Identifying and Rank-Ordering Large Volume Leaks in the Underground Natural Gas Distribution System of Massachusetts

Permanent link

Terms of Use

Share Your Story

Identifying and Rank-Ordering Large Volume Leaks

in the Underground Natural Gas Distribution System of Massachusetts

Zeyneb Pervane Magavi

A Thesis in the Field of Sustainability

for the Degree of Master of Liberal Arts in Extension Studies

Harvard University

May 2018

Abstract

Rising methane in earth's atmosphere accelerates climate change, and natural gas is a major driver of that increase. In 2016, Massachusetts passed a law requiring that 'environmentally significant' leaks in the aging natural gas distribution network be prioritized for repair in an effort to reduce methane emissions. This research seeks to inform implementation of this legislation by determining an efficient method for identifying and rank-ordering leaks according to volume. Participating gas utilities selected 72 Grade 3 gas leaks across the state, representing all leak-prone pipe materials (cast iron, wrought iron, bare steel, coated steel, and old plastic) and pressures ranging from 0.5 – 99 PSI. A previous study found a heavy-tailed distribution of natural gas leaks by volume in a cast iron low-pressure leak population, and I used the same verified chamber measure of leak volume to test whether that relationship held in a diverse set of pipe materials and pressures. The chamber method flux measures were then used to benchmark other methods, including the initially proposed bar hole method. Suspecting that the bar hole method may be insufficient to rank-order leaks by volume, we also tested four additional methods, including the leak footprint, ringdown spectrometer, FLUXBar , and MSS camera. Both the FLUXBar and the MSS camera are innovative new technologies, with the FLUXBar a co-creation of my research coalition.

I helped to assemble and maintain an unusually broad coalition of stakeholders in order to carry out this research collaboration between the utilities and local environmental organizations, including legislators and regulators to ensure that the science would drive

policy. By replicating the heavy-tail distribution in our more varied leak population, I was able to confirm that the identification of the largest volume leaks (LVLs) would maximize emissions reduction per dollar spent. As the 'bar hole %gas' method showed no correlation with leak volume, employing it to identify those LVLs would be as efficient as random selection.

Alternate methods did better, with the ringdown spectrometer method, the FLUXBar, and leak footprint methods all correlating with leak volume. The ringdown spectrometer demonstrated the weakest correlation and the use of the FLUXBar is limited by the need for a compressor truck. Leak footprint is not, and can be easily deployed in standard leak surveys. The leak footprint method correlates strongly, so selects leaks that are larger than average leaks, resulting in a return on investment to the ratepayer of less than a year. The originally proposed bar hole method's return on investment to the ratepayer would be more than six years. These data suggest that the leak footprint is the best available rapid indicator of leak volume, with the FLUXBar measure a potential quantification and verification tool. Continued research is needed as technology-based options advance to meet this challenge.

The stakeholder coalition, in response to these data, agreed to a plan to implement the leak footprint method, accelerate repair, and establish transparency, verification and reassessment processes. The agreement between the three largest gas utilities in Massachusetts and my research team, if enacted as designed over the next two years, has the potential to result in a methane emissions reduction equivalent to 4% of the greenhouse gas emissions inventory for Massachusetts.

Dedication

I dedicate this thesis to Bora M. Pervane, who strove to write his regional planning thesis on the biological nature of urban growth patterns while caring for me as an infant. Thanks to his foresight and to his ethic of care, I complete mine today.

Acknowledgments

Table of Contents

Definition of Terms

Natural Gas - A fossil fuel that, when processed and distributed as 'pipe quality', is roughly 97% methane or CH_4.

Natural Gas Leak (distribution system) – The location of measured CH_4 emissions, which may contain one or more underground physical pipeline breaches or leaks.

Large Volume Leaks (LVLs) – The largest leaks on the distribution system, defined by a threshold leak size. Considered environmentally significant.

Local Distribution Companies (LDCs) – The regulated utility companies that purchase natural gas from pipelines and deliver it to customers for a preset rate.

Department of Public Utilities (DPU) – In MA, the government agency charged with regulating the utility companies, with leadership appointed by the governor.

Flux – The rate of flow of a gas, such as methane, where units are volume over time.

Grade 3 Gas Leak – A leak classified as non-hazardous by utility workers, considered unlikely to explode. Flux is not a consideration in this classification.

Viscous Flux – The high flow gas often found escaping pathways such as cracks and drains, able to be directly measured above a 500 ppm or 0.05% gas threshold.

Diffuse Flux – The low flow gas found diffusing through unbroken surfaces, requiring instruments sensitive in the 1-500 ppm range for direct measurement.

List of Tables

List of Figures

Chapter I

Introduction

Methane, CH_4, is a potent greenhouse gas that is increasing in our atmosphere, making it a key leverage point in the effort to slow climate change. Increasing awareness of methane's impact has resulted in increased research activity in the field of fugitive methane emissions of natural gas systems, but much of the research is focused on 'upstream' aspects of the natural gas system, including production, processing and interstate pipelines (Mitchell et al., 2015). Methane emissions reductions in our communities, streets, and yards, in the last miles of the system, offer a recently understood potential opportunity for greenhouse gas reduction (Phillips et al., 2013: McKain et al., 2015) that also saves money and increases safety.

Increasing understanding of the scale, and corresponding climate impact, of fugitive methane emissions (Worden et al., 2017) from the entire natural gas system has challenged the concept of natural gas as a clean bridge fuel to a renewable future (pipe quality natural gas is ~97% CH_4). Fugitive emissions from aging local natural gas distribution pipelines are more common and larger than assumed, and a 2016 law passed in Massachusetts (MA) to prioritize repair of 'environmentally significant' leaks seeks to target this lost gas for GHG reduction. It is the first such law in the U.S. and the first time natural gas distribution companies are asked to measure or assess, and prioritize, gas leaks by emissions volume. There was no existing verified method to accomplish this task, and the proposed method in drafted regulation had never been tested.

Research Significance and Objectives

This research tests a proposed method to measure, regulate, and optimize this natural gas emissions reduction opportunity. The proposed method is compared with alternate methods in order to provide scientific basis for the final regulation, ensuring it has the intended impact of optimizing methane emissions reduction. Efforts to pass similar laws in other states have already begun, ensuring that the proposed research could have national and international impact.

Therefore my objectives are:

- To test and compare proposed and available alternate methods for identifying and rank ordering large volume leaks (LVLs)

- To increase understanding of on the ground challenges, and utility norms and practices, in order to inform the regulatory design and method implementation

- To contribute to current scientific and industry understanding of the distribution of gas leaks by volume, and natural gas distribution system methane emissions measurement and related technologies

- To build a stakeholder ecosystem connecting and motivating the people and organizations necessary to this research and to it's implementation.

It is of note that this research was a coordinated team effort by many collaborators with many different roles, as detailed in the Methods.

Background

Climate change, driven by anthropogenic greenhouse gas production, is currently the greatest threat to life on planet earth. While humans are slowly realizing the urgent

need to reduce greenhouse gases, much of the focus, and measured success, is for carbon dioxide (CO_2). Yet methane (CH_4) is 86 times more potent as a greenhouse gas than CO_2 in the first twenty years spent in the atmosphere. Also, global atmospheric methane has been rising significantly since 2007 with approximately 2/3 of that rise attributable to anthropogenic sources (Turner et al., 2016; Nisbet, Dlugokencky & Bousquet 2014). A recent NASA study attributes 12-19 Tg CH_4 per year of the rising methane to the fossil fuel industry (Worden et al. 2017). More specific attribution by source or by region is widely debated, with bottom-up inventories and top-down estimates resulting in very different conclusions (Maasakkers et al., 2016; Brandt et al., 2014; Miller et al., 2013) For example, surface observations indicate U.S. methane emissions increased more than 30% between 2002 and 2014 (Turner et al., 2016), during a time of booming natural gas production and fracking (US EIA, 2015), while U.S. EPA inventory suggests a 3% decrease in fossil fuel derived methane emissions over the same period. Regardless, there is broad consensus that the rapid reduction of CH_4 emissions is an urgent and powerful leverage point in the effort to slow climate change.

The Natural Gas System's Role in Global CH_4 Emissions

What we call 'natural' gas, delivered to our homes through underground pipes, is 97% CH_4. This cleaner burning fuel was seen as a 'bridge' to a decarbonized global energy system, with widespread, and continuing, effort to switch power generation and heating systems from coal or oil to natural gas. Unfortunately, methane's disproportionate impact on global warming means that even a seemingly small amount of system leakage may mean this shift had no net impact, or even an accelerating effect, on climate change: it all depends on how much CH_4 is leaking out of the entire natural gas

system (Brandt et al., 2014). Given that "measurements at all scales show that official inventories consistently underestimate actual CH4 emissions" (Brandt et al., 2014), it is of value to look at fugitive methane throughout the system; from extraction, including hydraulic fracturing of shale gas, through large interstate pipelines and compressor stations, to local distribution systems delivering gas to customers (Figure 1).
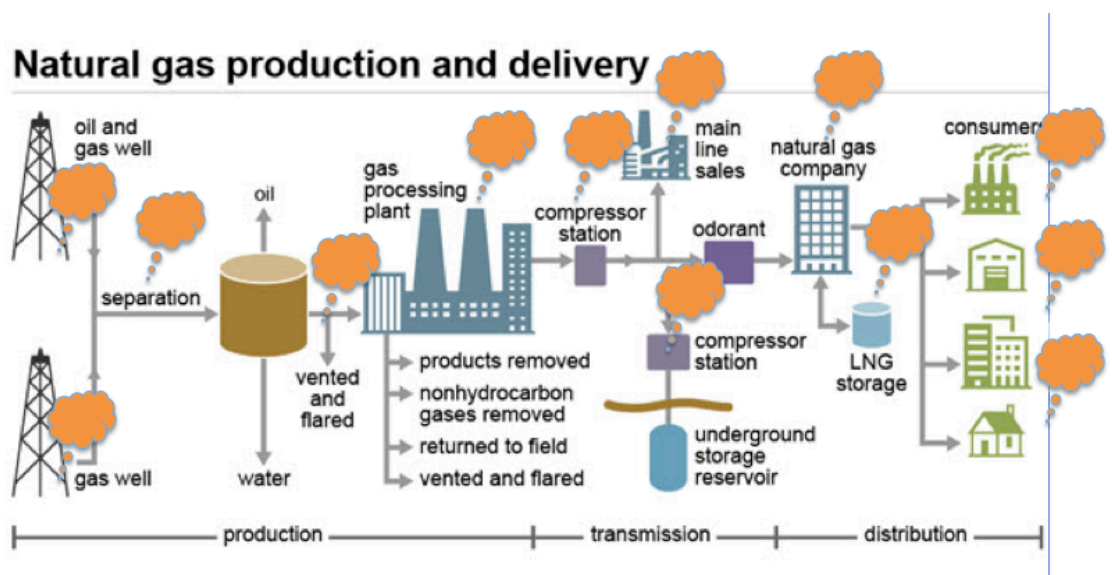
Figure 1. Natural gas system leakage: production to consumer (modified from U.S. Energy Information Administration, 2017).

Efforts to measure, quantify, and reduce methane emissions, for this system, have focused on production, processing, power generation plants, and compressor stations. One consistent outcome of this research is that methane leakage measurements show a statistically heavy-tailed distribution, meaning that roughly the largest 5% of leaks documented emit 50% of the total leaked CH_4 (Brandt, Heath, & Cooley 2016). This remains consistent from wellhead to processing plant to compressor station (Brandt,

Heath, & Cooley, 2016) and these largest leaks are defined in the literature as superemitters.

This same distribution pattern was recently demonstrated in local distribution pipeline leaks in Boston (Hendrick, Ackley, Sanaie-Movahed, Tang, & Phillips 2016) (Figure 2). Previous efforts to map leaks in aging distribution systems have consistently shown high leak rates with 4.25 leaks/mi in Manhattan, 4.28 leaks/mi in Boston, and 3.93 leaks/mi in Washington, DC (Gallagher et al., 2015). This pattern is consistent across local distribution pipeline systems in older U.S. cities that are a patchwork of different age pipes of varying materials – some pipes currently in use in Massachusetts dating to the Civil War. These leak prone pipe materials include cast iron, wrought iron, bare steel, coated steel, and older plastic pipes, and pressures in distribution pipes range from 0.5 to 99 PSI (lbs/inch^2).

Hendrick Study
Emissions from Largest 7% of Leaks vs.
Emissions from all other Leaks in Study
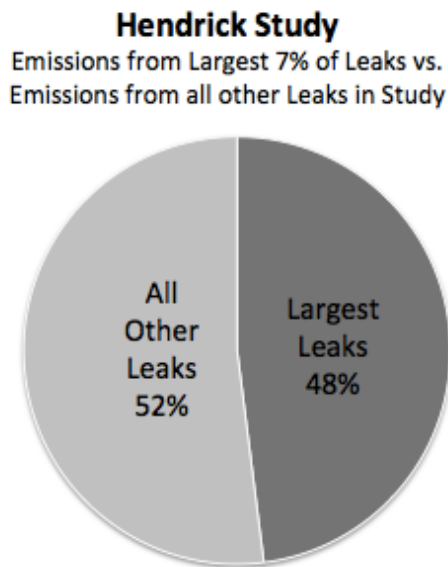
Figure 2. Just 7% of leaks contribute half of total leak emissions in Boston. Distribution of emissions in ft^3 CH$_4$/day from a study of 100 Cast Iron mostly low pressure Boston gas leaks (Hendrick et al., 2016).

Widely considered smaller than, and of little consequence compared to upstream system leaks, these local distribution leaks may be a larger piece of the puzzle than was suspected. A long term monitoring study of atmospheric methane in Massachusetts found that 2.7% of all natural gas entering the state was lost to the atmosphere pre-combustion (McKain et al., 2015). With limited miles of interstate pipelines, few compressor stations, and no production or processing, the contribution of leaks from the local distribution pipelines is estimated to be 50% of the measured total. This is equivalent to 10% of the calculated annual MA greenhouse gas emissions, though these emissions are not currently included in the state's greenhouse gas inventory (Phillips et al., 2013). In 2016, the MA utility industry reported a LAUF (lost and unaccounted for) of 3.3% of all gas consumed, with known volume of lost gas 1.65% and remaining unaccounted for (EIA 2017), which comes closer to the direct atmospheric measurement than previous years reported LAUF. Regardless of estimation, the potential to reduce global methane emissions by efforts at the local distribution level must be considered.

