure E.4 Drier System and Compressor Skid at Station W1
The large silver tank at the far right is the captive receiver tank used to store dry gas. The gray cylinders in front of and to the left of the tank are inlet and outlet filters. The desiccant drier cylinder is visible above and behind the equipment panel, to the left of the filters. After drying, the gas travels to the multistage compressor housed in the skid on the left.

Figure E.5. CNG Storage Tanks at Station W1
Gas received from the compressor is stored a cascade storage system with reservoirs at low, medium, and high pressures.

Figure E.6. Dispenser at Station W1
The left-hand photo shows one dispenser at the station being used with the sampling manifold to collect CNG and liquid samples. The right-hand photo shows the moisture analyzer being used to measure moisture levels in the dispensed CNG.

Station W2 Layout and Photographs

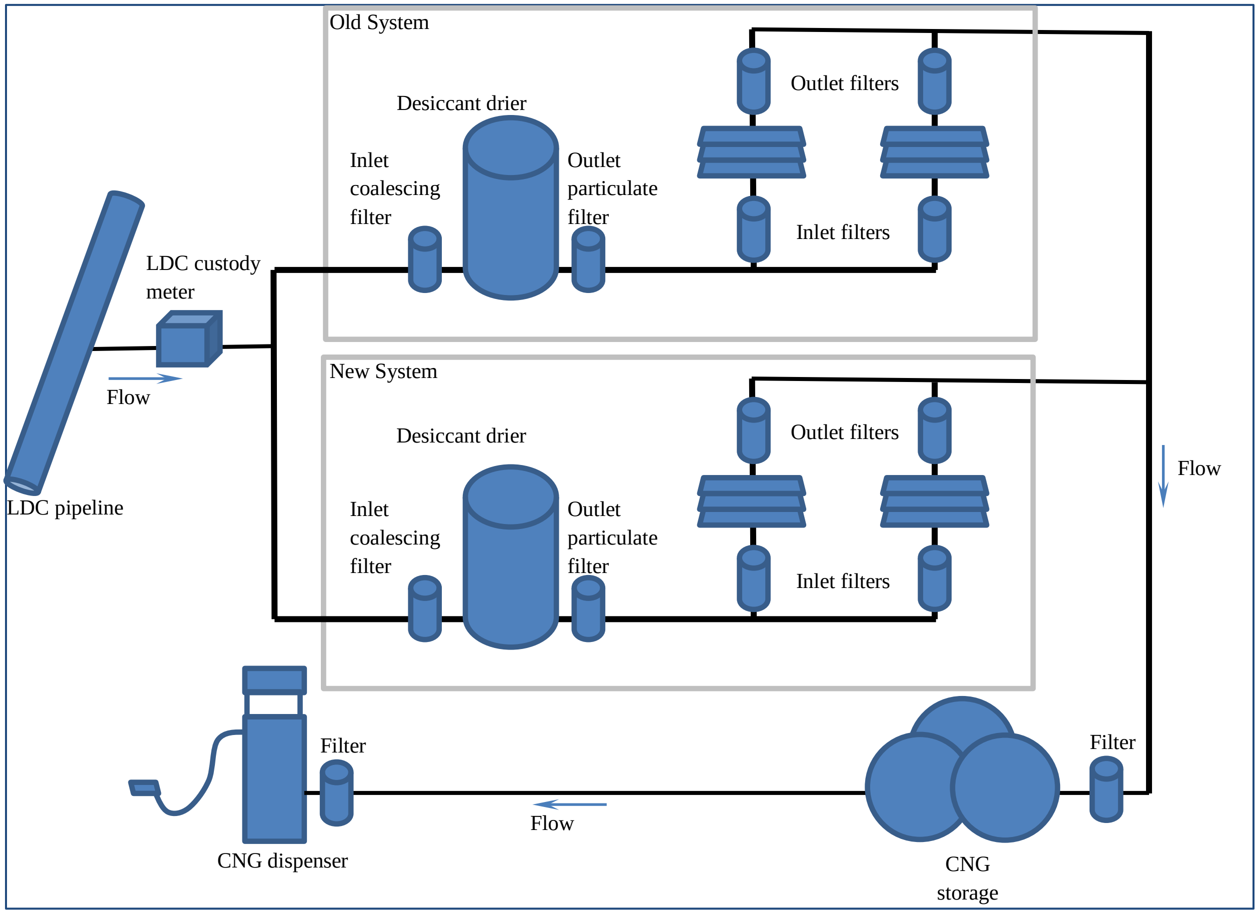

Figure E.7. Equipment Arrangement at Station W2

The station includes two parallel streams for drying and compression, with two parallel compressors on each stream. The second stream was added in a station expansion. Only one stream is used at any one time, with the other serving as a backup.

Figure E.8. LDC Custody Transfer Meter Run at Station W2
Moisture measurements of the incoming gas were taken from a sample tap downstream of the rotary meter used for custody transfer.

Figure E.9. Drying Skid at Station W2
The tall cylinder toward the right is the desiccant stack where drying occurs. Dry gas passes through the receiving tank and filter in the center of the photo on its way to the compressors (in the white structure behind the drying skid).

Figure E.10. CNG Storage Tanks at Station W2
Unlike most CNG stations, station W2 uses spherical CNG storage tanks.

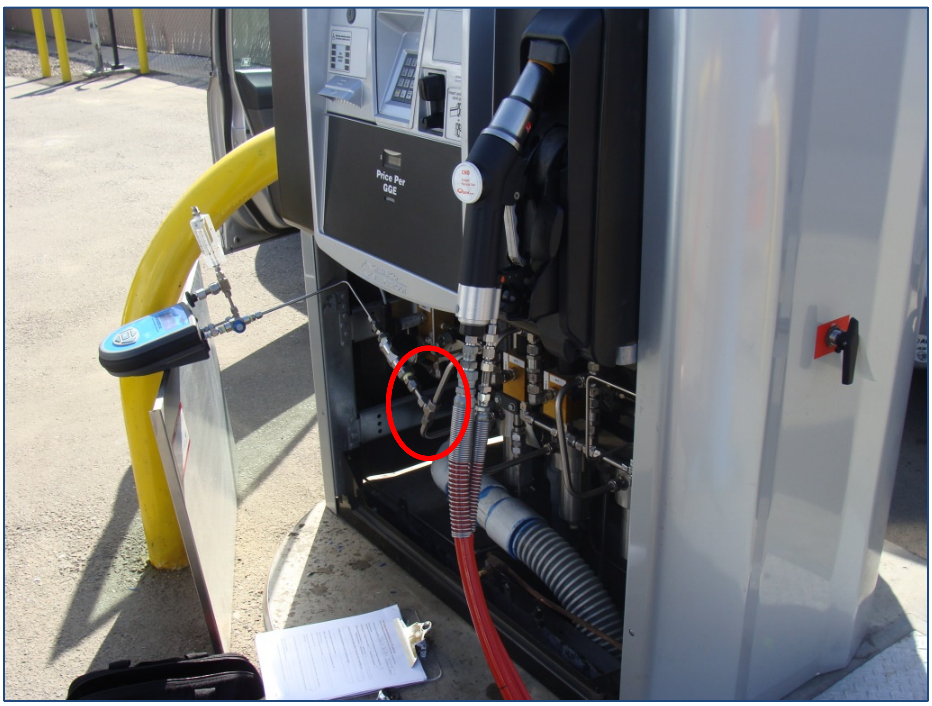

Figure E.11. Dispenser at Station W2
The control panel, credit card reader, and nozzle are designed much like a gasoline dispenser. The shutoff valve interfered with the flow to the moisture analyzer when the analyzer was connected directly to the nozzle. To obtain a steady sample stream, the analyzer was connected to a point (circled in the photo) upstream of the shutoff valve.

Station W3 Layout and Photographs

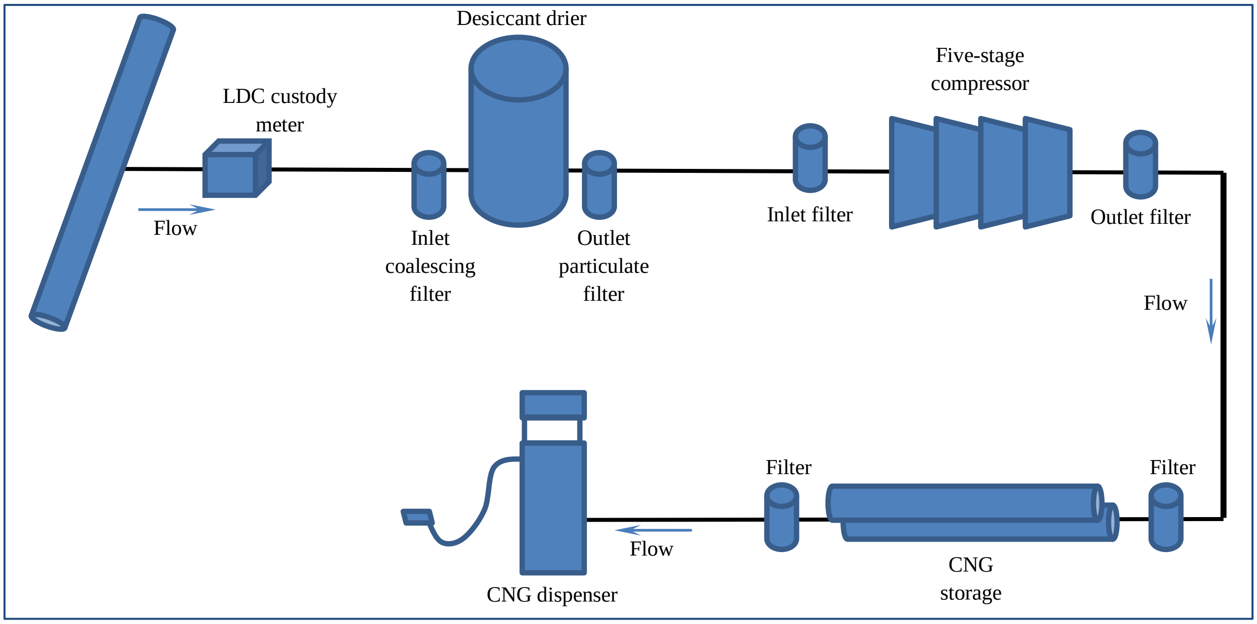

Figure E.12. Equipment Arrangement at Station W3
This station uses a single drying and compression stream, with filters at the inlet and outlet of each major component.

Figure E.13. LDC Custody Transfer Meter Run at Station W3
Moisture measurements of the incoming gas were taken from a sample tap on the rotary meter used for custody transfer.

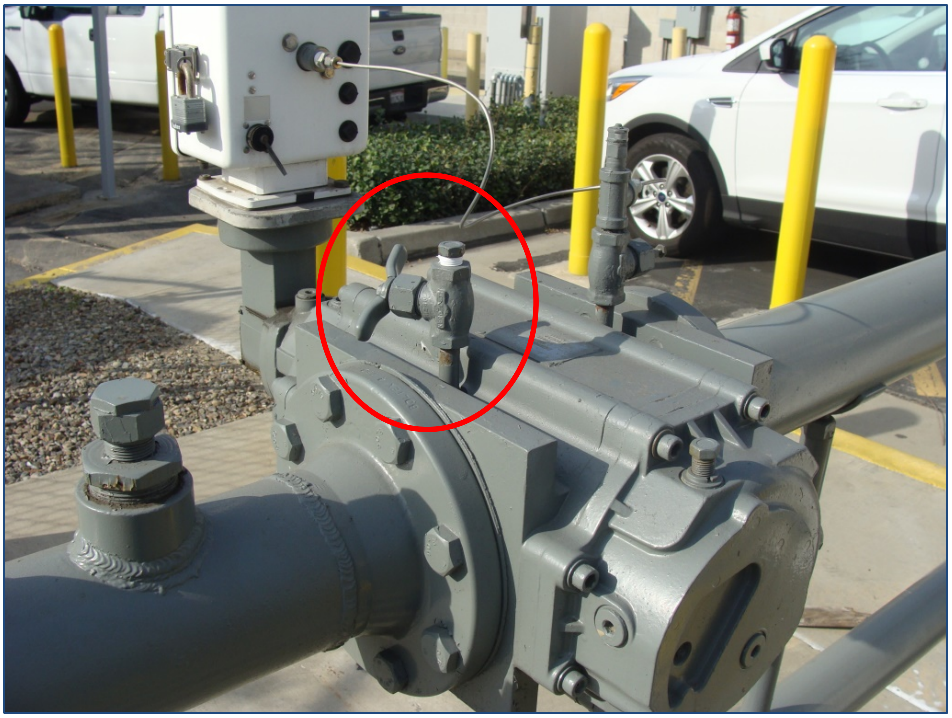

Figure E.14. Sample Tap Used for Moisture Measurements of Incoming Gas
The Michell moisture analyzer was connected directly to the tap circled above, on the downstream side of the meter.

Figure E.15. Interior of the Drying and Compression Skid at Station W3
All drying, compression, and filtration equipment at this station is enclosed in a prefabricated skid. Parts of the compressor can be seen in the foreground and at the left rear. The desiccant stack is behind the wall at the left rear of the photo.

Figure E.16. CNG Storage Tanks at Station W3

The prefabricated drier/compressor skid supplies a pair of storage tanks, fewer than most stations using cylindrical CNG tanks.

Figure E.17. Dispenser at Station W3

This style of dispenser has separate nozzles for NGV tanks rated to 3,000 psig and 3,600 psig.

Station W4 Layout and Photographs

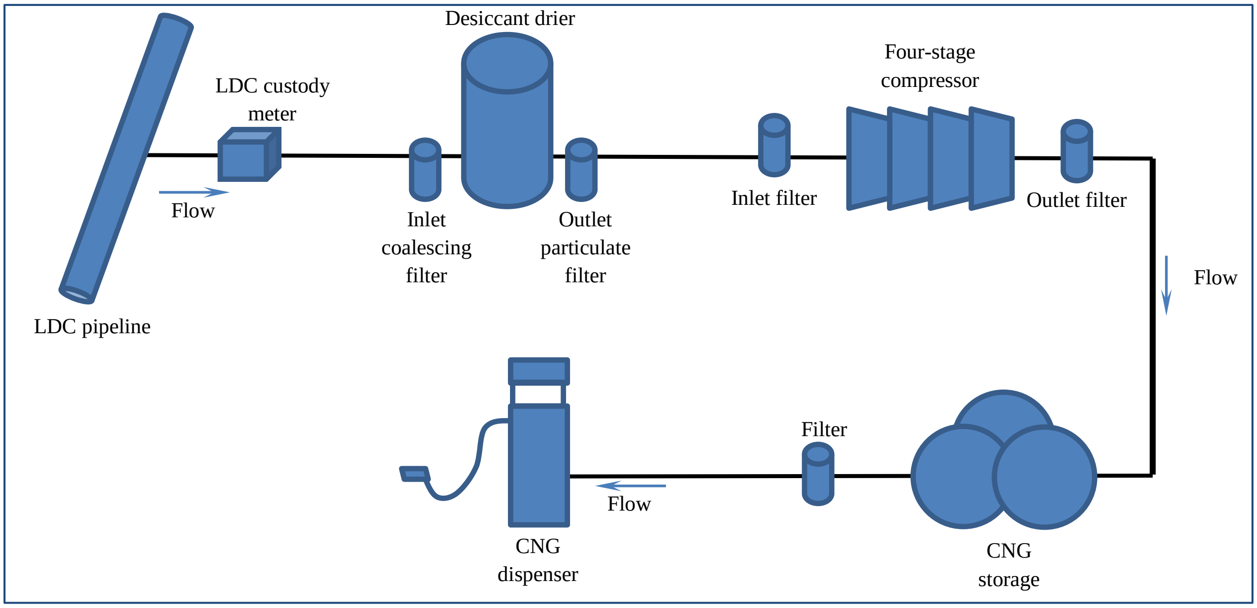

Figure E.18. Equipment Arrangement at Station W4
This station uses a single drying and compression stream, with filters at the inlet and outlet of the drying and compression steps and at the inlet to the dispensers.

