August 16, 2023

US Department of Transportation
Docket Management System
West Building, Ground Floor, Room W12-140
1200 New Jersey Ave., SE
Washington, DC 20590-0001

Attention: Docket No. PHMSA-2021-0039

Re: In the Matter of the Gas Pipeline Leak Detection and Repair Notice of Proposed Rulemaking 49 CFR Parts 191, 192, and 193, Comments of The Northeast Gas Association to PHMSA Notice and Request for Revision.

Via Email

Dear Sir or Madam:

The Northeast Gas Association[1] ("NGA") respectfully submits the following comments and request for revision on behalf of our natural gas local distribution company members ("NGA LDCs") in response to the above referenced Notice.

PHMSA proposes regulatory amendments that implement congressional mandates in the Protecting our Infrastructure of Pipelines and Enhancing Safety Act of 2020 ("Pipes Act of 2020") to reduce methane emissions from new and existing gas transmission pipelines, distribution pipelines, regulated (Types A, B, C and offshore) gas gathering pipelines, underground natural gas storage facilities, and liquefied natural gas facilities. Among the proposed amendments for part 192-regulated gas pipelines are strengthened leakage survey and patrolling requirements; performance standards for advanced leak detection programs; leak grading and repair criteria with mandatory repair timelines; requirements for mitigation of

[1] NGA is a regional trade association that focuses on pipeline safety and safety culture, education and training, technology research and development, operations, planning, and increasing public awareness of natural gas in the Northeast U.S. NGA supports a culture of pipeline safety and environmentally responsible energy delivery practices. NGA represents natural gas distribution companies, transmission companies, liquefied natural gas suppliers and associate member companies. Its member companies provide natural gas service to 14 million customers in 9 states (CT, MA, ME, NH, NJ, NY, PA, RI, VT).

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emissions from blowdowns; pressure relief device design, configuration, and maintenance requirements; and clarified requirements for investigating failures. Finally, PHMSA proposes expanded reporting requirements for operators of all gas pipeline facilities within DOT's jurisdiction, including underground natural gas storage facilities and liquefied natural gas facilities. NGA supports initiatives that further enhance pipeline safety value including broader industry recognition and incorporation of operating practices that support managing and reducing methane emissions risk as a component of pipeline safety.

NGA continues to work collaboratively with the American Gas Association ("AGA"), American Public Gas Association ("APGA"), Interstate Natural Gas Association of America ("INGAA"), American Petroleum Institute ("API"), GPA Midstream, and American Fuel & Petrochemical Manufacturers ("AFPM") (jointly "the Associations") and other participating organizations in developing Joint Industry Comments supported by a broad spectrum of stakeholders from across the industry. NGA supports these comments and offers the following additional comments for consideration. The comments submitted herein build upon the Associations comments focusing on proposed code sections that will have substantial regional Local Distribution Company ("LDC") impacts for NGA members and as such require further clarification for adoption and/or revisions to achieve intended goals of maximizing public safety value while supporting a practical focus on methane emission reductions.

General Comments:

1. Leak Detection and Repair Final Rule Proposed 6-Month Effective Date and Management of Change

PHMSA proposes only a 6-month effective date for the provisions within the NPRM. The proposed requirements include a broad range of changes to operator's procedures and will result in substantial management-of-change process considerations for data collection practices, work management systems, information technology systems, equipment, staffing, training, bargaining unit contract negotiations/agreements and Operator Qualification ("OQ") programs. Operators will need significantly more than 6 months to take all the necessary actions for compliance. These changes are comprehensive, for example, will require a restructuring of how patrols and surveys are performed in the natural gas industry, potential restructuring of previously approved rate-based pipe replacement programs and how leaks are determined and ultimately addressed. Proposing a uniform effective date of six months is not reflective of the complexity of various components of the proposal and does not address the myriad of management-of-change considerations necessary to ensure sustainable results the proposal is intended to provide.