MA Natural Gas Leak Legislation and Regulation

State legislation in 2014 (Commonwealth of Massachusetts, 2014) resulted in required public reporting of all gas leaks annually by the utility companies, driven by publication of methane emissions maps of Boston (Figure 3). These annual reports of natural gas leaks have been submitted to the Department of Public Utilities (DPU) for three years, with new data for 2017 released in April of 2018. The 2016 leak report (MA Department of Public Utilities, April 2017) lists 16,944 leaks, with 11,930 repaired and

the 2015 leak report lists 16,705 leaks. Not only are the overall sum not decreasing

significantly, but both a MIT CSAIL analysis and a HEET analysis of the data
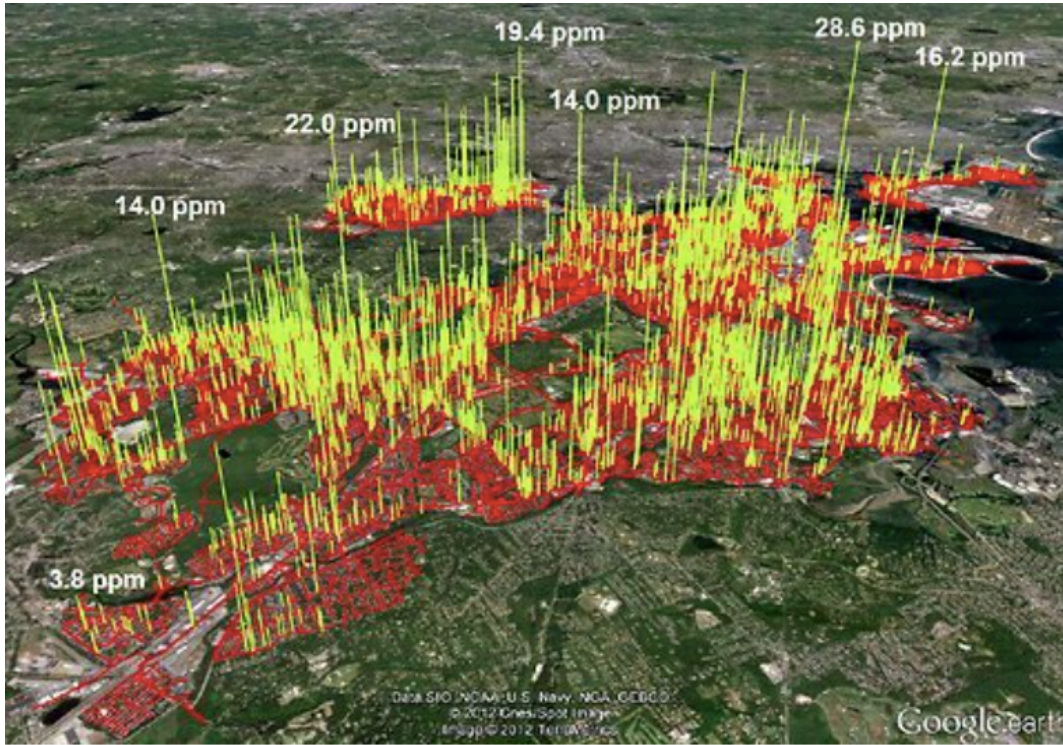
Figure 3. Methane emissions map of Boston. Red is the driving route of the Cavity Ringdown Spectrometer used to analyze methane, and yellow represents the size of the methane ppm recorded at that GPS location, with the largest peaks labeled by size (Phillips et al., 2013).

identified missing leaks from one year's report to the next, raising questions on the data's

accuracy and completeness (Figure 4). This is not of concern in this research, instead

what matters is that the utilities are not currently prepared to repair all the leaks (they

propose to resolve the backlog through infrastructure replacement over 20yrs) and that

each year brings a new crop of leaks roughly equal to the number repaired the year before

(Department of Public Utilities, 2017).
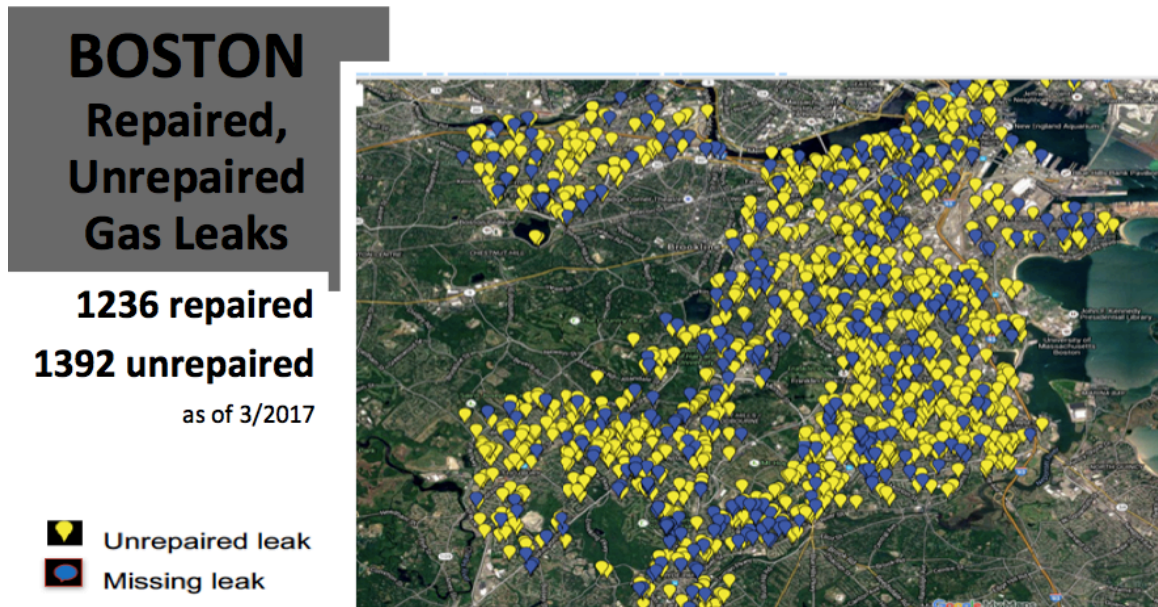
Figure 4. Utility company reported gas leaks in Boston. Yellow marks leaks reported unrepaired as of January 2017 and blue marks leaks missing from the January 2017 report, yet reported unrepaired in January 2016 and not reported as repaired. (HEET 2017)

Therefore, the potential to reduce climate hazard rapidly by prioritizing the largest leaks is clear. The previously mentioned Boston study, of emissions volume in 100 of these leaks in low-pressure cast iron pipes, found that just 7% of the leaks contributed 50% of total measured emissions (Hendrick et al., 2016) (Figure 2). If this distribution applies to all pipes and pressures, then the annual prioritized repair of the largest 7% of the leaks could result in a rapid 50% methane emissions reduction.

This possibility, together with outrage over publically available maps of the reported leaks for all MA towns (Figure 4), resulted in further activist driven legislation passed in August 2016. This new law requires that the utilities begin to prioritize leaks by 'environmental significance', an undefined term. The Department of Public Utility (DPU) began deliberations on how to create regulation for this law and released a straw proposal

in early 2017 (DPU 2016), suggesting the untested bar hole %gas method be used to select the largest leaks and that the utilities would then be paid more and faster to fix those leaks. It is expected that a final ruling will be made in 2018, putting this regulation in place. This provided a window of opportunity in 2017 to optimize the outcomes of the 'environmental significance' legislation by determining the most efficient method to find and prioritize the largest volume leaks.

Regulatory Possibilities: Current Methods of Gas Leak Assessment and Ranking

In order to capitalize on this window of opportunity, it is essential to understand available methods and current norms. The natural gas industry is self-described as risk-averse, slow to change, and rooted in the prioritization of safety. The measure of natural gas leaks is primarily done through the use of a tool called the Combustible Gas Indicator (CGI) that assesses, within 0.05% or 500ppm, the % CH_4 at a single point of measure. The standard utility leak assessment method is to take this measure in a subsurface "bar hole" in the ground or pavement, made by a bang bar (a large tamping iron-like spike banged into the ground). The leak report generated at the leak assessment includes the highest bar hole %gas read as well as a sketch of the leak migration pattern. This existing CGI technology with it's %CH_4 bar hole measure was proposed as a possible indicator of leak size because the barhole data is already collected. However, the use of this measure as an indicator of leak volume had not been tested.

Also assessed is the gas buildup or proximity to possible 'containers' for the escaping gas, including manholes and buildings, in order to determine the hazard of explosion. For example, if a leak has gas building up in a manhole that has reached 5% gas (the lower explosive limit (LEL) of CH_4) then the leak is ranked a Grade 1 and

required fixed within 24 hrs. Proximity in feet to a building, or presence in a manhole, can result in a Grade 2 assignment, which results in the leak being monitored and prioritized for repair within the year. Those leaks that are unconstrained by, and non-adjacent to, infrastructure, and are leaking freely into the atmosphere, are all Grade 3 and have not until now had any regulatory requirement for repair or prioritization, regardless of the volume of gas leaked (Commonwealth of Massachusetts 2014; DPU 2016).

Regulatory Possibilities: Available and Potential Technologies

The lack of regulatory requirement to date also means a lack of an existing market for technology designed to measure and sort distribution pipeline leaks by volume. There are some larger scale methane detection tools for extraction fields, etc., but they are not designed for the volume of methane in this context and their cost is prohibitive. Other alternatives do exist, however.

The Cavity Ringdown Spectroscopy technology was used in several studies to map gas leaks (von Fischer et al., 2017; Jackson et al., 2014; Phillips et al., 2013), but has been rejected by the utility industry, mostly due to its excess cost and to apparent issues with wind-generated error. The Picarro Corporation has a fee for service cost model that the utilities dislike, but a new competitor, Los Gatos, may make this technology more feasible to implement at scale. Concern over wind error may potentially be addressed by protocol design or data processing, as we attempted to do.

The use of Infrared Spectroscopy has been led by the FLIR camera, which does not capture small volumes and cannot measure quantity, but is a widely appreciated visual tool. The MSS Camera is an infrared multispectral camera designed to provide live visualization, like the FLIR, but with greater sensitivity, data capture, and the

capacity to quantify. Developed by a local startup in Greentown Labs in Somerville, the innovators were enthusiastic participants in this study, primarily as a proof of concept.

Given the lack of any tool that would allow a rapid measure of flux by the utility workers at the time of excavation, we co-designed, built, and tested a new tool, the FLUXBar, to meet that need (Appendix 1). It is based on the bar hole purger tool used to rapidly clear built up gas from under a street and is being produced by Millibar, Inc in Hopkinton, MA. This tool is comprised of a standpipe inserted into a drill hole over the highest percent gas measure and, at the head of the standpipe, the tool attaches to a truck compressor. It uses the venturi effect to generate a vacuum pull in the standpipe of a constant 3 SCFM, and an attachment port for a CGI allows for direct %gas measures in this known flow. Measuring the %gas over time can provide flux measures at the time of repair. This approach is rapid and eliminates a number of variables, but does not address variation of soil porosity and tortuosity.

It is assumed that the market will respond with more options as more states seek to reduce methane from distribution pipelines, but a viable solution is needed now in MA. The law in MA to prioritize large leaks is the first time natural gas distribution companies must measure or assess leaks by size, volume, or flux. They have, until now, been entirely focused on reduction of hazard, ranking and repairing leaks based on their potential to explode. The gas lost to the atmosphere was seen as non-hazardous and a cost of business, with the lost gas cost rolled into the customers' price of gas. Recent awareness of the outsize impact of methane in driving climate change and public concern around the impact of these gas leaks on health, environment, and the pocketbook, has led to grassroots driven legislative action in MA. The rest of the country (and the gas utility

industry) is watching what happens next. Quickly determining a viable method for identifying the largest leaks has the potential to lead to rapid and significant greenhouse gas reductions for the state. If successful, this method and policy change will be an example for other locations with similar aging piping, such as New York, Pennsylvania, and San Francisco.

Research Questions, Hypotheses and Specific Aims

My research seeks to address a series of linked questions and hypotheses:

1. Do the gas leaks studied replicate a heavy tail volume distribution curve despite their more variable pipe material and pressure?

   H1: 5-10% of the leaks will produce 50% of the total measured methane emissions.

2. Does the DPU initially proposed bar hole %gas method successfully select the largest volume leaks for prioritized repair?

   H2: the bar hole method will not serve to accurately indicate the size of the leaks, resulting in no significant correlation between bar hole %gas and volume of leak. Given its' nature as a measure of % gas at a single point, hypothetically every leak could have a location that measures 100% gas, regardless of the volume of gas leaked

3. Do alternate methods successfully select the largest volume leaks (LVLs) for prioritized repair?

   H3: the physical breadth, or leak footprint, is associated with the volume of the leak

H4: newer technologies (such as the Cavity Ringdown Spectrometer, the

FLUXBar, and the MSS Camera) will be useful in selecting the LVLs, but it is

difficult to predict their ease of implementation, use, or efficiency given their

novelty and higher costs

Specific Aims

Testing these hypotheses required that I, with the research team I led:

1. Request that the three largest utility companies in the state (Eversource Gas,

    Columbia Gas, and National Grid Gas) select leaks across their service areas, of all

    pipe materials and all pipe pressures, using the proposed bar hole method, and share

    the selected standard utility leak reports.

2. Work with town Department of Public Works to have selected leaks permitted and

    approved for survey and repair with call in to DigSafe completed on schedule.

3. Perform a second, replicate, 'standard' leak survey on each of the selected leaks,

    using a Flame Ionization unit (FI), a Combustible Gas Indicator (CGI) and a bang bar

    to get %gas bar hole measures and leak footprint.

4. Measure the direct passive methane emissions of each leak using the Chamber

    Method in order to determine Flux, or cubic feet methane emitted per day.

5. Drive by each leak at a constant speed multiple times using a Picarro GPS enabled

    Cavity Ringdown Spectrometer, saving data to .klm files.