Figure E.19. LDC Custody Transfer Meter Run at Station W4
A tap downstream of the bypass valve and upstream of the custody transfer rotary meter (in the circled region to the left) was used for moisture measurements of the incoming gas stream (as shown at right).

Figure E.20. Dehydration Skid at Station W4

Xebec moisture removal skids such as this one were in use at many stations visited during the project. The tall cylinder marked "Hot" is the desiccant stack, while the tank on the right serves as a reservoir before compression. The gray cylinders are inlet and outlet filters; the gray cabinet on the left incorporates a moisture analyzer.

Figure E.21. Compressor Skid and CNG Storage Tanks at Station W4
The station uses an ANGI compressor housed in the white enclosure behind the tanks. Like the Xebec drier skid, ANGI compressors were in use at many stations visited during the project. The drier skid (visible behind the rightmost tank) sends gas to the compressor, which then supplies CNG to the spherical tanks.

Figure E.22. Dispenser at Station W4
The photo shows a 3,600-psig nozzle being used with a sampling manifold to collect CNG and liquid samples.

Station W5 Layout

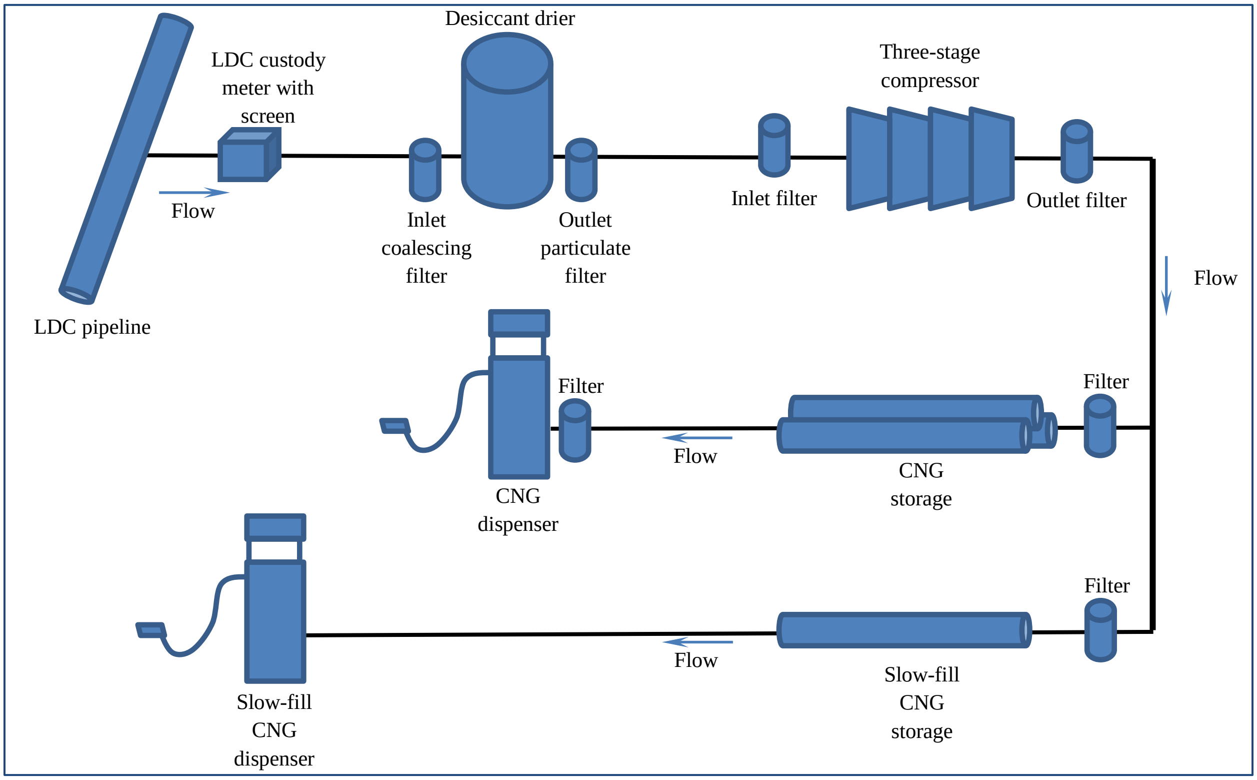

Figure E.23. Equipment Arrangement at Station W5
One drier and one compressor supply two storage and dispenser streams, one for fast fills and one for slow fills of fleet vehicles.

Station W6 Layout

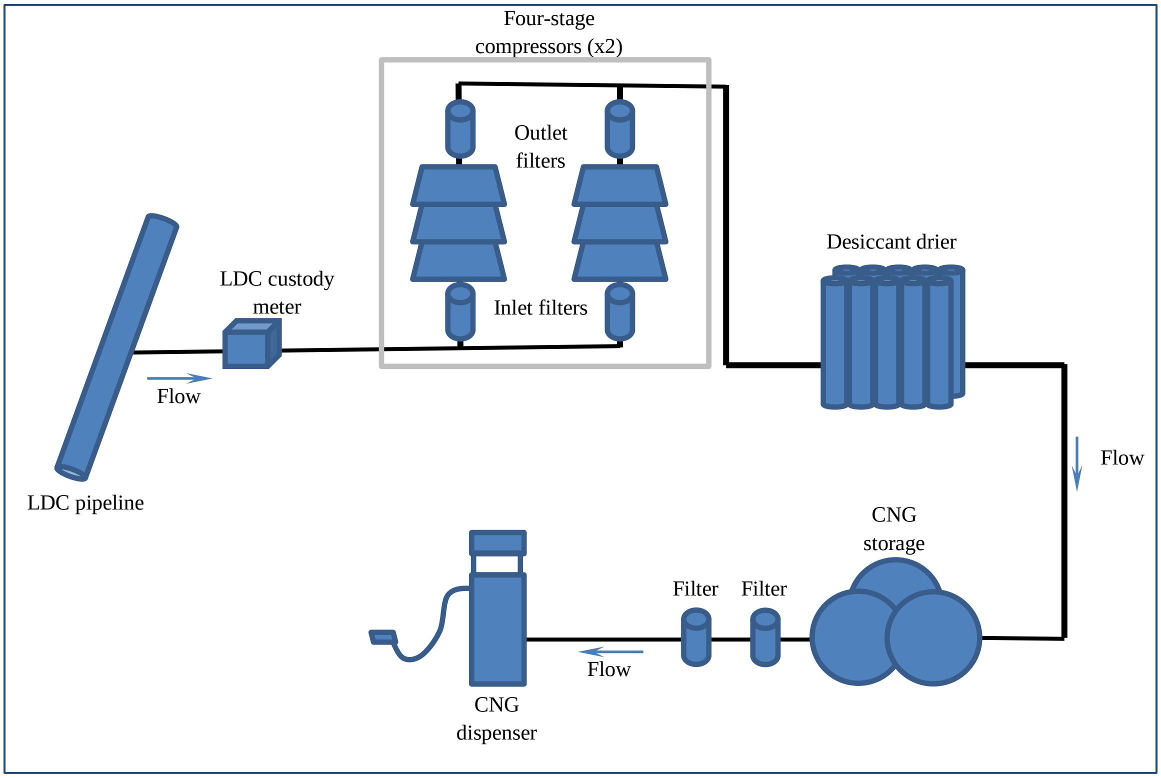

Figure E.24. Equipment Arrangement at Station W6

This station design includes two compressors in parallel upstream of the desiccant drier stacks. Filters are located on either side of the compressors and downstream of the drier and storage cylinders.

Station W7 Layout

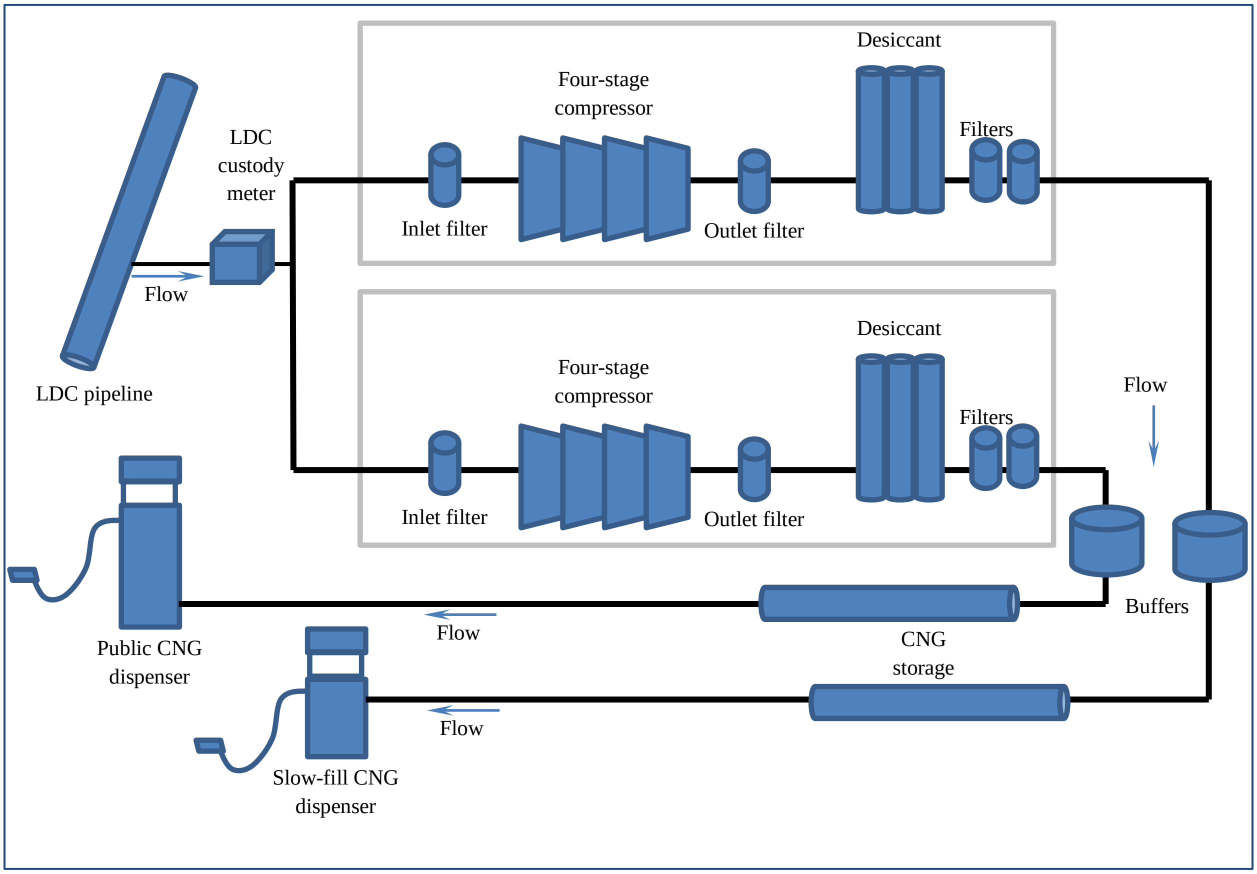

Figure E.25. Equipment Arrangement at Station W7

This station has two parallel runs consisting of a single compressor followed by a desiccant drier. The station also has separate dispensers for public vehicles (fast-fill) and fleet vehicles (time-fill). Each dispenser is supplied by one compressor/drier run.

Station W8 Layout

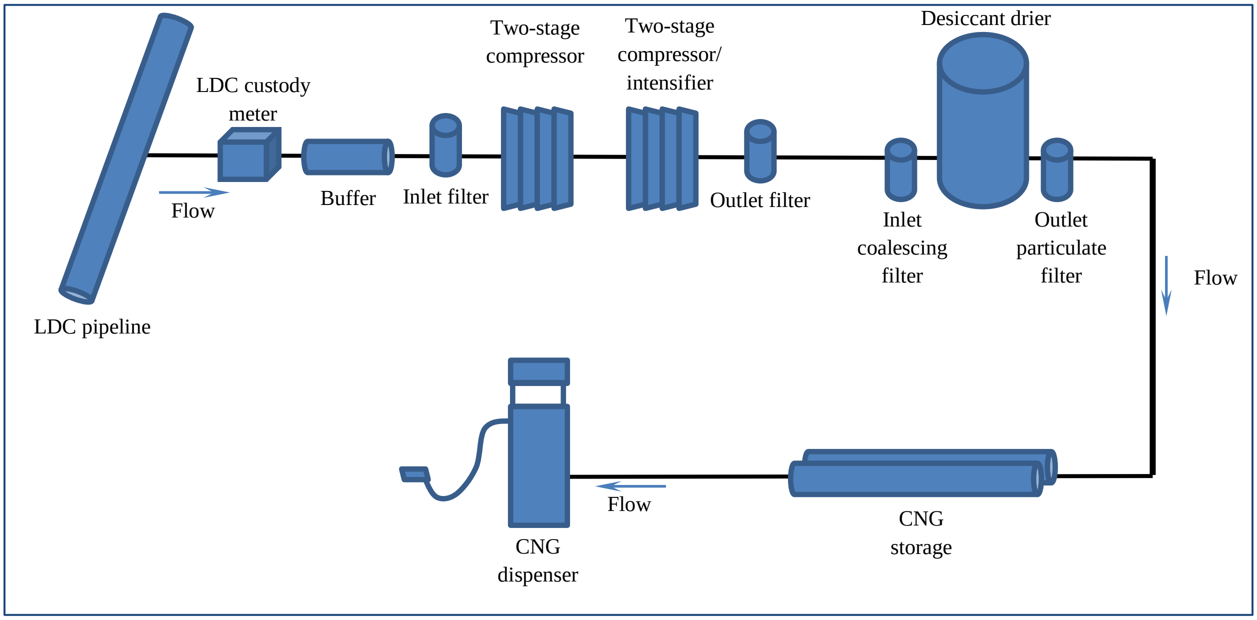

Figure E.26. Equipment Arrangement at Station W8

This station uses a pair of two-stage compressors in series upstream of the drier, one of the few station layouts to use compressors in series.