NGA is supportive of a logical phase-in approach to the final rule with effective dates for different provisions within the rule based upon the proposed changes in each Subpart within a 3-year glidepath. While some specific elements of the proposal may be implemented within 6 months, some Subparts warrant a 1-year, 18-months, or longer timeframes based on the significance of the needed modifications to an operators' training, OQ, leak management, data collection, reporting systems, procurement, standards manuals, jurisdictional rate agreements etc.

Implementation timeframes will vary as the complexity is commensurate with the nature of organization specific assets and operations. Operators need sufficient time to develop management of change plans that will provide a roadmap addressing final rule requirements. The complexity of these changes to specific operations varies greatly based on the specific regulation that is being added or changed. NGA respectfully requests that the final rule feature effective dates that are practical and reasonable to facilitate sustainable management-of-change and to ensure a compliance glidepath that meets the intent of the proposal. Operators cannot begin implementation efforts until they know the exact requirements in the Final Rule. Operators cannot speculate how the requirements will be modified throughout the rulemaking process and, therefore, do not change procedures or operating policies based on the NPRM.

If a 36-month phase-in glidepath is not acceptable to PHMSA, while not desirable, at a minimum, NGA is recommending a Stay of Enforcement be considered for a period of 36 months following final rule effective date(s) to allow operators adequate time to implement changes in a manner that will maximize compliance. In consideration of a 36 month Stay, operators would agree to develop and implement a Leak Detection and Repair ("LDAR") Management of Change Compliance Workplan ("MOC Plan") within 90 days of the publication of the final rule. The plan would include detailed analysis of organization specific impacts, training, OQ implications, O&M Plan revisions audit and QA/QC Plan revisions, contractor training and qualification, DIMP/TIMP plan revisions contractual and supply chain considerations and cost recovery rate plan revision considerations. The proposed MOC Plan would be subject to review upon request.

NGA also recommends that PHMSA align the effective date of the final rule with the calendar year, January 1, versus time after the final rule publication. Leak surveys are not simple week-long, month-long, or seasonal initiatives. They are complex year-long endeavors that involve significant planning. Modifying leak survey cycles should not be changed in the middle of the year. This would require operators to shift their program in the middle of a cycle of a recurring year long process. Changing survey equipment, leak survey frequencies, how patrols and surveys are performed, and IT systems, and having to train and qualify all the new personnel on these new requirements in the middle of an active leak survey year will cause unnecessary confusion. The effective date for the final rule should therefore occur at the start of a calendar year in order to ease transition and enable operators to submit accurate data to PHMSA on their annual reports.

In summary, taking a *"one size fits all* "implementation approach with arbitrary, policy driven implementation dates does not address the disproportionate operational impacts these sweeping changes represent to our members, particularly within the northeast region. Considering specific regional variables such as the total population of legacy pipe materials identified for replacement and the associated regional complexity of executing work - permitting requirements and local jurisdictional resistance to allowing work on pipelines, state commissions re-thinking rate case recovery options due to policy decarbonization pressure etc. all need to be carefully integrated into each operator specific LDAR MOC Compliance Workplan. NGA strongly supports the Associations recommendation that PHMSA provide a three-year effective date of the final rule running from the first day of the calendar year.

2. Regulatory Overlap; Coordination and Consideration of Existing and Proposed Jurisdictional and Other Federal Regulatory Requirements

Natural gas and the extensive infrastructure network that supports it has been a cornerstone of America's energy economy for more than a century and will be needed into the future. Today, hundreds of millions of Americans rely on natural gas infrastructure and the energy it delivers to heat their homes, power their businesses, and manufacture goods. Policymakers' increased emphasis on climate change and reducing emissions has complemented the natural gas utility industry's focus on safety and reliability and therefore, enabled a steep decline in methane emissions through pipeline replacement and modernization efforts. The collaboration of policymakers with parallel goals of infrastructure modernization and resulting emission risk reductions is best summarized in the 2020 NARUC report Natural Gas Distribution Infrastructure Replacement and Modernization: A Review of State Programs[2].