6. Trial the prototype MSS Infrared Spectroscopy Camera, from a startup at Greentown

    Labs, on a subset of leaks, to image the leak and to potentially calculate the emitted

    methane using column density.

7. Attend the repair of the leak with the utility truck crew and document the process. At the time of repair, crews will assess each leak with the FLUXBar, a second innovative method of leak measurement.

8. Record observations throughout this research process.

9. Return to the leak and confirm the success, or record the failure, of the leak repair.

10. Analyze the data collected for each method and its' relationship with the reference Chamber method results for total flux.

11. Analyze the relationship between other known variables such as pipe size, pressure, or material and leak volume in an effort to narrow the pool of potential LVLs.

12. Calculate the differential environmental and financial impact of potential method choices.

13. Estimate the cost to the ratepayer and the return on investment of LVL repair for the methods shown to be effective.

Chapter II

Methods

As the Research Lead of this large volume leak study (and a volunteer), I am grateful for the team of HEET employees, Mothers Out Front volunteers, consultants, and gas utility workers who agreed to work together with me. The logistics and management of the study and its participants were shared between Audrey Schulman (President of HEET), Debbie New (Mothers Out Front Gas Leaks Task Force Leader), and myself. I designed the study with input and advice from Bob Ackley of Gas Safety Inc., Audrey Schulman, and Professor Nathan Phillips of Boston University. The fieldwork team included Bob Ackley (a certified gas technician), Jason Taylor, Audrey Schulman and myself, working together with gas utility workers from the trucks assigned. I analyzed the data with assistance from HEET intern Eddy Salgado, and guidance from Margaret Hendrick and Nathan Phillips. Finally, Barr Foundation and Putnam Foundation provided funding, and Eversource Gas, Columbia Gas, and National Grid Gas were essential partners in the entire effort.

With the assistance of this team, I sought to confirm the long-tail distribution of leak volume for a more diverse set of pipe materials and pressures in MA, evaluate the success of the bar hole method in identifying and rank ordering large volume leaks, determine if there are other alternate methods that can improve the identification and rank ordering of large volume leaks, and assess the relative feasibility of implementing the

viable methods found. Selection of leaks, protocol for reference method, protocol for tested methods, and the approach to analysis of the resulting data are described below.

Leak Selection

In order to accomplish these objectives, I needed appropriate leak selection. Selection was a challenge both because thorough scientific assessment of chamber measures of 16,944 leaks is impossible due to cost and time constraints, and because utility data and understanding of grade 3 leaks is limited. I avoided these challenges by requesting that each utility use the DPU's straw proposal leak selection protocol to provide us with Grade 3 Leaks suspected to be large volume from any pipe material or pressure across their distribution system. This allows for a realistic test of the proposed method without variability in interpretation or application that might occur between utility companies compromising the results, because the test is of the method's efficacy implemented as proposed. Utility A initially selected 35 Grade 3 leaks, Utility B selected 15 leaks, and Utility C selected 30 leaks. These Grade 3 leaks were located throughout the aging pipe network under Massachusetts' streets, so their excavation and repair need to be permitted by the municipality the leak was located in, scheduled, and provided with police detail. Once the barriers of municipality permitting and other timing and logistical constraints were met, I ended up with a final study population of 72 Grade 3 leaks. The resulting leaks were inclusive of all leak prone pipe materials and pressures, so I did not need to supplement the initial study population. Resource constraints and logistics set a limit on the study population, but did not add bias to the selection process as the constraints are the same across utilities and are independent of the method of assessing volume.

We selected an additional 14 leaks by choosing the highest possible values from Cavity Ringdown Spectrometer surveys of greater Boston, using the area under the curve method described below. This was a separate test of this technology and method's ability to pick large leaks rapidly, and this second leak population was kept separate and specific to the question asked.

All leak assessment should be done during consistent weather conditions; therefore all study measures, including chamber, were taken in dry conditions and other weather data was recorded. To demonstrate the importance of this, I returned to a single leak at Linnean Street in Cambridge repeatedly over a two week period measuring (with a Sentry CGI) the change in %gas at three marked locations and I recorded variables such as temperature and humidity.

I did a further demonstration of leak character on a representative subset of leaks, using a standard grid transect method to select random sample locations of even spacing across the leak footprints. While the gas leaks studied were physically located in pipes under streets, the resulting gas soaked surface or footprint often extended beyond the street into sidewalks, lawns, tree pits and so on. Using the 0% gas edges of the leak footprint, regardless of surface, and a combination of chalk and plastic markers, we defined the midpoint of the leak footprint, set the main transect as the longest distance through the midpoint and then created perpendicular transects and intersecting transects at even intervals. We then used a Rover CGI with wand cone placed directly on the surface for one minute to take a ppm gas measurement at each transect intersect and recorded the highest and lowest reading. Transect intersects were often marked on solid pavement or concrete, but we took direct measurements regardless of surface type.

Leak Volume Assessment Methods

In order to identify the largest leaks by volume of methane emissions and to rank-order them by volume, allowing for the identification of the largest volume leaks for prioritized repair, we tested five available measures or proxy measures. Each measure tested was chosen for it's potential to effectively and rapidly identify LVLs, while being potentially practical and cost-effective to deploy given current utility personnel and protocols.

Reference Measure: Chamber Method

In order to assess the methods proposed, I needed a reference method by which to determine the accuracy of all other proposed methods. The Chamber method is a lab-tested and verified method of measuring fugitive methane emissions, known to be an underestimate of total emissions (Hendrick et al., 2016). This method's protocol is time-consuming and requires the researcher to be consistent and careful and use a calibrated CGI at all times (with 2.5% gas every 30 days). Each chamber used had a vent to attach to the CGI as well as a vent with a 'pigtail' extension to allow for normalization of pressure changes in the chamber. The CGI pump removed sample gas at a rate of 0.05-0.06 liters/minute and the pigtail valve balanced that.

The research team placed a suitable shape chamber to record the measure over any gas pathway in the leak footprint measured as 0.05% or higher gas by the Sentry CGI (Range 0.05% - 100%). Then using a prepared data collection sheet, we recorded methane %gas in 30 second intervals for a minimum of two full minutes (Figure 5). After completing the chamber measure for a gas pathway, the chamber was fully ventilated to remove gas residue before the next chamber measure.

A simple linear regression fit to plotted chamber data (% CH₄/second) provided a slope that approximates CH₄ flux. The y-intercept is set to zero when curve fitting for this set of analyses and the slope is then adjusted using Hendrick's formula to correct for sample gas removed by the analyzer pump, which is applied after curve fitting.
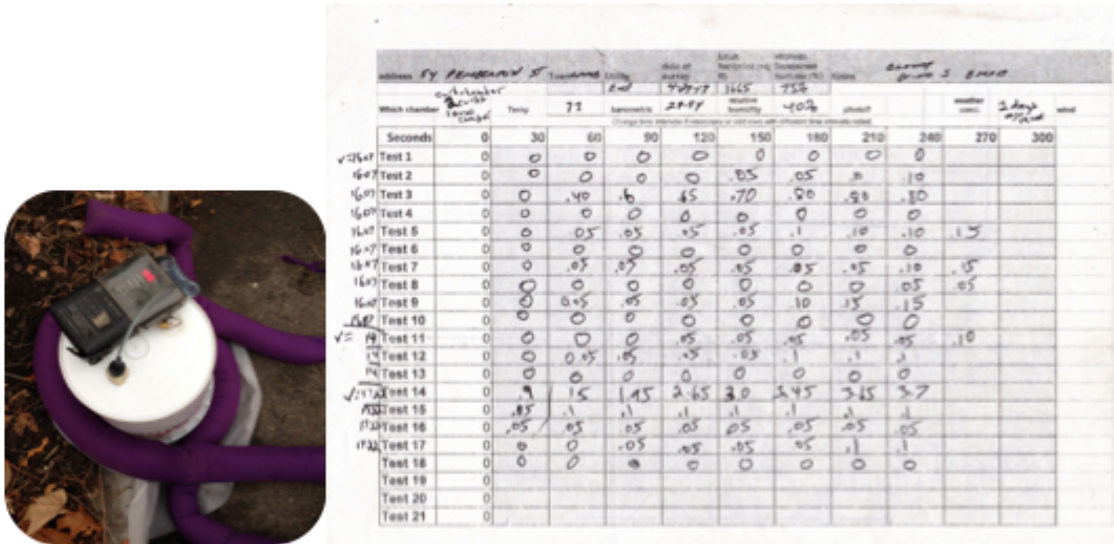
Figure 5. A curb cut chamber in use and an example data record sheet.

The equation is: SCGI Corrected = (SCGI((RT)/V)) + SCGI

where SCGI is the slope of the line fit to chamber data (% CH₄/second), R is the CGI sample gas removal rate (0.0092 Lsec-1), T is the total sampling time (sec), and V is the chamber volume (L). This correction factor allowed us to mimic the closed dynamic chamber approach by accounting for all sample gas that would have accumulated in the chamber space during the two-minute sampling event (text excerpted with modifications from Hendrick et al., 2016 Supplementary Material). Summing these calculated fluxes of

each chamber measurement taken for a leak location provided a total CH_4 flux measure of methane emissions for the given leak.

An identical chamber method, but using the Rover CGI (Range 1ppm-100%gas), was completed on 22 of the leaks in order to capture flux below the 0.05% threshold of the Sentry CGI range. This diffuse flux was assessed using the same analysis method as the above viscous flux calculations, and a scalar was determined from the average diffuse flux/square foot of chamber measurements. This allowed us to increase the accuracy of the chamber flux measurement by summing viscous and diffuse flux to get total flux.

Test Method 1: Bar Hole %gas Measure

A standard utility procedure across the world, this measure begins with the rough assessment of the extent of the leak through a tool like the Flame Ionizer Unit (FI) that is sensitive to the presence of gas, followed by a systematic producing of holes in the surface (grass, pavement, etc.) using a bang bar. Starting in the perceived center of the suspected leak, the bang bar holes were tested with the CGI by inserting a wand into the bar hole, subsurface, and then recording the %gas measure found on the CGI screen. An additional bar hole, several feet from the last, was made and measurements repeated, until the %gas reading was 0% gas in every direction. The highest %gas measure taken at the leak location was recorded on the leak report, and is proposed as an indicator of volume of the leak (Figure 6).

Test Method 2: Leak Footprint Measure

Following the bar holing measurement process, a sketch was made of the leak (Figure 6), with the edges defined by the 0% gas readings. A simple length and width

distance measurement with a tape measure allowed for a rough calculation of the area of the leak by multiplying the two measures to get square feet - or the leak footprint proxy measure.
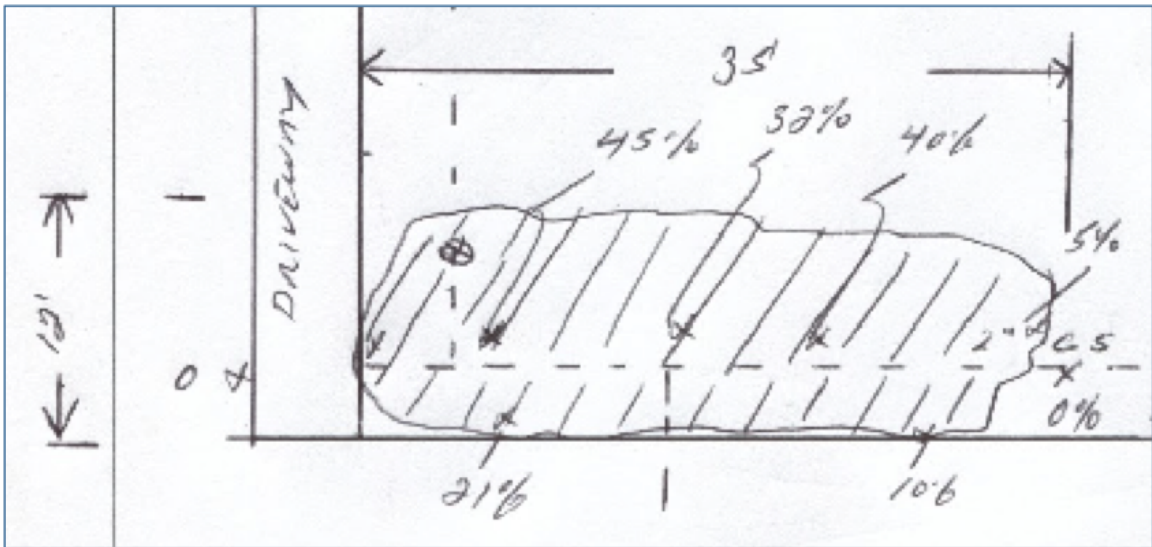
Figure 6. Example of a leak survey diagram. Bar hole %gas measures are marked by an x, and leak extent marked in feet on the horizontal and vertical axes (35'x12').

Test Method 3: Cavity Ring down Spectrometer Measure

We used a Picarro brand cavity ring down spectrometer to directly collect ppm gas measures into .kml files (Figure 7), while driving by leak locations. Our protocol, intended to decrease the effect of wind, was to drive multiple passes in opposite directions at constant speed and average the results together. Data analysis first required removing points that are stacked in the same location (parked data that often occurs at red lights for instance). The remaining point locations were smoothed for ease of analysis using a 3rd order polynomial interpolation with frame length of 9 data points.