Station C1 Layout

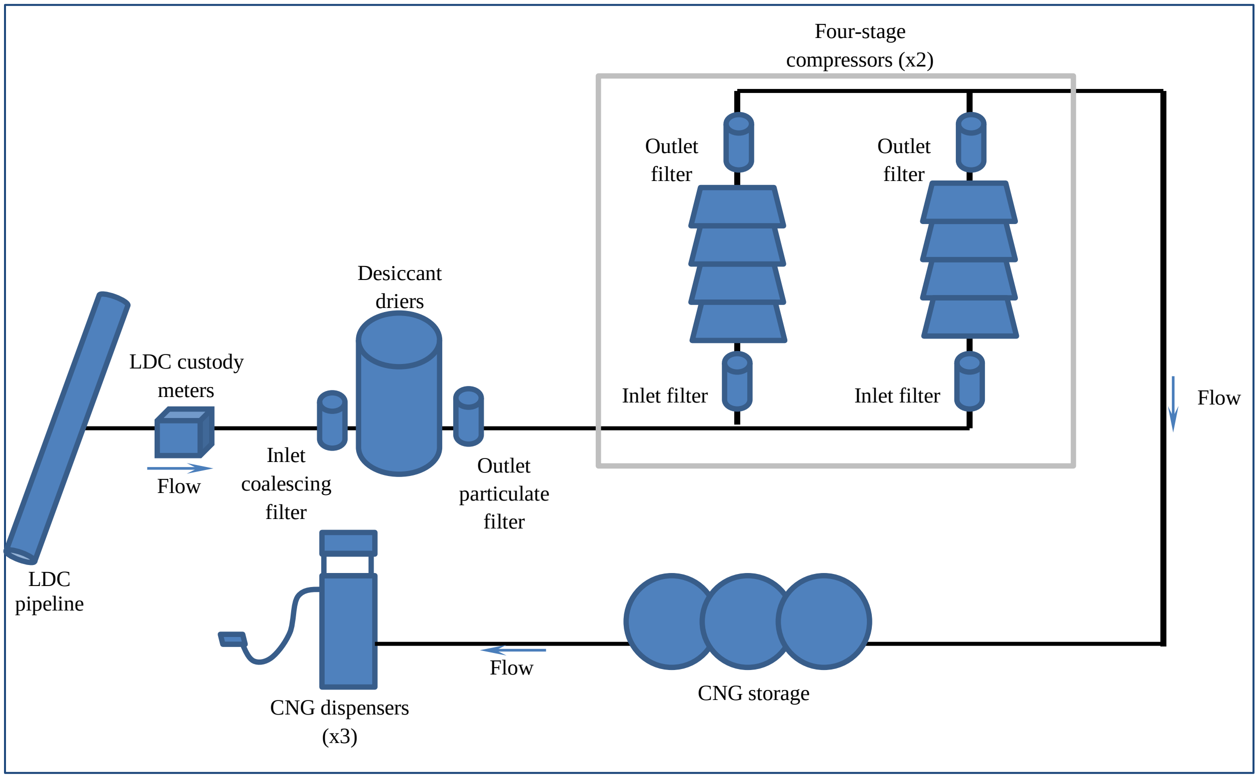

Figure E.27. Equipment Arrangement at Station C1

A single desiccant drier supplies a pair of four-stage compressors in parallel. Besides the filters shown in the diagram, the station operator also notes that there are filters between the compressor stages and on the individual storage tanks. The tanks use a cascade arrangement, with one tank each at high, medium, and low pressures.

Station C2 Layout

0

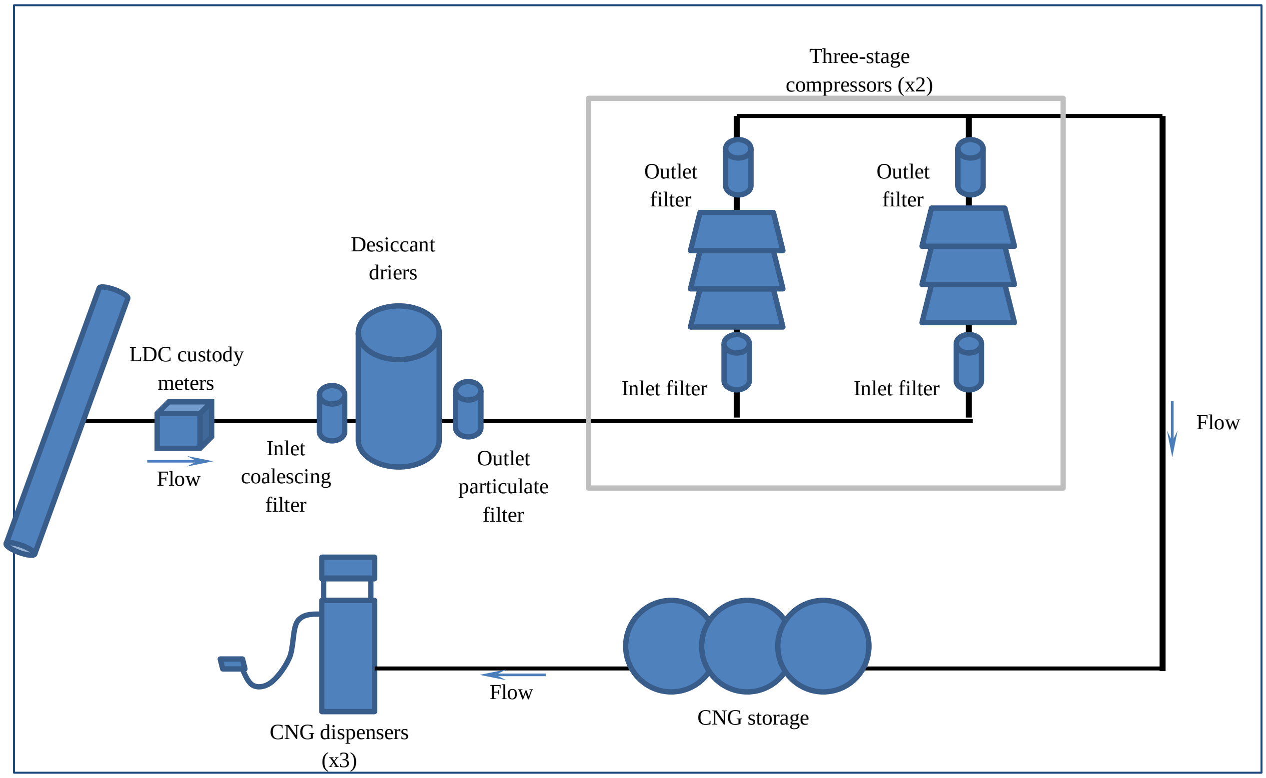

Figure E.28. Equipment Arrangement at Station C2
The arrangements at stations C1 and C2 are identical, except that station C2 uses three-stage compressors instead of four-stage compressors.

Station C3 Layout

The flow arrangement for this station was not recorded during the site visit.

Station C4 Layout

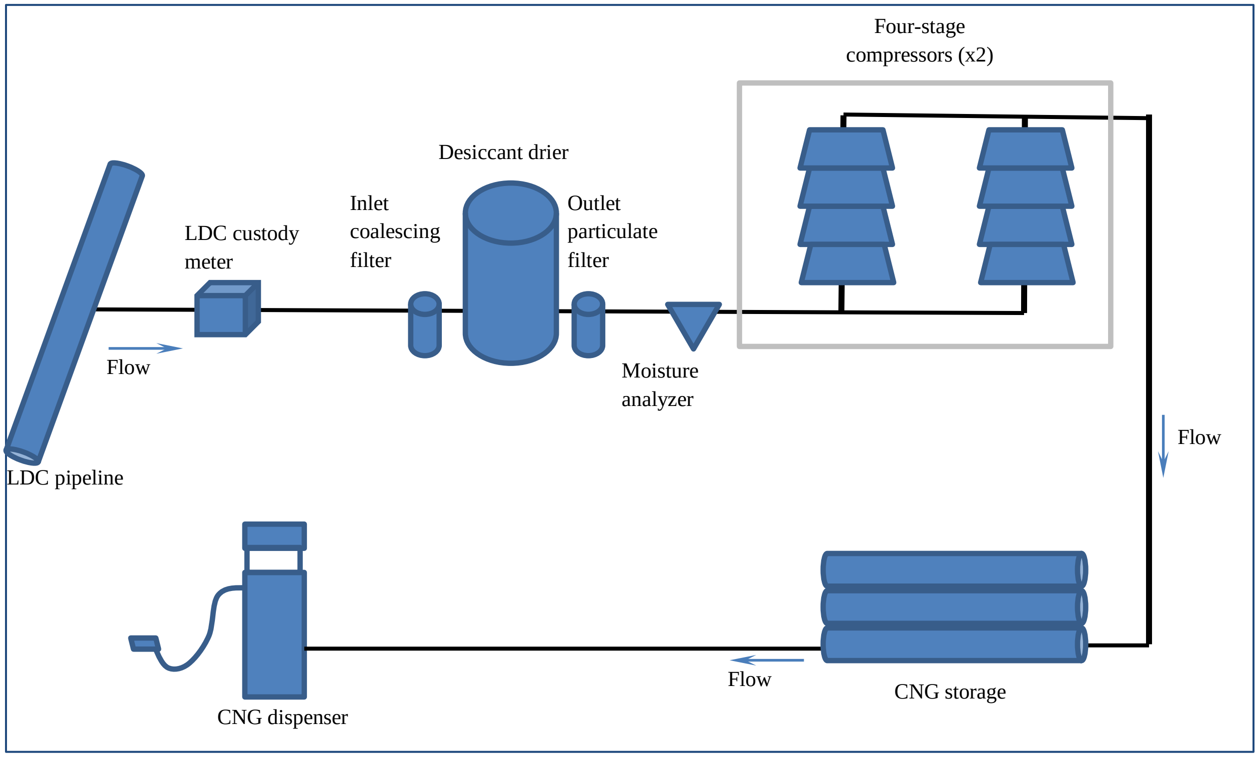

Figure E.29. Equipment Arrangement at Station C4

This station layout only incorporates filters at the inlet and outlet of the desiccant drier. A Xentaur series moisture analyzer has been installed immediately downstream of the drier.

Station C5 Layout

The flow arrangement for this station was not recorded during the site visit.

Station E1 Layout

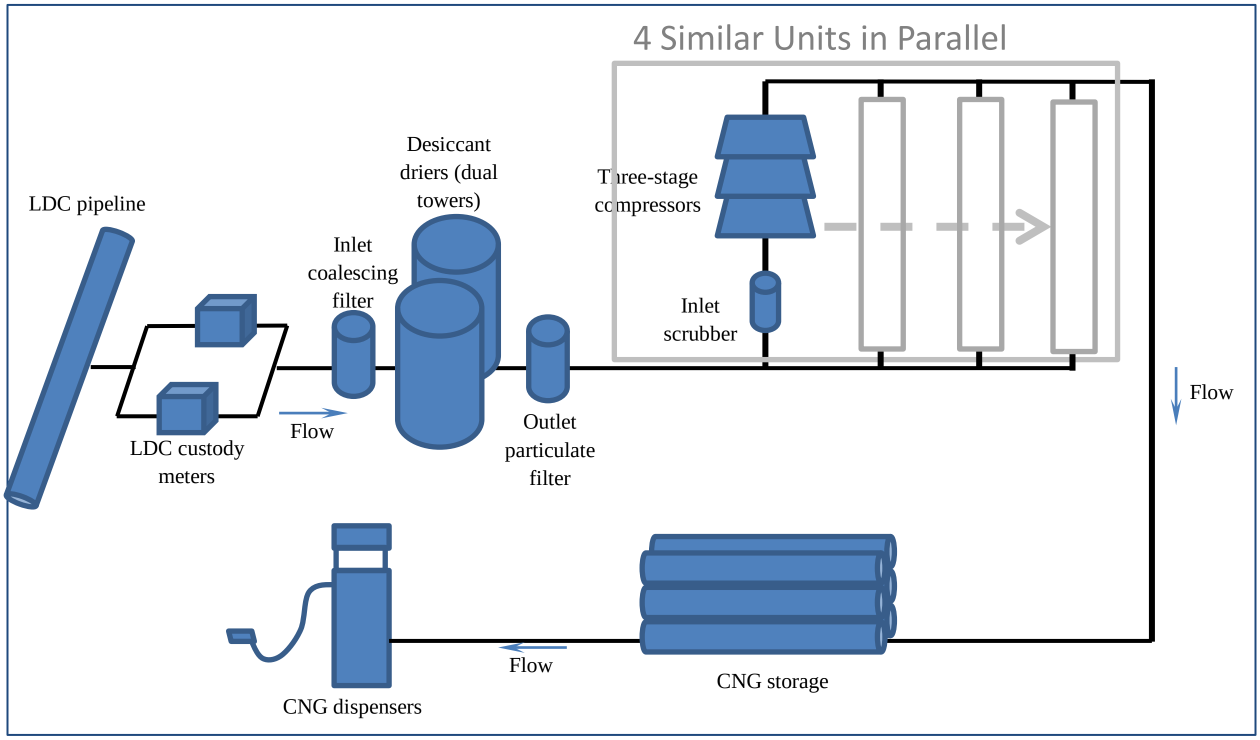

Figure E.30. Equipment Arrangement at Station E1

This station uses a dual-bed drier system that automatically sends flow through one bed while the other bed is regenerating. The station operator notes that filters and scrubbers are installed before and after all of the process points, including the compressors.

Station E2 Layout

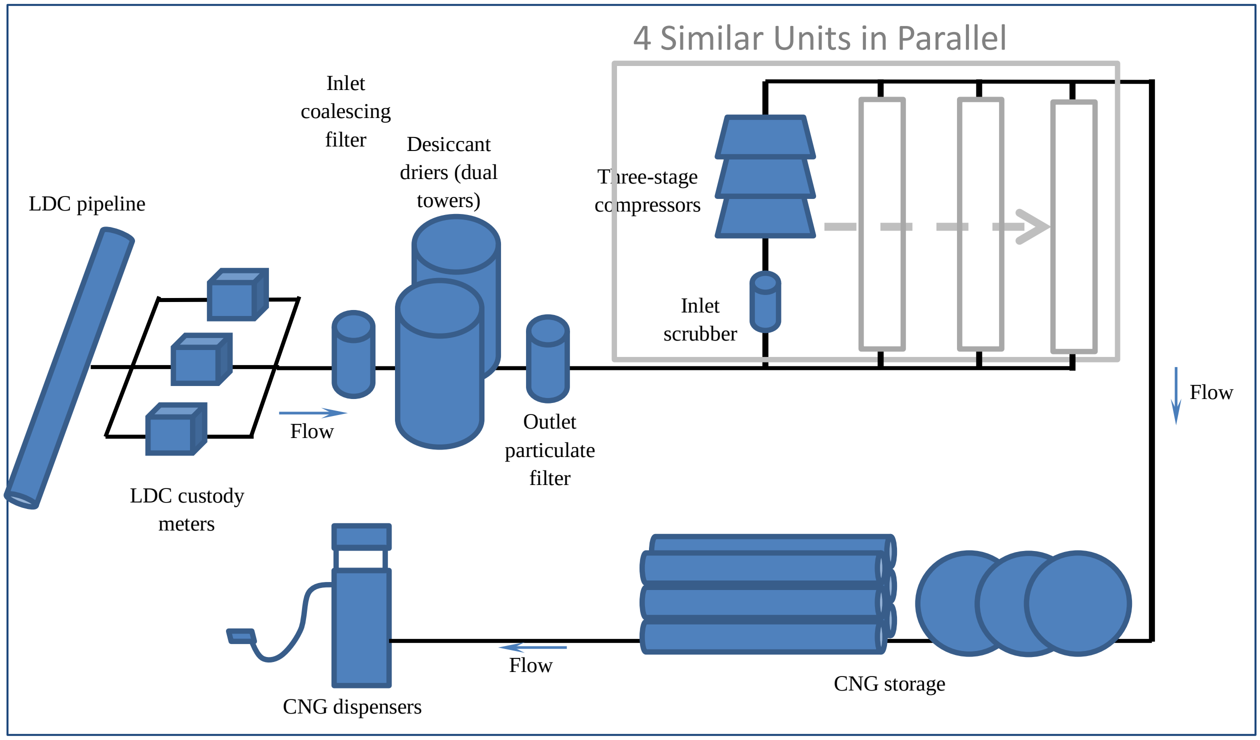

Figure E.31. Equipment Arrangement at Station E2

This station is nearly identical to station E1, except for the use of three custody transfer meters instead of two and the addition of spherical CNG storage tanks. The station operator notes that filters and scrubbers are installed before and after all process points, including the compressors.