NGA and our members are committed to working with policymakers in applying a *good science common sense approach* to reducing GHG emissions through smart innovation, new and modernized infrastructure, and advanced technologies that maintain reliable, resilient, and cost-effective energy service choices for consumers. In collaboration with policymakers and regulators, NGA members continuously invest in the modernization of the northeast regional natural gas delivery infrastructure to distribute safe, reliable, and cost-effective energy in an environmentally responsible manner. Methane emissions from natural gas distribution systems across the country have declined by 70 percent from 1990 – 2021.[3] The data reflects the work NGA member gas utilities have been doing to modernize their systems and implement leading practices.

NGA understands PHMSA's position to address aspects of the Pipes Act of 2020 and where reasonable, enhance existing pipeline safety regulations to address emission risks as well as

[2] National Association of Regulatory Utility Commissioners (NARUC) Report January 2020
[3] *See* 2023 Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020 (April 15, 2023) (2022 GHGI).

public safety risk. Several of PHMSA's proposals conceptually overlap with existing industry voluntary programs (e.g., EPA STAR Program) as well as fundamental regulatory requirements of EPA in 40 CFR Part 98 Subpart W.

Further complicating the federal layers of regulation regarding existing and emerging emission monitoring and mitigation regulations are recently enacted state jurisdictional requirements such as the New York State Department of Environmental Protection Air Pollution and Control Regulatory Revisions NYSDEC Rule 203, in Massachusetts, 220 CMR 114.00 Uniform Natural Gas Leaks Classification and recently enacted statutes in New Jersey, Section 14:7-1.19 - Gas Leak Classification and Repair just to highlight three northeast regional requirements.

PHMSA has recognized the importance of regulatory coordination as industry and policymakers alike pursue parallel goals to minimize greenhouse gas emissions while ensuring pipeline safety goals are achieved. For example, PHMSA proposes to exempt pipeline compressor stations from leak repair, survey, and ALDP obligations to the extent they are subject to EPA regulations under the Clean Air Act. NGA agrees with the logic in minimizing overlap of regulatory requirements where these requirements have similar intent to extract the greatest degree of public safety value and to avoid unintentional conflicting requirements.

However, PHMSA has not applied this logic consistently throughout the proposal which will ultimately result in duplication of monitoring, repair, and reporting requirements. Similarly, these duplicative, non-value-added regulatory requirements will only serve to add additional confusion and unnecessary cost burdens to the consumer. A wholistic end-to-end cost assessment associated with these compounding regulatory requirements has not been adequately captured in the Proposal Regulatory Impact Analysis ("PRIA") and as a result, total cost implications are misleading. A key overall safety value consideration was overlooked in the PRIA including analysis of the end-to-end carbon footprint of proposed regulatory changes. For efficiency and consistency purposes, PHMSA should also consider incorporating facilities that are subject to these confounding federal and state regulations in an expanded section 192.703(d) exception. Similar logic in the 192.703(d) exception should also apply to distribution facilities such as LNG peak shaving plants, city gate and pressure regulation stations already incorporated in EPA and state regulatory mandates.

Last, operators should not be required to create a new program in compliance with PHMSA's leak detection and repair requirements only to pivot to the EPA requirements when they are finalized. This position is not reasonable, cost-effective, or practical. Instead, the agency should provide a three-year effective date for the final rule in this proceeding. A longer effective date would allow those facilities that would otherwise be accounted for by the proposed expanded section 192.703(d) referenced above to accommodate any delays in finalizing the EPA rule and minimize duplicative efforts.