Specifically, the MatLab function sgolayfit was used. There are sometimes sudden jumps in the GPS location due to a communication lag with the Picarro and this technique addresses this. Then, a flat baseline was fitted and subtracted from the data, allowing for any shift above a 0.1ppm threshold to define the beginning and end of each 'peak'. Finally, the area of each of these peaks, or the 'area under the curve' was calculated by a trapezoidal sum with slice area = $\frac{1}{2}(y_1+y_2)*(x_2-x_1)$. The summed area of each peak is the testable proxy measure for volume of the leak used in this study.
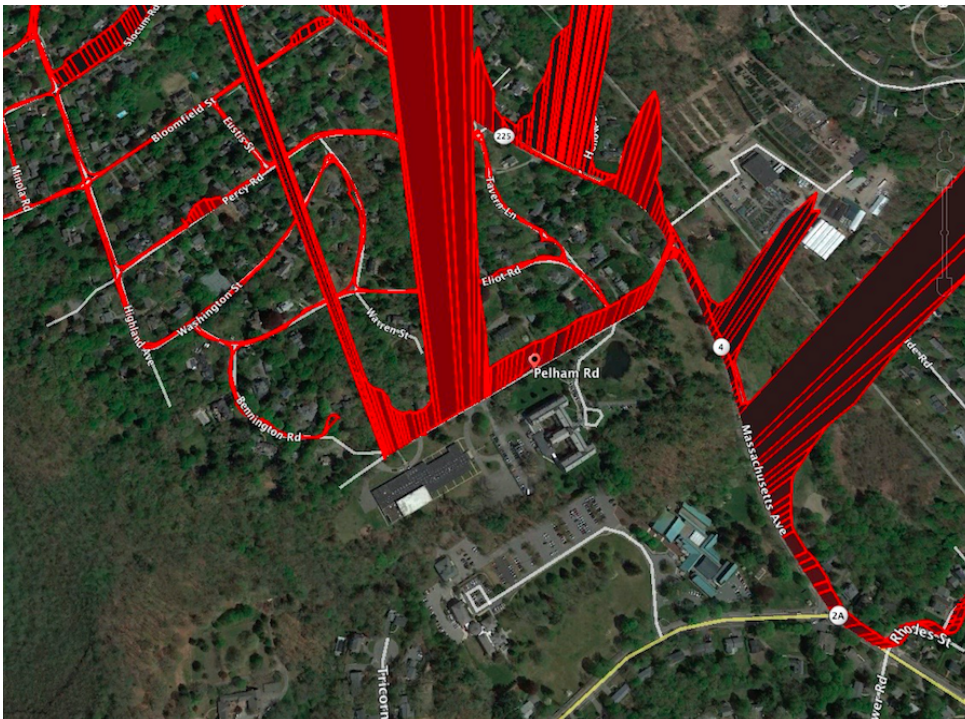
Figure 7. Example of cavity ringdown spectrometer data. This shows the .kml data file for a leak prone section of piping in the town of Lexington, mapped onto Google maps to visualize the data.

Test Method 4: MSS Infrared Spectroscopy Camera Measure

The MSS multispectral camera is a proof of concept innovation that uses infrared wavelength to capture density of methane molecules in a 30-degree angle field through a

continuous live data feed (Figure 8). With the camera secured to a stable tripod and pointed at the gas leak, a video image of the methane in the camera's view appeared on a handheld screen. Then the camera was repositioned in order to capture the entire extent of the leak, or if the leak was too large, multiple positions and images were recorded. The capacity to estimate volume from that recorded data, adjusting for wind, surface reflectivity variation, and shadow, was still in development with the MSS research team.
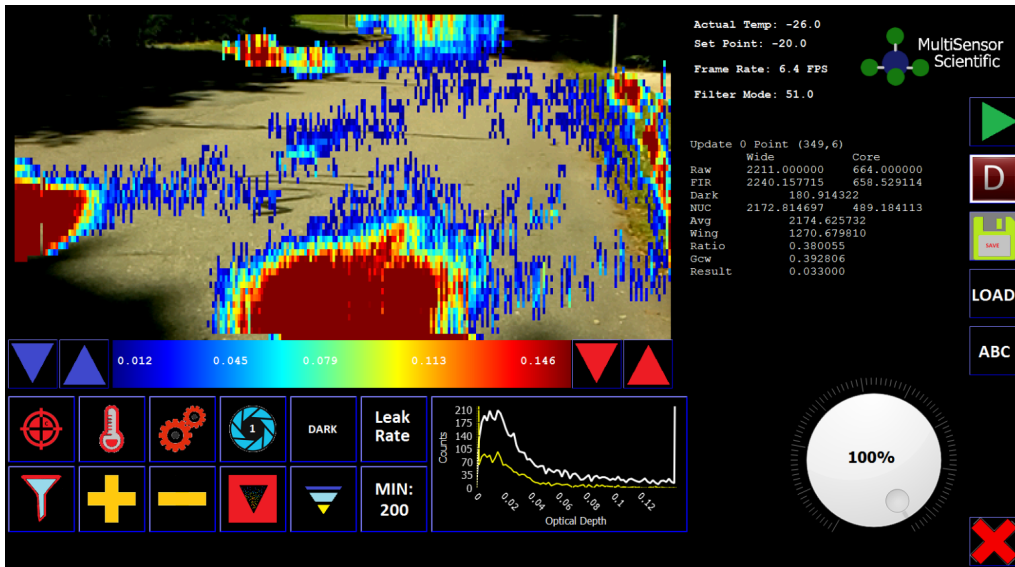
Figure 8. Photo of the MSS camera monitor pointed at a known leak. The gas can be seen escaping primary pathways including both the manhole in the center bottom of the image and a drain in the left, but also from cracks in the street and from the grass on the right side of the street.

Test Method 5: FLUXBar Plateau %Gas Measure

The FLUXBar was co-created by Audrey Schulman (HEET), Kevin Kelley (Eversource Gas), Dan Cote (Columbia Gas), Brian Ferri (Millibar Inc.), and myself during our preparation for this research (Appendix 1). It is a new technology and our

protocol (Appendix 2) may require some adaptation. After localizing the leak using a utility drill hole based protocol, the FLUXbar was firmly inserted into the drill hole directly over the suspected leak location (Figure 9). After hooking up the FLUXBar to the truck compressor and to a CGI, a timer was set to begin when the compressor air lever was turned on. The % CH4 was recorded every 2 min for a duration of 16min, on a data collection sheet by the utility crew together with a researcher overseeing data collection. This data was then fit to an exponential decay curve in order to predict the plateau or steady state % gas. This predicted plateau % gas is the proxy measure for leak volume used in this study.

In an effort to capture all data we might need to evaluate and test the operation of the FLUXBar, and to understand the leaks, we also took soil samples (2" x 10" cores) at most excavations directly over the leak location after the pavement was removed. We recorded soil moisture, and then later assessed soil density and porosity through weighing, drying, weighing again, then saturating the samples, and weighing again.
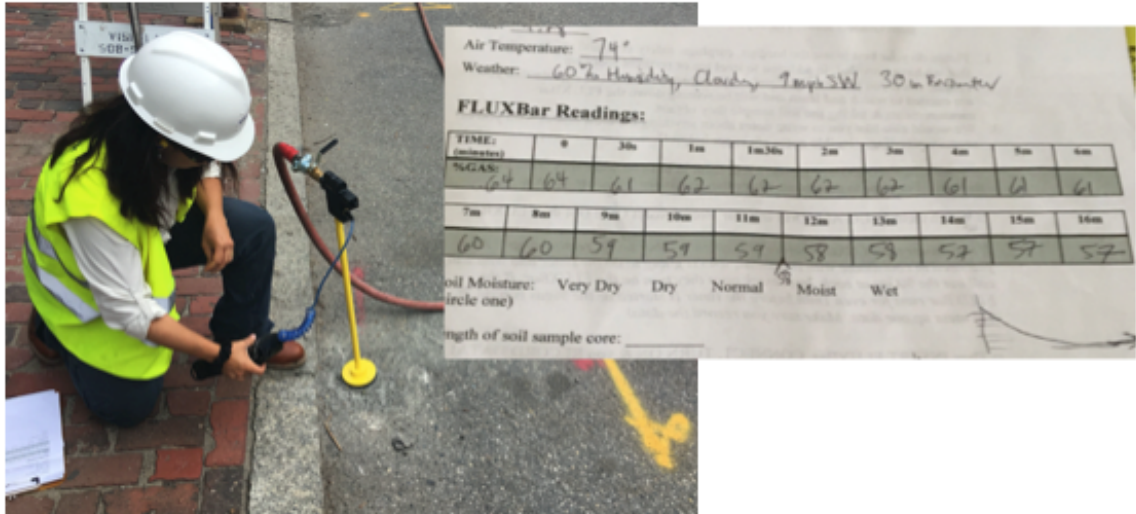
Figure 9. The FLUXBar in use and an example data sheet. The FLUXBar is hooked up to the truck compressor by the red hose and to a handheld CGI by the blue hose, and the CGI read is recorded every 30sec on the data sheet.

Other Methods

All methods assessed were directly compared to the Chamber Method to determine correlations between them. Calculation of correlation with r^2 and p values allowed determination of the relative success of each method at matching the chamber method in selecting and rank-ordering the leaks by leak volume. Additional analysis using the machine learning K_{MEANS} analysis algorithm in MatLab explored the weighting of multiple variables in a 'natural', machine driven clustering of studied leaks.

Qualitative & Collaborative Methods

Throughout the research process, relevant observations and feedback were recorded as qualitative data and used to inform assessment of the practicality, feasibility, and return on investment of all viable options.

Additionally, this qualitative data informed interactions between collaborators. This research required working closely with an unusually diverse team of gas utility executives and workers, natural gas measurement experts, scientists, activist volunteers, regulators, and funders. It is of note that coordinating this stakeholder ecosystem to work together towards the shared purpose of methane emissions reduction in the natural gas system was as essential to the research as the data collection and analysis described above, and that it was done using a combination of the leadership methods taught by Leith Sharp, Adrienne Maree Brown, Marshall Ganz, and Mothers Out Front.

A prioritization of careful listening, attention and adaptation to differences in language, and careful curating of all participants sense of security and safety in their participation allowed for the convening of traditionally opposing stakeholders. I strove to reduce risk, (economic, physical and social) for all involved and to find solutions that emphasized mutuality. Repeatedly re-centering collaborators through restatement of common ground and the use of stories of self, centered on our children, kept engagement and commitment high.

Chapter III

Results

The studied leak population replicated leak volume distributions found previously despite the more varied pipe material and pressure. I observed that %gas measures at a single leak vary over time in response to temperature and humidity. I also observed that within each leak, the emissions of gas per square foot shows a similar long tail distribution, with the viscous flux contributing the majority of emissions in comparison with the diffuse flux.

The results of the bar hole %gas measure was shown to be both non-replicable and not correlated with the chamber measure values of leak flux. The leak footprint, was, in contrast highly correlated with the measured leak flux, whether considering viscous flux, diffuse flux or both. The cavity ringdown spectrometer area under the curve method did improve the GPS location of the leak, but was not highly correlated with leak flux. The FLUXBar, used on a subset of the leak population, showed significant correlation with the leak flux despite a smaller sample size. The MSS camera, also used on a subset of the leak population, was unable to provide confirmed quantification numbers for this study but provided instructive visual evidence.

Leak Population Distribution & Leak Characterization Results

Our leak population included all leak prone pipe materials and pressures in the distribution system of Massachusetts with cast iron, bare steel, coated steel, plastic, and even the rarer wrought iron, in pressures ranging from 0.5 PSI to 99 PSI (Figure 10).
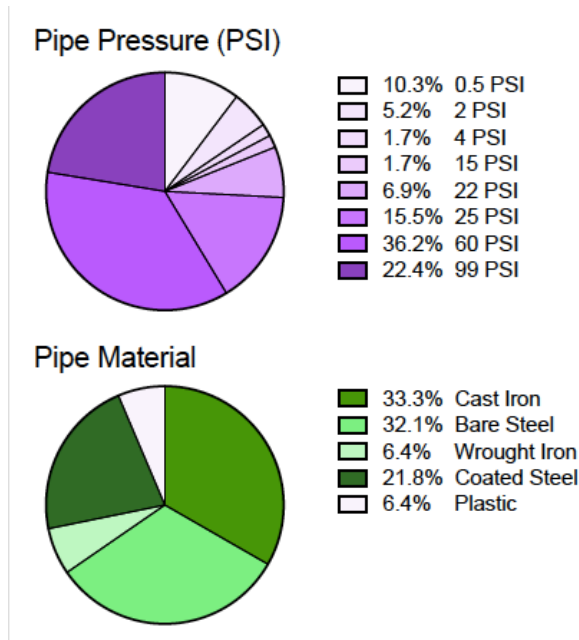
Figure 10. Pipe material and pressure of leak population studied.

Despite this varied material and pressure, the distribution of the volume of leaks fit well with the findings in the field (Hendrick et al., 2016), as 7% of the leaks had a total volume equal to 46% of the total volume of all leaks studied (Figure 11). Furthermore, the distribution of the volume of leaks replicates the heavy-tailed distribution found throughout methane emissions quantification research (Figure 12).

Hendrick Study
Emissions from Largest 7% of Leaks vs. Emissions from all other Leaks in Study

All Other Leaks 52%

Largest Leaks 48%

LVL Study
Emissions from Largest 7% of Leaks vs. Emissions from all other Leaks in Study

All Other Leaks 54%

Largest Leaks 46%

Figure 11. Replication of largest 7% of leaks emit half of total emissions.

Distribution of Total Flux for Leak Population

Total Flux (ft^3 CH4/day)

Figure 12. Frequency distribution of total flux for sample leak population.