Station E3 Layout

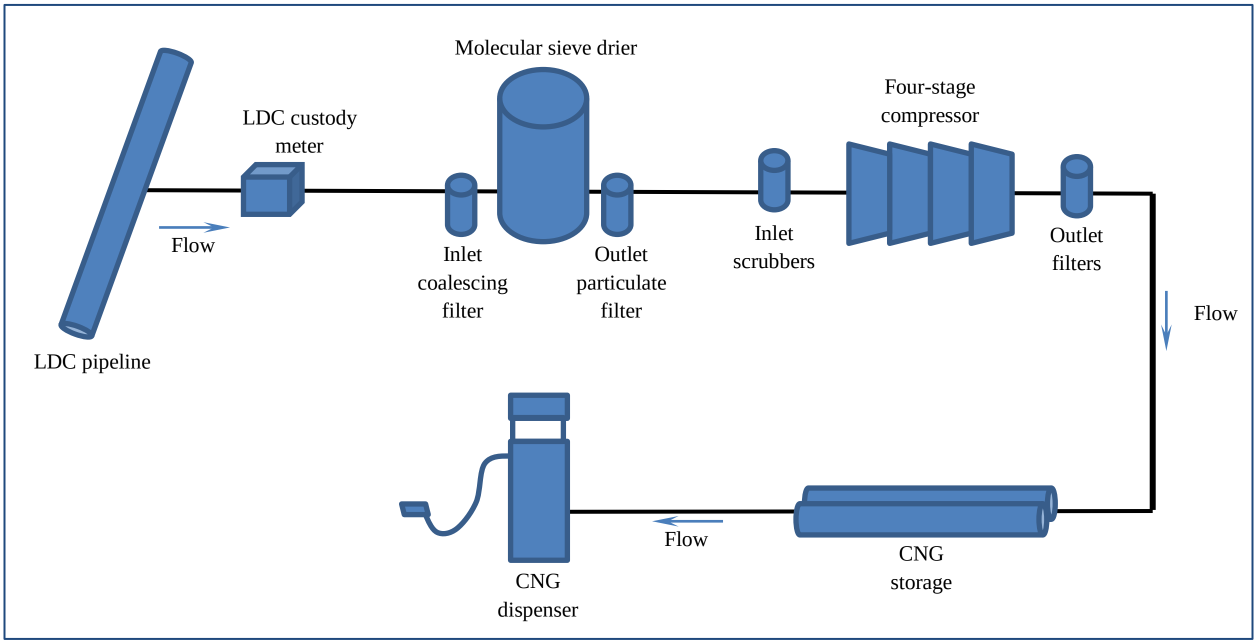

Figure E.32. Equipment Arrangement at Station E3
This station layout involves a single molecular sieve drier and a single four-stage compressor, with filters and scrubbers at the inlet and outlet of each.

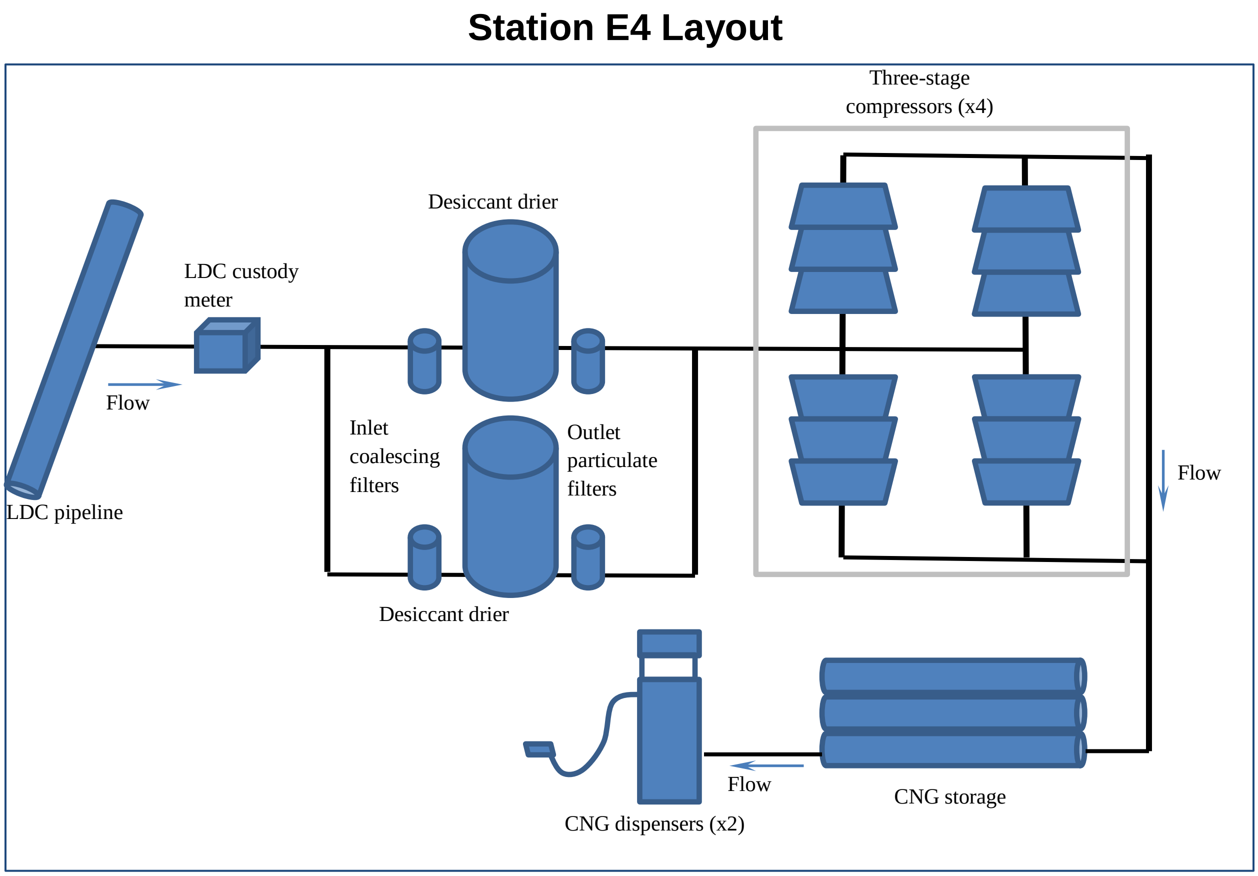

Figure E.33. Equipment Arrangement at Station E4
This station is one of the few visited for this project with multiple drier skids arranged in parallel. The station also uses four small reciprocating compressors in parallel.

Station E5 Layout

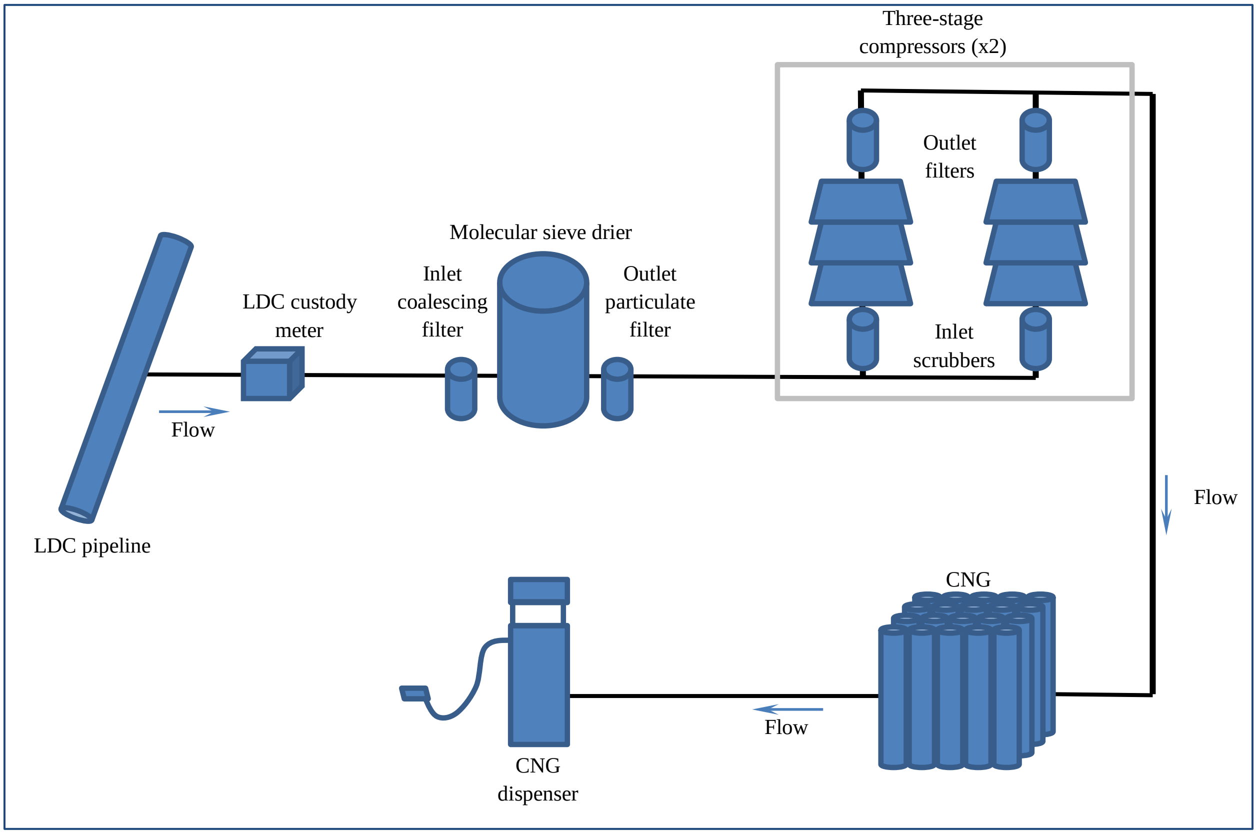

Figure E.34. Equipment Arrangement at Station E5

This station layout is similar to several stations in the Central region, with the main difference being the array of small tanks used for CNG storage.

Station E6 Layout

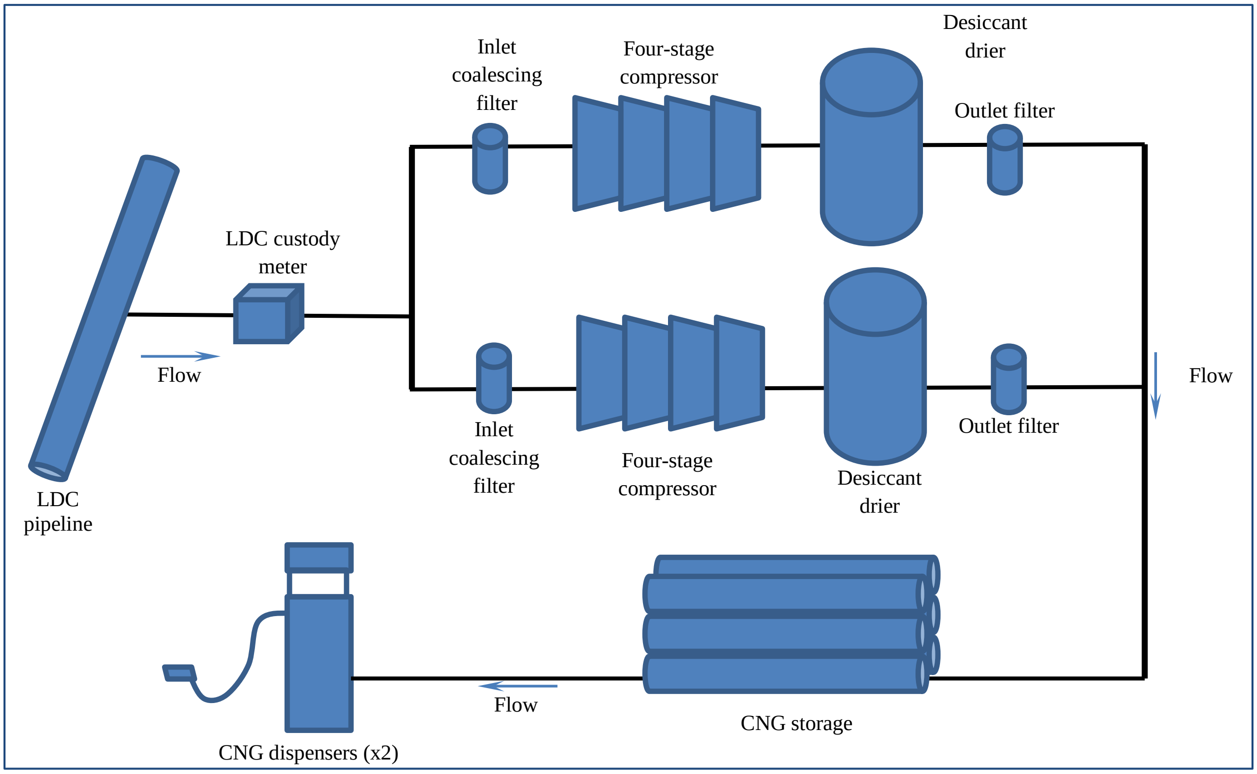

Figure E.35. Equipment Arrangement for Station E6

This is one of the few stations layouts surveyed for the study that compresses the gas before drying it. The station layout is also notable for having two complete compression/drying chains in parallel. Note that no filtration takes place between the compressors and the driers.