If PHMSA proceeds with requiring operators of these facilities to comply with the Final Rule first and then subsequently Quad-Ob ("OOOOb") or Quad-Oc ("OOOOc"), the agency will need to incorporate these costs into its Final Regulatory Impact Analysis. In the PRIA, PHMSA examined these costs but framed them up as a regulatory alternative that the agency chose to not select.[4] This is confusing because in the NPRM, the agency has clearly chosen to proceed with applying its proposed requirements to facilities subject to OOOOb or OOOOc, if the EPA rules are not finalized at the time of PHMSA's publication.[5] The agency's estimate of the costs of eliminating the exception are $11.9 million per year. However, it is not clear if that cost estimate also included the effort to move these facilities to an EPA directed program once the OOOOb and c rules are finalized. In summary, PHMSA's incorporation of environmental protection jurisdiction in this proposal will result in unaccounted complexity due to lack of synchronization with other emerging federal regulations unless logic is incorporated in the final rule that allows for exceptions for those facilities that must conform with a multitude of confounding requirements.

3. Notice of Proposed Rulemaking (NPRM) Code Section Comments

3.1 Leak Definition, Grading and Repair

Leak or Hazardous Leak - PHMSA's Proposed Definition of a Leak is Overbroad and Inconsistent with Section 113 of the PIPES Act of 2020.

PHMSA proposes to define both leaks and hazardous leaks as "any release of gas from a pipeline that is uncontrolled at the time of discovery and is an existing, probable, or future hazard to persons, property, or the environment, or any uncontrolled release of gas from a pipeline that is or can be discovered using equipment, sight, sound, smell or touch."[6] The agency proposes to treat all leaks as hazardous and apply this new definition across all Part 192 subparts with the exception of the underground natural gas storage requirements (section 192.12) and the integrity management requirements (subpart O and P).

NGA contends not all leaks are hazardous. Treating all leaks as hazardous dilutes the importance of a prompt response when there is an immediate risk to life or property. Congress clearly acknowledged the existence of <u>non-hazardous</u> leaks in section 113 of the PIPES Act. Congress directed PHMSA to focus its leak detection and repair programs on leaks that are "hazardous to human safety or the environment" or "have the *potential* to become explosive or otherwise hazardous to human safety."[7] Congress also recognized that some "leaks [are] so small that

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[4] PRIA, at 7 ("In the event EPA does not finalize the proposed requirements, PHMSA *could* proceed with setting equivalent requirements for gas transmission compressor stations and gathering and booting stations by eliminating the exemption"). *See also,* PRIA at 20 ("Although PHMSA assessed an alternative where no such exemption would be provided, PHMSA did not propose that alternative to avoid duplicative regulation of those facilities.")
[5] 88 Fed. Reg. 31,890, at 31,939; *See also,* 88 Fed. Reg. 31,939, fn. 245.
[6] Proposed 192.3.
[7] 49 U.S.C. § 60102(q)(2)(B)(i)-(ii).

[they] pose no potential hazard" and therefore do not need to be repaired immediately.[8] PHMSA's proposal implied or otherwise, to treat *all* leaks as hazardous, is not consistent with this language.

PHMSA's Proposed Definition of a Leak is Also Contrary to PHMSA's Well-Developed Position on Hazardous Leaks.

The agency asserts in the NPRM that its regulations have lacked "meaningful guidance regarding which leaks are hazardous"[9] which may be misleading. Since 2009, PHMSA has defined a "hazardous leak" as "a leak that represents an existing or probable hazard to persons or property and requires immediate repair or continuous action until the conditions are no longer hazardous."[10] PHMSA has also encouraged gas transmission operators to use this definition.[11] The agency included a definition of leaks in the annual report instructions ("unintentional escapes of gas from the pipeline that are not reportable as incidents under section 192.3.") and for years, applied it to transmission operators.[12] The agency has consistently stated in guidance starting in 1972 that while hazardous leaks must be repaired promptly, the decision as to which leaks are hazardous, depends on the nature of the operation and local conditions.[13] The agency has acknowledged that the "nature and size of the leak, its location, and the danger to the public are among factors that must be considered by the operator"[14]

PHMSA may not have completely considered the impact that the conflation of these two definitions would have on the tracking and trending of leak data by individual operators and across the industry. Any change to definitions in Part 191 or section 192.3 must be mirrored in the instructions for §§ 191.11 and 191.17 annual reports.