While the distribution of emissions volume results replicated results found in other methane leak populations, I also collected data within the leaks themselves, on the distribution of methane across the leak footprint. This data collected through grid transect sampling across leaks allowed for a novel visualization of individual leaks at one point in time (Figure 13). The distribution of ppm gas measures across the foo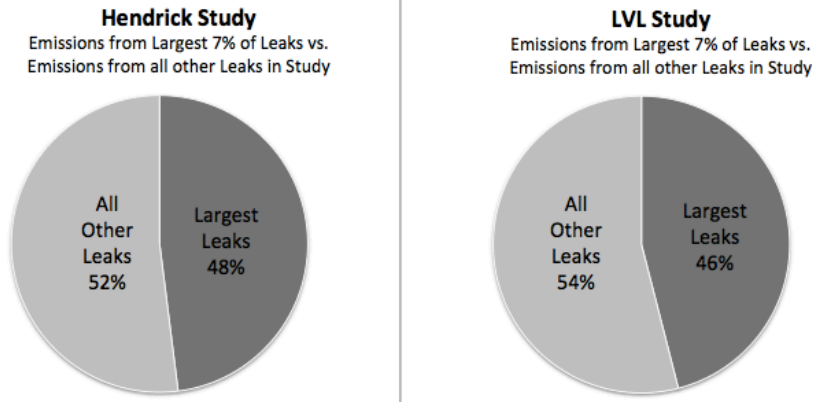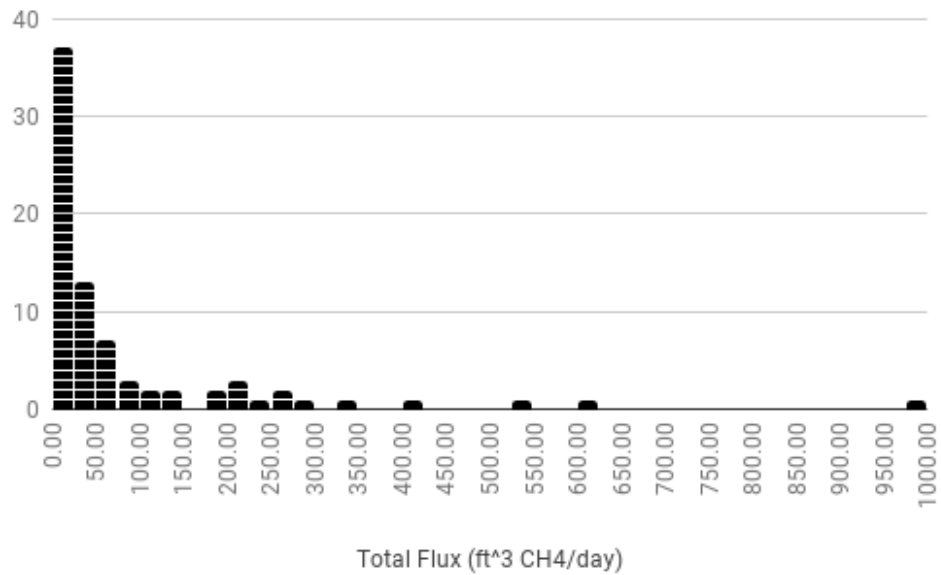tprint of the leak - within each leak evaluated, mirrored the heavy tailed distribution found between leaks in our leak population. Our standard chamber measure protocol used a CGI that captured gas emissions above the 0.05% gas or 500ppm threshold (viscous flux), but having visualized the widespread presence of gas below this threshold (Figure 13), we sought to directly measure this diffuse flux, expanding the sensitivity of the chamber measure. The additional measures of diffuse flux, below the 500ppm threshold, done on 23 of the leaks, were also found to follow a heavy tailed distribution both between leaks, and within leaks. The viscous flux, or flux above the 500ppm threshold, contributed the majority of the total flux, with the diffuse flux, or flux between background and 500ppm, contributing a fraction of the total emissions, despite covering a larger proportion of the footprint of the leak. The relationship between both viscous and diffuse flux with footprint area is consistent and the best-fit line is a power function (linear after log-log transformation). The r^2 of the viscous flux fit is 0.468 (n=33) and the r^2 of the diffuse flux fit is 0.793 (n=21) (Figure 14).
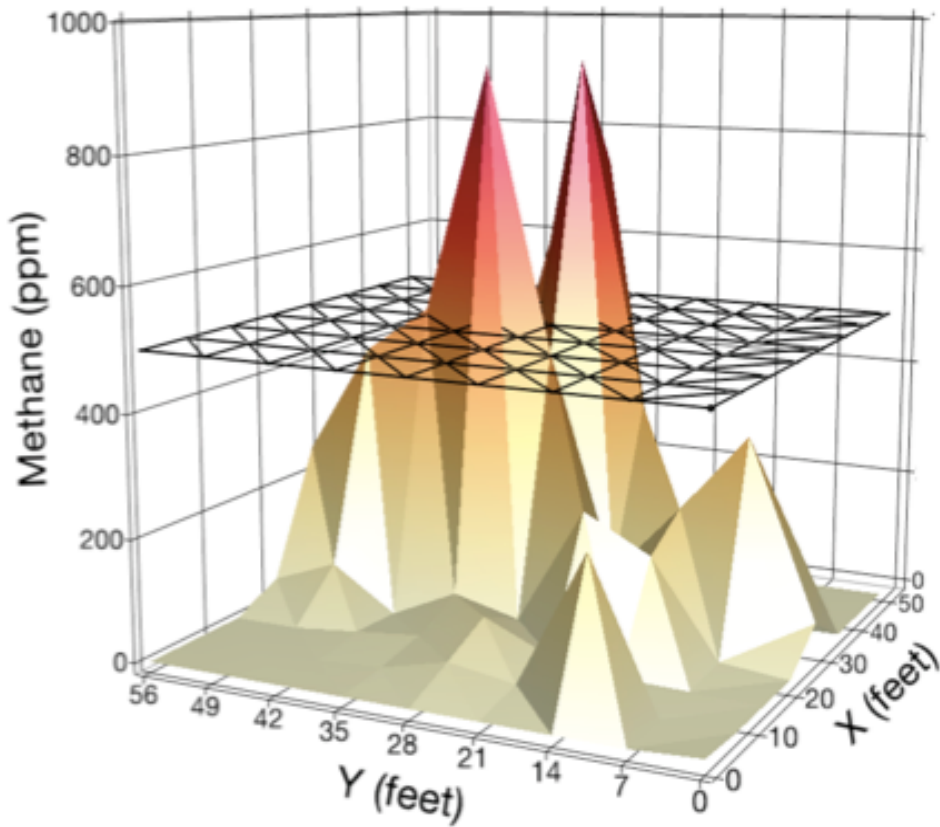
Figure 13. Example of direct sampled ppm CH4 at a single leak. The methane peaks above the 500ppm threshold grate are the viscous flux observed by the original chamber protocol, and the methane shown below the grate is the diffuse flux I was able to quantify through the use of the more sensitive Rover CGI.
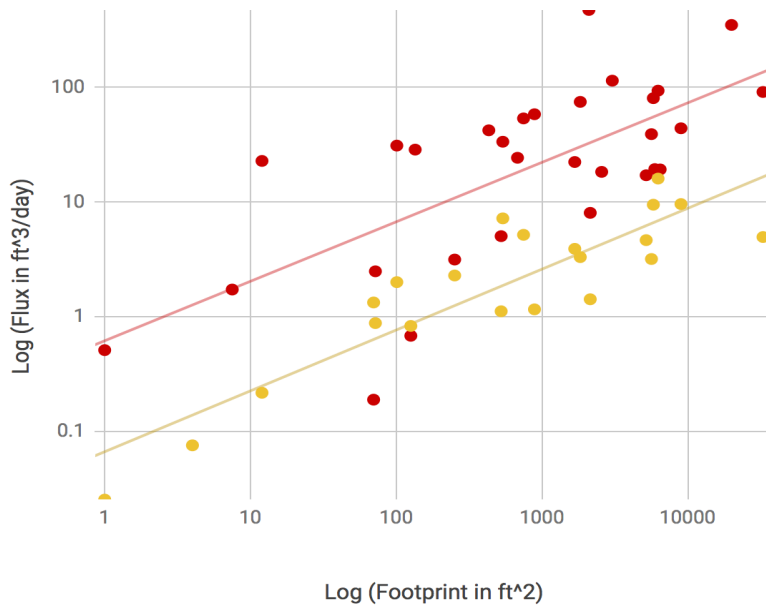
Figure 14. Log viscous flux (red) and diffuse flux (yellow) in relationship to log footprint area.

Finally, the results of the observation of a single leak over time were consistent with the widely understood influence of weather on %gas measures (Figure 15). As ambient air temperature rose, so did the %gas measure, with warmer temperatures occurring together with higher emissions of gas. As humidity rose, %gas fell, with high humidity entirely eliminating gas emissions. This reaffirmed the importance of always recording weather data when taking emissions measurements and scheduling gas emissions research to hold weather variables as constant as possible.
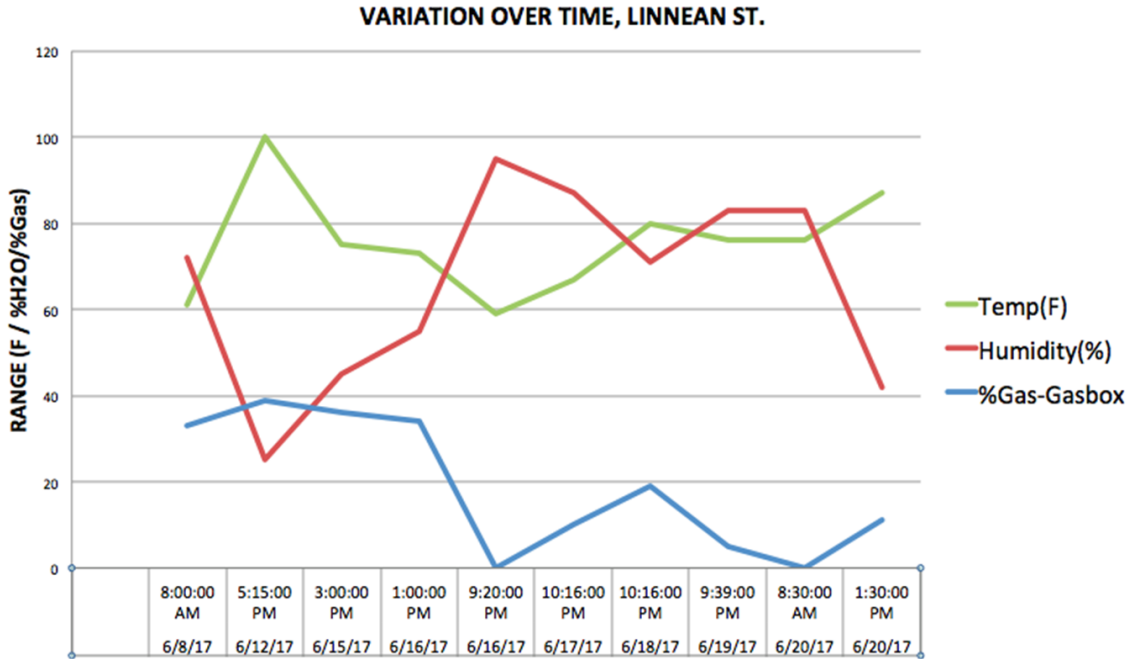
Figure 15. Leak variation in response to weather. The two %gas measurements that are at zero coincide with rain events, as can be observed by coinciding %humidity.

Correlation Analysis Results

The bar hole %gas measure was compared to the bar hole %gas measure, a comparison of the first and second times this measure was taken for the studied leak. These measurements were done by trained utility workers using the same CGI in the same location, yet there was no correlation ($r^2 = 0.06$, n=68, p=0.69) between the first measure and the second, repeated measure (Figure 16). While the time interval between the measures was variable, there was no change in this result when looking only at measures done with a shorter time interval vs. a longer time interval. During the monitoring of a single leak over time with a Sentry CGI, I observed that there is variability in response to temperature, humidity, and wind as expected, but also that there is variability in outcomes for this %gas CGI measure when the depth of the probe is

33

varied and when the duration of the reading is varied, necessitating a standard depth and standard reading time.
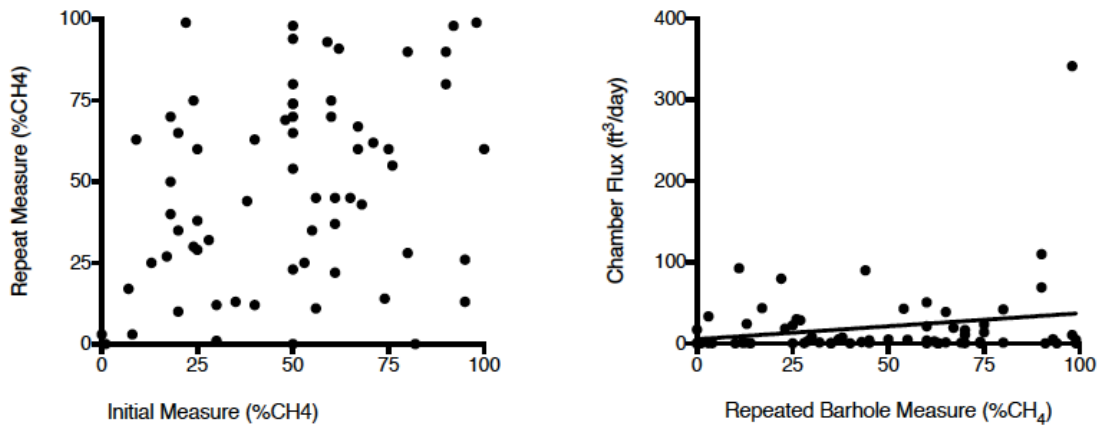
Figure 16. The bar hole %gas measure is not replicable and doesn't indicate LVLs. On left a comparison of initial bar hole measure to repeated bar hole measure, and on right the repeated bar hole measure vs. the total chamber flux.

There was also no correlation (r^2=0.008, n=68, p=0.45) between the repeated bar hole measure and the total chamber flux (Figure 16). The result was not different if the initial bar hole measure was used or if only the viscous flux was used. There was no variation in these results between utilities.

In contrast, the leak footprint measure was highly correlated with total chamber flux (r^2=0.862, n=67, p= 1.76E-23) and remained correlated when only viscous flux or only diffuse flux was compared (Figure 17). Leaks with large areas of their footprint outside of paved surfaces were observed to be slightly smaller than leaks of similar

volume but entirely under pavement, but this difference was not large and the correlation between leak footprint and leak total flux remained strong with and without these leaks.
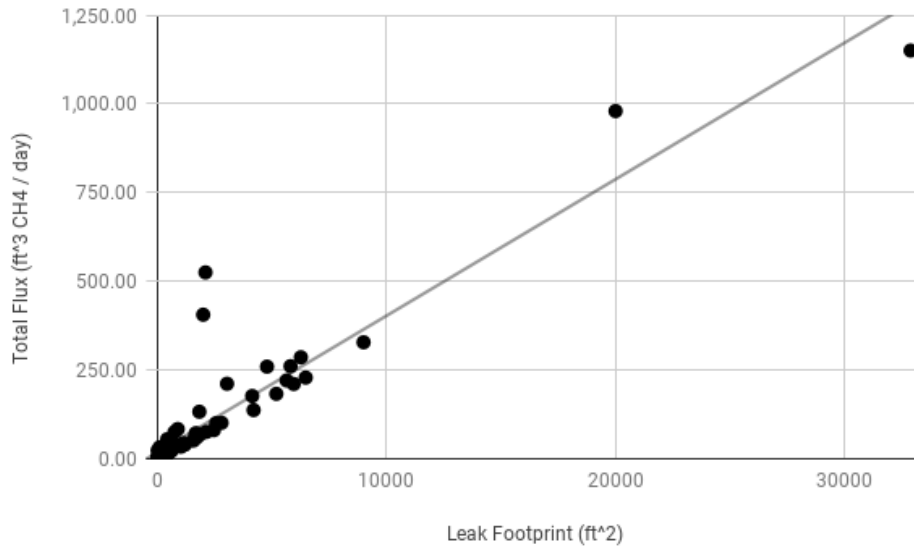
Figure 17. Leak footprint vs. total flux.