Station E7 Layout

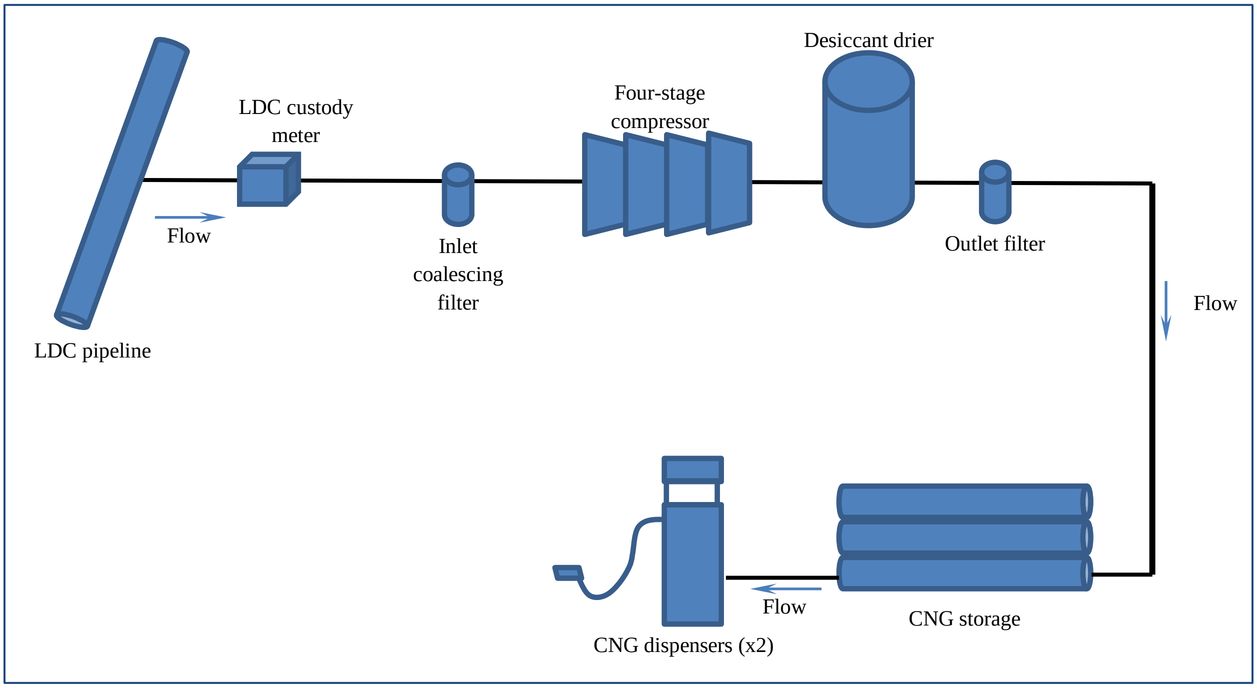

Figure E.36. Equipment Arrangement for Station E7
This layout is nearly identical to that of station E6, but has only one compression/drying stream instead of two parallel streams.

Station E8 Layout

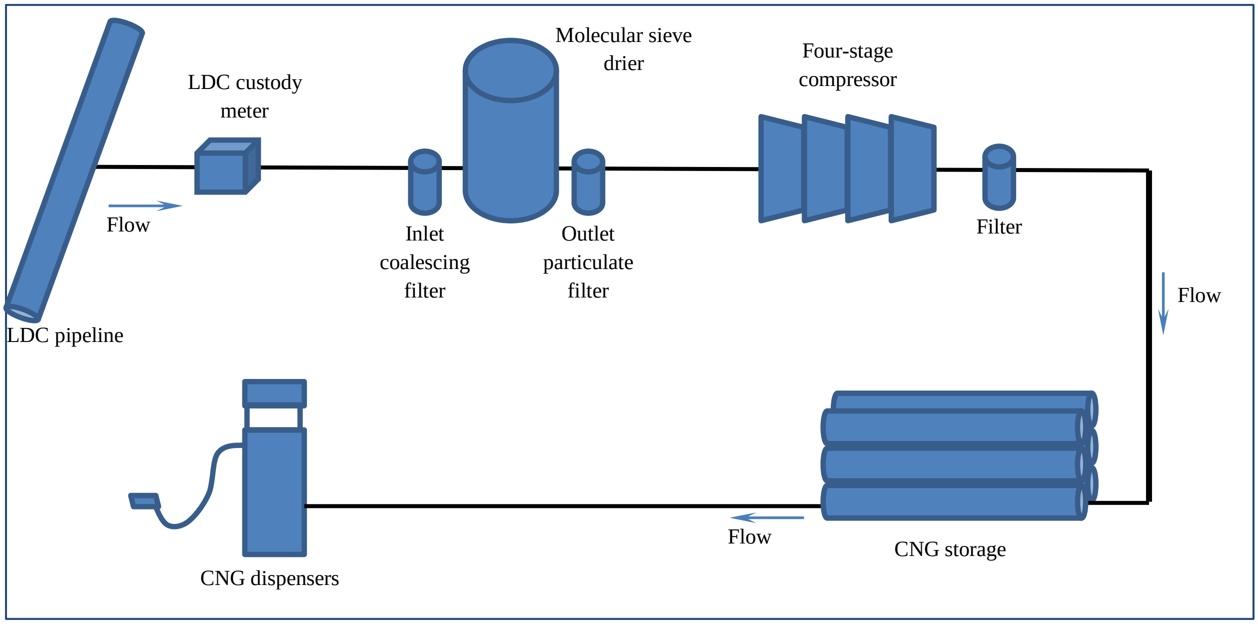

Figure E.37. Equipment Arrangement for Station E8
This station is an example of the most common and basic equipment layout among the stations visited. The station staff noted that each dispenser also incorporates a filter (not shown here).

Station E9 Layout

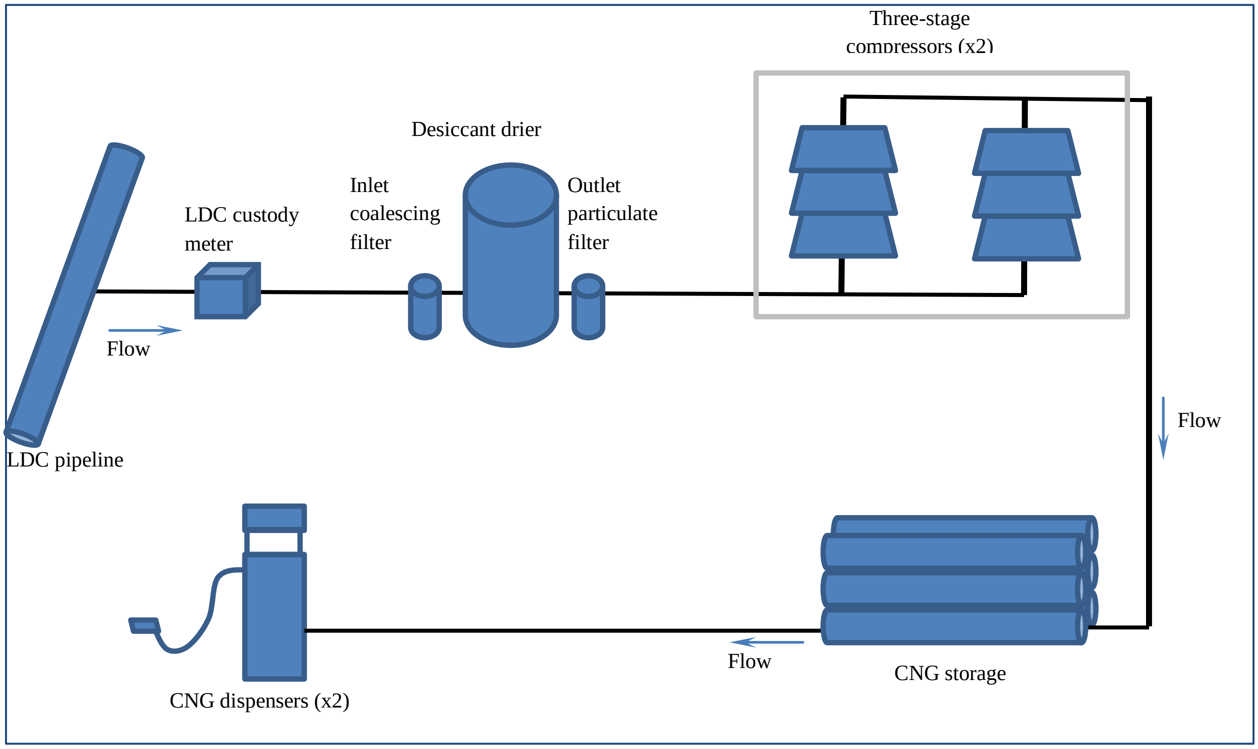

Figure E.38. Equipment Arrangement for Station E9

A single desiccant drier supplies a pair of three-stage compressors installed in parallel. The only filters observed during the visit are at the inlet and outlet of the drier.

Station E10 Layout

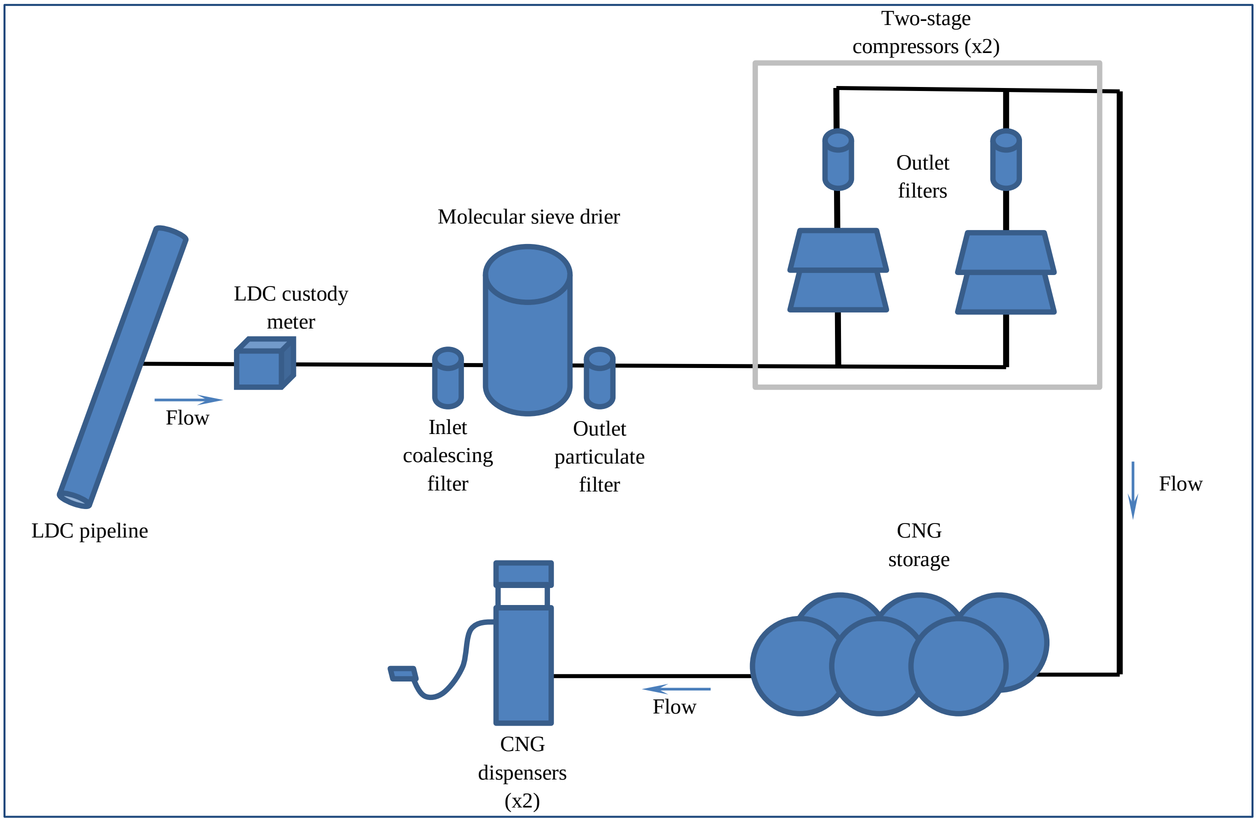

Figure E.39. Equipment Arrangement for Station E10

This station uses two-stage compressors and spherical storage tanks. Station staff report that filters are also located upstream of each dispenser line (not shown here).

APPENDIX F
RESULTS OF SAMPLE ANALYSES AND MOISTURE MEASUREMENTS

This appendix presents tabulated results of the moisture measurements, CNG sample analyses, and liquid analyses from each CNG station. For each station, the moisture data and the GC analyses of hydrocarbon and diluent content are presented first. These analyses are presented in their original mass-based units (lb_m/MMscf or ppmw). These are followed by a combined CNG composition created from the moisture, hydrocarbon, and diluent data, in units of mole percent, and gas quality parameters calculated from the combined composition. Lastly, the analyses of total sulfur content and sulfur species are tabulated, followed by the liquid sampling results and the qualitative FTIR analysis of the liquid samples.

Table F.1. Data from Stations W1 through W4

These data were collected at stations in the Western region of the United States.

Site code	W1		W2		W3		W4	
Sampling notes					Moisture measurement at inlet much lower than at dispenser; re-measured to verify value at dispenser			
Sample cylinder #	21	1	19	26	24	23	25	4
MDM-300 moisture measurements								
Value at LDC connection (lbm/MMscf)	5.22		2.51		4.84		1.78	
repeat analysis								
Value at dispenser (lbm/MMscf)	3.77		0.42		8.60		2.06	
repeat analysis					8.55			
ASTM D1945/D1946 analyses All values in weight %								
Helium								
Hydrogen								
Carbon monoxide								
Oxygen	0.144						0.034	0.034
Nitrogen	0.725	0.784	2.588	2.753	1.026	1.019	0.931	0.954
Methane	92.740	92.558	88.318	88.020	92.360	93.000	85.771	85.709
Carbon dioxide	2.170	2.377	1.097	1.166	2.326	2.523	2.012	2.195
Ethane	3.795	3.838	6.378	6.409	2.606	2.577	7.446	7.390
Propane	0.276	0.275	1.097	1.113	0.668	0.533	2.248	2.161
Isobutane	0.036	0.042	0.117	0.123	0.143	0.090	0.500	0.500
n-Butane	0.048	0.048	0.223	0.228	0.286	0.108	0.569	0.569
Neopentane								
Isopentane	0.018	0.018	0.053	0.047	0.173	0.030	0.207	0.195
n-Pentane	0.006	0.012	0.053	0.053	0.179	0.024	0.121	0.126
i-Hexanes	0.010	0.013	0.027	0.020	0.056	0.021	0.045	0.050
n-Hexane	0.004	0.006		0.016	0.035	0.012	0.024	0.021
Benzene		0.002	0.003	0.001	0.005	0.002	0.005	0.006
Cyclohexane	0.003	0.005		0.008	0.019	0.007	0.012	0.013
i-Heptanes	0.005	0.009	0.018	0.018	0.038	0.015	0.026	0.031
n-Heptane	0.002	0.002	0.007	0.006	0.012	0.006	0.006	0.007
Toluene	0.003	0.003		0.002	0.007	0.003	0.007	0.006
i-Octanes	0.007	0.005	0.018	0.010	0.039	0.016	0.021	0.024
n-Octane	0.004			0.002	0.004	0.002	0.002	0.002
ethylbenzene								
m, o, and p-Xylenes	0.004		0.003	0.002	0.008	0.004	0.004	
i-Nonanes		0.003		0.003			0.004	0.002
n-Nonane								0.001
i-Decanes					0.005	0.005	0.002	0.002
n-Decane					0.005		0.002	0.002
Undecanes +						0.003	0.001	
Total weight percent, ASTM D1945/1946	100.000	100.000	100.000	100.000	100.000	100.000	100.000	100.000
Molecular weight from ASTM analysis	16.6798	16.7003	17.0426	17.0701	16.7695	16.6841	17.3920	17.4004