The cavity ringdown spectrometer results were varied. The averaging of multiple passes successfully improved the overlap between the recorded GPS of the spectrometer and the directly measured GPS during the leak survey. However the correlation (r^2=0.52, n=61, p=5.46E-11) between the area under the curve measure and the leak's total flux was not as strong as other methods (Figure 18). The selection of 14 leaks by choosing very large peaks from regional .kml files resulted in 3 errors, 3 Grade 3, and 8 leaks that were classified as Grade 1 or 2, and fixed immediately, not allowing for assessment of volume.
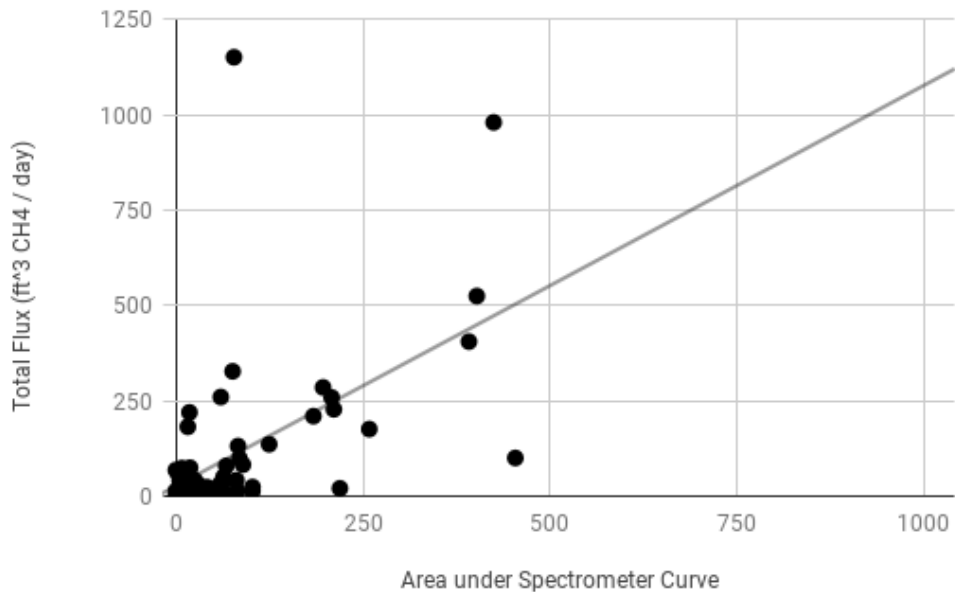
Figure 18. Area under the curve of cavity ringdown spectrometer vs. total flux.

The FLUXBar predicted plateau measure was correlated ($r^2 = 0.56$, n=28, p = 5.5E-06) with the Total Flux of the leak (see Figure 19) despite some variability in the implementation of a novel tool by the utility crews. One of the FLUXBars was damaged in the utility truck and though the utility crews reattached the standpipe and continued to follow the protocol, the results were consistently skewed, showing a dramatic drop in %gas that did not fit the single phase exponential decay curve shape of all other FLUXBar data. I confirmed that the loose connection and bent standpipe took in ambient air by duct taping the standpipe after an initial measure and repeating the measure. That tool was sent back to the manufacturer for repair and all data from the damaged FLUXBar was thrown out. Another test was thrown out because utility crew turned on a purger in an adjacent bar hole during the middle of the test. (A purger uses a strong

36

vacuum to clear out the gas under the street). Removing just three outliers improves the r^2 to 0.7, indicating the possibility that other variability could be the result of misuse of a novel tool.

Figure 19. The FLUXBar plateau vs. the total flux.

The soil samples collected at the time and location of the FLUXBar measure were found to be remarkably consistent in porosity and moisture. The fill used under streets and in gas pipe trenches is regulated and the pavement keeps the soil dry, so the variability I expected did not exist. No correlations were found between FLUXBar results and soil porosity or moisture measures.

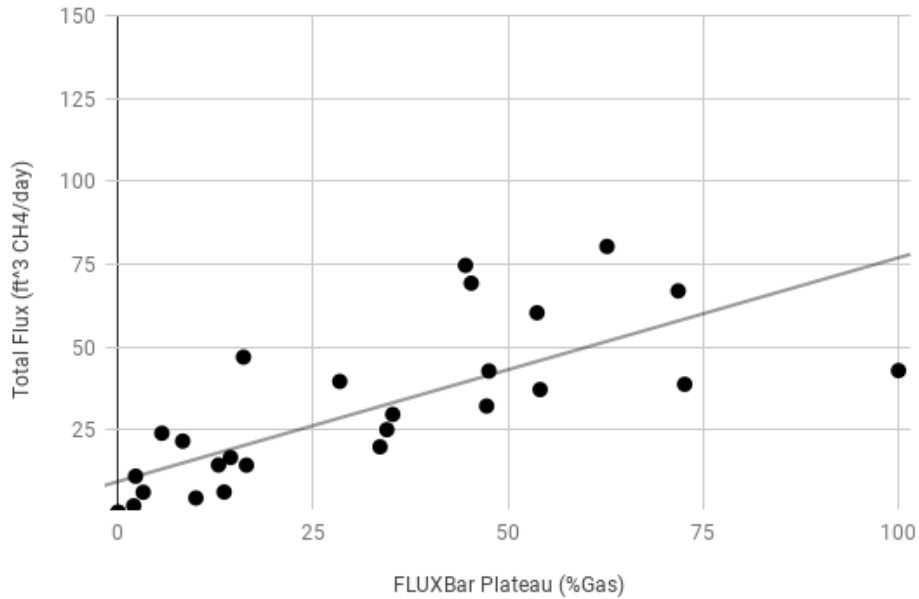The Multi Sensor Scientific Camera was used on a subset of the leaks studied and was enormously successful at visualizing the leaks. The images themselves helped increase the gas utility employees's understanding of these Grade 3 leaks. An opportunity to 'see' the gas flowing out of the ground was exciting after years of working with an invisible substance, and the workers were quickly able to match the images to their own experience and understanding of the behavior of escaping gas. Despite it's observed success as a proof of concept, and overlap with other measures, the camera is still in the process of developing accurate algorithms for determining volume from its images. We tested the camera's utility as a tool to confirm the repair of a leak by imaging before, during and after (Figure 20).

We also used the entire data set to run a Kmeans clustering analysis – a machine-learning algorithm that uses a large amount of computational power to group a set of data observations into clusters. The algorithm chooses the weight of different data categories through exploration of the relationships between the data. We did this to test whether such analysis might be useful to the utilities in categorizing leaks and it resulted in a division of the studied leaks into three clusters of very large, large, and small leaks that tracked with leak footprint and total chamber flux, consistent with the other analysis approaches (Figure 21).

Documentation of Leak Repair Success (Proof-of-Concept Results)
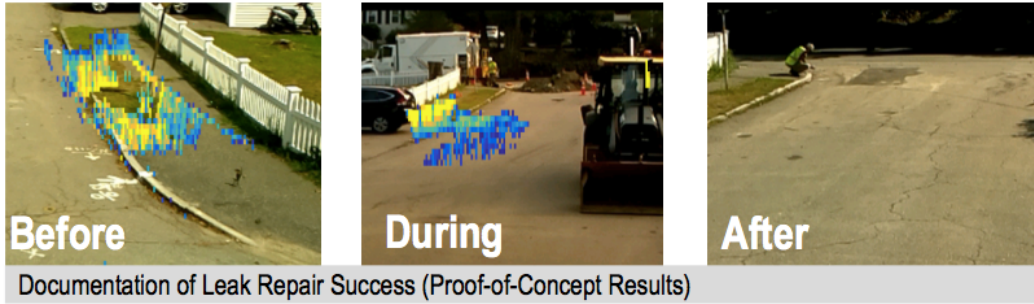
Figure 20. MSS camera images of a leak before, during and after repair. The image on the left shows the methane (CH4) leaking through the pavement, the middle image shows leaking methane on the day of the repair, and the last image shows the site the same day after the completion of the repair.
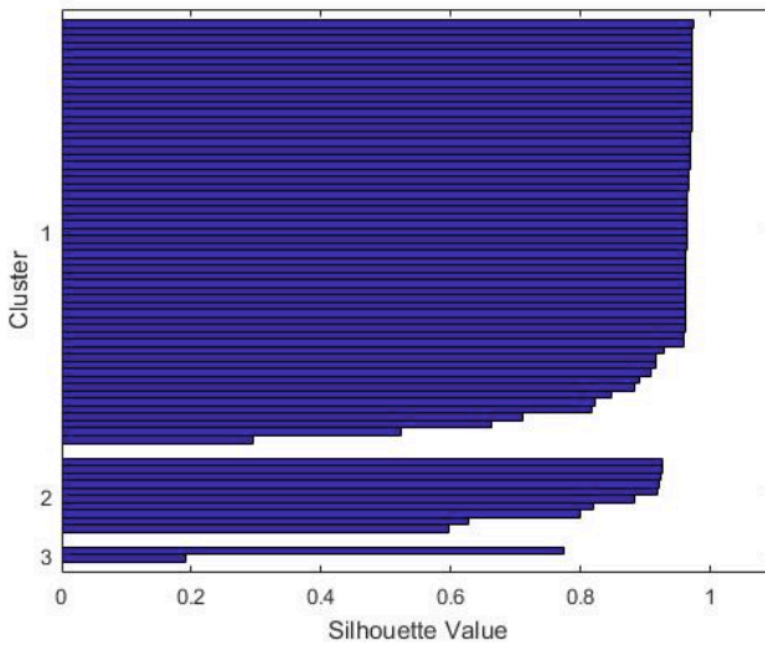
Figure 21. The output from kmeans analysis showing three clusters.

To conclude the data collection, we returned to each leak location to confirm that no gas remains after the repair. This process was not done with consistent time intervals or robust quantification such as chamber flux measures, as it was intended only as a confirmation of completion. Gas was found to be remaining or residual in the majority of locations across all three utilities. This final leak report was completed on 60 of the study leaks post repair (Figure 22) and there is no clear correlation between unrepaired leaks and pipe material, pressure, or other variables.
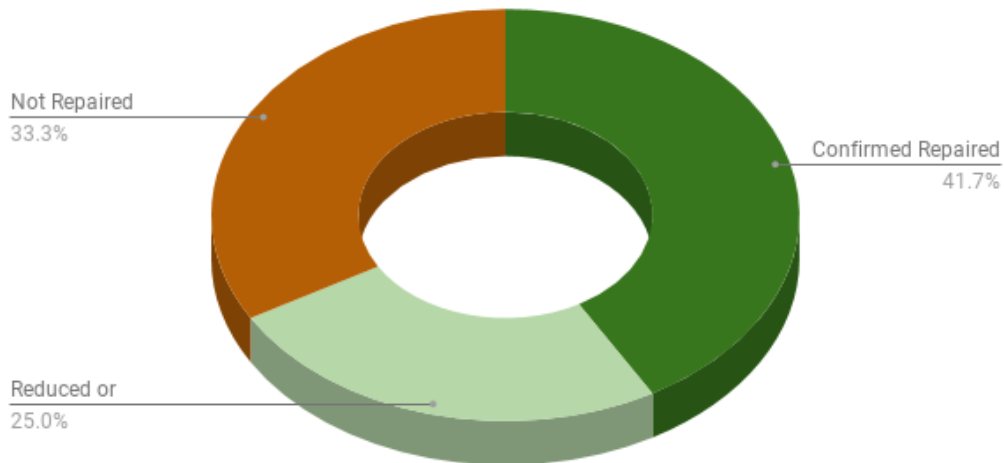
Figure 22. Post repair leak survey results. The section in orange, 'Not Repaired' had the same leak footprint as before repair, the 'Reduced or residual' had a smaller leak footprint than before repair, and the 'Confirmed repaired' had no gas present at the location of the leak repair.

The total annual emissions of the leaks that were verified completely repaired was equal to 1,613 (ft^3 CH_4 / day). This is an underestimate of the initial climate impact of this study, as there were additional methane reductions from the leaks reduced in size and repeat repairs are ongoing, with the intention of completion.

Collaboration Results

Directly resulting from the large stakeholder collaboration developed throughout this study, we were able to leverage the relationships and trust built, as well as the data gathered, to agree to a Shared Action Plan (Appendix 1). Presented to more than 300 attendees at MIT on October 3, 2017, this plan details a shift to leak footprint as the method of identification of LVLs, further use of the FLUXBar to verify emissions, an accelerated timeline for repair, and a system of verification, transparency of data, and annual reassessment to allow for a natural evolution of best practice as technology develops. The presence of multi-national gas utility company presidents and other executives, together with environmental activist leaders, scientists, technology and innovation leaders, interested legislators and scientists from NY and PA, and numerous representatives of MA state and local government including State Rep Lori Ehrlich, Attorney General Maura Healey, was a groundbreaking result.

This study led to a reopened hearing on the 'Environmentally Significant' leak regulation and, held to their commitment by their word alone, the utilities then jointly testified at the DPU with myself and other environmental scientists and activists, as well as jointly submitting comments (DPU 2017) with the Shared Action Plan. The participating executives from Columbia Gas had their flight cancelled the evening before

and together drove a rental car through the night to arrive bleary eyed, yet committed, to testify together with me at the hearing.

While the DPU ruling remains open in May of 2018, each of the utilities has held to their commitment on the Shared Action Plan and the footprint protocol has been standardized across utilities, the surveyors have been trained in the new protocol and are, as of April 2018, using the leak extent method to identify LVLs for accelerated repair.