Table F.1. Data from Stations W1 through W4 (Continued)

Site code	W1		W2		W3		W4	
Combined MDM-300/ASTM D1945/ASTM D1946 composition All values in mol %								
Water vapor	0.00795	0.00795	0.00089	0.00089	0.01815	0.01804	0.00435	0.00435
Helium								
Hydrogen								
Carbon monoxide								
Oxygen	0.07506						0.01848	0.01849
Nitrogen	0.43165	0.46735	1.57445	1.67754	0.61408	0.60678	0.57798	0.59255
Methane	96.41668	96.34576	93.82283	93.65742	96.52802	96.70191	92.98226	92.95946
Carbon dioxide	0.82238	0.90193	0.42481	0.45226	0.88615	0.95630	0.79508	0.86782
Ethane	2.10499	2.13146	3.61490	3.63835	1.45310	1.42962	4.30661	4.27627
Propane	0.10439	0.10414	0.42398	0.43086	0.25399	0.20163	0.88661	0.85270
Isobutane	0.01033	0.01207	0.03431	0.03612	0.04125	0.02583	0.14961	0.14968
n-Butane	0.01377	0.01379	0.06539	0.06696	0.08250	0.03100	0.17026	0.17034
Neopentane								
Isopentane	0.00416	0.00417	0.01252	0.01112	0.04020	0.00694	0.04990	0.04703
n-Pentane	0.00139	0.00278	0.01252	0.01254	0.04160	0.00555	0.02917	0.03039
i-Hexanes	0.00194	0.00252	0.00534	0.00396	0.01090	0.00406	0.00908	0.01010
n-Hexane	0.00077	0.00116		0.00317	0.00681	0.00232	0.00484	0.00424
Benzene		0.00043	0.00065	0.00022	0.00107	0.00043	0.00111	0.00134
Cyclohexane	0.00059	0.00099		0.00162	0.00379	0.00139	0.00248	0.00269
i-Heptanes	0.00083	0.00150	0.00306	0.00307	0.00636	0.00250	0.00451	0.00538
n-Heptane	0.00033	0.00033	0.00119	0.00102	0.00201	0.00100	0.00104	0.00122
Toluene	0.00054	0.00054		0.00037	0.00127	0.00054	0.00132	0.00113
i-Octanes	0.00102	0.00073	0.00269	0.00149	0.00572	0.00234	0.00320	0.00366
n-Octane	0.00058			0.00030	0.00059	0.00029	0.00030	0.00030
ethylbenzene								
m, o, and p-Xylenes	0.00063		0.00048	0.00032	0.00126	0.00063	0.00066	
i-Nonanes		0.00039		0.00040			0.00054	0.00027
n-Nonane								0.00014
i-Decanes					0.00059	0.00059	0.00024	0.00024
n-Decane					0.00059		0.00024	0.00024
Undecanes +						0.00032	0.00011	
Total	100.00000	100.00000	100.00000	100.00000	100.00000	100.00000	100.00000	100.00000
Properties calculated from combined composition								
Higher heating value, dry basis (Btu/scf)	**1017.3**	**1017.2**	**1029.4**	**1028.5**	**1018.8**	**1012.6**	**1055.2**	**1053.6**
Lower heating value, dry basis (Btu/scf)	**916.6**	**916.5**	**928.2**	**927.3**	**918.1**	**912.3**	**952.0**	**950.5**
Real relative density	**0.5769**	**0.5776**	**0.5895**	**0.5904**	**0.5800**	**0.5770**	**0.6017**	**0.6019**
Wobbe index	**1339.3**	**1338.4**	**1340.8**	**1338.5**	**1337.7**	**1333.0**	**1360.4**	**1358.0**
Methane number, AGA GQMM/SAE 922359	**101.75**	**101.64**	**95.72**	**95.58**	**100.59**	**102.51**	**90.32**	**90.50**
Total C_{4+} content (mol %)	0.04	0.04	0.14	0.14	0.25	0.09	0.43	0.43
Total C_{5+} content (mol %)	0.01	0.02	0.04	0.04	0.12	0.03	0.11	0.11
Hydrogen to carbon ratio	3.95	3.95	3.90	3.90	3.94	3.96	3.86	3.86
Total diluents (mol %)	1.34	1.38	2.00	2.13	1.52	1.58	1.40	1.48

Table F.1. Data from Stations W1 through W4 (Continued)

Site code	W1		W2		W3		W4	
Sample cylinder #	21	1	19	26	24	23	25	4
ASTM D6667 total sulfur								
ppmw	2.3	3.0	1.4	1.6	2.5	3.6	7.8	7.9
grains/100 cu.ft.	0.072	0.095	0.044	0.050	0.079	0.113	0.246	0.249
ASTM D5504 sulfur speciation (normalized to ASTM D6667 total, ppmw)								
Sulfides								
Hydrogen sulfide								
Carbonyl sulfide	0.0						0.4	0.3
Dimethyl sulfide			0.2					
Methyl ethyl sulfide							4.0	4.4
Diethyl sulfide								
Mercaptans								
Methyl mercaptan								
Ethyl mercaptan		0.2			0.0			
Isopropyl mercaptan	0.2							
n-propyl mercaptan								
sec-butyl mercaptan								
tert-butyl mercaptan	2.1	2.0			1.7	2.1		
n-butyl mercaptan								
Disulfides								
Carbon disulfide								
Dimethyl disulfide			0.5	0.6			3.2	3.2
Methyl ethyl disulfide				0.3				
Diethyl disulfide				0.6				
Other target sulfur compounds	0.1	0.8	0.7		0.8	1.5	0.2	
FTIR analyses								
CRC liquid sample #	38		36		31		37	
Significant amount of liquids drained from cylinder?	no (acetone rinse used)		no (acetone rinse used)		no (acetone rinse used)		yes	
Water identified by FTIR?	no		no		no		yes	
Hydrocarbon liquids identified by FTIR?	yes		yes		yes		yes	
Known compressor oil identified?	no		Similar to Summit TM-30 (SAE-30)		no		no	

Table F.2. Data from Stations W5 through W8

These data were collected at stations in the Western region of the United States.

Site code	W5			W6		W7		W8	
Sampling notes									
Sample cylinder #	2	20	22	16	18	12	7	6	11
MDM-300 moisture measurements									
Value at LDC connection (lbm/MMscf)	1.45			3.50		3.87		2.69	
repeat analysis									
Value at dispenser (lbm/MMscf)	1.30			1.68		8.16		4.12	
repeat analysis									
ASTM D1945/D1946 analyses All values in weight %									
Helium									
Hydrogen									
Carbon monoxide									
Oxygen	0.034	0.029	0.040						
Nitrogen	0.918	0.918	0.918	2.508	2.610	0.877	0.858	0.691	0.732
Methane	85.486	85.474	84.525	88.536	88.292	90.698	90.464	91.576	91.446
Carbon dioxide	2.048	2.226	2.023	1.145	1.220	2.176	2.367	1.978	2.125
Ethane	7.406	7.412	7.672	6.173	6.217	5.158	5.167	4.843	4.810
Propane	2.381	2.335	2.913	1.092	1.103	0.753	0.752	0.608	0.601
Isobutane	0.528	0.539	0.661	0.117	0.123	0.101	0.101	0.083	0.089
n-Butane	0.585	0.574	0.610	0.223	0.235	0.130	0.130	0.113	0.101
Neopentane									
Isopentane	0.201	0.195	0.211	0.059	0.053	0.036	0.030	0.036	0.024
n-Pentane	0.132	0.126	0.142	0.053	0.047	0.024	0.024	0.024	0.024
i-Hexanes	0.084	0.053	0.086	0.024	0.026	0.011	0.031	0.013	0.012
n-Hexane	0.040	0.025	0.030	0.012	0.015	0.006	0.014	0.012	0.015
Benzene	0.010	0.006	0.011	0.003	0.003	0.001	0.002	0.001	0.001
Cyclohexane	0.020	0.014	0.024	0.007	0.007	0.004	0.008	0.004	0.003
i-Heptanes	0.051	0.033	0.048	0.019	0.019	0.007	0.019	0.006	0.006
n-Heptane	0.010	0.006	0.010	0.006	0.006	0.002	0.005	0.002	0.002
Toluene	0.009	0.006	0.010	0.003	0.003	0.001	0.002	0.001	0.001
i-Octanes	0.032	0.022	0.044	0.012	0.011	0.004	0.015	0.004	0.004
n-Octane	0.006		0.003	0.002	0.002	0.001	0.002	0.001	0.001
ethylbenzene									
m, o, and p-Xylenes	0.004	0.004	0.004	0.002	0.002		0.002		
i-Nonanes	0.007	0.002		0.002	0.001				
n-Nonane					0.001				
i-Decanes	0.003		0.007	0.002	0.004				
n-Decane									
Undecanes +	0.005	0.001	0.008			0.010	0.007	0.004	0.003
Total weight percent, ASTM D1945/1946	100.000	100.000	100.000	100.000	100.000	100.000	100.000	100.000	100.000
Molecular weight from ASTM analysis	17.4333	17.4303	17.5445	17.0275	17.0506	16.8684	16.8971	16.7855	16.7991

Table F.2. Data from Stations W5 through W8 (Continued)

Site code	W5			W6		W7		W8	
Combined MDM-300/ASTM D1945/ASTM D1946 composition All values in mol %									
Water vapor	0.00274	0.00274	0.00274	0.00354	0.00354	0.01722	0.01722	0.00869	0.00869
Helium									
Hydrogen									
Carbon monoxide									
Oxygen	0.01852	0.01580	0.02193						
Nitrogen	0.57128	0.57118	0.57492	1.52440	1.58854	0.52800	0.51744	0.41401	0.43893
Methane	92.89479	92.86563	92.43640	93.96894	93.83691	95.35088	95.26687	95.80910	95.75057
Carbon dioxide	0.81124	0.88160	0.80645	0.44299	0.47265	0.83390	0.90864	0.75436	0.81108
Ethane	4.29371	4.29645	4.47630	3.49554	3.52522	2.89309	2.90307	2.70329	2.68704
Propane	0.94131	0.92296	1.15898	0.42166	0.42649	0.28800	0.28811	0.23142	0.22894
Isobutane	0.15837	0.16164	0.19952	0.03428	0.03608	0.02931	0.02936	0.02397	0.02572
n-Butane	0.17546	0.17213	0.18413	0.06533	0.06894	0.03772	0.03779	0.03263	0.02919
Neopentane									
Isopentane	0.04857	0.04711	0.05131	0.01392	0.01252	0.00842	0.00702	0.00837	0.00559
n-Pentane	0.03189	0.03044	0.03453	0.01251	0.01111	0.00561	0.00562	0.00558	0.00559
i-Hexanes	0.01699	0.01072	0.01751	0.00474	0.00514	0.00215	0.00608	0.00253	0.00234
n-Hexane	0.00809	0.00506	0.00611	0.00237	0.00297	0.00117	0.00274	0.00234	0.00292
Benzene	0.00223	0.00134	0.00247	0.00065	0.00065	0.00022	0.00043	0.00021	0.00022
Cyclohexane	0.00414	0.00290	0.00500	0.00142	0.00142	0.00080	0.00161	0.00080	0.00060
i-Heptanes	0.00887	0.00574	0.00840	0.00323	0.00323	0.00118	0.00320	0.00101	0.00101
n-Heptane	0.00174	0.00104	0.00175	0.00102	0.00102	0.00034	0.00084	0.00034	0.00034
Toluene	0.00170	0.00114	0.00190	0.00055	0.00056	0.00018	0.00037	0.00018	0.00018
i-Octanes	0.00488	0.00336	0.00676	0.00179	0.00164	0.00059	0.00222	0.00059	0.00059
n-Octane	0.00092		0.00046	0.00030	0.00030	0.00015	0.00030	0.00015	0.00015
ethylbenzene									
m, o, and p-Xylenes	0.00066	0.00066	0.00066	0.00032	0.00032		0.00032		
i-Nonanes	0.00095	0.00027		0.00027	0.00013				
n-Nonane					0.00013				
i-Decanes	0.00037		0.00086	0.00024	0.00048				
n-Decane									
Undecanes +	0.00056	0.00011	0.00090			0.00108	0.00076	0.00043	0.00032
Total	100.00000	100.00000	100.00000	100.00000	100.00000	100.00000	100.00000	100.00000	100.00000
Properties calculated from combined composition									
Higher heating value, dry basis (Btu/scf)	**1057.1**	**1055.3**	**1063.2**	**1029.0**	**1028.4**	**1027.0**	**1026.9**	**1026.5**	**1025.3**
Lower heating value, dry basis (Btu/scf)	**953.8**	**952.1**	**959.4**	**927.7**	**927.2**	**925.7**	**925.6**	**925.1**	**924.1**
Real relative density	**0.6031**	**0.6030**	**0.6070**	**0.5890**	**0.5898**	**0.5835**	**0.5845**	**0.5806**	**0.5810**
Wobbe index	**1361.3**	**1359.0**	**1364.6**	**1340.8**	**1339.2**	**1344.6**	**1343.2**	**1347.1**	**1345.1**
Methane number, AGA GQMM/SAE 922359	**89.77**	**90.09**	**88.24**	**95.95**	**95.82**	**98.50**	**98.33**	**99.32**	**99.40**
Total C_{4+} content (mol %)	0.47	0.44	0.52	0.14	0.15	0.09	0.10	0.08	0.07
Total C_{5+} content (mol %)	0.13	0.11	0.14	0.04	0.04	0.02	0.03	0.02	0.02
Hydrogen to carbon ratio	3.85	3.86	3.84	3.91	3.90	3.93	3.92	3.93	3.93
Total diluents (mol %)	1.40	1.47	1.41	1.97	2.06	1.38	1.44	1.18	1.26

Table F.2. Data from Stations W5 through W8 (Continued)

Site code	W5			W6		W7		W8	
Sample cylinder #	2	20	22	16	18	12	7	6	11
ASTM D6667 total sulfur									
ppmw	7.2	7.4	7.9	1.9	2.2	2.7	2.7	2.9	3.0
grains/100 cu.ft.	0.227	0.233	0.249	0.060	0.069	0.085	0.085	0.091	0.095
ASTM D5504 sulfur speciation (normalized to ASTM D6667 total, ppmw)			Insufficient sample						
Sulfides									
Hydrogen sulfide									
Carbonyl sulfide	0.4	0.3				0.0	0.0	0.1	0.1
Dimethyl sulfide				0.3					
Methyl ethyl sulfide	3.5	2.4							
Diethyl sulfide									
Mercaptans									
Methyl mercaptan							0.0		
Ethyl mercaptan							0.0		
Isopropyl mercaptan					0.3	0.0			
n-propyl mercaptan					0.3				
sec-butyl mercaptan									
tert-butyl mercaptan		0.1				1.7	1.5	1.2	1.1
n-butyl mercaptan		0.4							
Disulfides									
Carbon disulfide		1.1							
Dimethyl disulfide	3.1	2.6		0.5	0.3				
Methyl ethyl disulfide				0.6	0.5				
Diethyl disulfide		0.3							
Other target sulfur compounds	0.3	0.3		0.5	0.7	1.0	1.2	1.6	1.9
FTIR analyses									
CRC liquid sample #	33			34		35		40	
Significant amount of liquids drained from cylinder?	yes			no (acetone rinse used)		no (acetone rinse used)		no (acetone rinse used)	
Water identified by FTIR?	yes			no		no		no	
Hydrocarbon liquids identified by FTIR?	yes			yes		yes		yes	
Known compressor oil identified?	no			Similar to Summit TM-30 (SAE-30)		Similar to Summit TM-30 (SAE-30)		Similar to Summit TM-30 (SAE-30)	

Table F.3. Data from Stations C1 through C5

These data were collected at stations in the Central region of the United States.

Site code	C1		C2		C3		C4		C5
Sampling notes	No pressure gauge at dispensers, had to assume pressure value for moisture analyzer.		No pressure gauge at dispensers, had to assume pressure value for moisture analyzer. Pressure likely decreasing during dispenser analysis, since had to open valve to keep flow constant. Hand warmers on analyzer valve produced a more constant flow at the dispenser.				Moisture measurement at inlet much lower than at dispenser; re-measured to verify value at LDC connection		No gas sample sent for analysis
Sample cylinder #	5	26	16	19	18	19	17	26	No gas sample sent for analysis
MDM-300 moisture measurements									
Value at LDC connection (lbm/MMscf)	5.15		4.34		1.57		1.07		3.07
repeat analysis							1.94		
Value at dispenser (lbm/MMscf)	2.99		1.36		1.59		11.12		4.01
repeat analysis									
ASTM D1945/D1946 analyses All values in weight %									
Helium									
Hydrogen									
Carbon monoxide									
Oxygen	0.018	0.036	0.006	0.006					
Nitrogen	0.722	0.835	0.760	0.784	2.816	2.759	1.264	1.242	
Methane	93.457	93.242	92.260	92.319	84.864	84.931	89.142	89.138	
Carbon dioxide	2.405	2.391	1.908	2.016	0.698	0.693	1.417	1.423	
Ethane	2.905	2.992	4.252	4.151	9.740	9.707	7.747	7.694	
Propane	0.385	0.390	0.544	0.508	1.471	1.472	0.367	0.429	
Isobutane	0.030	0.030	0.054	0.048	0.098	0.098	0.018	0.021	
n-Butane	0.030	0.030	0.078	0.066	0.214	0.219	0.025	0.030	
Neopentane									
Isopentane	0.006	0.012	0.024	0.018	0.012	0.017	0.001	0.001	
n-Pentane	0.006	0.006	0.018	0.018	0.012	0.017	0.001	0.001	
i-Hexanes	0.006	0.005	0.018	0.014	0.014	0.017	0.002	0.004	
n-Hexane	0.002	0.003	0.008	0.007	0.019	0.021	0.007	0.008	
Benzene		0.001		0.001	0.001	0.001		0.001	
Cyclohexane	0.002	0.001	0.006	0.005	0.005	0.006	0.001	0.001	
i-Heptanes		0.002	0.013	0.006	0.012	0.015	0.003	0.003	
n-Heptane	0.002	0.002	0.005	0.004	0.005	0.005	0.001	0.001	
Toluene	0.004	0.003		0.003	0.003	0.004			
i-Octanes	0.005	0.005	0.021	0.018	0.009	0.012	0.003	0.002	
n-Octane	0.002	0.001	0.002	0.002	0.001	0.001	0.001		
ethylbenzene									
m, o, and p-Xylenes			0.006	0.002					
i-Nonanes	0.006	0.006	0.008	0.002		0.002		0.001	
n-Nonane	0.002	0.002	0.003			0.001			
i-Decanes	0.004	0.004	0.003	0.002	0.005	0.001			
n-Decane					0.001				
Undecanes +	0.001	0.001	0.003			0.001			
Total weight percent, ASTM D1945/1946	100.000	100.000	100.000	100.000	100.000	100.000	100.000	100.000	
Molecular weight from ASTM analysis	16.6294	16.6461	16.7247	16.7187	17.3307	17.3268	16.9467	16.9498	

Table F.3. Data from Stations C1 through C5 (Continued)

Site code	C1		C2		C3		C4		C5
Combined MDM-300/ASTM D1945/ASTM D1946 composition All values in mol %									
Water vapor	0.00631	0.00631	0.00287	0.00287	0.00335	0.00335	0.02346	0.02346	
Helium									
Hydrogen									
Carbon monoxide									
Oxygen	0.00935	0.01873	0.00314	0.00313					
Nitrogen	0.42857	0.49614	0.45373	0.46789	1.74208	1.70643	0.76448	0.75131	
Methane	96.86986	96.74406	96.18056	96.20738	91.67554	91.72710	94.14416	94.15715	
Carbon dioxide	0.90869	0.90431	0.72507	0.76583	0.27486	0.27283	0.54551	0.54792	
Ethane	1.60648	1.65626	2.36494	2.30793	5.61361	5.59332	4.36513	4.33606	
Propane	0.14518	0.14722	0.20632	0.19260	0.57812	0.57838	0.14101	0.16486	
Isobutane	0.00858	0.00859	0.01554	0.01381	0.02922	0.02921	0.00525	0.00612	
n-Butane	0.00858	0.00859	0.02244	0.01898	0.06381	0.06528	0.00729	0.00875	
Neopentane									
Isopentane	0.00138	0.00277	0.00556	0.00417	0.00288	0.00408	0.00023	0.00023	
n-Pentane	0.00138	0.00138	0.00417	0.00417	0.00288	0.00408	0.00023	0.00023	
i-Hexanes	0.00116	0.00097	0.00349	0.00272	0.00282	0.00342	0.00039	0.00079	
n-Hexane	0.00039	0.00058	0.00155	0.00136	0.00382	0.00422	0.00138	0.00157	
Benzene		0.00021		0.00021	0.00022	0.00022		0.00022	
Cyclohexane	0.00040	0.00020	0.00119	0.00099	0.00103	0.00124	0.00020	0.00020	
i-Heptanes		0.00033	0.00217	0.00100	0.00208	0.00259	0.00051	0.00051	
n-Heptane	0.00033	0.00033	0.00083	0.00067	0.00086	0.00086	0.00017	0.00017	
Toluene	0.00072	0.00054		0.00054	0.00056	0.00075			
i-Octanes	0.00073	0.00073	0.00307	0.00263	0.00137	0.00182	0.00044	0.00030	
n-Octane	0.00029	0.00015	0.00029	0.00029	0.00015	0.00015	0.00015		
ethylbenzene									
m, o, and p-Xylenes			0.00095	0.00031					
i-Nonanes	0.00078	0.00078	0.00104	0.00026		0.00027		0.00013	
n-Nonane	0.00026	0.00026	0.00039			0.00014			
i-Decanes	0.00047	0.00047	0.00035	0.00024	0.00061	0.00012			
n-Decane					0.00012				
Undecanes +	0.00011	0.00011	0.00032			0.00011			
Total	100.00000	100.00000	100.00000	100.00000	100.00000	100.00000	100.00000	100.00000	
Properties calculated from combined composition									
Higher heating value, dry basis (Btu/scf)	**1013.6**	**1013.3**	**1023.2**	**1021.6**	**1046.2**	**1046.6**	**1034.7**	**1035.1**	
Lower heating value, dry basis (Btu/scf)	**913.2**	**912.9**	**922.0**	**920.6**	**943.8**	**944.2**	**932.9**	**933.2**	
Real relative density	**0.5751**	**0.5757**	**0.5785**	**0.5783**	**0.5995**	**0.5994**	**0.5862**	**0.5863**	
Wobbe index	**1336.6**	**1335.5**	**1345.3**	**1343.4**	**1351.2**	**1351.9**	**1351.5**	**1351.8**	
Methane number, AGA GQMM/SAE 922359	**102.93**	**102.77**	**100.32**	**100.65**	**90.99**	**90.98**	**96.34**	**96.27**	
Total C_{4+} content (mol %)	0.03	0.03	0.06	0.05	0.11	0.12	0.02	0.02	
Total C_{5+} content (mol %)	0.01	0.01	0.03	0.02	0.02	0.02	0.00	0.00	
Hydrogen to carbon ratio	3.96	3.96	3.94	3.94	3.86	3.86	3.91	3.91	
Total diluents (mol %)	1.35	1.43	1.18	1.24	2.02	1.98	1.33	1.32	

Table F.3. Data from Stations C1 through C5 (Continued)

Site code	C1		C2		C3		C4		C5
Sample cylinder #	5	26	16	19	18	19	17	26	No gas sample sent for analysis
ASTM D6667 total sulfur									
ppmw	< 0.1	< 0.1	3.2	5.1	5.3	4.4	4.4	4.0	
grains/100 cu.ft.	< 0.032	< 0.032	0.101	0.161	0.167	0.139	0.139	0.126	
ASTM D5504 sulfur speciation (normalized to ASTM D6667 total, ppmw)					No speciation performed	No speciation performed	No speciation performed	No speciation performed	
Sulfides									
Hydrogen sulfide									
Carbonyl sulfide									
Dimethyl sulfide									
Methyl ethyl sulfide									
Diethyl sulfide									
Mercaptans									
Methyl mercaptan									
Ethyl mercaptan	< 0.1	< 0.1	0.0	0.1					
Isopropyl mercaptan			0.4	0.7					
n-propyl mercaptan			0.1	0.2					
sec-butyl mercaptan									
tert-butyl mercaptan	< 0.1	< 0.1	2.2	3.6					
n-butyl mercaptan									
Disulfides									
Carbon disulfide									
Dimethyl disulfide									
Methyl ethyl disulfide									
Diethyl disulfide									
Other target sulfur compounds	< 0.1	< 0.1	0.5	0.4					
FTIR analyses									
CRC liquid sample #	34		31		34		36		
Significant amount of liquids drained from cylinder?	no (acetone rinse used)		no (acetone rinse used)		yes		yes		yes
Water identified by FTIR?	no		no		yes		yes		yes
Hydrocarbon liquids identified by FTIR?	yes		yes		yes		yes		yes
Known compressor oil identified?	no		no		no		no		no

Table F.4. Data from Stations E1 through E5

These data were collected at stations in the Eastern region of the United States.

Site code	E1		E2		E3		E4		E5
Sampling notes	Moisture measurement at inlet much lower than at dispenser. Flow interrupted by automatic shutoff switches (possibly due to back pressure created by sampling equipment), unable to get accurate measurement of flow through cylinders before sampling.		Moisture measurement at inlet much lower than at dispenser; re-measured to verify value at dispenser.				No vehicle available for fueling; had to vent to atmosphere during sample collection.		
Sample cylinder #	18	21	11	3	7	23	15 (cylinder empty on arrival at the lab)	28	11, 12 (both cylinders empty on arrival at the lab)
MDM-300 moisture measurements									
Value at LDC connection (lbm/MMscf)	2.21		2.93		8.46		5.83		94.97
repeat analysis									
Value at dispenser (lbm/MMscf)	8.46		6.57		2.27		5.69		2.21
repeat analysis			6.84						
ASTM D1945/D1946 analyses All values in weight %									
Helium									
Hydrogen									
Carbon monoxide									
Oxygen	0.006	0.089	0.018	0.018					
Nitrogen	0.983	1.420	1.075	1.075	0.927	0.951		1.185	
Methane	91.660	91.078	91.026	91.045	85.317	85.396		93.612	
Carbon dioxide	2.287	2.429	2.506	2.500	2.839	2.869		1.020	
Ethane	4.116	4.122	4.555	4.548	9.293	9.234		3.930	
Propane	0.471	0.469	0.475	0.481	1.140	1.060		0.204	
Isobutane	0.119	0.095	0.089	0.077	0.121	0.115		0.014	
n-Butane	0.113	0.101	0.089	0.089	0.213	0.207		0.017	
Neopentane									
Isopentane	0.048	0.042	0.024	0.024	0.012	0.006		0.002	
n-Pentane	0.030	0.030	0.024	0.024	0.006	0.006		0.002	
i-Hexanes	0.032	0.022	0.016	0.019	0.036	0.036		0.005	
n-Hexane	0.013	0.015	0.012	0.012	0.026	0.030		0.005	
Benzene	0.009	0.005	0.005	0.006	0.004	0.004		0.000	
Cyclohexane	0.009	0.006	0.005	0.005	0.005				
i-Heptanes	0.031	0.019	0.016	0.015	0.024	0.030			
n-Heptane	0.009	0.007	0.006	0.006	0.011	0.014		0.003	
Toluene	0.007	0.005	0.006	0.004					
i-Octanes	0.030	0.023	0.019	0.018	0.017	0.025			
n-Octane	0.005	0.004	0.004	0.005	0.004	0.006			
ethylbenzene	0.002								
m, o, and p-Xylenes	0.006	0.006	0.008	0.010					
i-Nonanes	0.010	0.007	0.011	0.005	0.003	0.006		0.001	
n-Nonane		0.002	0.003	0.003	0.001	0.002			
i-Decanes	0.004	0.003	0.006	0.009	0.001	0.001			
n-Decane			0.002	0.002					
Undecanes +		0.001				0.002			
Total weight percent, ASTM D1945/1946	100.000	100.000	100.000	100.000	100.000	100.000		100.000	
Molecular weight from ASTM analysis	16.7921	16.8369	16.8433	16.8411	17.3669	17.3590		16.5651	

Table F.4. Data from Stations E1 through E5 (Continued)