Chapter IV

Discussion

This research confirmed the heavy tail distribution of leak volume despite including all leak prone gas distribution system pipe materials and pressures, and it demonstrated the inadequacy of the bar hole method for finding and prioritizing LVLs while successfully identifying alternate methods such as leak footprint and FLUXBar. The results clearly answer the research questions and match well with expected outcomes. In addition, the research was able to enhance the chamber method of leak flux measurement, and increase understanding of the physical character of gas leak emissions. Finally, the organizational and collaborative methods were highly successful in building an unusual coalition uniquely capable of answering these questions quickly and well - and maintaining commitment through the process of developing and implementing policy based on these scientific findings.

Leak Distribution and Leak Character

That a collection of leaks representing all pipes and pressures still demonstrated a heavy tail distribution was an expected outcome, as the same distribution has been observed across the natural gas system at many scales. Nevertheless, it was an important finding with clear policy implications, as it confirmed the potential to maximize methane emissions reduction per repair dollar spent. The wide variety of pipe material and pressure also allowed us to investigate the relationship between those variables and the

volume of leaks. While no statistically significant findings resulted, it was observed that the majority of leaked methane measured in the study was leaked from bare steel pipes. Some in the gas industry expected cast iron pipes would leak the majority of the gas. However, considering that steel pipes were more likely to be higher pressure and to have multiple holes vs. the joint leaks characteristic of cast iron, there is some physical logic to this observation. Further evaluation with a larger sample of leaks in cast-iron and steel pipes would be necessary to draw conclusions.

The exploration of individual leak character through visualization of individual gas leaks by grid transect sampling (Figure 14) provides a new perspective on the physical nature of underground gas leaks and informed my main research outcomes. It illustrates how, even at a frozen moment in time, small shifts in location can shift the result. This increases understanding of the barhole %gas outcomes. It also illustrates the limitations of the chamber method when done with a standard CGI and a threshold at 500ppm. While the peaks are the highest rate or flux of gas, or viscous flux, and contribute the majority of the total leak flux, adding the diffuse emissions below 500ppm, that were previously below our level of quantification, enhanced the chamber method. The chamber measure is a 'known underestimate' and this inclusion of the widely distributed but low emissions volume diffuse flux allows the measure to come closer to estimating the real total leak flux.

The relationships observed between the viscous and diffuse flux are consistent with regards to footprint and to each other, as expected, so the inclusion of the diffuse flux does not change the research outcomes, but does change the potential impact of repair of each leak. One further note is that the difference in r^2 values for the fit lines of

viscous and diffuse flux in relation to footprint make sense given the difference in range between diffuse and viscous flux (Figure 15). Diffuse flux has a fixed ceiling and is therefore constrained in a way that viscous flux is not and therefore variability is greater in viscous flux, as observed.

The secondary explorations of leak character increased understanding of the dynamic and complex phenomenon I was attempting to assess and helped in the acceptance of the results of this study. Further inquiry into the nature of volume distribution within leaks, and the variability of leaks over time, is warranted.

Methods of Identifying LVLs

While the chamber method was laborious, it's process and outcomes were exactly as expected, and the resulting data allow for the assessment of more time and cost efficient methods. The expansion of the chamber method to capture diffuse flux only strengthened this measures capacity to accurately define the flux of underground gas leaks and confirmed the relationships already observed.

Test Method 1: Bar Hole %gas. The finding of the non-replicable nature of the bar hole %gas measure, as used by the gas industry, went against some industry assumptions. When sharing this result with the utilities, I began with the presentation of variations in a single leak over time. This observation matched with their field experience and began by acknowledging the challenging combination of variables dealt with in attempting to assess underground gas leaks. Emphasizing that the %gas measure itself is not inaccurate – there is, indeed, the measured %gas at that location and moment that it is recorded. However, variation in the leak itself due to temperature, humidity, wind, and other

45

physical variables (as demonstrated by my individual leak over time observations), as well as human operator variation in the depth, duration, and location of the CGI probe, all combine to result in a measure with limited meaning with regards to leak volume.

This outcome has clear physical explanation, as the bar hole %gas reading is a measure of one point in time and space. A gas leak changes over both space and time – it is a dynamic and often physically diverse phenomenon. So it is not unexpected that a measure of %gas at a single point would be unable to indicate the volume, flux, or magnitude of the leak. Furthermore, in theory any gas leak, if measured in exactly the right spot, could give a 100% CH_4 CGI read. The CGI is a useful tool, as is the bar hole %gas measure. It is useful to determine the buildup of gas inside a manhole for example, to check the leak migration towards a home, or useful to check a valve box to ensure it is not leaking, but the %gas bar hole measure is not useful as an indicator of leak emissions, as it is currently performed, and should not be used for this purpose.

Test Method 2: Leak Footprint. The leak footprint, in contrast, is a measure that captures the physical impact of the volume of gas flow. Given that all underground gas leaks by definition have to diffuse through soil with it's varying permeability and tortuosity, it is physically intuitive why a larger leak would 'fill' the air space in a wider area, but it was initially surprising that the variation in soil didn't result in wider variation between leak total flux and footprint. The soil samples, however, illustrated that the variation in soil is limited, as most under pavement soil is dry fill, the specifications of which is currently regulated by the state. I did observe that a couple of leaks that were entirely found in bare soil or grass showed a smaller footprint to total flux ratio, but even with this variation the

correlation between footprint and leak flux remained. Given the low cost, feasibility, and simplicity of capturing the leak footprint, this finding is very exciting and can have immediate positive impact on methane emissions reduction efforts.

Test Method 3: Cavity Ringdown Spectrometer. While the simplest method proved the most effective in this study, the potential for technology such as the driveby spectrometers and MSS camera to greatly enhance speed and accuracy of leak identification and ranking remains large. Our attempt to reduce the location error associated with the cavity ringdown spectrometer was a step in the right direction, but the measure remained lacking in sensitivity. I believe further attempts are warranted given the high potential for improvements in both speed and reduction of human error.

Test Method 4: MSS Camera. The MSS camera also shows high potential as a single step LVL identification and quantification technology. Through the use of column density and adjustments for wind and background reflectivity, the MSS team hopes to be able to begin to provide accurate volume calculations in 2018, together with their images, thanks in part to the opportunity provided by the fieldwork on this study. The possibility of using this visualization aid to diagnose the challenges of leak repair by imaging the leak repair process is already submitted to funders as a next step.

Test Method 5: FLUXBar. The FLUXBar plateau measure was also correlated with leak total flux, as expected, but had a higher variability. As a first prototype, initial design and use challenges may have had some impact on the outcomes, and with improved

familiarity the accuracy of the measure in rank ordering LVLs may exceed that of footprint. However, given the FLUXBar protocol's need for a truck compressor and drill holes, it is not feasible for it to be used to identify leaks. Leak surveys are currently completed without a truck crew and therefore without a compressor. Using the FLUXBar to verify the selection of LVLs by an alternate method such as the footprint method is, however, a viable proposal. As a mechanical direct measure, the FLUXBar has some potential as a legal quantification method for carbon offset calculation and further use and study is warranted. All three utilities have ordered additional FLUXBar's for the 2018 season and will continue to use them to verify LVL identification done by leak footprint.

Leak Repair Success Rate

The repair success rate outcomes were unexpected. Having observed the crews verify a leak on the exposed pipe, repair it, and verify the repair, the success rate raises a number of questions. I do not know if the repair observed failed, if the leak repaired was not the leak producing the footprint observed on the surface, or if the process of excavation and repair had created a new leak. Given our definition of leak location, the locations that had an observable decrease in leak footprint, without going entirely away, would seem to indicate that there was more than one leak present to begin with and that the reduction in footprint correlated to the leak repaired, with the remaining footprint resulting from an additional unrepaired leak. The locations that remained the same may indicate that the repair either failed or the crews failed to identify the dominant leak causing the emissions. The locations that increased in methane are a confirmation of the risk of doing anything to aging infrastructure, and these leaks were predominantly cast

iron, the oldest and least flexible pipe in the ground. Truck crews suggest that the jostling created by the backhoe, excavation, and repair of one cast iron joint leak may loosen the aging jute seals on adjacent cast iron joints, creating new leaks. Further investigation is urgently needed to answer the questions this outcome raises.

Economic and Environmental Policy Impact

While the cheapest time to fix a leak is always the first time, the economic and environmental impact of all gas leak repair varies by the flux of the leak (Table 1), with economic and environmental benefits much higher for larger volume leaks. It is therefore in the interest of both the utility company and the ratepayer to prioritize LVLs.

When all studied leaks are confirmed completely repaired, the annual greenhouse gas impact will be equivalent to the annual emissions of 724 passenger cars (again using the 20 year impact of methane). Assuming these repairs hold for the remaining twenty years we will use the natural gas system (an optimistic estimate), the repair of the leaks studied has a twenty year impact equivalent to taking 15,000 passenger vehicles off the road. This population of leaks is not selected by volume and includes many very low volume leaks.

By instead targeting the largest, environmentally significant leaks among the more than16,944 Grade 3 leaks, the utility companies have an opportunity to maximize the return on investment to the ratepayer in addition to maximizing methane emissions reduction (Table 2) Using conservative estimates and utility provided data, the cost of repair for the largest leaks is recovered within the year of repair, making it an excellent investment for the ratepayer.

Table 1. Economic and environmental impact of studied leaks by footprint

Leak Footprint (ft²/day)	Average Flux (ft³ / day)	Cost of lost gas/year (wholesale price)	20 yr. CH4 Emissions Impact (# passenger cars annual emissions equivalent)
Less than 2,000	26	$28	55
Greater than 2,000	280	$307	591
Largest Two	800	$876	1687

Note: Footprint and flux numbers are from this research, wholesale price used is $0.30/therm, and EPA passenger car equivalent is 4.67 metric tons CO_2/vehicle/yr.

Using the direct top down measure of methane in the region's atmosphere (McKain et al., 2015), attributing 30% of that to distribution network leaks, and using a twenty year impact of methane, I estimated the greenhouse gas impact of our shared action plan. If enacted as intended, the methane emissions reduction will be equivalent to 2.7 million metric tons of CO2 over the next two years. This is equivalent to taking half a million gasoline powered passenger cars off the road and is equal to roughly 4% of the annual Massachusetts greenhouse gas inventory.

We do not know the actual total emissions of all underground natural gas leaks in Massachusetts, which is reflected in the gap between a bottom up estimate of a random population of leaks, as in this research, and a top down estimate from direct atmospheric measures. The truth is somewhere between the two, which still leaves us with an opportunity to reduce greenhouse gas emissions significantly by targeting the largest underground gas distribution network leaks.

Table 2. Return on investment.

(Top Down Estimation)	Utility Reported LUAF 2016	Harvard/BU Direct Measure
# of Grade 3 gas leaks at EOY 2016 (DPU 2017)	16,944	16,944
Total gas consumption 2016 (therms) (EIA 2017)	4,335,424,910	4,335,424,910
% lost gas (Total 2016 LAUF was 3.3%, with half unaccounted, half lost)	1.85%	2.7%
% allocated to distribution network leaks (30% of lost gas - conservative)	0.49%	0.81%
Therms total lost gas / year	71,534,511	35,116,942
Total Cost to fix all leaks (40,325 leaks – all grades, DPU)	$101,855,788	$101,855,788
Average repair cost per leak across state	$2,526	$2,526
Value of lost gas / year *Retail (residential) price: $1.20/therm*	$85,841,413	$70,233,884
Value of lost gas / year *Wholesale price: $0.30/therm*	$12,876,212	$10,535,083
AVERAGE LEAK: Value lost gas / year	$760	$622
SUPEREMITTER: Value of lost gas / year	$5,428	$4,441
AVERAGE LEAK REPAIR ROI / year	30%	25%
SUPEREMITTER REPAIR: ROI / year	215%	176%
SUPEREMITTER REPAIR: Time to recoup cost	6 months	7 months

As a result of the combination of the financial practicality, political pressure, and the trust built over the course of this research, the utilities have agreed to, and begun enacting, a Shared Action Plan (Appendix 3). The impact of this plan, when executed, will be to cut methane emissions from natural gas leaking under Massachusetts streets by half within three years (including a year of transition). This is equivalent, using a conservative top down estimation, to a decrease in the Massachusetts greenhouse gas

footprint of roughly 4%, almost equal to the emissions of all the state's stores and businesses. This would be a greenhouse gas reduction of unprecedented speed with co-benefits of reducing ratepayer cost, slowing the need for additional pipelines, and decreasing the risk of explosion. Given the immediacy of the climate challenge, and the mandate to act under the Global Warming Solutions Act, we should all, public and government, get behind the utilities on this action to ensure it is well and rapidly executed. This research provided the science needed to inform this policy and has additionally resulted in a mutual will to act.

Appendix 1

FLUXBar Informational Sheet

MiLLibar

INTELLIGENT VACUUM SOLUTIONS

1/4 TURN COMPRESSED AIR VALVE

VISUAL INDICATOR
MONITORS VACUUM FLOW AND LEVEL

DUAL LOCK
COMPRESSED AIR CONNECTOR

TUNED EXHAUST SILENCER,
QUIET OPERATION, 76 dB

CGI CONNECTOR

CGI CONNECTOR
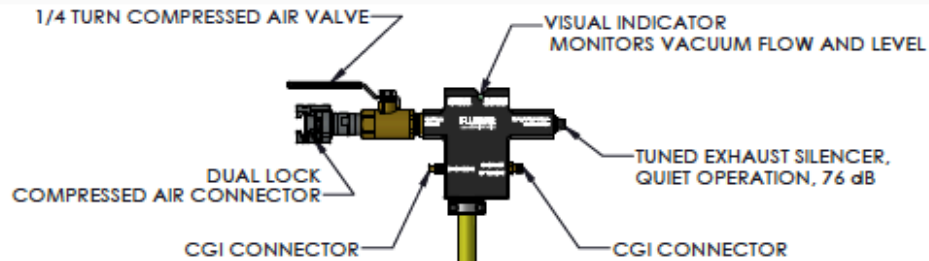
FLUXBAR
LEAK COMPARISON DEVICE

Note: Proper performance is achieved
when the supply pressure is between
80 and 120 PSI

Operating Instructions:

After locating the drill hole with the largest
percent gas based on CGI readings, then:

1. Connect compressed air line to Fluxbar
   using the dual lock quick connector.
2. Connect CGI to one of the two ports on
   the Fluxbar, block unused port.
3. Insert Fluxbar standpipe into drill hole
   over leak.
4. Rotate ball valve ¼ turn to turn on flow
   of compressed air to Fluxbar.
5. Apply downward pressure to compress
   foam, forming a seal around drill hole.
6. Record reading on CGI for 16 minutes
   at 2 minute intervals.