Site code	E1		E2		E3		E4		E5
Combined MDM-300/ASTM D1945/ASTM D1946 composition All values in mol %									
Water vapor	0.01785	0.01785	0.01386	0.01443	0.00479	0.00479		0.01201	
Helium									
Hydrogen									
Carbon monoxide									
Oxygen	0.00315	0.04682	0.00947	0.00947					
Nitrogen	0.58914	0.85331	0.64626	0.64618	0.57466	0.58928		0.70064	
Methane	95.92605	95.57126	95.55631	95.56358	92.35578	92.39950		96.64977	
Carbon dioxide	0.87247	0.92911	0.95896	0.95654	1.12026	1.13159		0.38388	
Ethane	2.29819	2.30768	2.55115	2.54689	5.36707	5.33059		2.16479	
Propane	0.17933	0.17905	0.18141	0.18368	0.44896	0.41727		0.07663	
Isobutane	0.03437	0.02751	0.02579	0.02231	0.03615	0.03434		0.00399	
n-Butane	0.03264	0.02925	0.02579	0.02578	0.06364	0.06182		0.00484	
Neopentane									
Isopentane	0.01117	0.00980	0.00560	0.00560	0.00289	0.00144		0.00046	
n-Pentane	0.00698	0.00700	0.00560	0.00560	0.00144	0.00144		0.00046	
i-Hexanes	0.00623	0.00430	0.00313	0.00371	0.00725	0.00725		0.00096	
n-Hexane	0.00253	0.00293	0.00235	0.00234	0.00524	0.00604		0.00096	
Benzene	0.00193	0.00108	0.00108	0.00129	0.00089	0.00089		0.00000	
Cyclohexane	0.00180	0.00120	0.00100	0.00100	0.00103				
i-Heptanes	0.00519	0.00319	0.00269	0.00252	0.00416	0.00520			
n-Heptane	0.00151	0.00118	0.00101	0.00101	0.00191	0.00243		0.00050	
Toluene	0.00128	0.00091	0.00110	0.00073					
i-Octanes	0.00441	0.00339	0.00280	0.00265	0.00258	0.00380			
n-Octane	0.00073	0.00059	0.00059	0.00074	0.00061	0.00091			
ethylbenzene	0.00032								
m, o, and p-Xylenes	0.00095	0.00095	0.00127	0.00159					
i-Nonanes	0.00131	0.00092	0.00144	0.00066	0.00041	0.00081		0.00013	
n-Nonane		0.00026	0.00039	0.00039	0.00014	0.00027			
i-Decanes	0.00047	0.00035	0.00071	0.00107	0.00012	0.00012			
n-Decane			0.00024	0.00024					
Undecanes +		0.00011				0.00022			
Total	100.00000	100.00000	100.00000	100.00000	100.00000	100.00000		100.00000	
Properties calculated from combined composition									
Higher heating value, dry basis (Btu/scf)	**1020.8**	**1016.6**	**1020.3**	**1020.3**	**1046.2**	**1045.2**		**1019.1**	
Lower heating value, dry basis (Btu/scf)	**919.9**	**916.1**	**919.5**	**919.5**	**943.7**	**942.8**		**918.2**	
Real relative density	**0.5808**	**0.5823**	**0.5826**	**0.5825**	**0.6008**	**0.6005**		**0.5729**	
Wobbe index	**1339.5**	**1332.2**	**1336.8**	**1336.8**	**1349.7**	**1348.8**		**1346.4**	
Methane number, AGA GQMM/SAE 922359	**100.08**	**100.24**	**99.75**	**99.77**	**91.92**	**92.11**		**102.01**	
Total C_{4+} content (mol %)	0.11	0.09	0.08	0.08	0.13	0.13		0.01	
Total C_{5+} content (mol %)	0.05	0.04	0.03	0.03	0.03	0.03		0.00	
Hydrogen to carbon ratio	3.94	3.94	3.94	3.94	3.87	3.87		3.95	
Total diluents (mol %)	1.48	1.85	1.63	1.63	1.70	1.73		1.10	

Table F.4. Data from Stations E1 through E5 (Continued)

Site code	E1		E2		E3		E4		E5
Sample cylinder #	18	21	11	3	7	23	15 (cylinder empty on arrival at the lab)	28	11, 12 (both cylinders empty on arrival at the lab)
ASTM D6667 total sulfur									
ppmw	6.1	6.7	5.2	3.6	3.5	5.1		< 0.1	
grains/100 cu.ft.	0.192	0.211	0.164	0.113	0.110	0.161		< 0.032	
ASTM D5504 sulfur speciation (normalized to ASTM D6667 total, ppmw)					No speciation performed	No speciation performed			
Sulfides									
Hydrogen sulfide									
Carbonyl sulfide	0.1	0.1							
Dimethyl sulfide	0.2	0.2	0.1	0.1					
Methyl ethyl sulfide									
Diethyl sulfide									
Mercaptans									
Methyl mercaptan									
Ethyl mercaptan		0.0	0.0	0.1					
Isopropyl mercaptan	1.0	1.1	0.7	0.5					
n-propyl mercaptan	0.2	0.3	0.1	0.1					
sec-butyl mercaptan	0.1	0.1							
tert-butyl mercaptan	4.5	4.9	4.0	2.8					
n-butyl mercaptan	0.1	0.1							
Disulfides									
Carbon disulfide									
Dimethyl disulfide									
Methyl ethyl disulfide									
Diethyl disulfide									
Other target sulfur compounds			0.3	0.0					
FTIR analyses									
CRC liquid sample #	38		39		38		35		40
Significant amount of liquids drained from cylinder?	no (acetone rinse used)		yes		no (trace)		yes		yes
Water identified by FTIR?	yes		yes		yes		yes		yes
Hydrocarbon liquids identified by FTIR?	yes		yes		yes		yes		yes
Known compressor oil identified?	no		no		no		no		no

Table F.5. Data from Stations E6 through E10

These data were collected at stations in the Eastern region of the United States.

Site code	E6		E7		E8		E9		E10	
Sampling notes			NGV receptacles and nozzles provided by station staff. Heat packs used on moisture analyzer valve in cold weather, but flow still "jumpy."		Low flow into vehicle caused check valve to not engage, so locked nozzle onto vehicle and vented vehicle tanks. Station staff was able to access tank fill valve for sample collection.		No vehicle available for fueling; had to vent to atmosphere during sample collection.		Low flow through sampling rig caused pump to kick off; had to restart pump multiple times	
Sample cylinder #	24	28	21	9	3	21	8	24	5	6
MDM-300 moisture measurements										
Value at LDC connection (lbm/MMscf)	4.16		5.17		2.47		2.33		1.20	
repeat analysis										
Value at dispenser (lbm/MMscf)	6.03		6.05		0.88		6.93		1.88	
repeat analysis										
ASTM D1945/D1946 analyses All values in weight %										
Helium										
Hydrogen										
Carbon monoxide										
Oxygen	0.024	0.024	0.018	0.012						
Nitrogen	1.034	1.103	1.004	1.015	1.102	1.231	0.816	0.841	1.163	1.209
Methane	91.198	90.870	91.151	91.163	89.695	89.490	94.078	94.033	90.000	89.804
Carbon dioxide	2.377	2.509	2.577	2.536	3.083	3.085	0.570	0.576	2.987	2.995
Ethane	4.457	4.597	4.311	4.329	5.370	5.387	4.249	4.261	4.988	5.089
Propane	0.511	0.522	0.511	0.511	0.531	0.577	0.230	0.235	0.596	0.625
Isobutane	0.095	0.095	0.101	0.095	0.065	0.071	0.014	0.014	0.077	0.083
n-Butane	0.101	0.095	0.101	0.101	0.083	0.088	0.023	0.023	0.094	0.100
Neopentane										
Isopentane	0.042	0.036	0.036	0.036	0.012	0.006	0.003	0.002	0.018	0.012
n-Pentane	0.030	0.030	0.036	0.036	0.006	0.006	0.002	0.001	0.006	0.006
i-Hexanes	0.015	0.020	0.022	0.023	0.017	0.015	0.004	0.002	0.021	0.017
n-Hexane	0.008	0.009	0.010	0.011	0.011	0.016	0.002	0.001	0.016	0.018
Benzene	0.005	0.005	0.007	0.007	0.001	0.001	0.002	0.001	0.003	0.002
Cyclohexane	0.005	0.005	0.006	0.007	0.003	0.002				0.004
i-Heptanes	0.020	0.017	0.025	0.021	0.011	0.009	0.002		0.017	0.014
n-Heptane	0.011	0.006	0.011	0.009	0.003	0.003	0.001		0.004	0.005
Toluene	0.008	0.006	0.007	0.010		0.001				0.002
i-Octanes	0.025	0.021	0.022	0.032	0.006	0.005	0.002	0.002	0.006	0.007
n-Octane	0.006	0.004	0.004	0.006	0.001	0.001				0.001
ethylbenzene	0.001	0.001								
m, o, and p-Xylenes	0.007	0.007	0.008	0.015						
i-Nonanes	0.005	0.004	0.007	0.010		0.004		0.003	0.001	0.001
n-Nonane	0.003	0.003	0.003	0.004						
i-Decanes	0.007	0.006	0.006	0.007		0.001			0.001	0.002
n-Decane		0.003	0.001	0.004						
Undecanes +	0.005	0.002	0.015			0.001	0.002	0.005	0.002	0.004
Total weight percent, ASTM D1945/1946	100.000	100.000	100.000	100.000	100.000	100.000	100.000	100.000	100.000	100.000
Molecular weight from ASTM analysis	16.8296	16.8590	16.8415	16.8396	16.9650	16.9834	16.5186	16.5223	16.9408	16.9586

Table F.5. Data from Stations E6 through E10 (Continued)

Site code	E6		E7		E8		E9		E10	
Combined MDM-300/ASTM D1945/ASTM D1946 composition All values in mol %										
Water vapor	0.01272	0.01272	0.01277	0.01277	0.00186	0.00186	0.01462	0.01462	0.00397	0.00397
Helium										
Hydrogen										
Carbon monoxide										
Oxygen	0.01262	0.01264	0.00947	0.00631						
Nitrogen	0.62112	0.66372	0.60352	0.61007	0.66736	0.74629	0.48110	0.49595	0.70328	0.73187
Methane	95.66038	95.48283	95.67833	95.68031	94.85117	94.73667	96.85611	96.83100	95.03562	94.92841
Carbon dioxide	0.90887	0.96102	0.98603	0.97024	1.18843	1.19049	0.21391	0.21621	1.14975	1.15405
Ethane	2.49426	2.57711	2.41426	2.42407	3.02972	3.04259	2.33388	2.34099	2.81011	2.87003
Propane	0.19500	0.19955	0.19514	0.19512	0.20429	0.22223	0.08615	0.08804	0.22896	0.24036
Isobutane	0.02750	0.02755	0.02926	0.02752	0.01897	0.02075	0.00398	0.00398	0.02244	0.02422
n-Butane	0.02924	0.02755	0.02926	0.02926	0.02423	0.02571	0.00654	0.00654	0.02740	0.02918
Neopentane										
Isopentane	0.00980	0.00841	0.00840	0.00840	0.00282	0.00141	0.00069	0.00046	0.00423	0.00282
n-Pentane	0.00700	0.00701	0.00840	0.00840	0.00141	0.00141	0.00046	0.00023	0.00141	0.00141
i-Hexanes	0.00293	0.00391	0.00430	0.00449	0.00335	0.00296	0.00077	0.00038	0.00413	0.00335
n-Hexane	0.00156	0.00176	0.00195	0.00215	0.00217	0.00315	0.00038	0.00019	0.00315	0.00354
Benzene	0.00108	0.00108	0.00151	0.00151	0.00022	0.00022	0.00042	0.00021	0.00065	0.00043
Cyclohexane	0.00100	0.00100	0.00120	0.00140	0.00060	0.00040				0.00081
i-Heptanes	0.00336	0.00286	0.00420	0.00353	0.00186	0.00153	0.00033		0.00287	0.00237
n-Heptane	0.00185	0.00101	0.00185	0.00151	0.00051	0.00051	0.00016		0.00068	0.00085
Toluene	0.00146	0.00110	0.00128	0.00183		0.00018				0.00037
i-Octanes	0.00368	0.00310	0.00324	0.00472	0.00089	0.00074	0.00029	0.00029	0.00089	0.00104
n-Octane	0.00088	0.00059	0.00059	0.00088	0.00015	0.00015				0.00015
ethylbenzene	0.00016	0.00016								
m, o, and p-Xylenes	0.00111	0.00111	0.00127	0.00238						
i-Nonanes	0.00066	0.00053	0.00092	0.00131		0.00053		0.00039	0.00013	0.00013
n-Nonane	0.00039	0.00039	0.00039	0.00053						
i-Decanes	0.00083	0.00071	0.00071	0.00083		0.00012			0.00012	0.00024
n-Decane		0.00036	0.00012	0.00047						
Undecanes +	0.00054	0.00022	0.00162			0.00011	0.00021	0.00053	0.00022	0.00043
Total	100.00000	100.00000	100.00000	100.00000	100.00000	100.00000	100.00000	100.00000	100.00000	100.00000
Properties calculated from combined composition										
Higher heating value, dry basis (Btu/scf)	**1021.2**	**1020.8**	**1020.3**	**1020.5**	**1021.0**	**1020.7**	**1024.5**	**1024.4**	**1020.1**	**1020.5**
Lower heating value, dry basis (Btu/scf)	**920.3**	**920.0**	**919.5**	**919.7**	**920.3**	**919.9**	**923.1**	**923.0**	**919.4**	**919.7**
Real relative density	**0.5821**	**0.5831**	**0.5825**	**0.5824**	**0.5868**	**0.5874**	**0.5713**	**0.5714**	**0.5860**	**0.5866**
Wobbe index	**1338.5**	**1336.8**	**1336.8**	**1337.2**	**1332.9**	**1331.7**	**1352.6**	**1355.2**	**1332.6**	**1332.4**
Methane number, AGA GQMM/SAE 922359	**99.70**	**99.52**	**99.81**	**99.76**	**98.78**	**98.63**	**101.53**	**101.51**	**99.08**	**98.85**
Total C_{4+} content (mol %)	0.10	0.09	0.10	0.10	0.06	0.06	0.01	0.01	0.07	0.07
Total C_{5+} content (mol %)	0.04	0.04	0.04	0.04	0.01	0.01	0.00	0.00	0.02	0.02
Hydrogen to carbon ratio	3.94	3.93	3.94	3.94	3.93	3.93	3.95	3.95	3.93	3.93
Total diluents (mol %)	1.56	1.65	1.61	1.60	1.86	1.94	0.71	0.73	1.86	1.89

Table F.5. Data from Stations E6 through E10 (Continued)

Site code	E6		E7		E8		E9		E10	
Sample cylinder #	24	28	21	9	3	21	8	24	5	6
ASTM D6667 total sulfur										
ppmw	4.8	3.9	4.7	4.2	4.0	3.6	< 0.1	< 0.1	8.5	7.7
grains/100 cu.ft.	0.151	0.123	0.148	0.132	0.126	0.113	< 0.032	< 0.032	0.268	0.243
ASTM D5504 sulfur speciation (normalized to ASTM D6667 total, ppmw)					No speciation performed	No speciation performed			No speciation performed	No speciation performed
Sulfides										
Hydrogen sulfide										
Carbonyl sulfide		0.0								
Dimethyl sulfide	0.1	0.1	0.1	0.1						
Methyl ethyl sulfide										
Diethyl sulfide	0.1	0.1	0.1							
Mercaptans										
Methyl mercaptan										
Ethyl mercaptan										
Isopropyl mercaptan	0.6	0.6	0.6	0.4						
n-propyl mercaptan	0.1	0.1	0.1							
sec-butyl mercaptan				0.1						
tert-butyl mercaptan	3.6	2.9	3.7	3.6						
n-butyl mercaptan										
Disulfides										
Carbon disulfide										
Dimethyl disulfide			0.0							
Methyl ethyl disulfide										
Diethyl disulfide										
Other target sulfur compounds	0.3	0.1	0.0							
FTIR analyses										
CRC liquid sample #	32		36		39		31		32	
Significant amount of liquids drained from cylinder?	yes		no (acetone rinse used)		no (trace)		no (no rinse performed)		no (trace)	
Water identified by FTIR?	yes		no		yes				yes	
Hydrocarbon liquids identified by FTIR?	yes		yes		yes				yes	
Known compressor oil identified?	no		no		no				no	