Sustained CGI reading ensures residual gas
has been drawn off.

*Note: Monitor visual indicator to confirm proper
function during test. With compressed air flowing, the
visual indicator should show green. If indicator turns red,
stop test and review troubleshooting procedures.*

HEIGHT STOP

FOAM SEAL

SUCTION PORTS
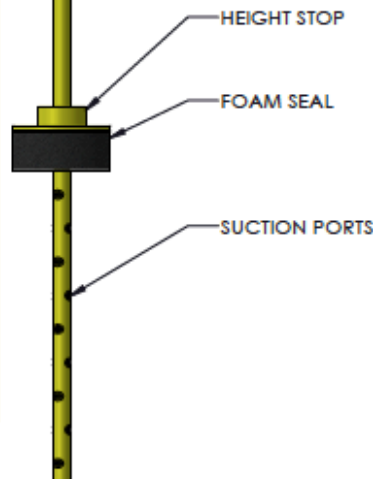
Millibar Inc. • 122 South St, Rear • Hopkinton, MA • 01748 • (508) 488-9870 • www.millibar.com

54

FLUXBar Study Protocol

Pilot Study FLUXBar PROTOCOL

Columbia Gas, Eversource & National Grid are all working together with a team of researchers this season to measure the volume of gas from Grade 3 leaks. Thank you for being part of the team. We are relying on your skill and accuracy!

(The normal operation of the FLUXBar is simpler. The method below is just for the pilot study).

- □ PINPOINT LEAK
  - ○ First bar the leak and identify the highest reading, making sure that drill holes are a consistent 6 to 12 inches from gas facilities.
  - ○ In order to be certain there's only one leak in the area, ensure that the barring extends far enough that the gas reads decline to 0. If there is more than one leak, please note it and the likely distance.
  - ○ Pinpoint the leak to no more than 18 inches from the adjacent drill holes.
- □ PLUG ALL Drill and Bar Holes except the one at the center of the leak.
- □ INSERT FLUXBar & CONNECT
  - ○ Follow all manufacturers recommended procedures related to the operation of the gas meter being used. Ensure the Sensit Gold, for example, is switched to "barhole setting".
  - ○ Connect compressed air line to FLUXBar using twist-claw connector (Check the compressor outlet pressure to confirm that the supply pressure is between 80 and 120 PSI.).
  - ○ Connect CGI to its port on the FLUXBar and close unused port.
  - ○ Insert FLUXBar standpipe into drill hole over leak.
  - ○ Apply downward pressure to compress foam height-stop, forming a seal around drill hole.
  - ○ Rotate ball valve ¼ turn to turn on flow of compressed air to FLUXBar.
  - ○ Confirm that indicator on top of FLUXBar is green. If indicator turns red, stop and reposition standpipe until it can be successfully operated in the green.
- □ RECORD DATA
  - • Start timer & take initial CGI reading.
  - • Take readings every 2 minutes for a period of 16 minutes. Record all readings. At the end of 16 minutes, take a final reading and record it.
- □ DISCONNECT, shut off air supply and secure FLUXBar.
- □ EXCAVATION – pavement removed.
- □ SAMPLE SOIL
  1. Use 2" Soil Auger to get a core sample directly over leak, ideally 10" or more.
  2. Hand to Research Team Rep for measurement and storage in pre-labeled plastic.
- □ EXCAVATION - complete, take a photo of exposed pipe & then repair leak.

Questions? Contact Brian Ferri of Millibar, the manufacturer at (508) 735 7203, or Audrey Schulman of HEET, the research nonprofit at (516) 900 4338, or Zeyneb Magavi, lead researcher at (617) 470 7682.

SHARED ACTION PLAN

IDENTIFICATION:
- Grade-3 Large Volume Leaks (Grade 3-LVL) determined using leak extent as sole proxy method, at least for the first year.
- Leak footprint evaluated with a consistent and defined method across utilities (i.e. either with CGIs/FIs, barhole or drillholes). Method to be decided by utilities.
- Leaks over 10 years old not prioritized for repair unless it is an LVL.

REPAIR:
- Leaks > 10,000 sq. ft. fixed within 12 months of determination by leak repair or main replacement.
- When 2,000 to 10,000 square foot leaks are discovered and verified, LDCs will endeavor to repair them within two years with the exception of inaccessible or challenging leaks which shall be repaired when access can be gained. If any 2,000 to 10,000 square feet leaks are on pipe that will be replaced through GSEP within five years, we will endeavor to eliminate the leak within three years.
- An LDC may choose to cap its environmentally significant leak repairs in any one calendar year at 7% of its total Grade 3 leak inventory as indicated in the previous year's final quarterly leak report on file with the Department of Public Utilities

VERIFICATION:
- For first year, at minimum, a statistically significant randomized sample of Grade 3-LVL leak repairs are FluxBarred prior to repair. Method of verification to be reassessed annually, see below.

REPORTING: (DPU)
- On GSEP reports, the number of known LVL leaks on each pipe segment.
- On Annual Service Quality reports the leak address, leak footprint, date leak was reported, LVL classification date and repair date.

REASSESSMENT:
- Methods and results reassessed and adjusted annually for at least five years by a panel made up of utilities, HEET research team, and a mutually agreed-upon independent third party to provide recommendations to DPU.

_____

COLLABORATION: An Initial Year Collaboration to support the transition. Leak addresses, reports and repair dates of all high emitters shared with HEET to allow for random survey of 100 leaks to ensure consistency across utilities. FluxBar data forms shared with HEET for the first year so we can provide any needed assistance. Fluxbar results will allow for apples-to-apples comparison between leaks, progress to be benchmarked and further learning to allow for more efficient allocation of resources.

References

Allen, D. (2016). Emissions from oil and gas operations in the United States and their air quality implications. *Journal of the Air & Waste Management Association, 66*(6), 549-575.

Balcombe, P., Anderson, K., Speirs, J., Brandon, N., & Hawkes, A. (2017). The natural gas supply chain: The importance of methane and carbon dioxide emissions. *Acs Sustainable Chemistry & Engineering, 5*(1), 3-20.

Balcombe, B., & Hawkes, A.. (2018). Characterizing the distribution of methane and carbon dioxide emissions from the natural gas supply chain. *Journal of Cleaner Production, 172*, 2019-2032.

Brandt, A., Heath, G., Kort, E., O'Sullivan, F., Petron, G., Jordaan, S., . . . Harriss, R. (2014). Methane leaks from North American natural gas systems. *Science, 343*, 733-735.

Brandt, A., Heath, G., & Cooley, D. (2016). Methane leaks from natural gas systems follow extreme distributions. *Environmental Science and Technology, 50*, 12512-12520.

Commonwealth of Massachusetts, Acts (2014) Chapter 149: *"An act relative to natural gas leaks."* Retrieved April 2017 from https://malegislature.gov/Laws/SessionLaws/Acts/2014/Chapter149

Department of Public Utilities (2016). 220 CMR 114.00: Uniform natural gas leaks classification. Retrieved April 2017 from http://170.63.40.34/DPU/FileRoomAPI/api/Attachments/Get/?path=16-31%2f1631A_Straw_Proposal_220CMR114.pdf

Department of Public Utilities (2017). Utility reported grade 3 leaks. Retrieved April, 2017 from https://www.mass.gov/orgs/department-of-public-utilities

Department of Public Utilities (2017). Docket 16-31 *"Joint comments of the researchers of the large volume leak study."* Retrieved November 2017 from http://170.63.40.34/DPU/FileRoomAPI/api/Attachments/Get/?path=16-31%2fResearchers_Joint_Comments_102.pdf

Energy Information Administration (2017), Form EIA-176, *"Annual report of natural and supplemental gas supply and disposition."* Retrieved October 2017 from https://www.eia.gov/naturalgas/annual/

Environmental Defense Fund Energy Exchange Blog (2017). *Super-emitters are real: here are three things we know*. New York: SyndiGate Media Inc. Retrieved from http://search.proquest.com.ezpprod1.hul.harvard.edu/docview/1860251904

Gallagher, M., Down, A., Ackley, R., Zhao, K., Phillips, N., & Jackson, R. (2015). Natural gas pipeline replacement programs reduce methane leaks and improve consumer safety. *Environmental Science & Technology Letters, 2*(10), 286-291.

HEET (2017), Mapped utility reported gas leaks by town. Retrieved October 2017 from https://www.heetma.org/squeaky-leak/natural-gas-leaks-maps/

Hendrick, M., Ackley, R., Sanaie-Movahed, B., Tang, X., & Phillips, N., (2016). Fugitive methane emissions from leak-prone natural gas distribution infrastructure in urban environments. *Environmental Pollution, 213*, 710-716.

Hendrick, M., Cleveland, S., & Phillips, N. (2017). Unleakable carbon. *Climate Policy, 17*(8), 1057-1064.

Hendrick, M., Phillips, N., Cleveland, S., Gopal, S., Hutyra, L., & Short-Gianotti, A.. (2016). *The Environmental and Political Ecology of Natural Gas,* ProQuest Dissertations and Theses.

Jackson, R., Down, A., Phillips, N., Ackley, R., Cook, C., Plata, D., & Zhao, K. (2014). Natural gas pipeline leaks across Washington, DC. *Environmental Science & Technology, 48*(3), 2051-8.

Johnson, D., Covington, A., & Clark, N. (2015). Methane emissions from leak and loss audits of natural gas compressor stations and storage facilities. *Environmental Science & Technology, 49*(13), 8132-8.

Johnson, M., Tyner, D., Conley, S., Schwietzke, S., & Zavala-Araiza, D. (2017). Comparisons of airborne measurements and inventory estimates of methane emissions in the Alberta upstream oil and gas sector. *Environmental Science & Technology, 51*(21), 13008-13017.

Lamb, B., Edburg, S., Ferrara, T., Howard, T., Harrison, M., Kolb, C., . . . Whetstone, J. (2015). Direct measurements show decreasing methane emissions from natural gas local distribution systems in the United States. *Environmental Science & Technology, 49*(8), 5161-9.

Maasakkers, J., Jacob, D., Sulprizio, M., Turner, A., Weitz, M., Wirth, T., . . . Fischer, M. (2016). Gridded national inventory of U.S. methane emissions. *Environmental Science & Technology, 50*(23), 13123-13133.

Mayfield, E., Robinson, A., & Cohon, J. (2017). System-wide and superemitter policy options for the abatement of methane emissions from the U.S. natural gas system. *Environmental Science & Technology, 51*(9), 4772-4780.

McKain, K., Down, A., Raciti, S., Budney, J., Hutyra, L., Floerchinger, C., . . .Wofsy, S., (2015). Methane emissions from natural gas infrastructure and use in the urban region of Boston, Massachusetts. *Proceedings of the National Academy of Sciences, 112*(7), 1941-6.

Miller, S., Wofsy, S., Michalak, A., Kort, A., Andrews, A., Biraud, S., . . . Sweeney, C. (2013). Anthropogenic emissions of methane in the United States. *Proceedings of the National Academy of Sciences, 110*(50), 20018-20022.

Mitchell, A., Tkacik, D., Roscioli, J., Herndon, S., Yacovitch, T., Martinez, D., . . . Robinson, A. (2015). Measurements of methane emissions from natural gas gathering facilities and processing plants: Measurement results. *Environmental Science & Technology, 49*(5), 3219-27.

Nisbet, E., Dlugokencky, E., & Bousquet, P. (2014). Atmospheric science. Methane on the rise--again. *Science, 343*(6170), 493-5.

NOAA, (2015). The NOAA annual greenhouse gas index; National Oceanic & Atmospheric Administration Earth System Research Laboratory. Global Monitoring Division, Boulder, CO, USA. http://www.esrl.noaa.gov/gmd/aggi/aggi.html

Phillips, N., Ackley, R., Crosson, E., Down, A., Hutyra, L., Brondfield, M., . . . Jackson, R. (2013). Mapping urban pipeline leaks: Methane leaks across Boston. *Environmental Pollution, 173*, 1-4.

Subramanian, R., Williams, L., Vaughn, T., Zimmerle, D., Roscioli, J., Herndon, S., . . . Robinson, A. (2015). Methane emissions from natural gas compressor stations in the transmission and storage sector: Measurements and comparisons with the EPA greenhouse gas reporting program protocol. *Environmental Science & Technology,49*(5), 3252-61.

Turner, A., Jacob, D., Benmergui, J., Wofsy, S., Maasakkers, J., Butz, A., . . . Biraud, S. (2016). A large increase in U.S. methane emissions over the past decade inferred from satellite data and surface observations. *Geophysical Research Letters, 43*(5), 2218-2224.

Von Fischer, J., Cooley, D., Chamberlain, S., Gaylord, A., Griebenow, C., Hamburg, S., . . . Ham, J. (2017). Rapid, vehicle-based identification of location and magnitude of urban natural gas pipeline leaks. *Environmental Science & Technology, 51*(7), 4091-4099.

Worden, J.R., Bloom, A., Pandey, S., Jiang, Z., Worden, H.M., Walker, T., Houweling, S., & Rockmann, T.. (2017). Reduced biomass burning emissions reconcile conflicting estimates of the post-2006 atmospheric methane budget. *Nature Communications, 8*, 2227.

Yacovitch, T., Herndon, S., Roscioli, J., Floerchinger, C., McGovern, R., Agnese, M., . . . Kolb, C.. (2014). Demonstration of an ethane spectrometer for methane source identification. *Environmental Science & Technology, 48*(14), 8028-34.

Zavala-Araiza, D., Lyon, D., Alvarez, R., Palacios, V., Harriss, R., Lan, X., . . . Hamburg, S.. (2015). Toward a functional definition of methane super-emitters: Application to natural gas production sites. *Environmental Science & Technology, 49*(13), 8167-74.

Zavala-Araiza, D., Alvarez, R., Lyon, D., Allen, D., Marchese, A., Zimmerle, D., & Hamburg, S. (2017). Super-emitters in natural gas infrastructure are caused by abnormal process conditions. *Nature Communications, 8*, 14012.