[8] The congressional mandate for advanced leak detection technologies requires a schedule for repairing each leaking pipe "***except a pipe with a leak so small that it poses no potential hazard…***" 49 U.S.C. § 60102(q)(3)(A)(iii)(emphasis added).
[9] 88 Fed. Reg.at 31,916.
[10] 49 C.F.R. § 192.1001; Pipeline Safety: Integrity Management Program for Gas Distribution Pipelines, 74 Fed. Reg. 63,906, 63,934 (Dec. 4, 2009).
[11] PHMSA acknowledged in its Operations and Maintenance enforcement guidance that "while this definition is only applicable to distribution systems, it may provide guidance for defining hazardous leaks." Operations and Maintenance Enforcement Guidance, at 92.
[12] Instructions for Form PHMSA F-7100.2-1 at 14.
[13] PHMSA Letter of Interpretation, PI-72-0109 (Aug. 4, 1972). This interpretation is also cited in the agency's PHMSA Operations and Maintenance Enforcement Guidance which has been in effect since 2010. *See* Operations and Maintenance Enforcement Guidance, at 92.
[14] *Id.*

Recommended Definition of a Leak

PHMSA's starting point for redefining a leak should be its existing definition and the statutory mandate Congress enacted. Congress directed PHMSA to identify, locate and categorize leaks that are:

1) Hazardous to human safety or the environment; or

2) Have the potential to become explosive or otherwise hazardous to human safety.[15]

NGA recognizes that PHMSA has defined a leak as "an unintentional escape of gas from the pipeline" for years in the annual report instructions. With that background and the text of the statute in mind, NGA supports the following enhanced definition of a leak:

> ***Leak*** **means any unintentional release of gas, detectable by equipment, odor, sight or sound, from a pipeline or structure that is designed to transport, deliver, or store gas.**

Section 113 of the PIPES Act of 2020 clearly acknowledges the existence of non-hazardous leaks (e.g., "potential to become…hazardous", "leak so small that it poses no potential hazard," etc.). Furthermore, a small and unquantified environmental harm is not consistent with PHMSA's historical definition of "hazardous": *an existing or probable hazard to persons or property [requiring] immediate repair or continuous action until the conditions are no longer hazardous.* Therefore, NGA strongly disagrees with PHMSA's proposal to make "hazardous leaks" and "leaks" synonymous and recommend codification for two separate definitions: "leak" and "hazardous leak."

NGA believes that criteria for "hazardous leaks" should remain primarily focused on existing or probable hazard to persons or property, as this determination is one that can be most realistically made using the judgment of operating personnel at the scene of a leak. PHMSA also failed to consider the impact the conflation of these two definitions would have on tracking and trending of leak data by individual operators and across the industry. Any change to definitions in 49 CFR 191 and 192 must be mirrored in Annual Report requirements per §§ 191.11 and 191.17.

For these reasons, NGA recommends PHMSA relocate the existing definition for *Hazardous leak* as defined in 192.1001 to the general section of Part 192, 192.3:

Hazardous leak means a leak that represents an existing or probable hazard to persons or property and requires immediate repair or continuous action until the conditions are no longer hazardous.

The proposal to define leak and hazardous leak separately allows PHMSA to stay true to its Congressional mandate, removes potentially confusing and conflicting definitions within 49 CFR 192, and continues to prioritize the safety of persons and property.

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[15] 49 U.S.C. § 60102(q)(2)(B)(i)-(ii).

PHMSA Should Replace 'Uncontrolled' with 'Unintentional'.

PHMSA should reconsider use of the term "uncontrolled" in defining a leak. It is concerning to NGA as with the Associations that the Agency states in the preamble that "unintended releases through intended release pathways" are leaks. PHMSA also specifically references releases from relief devices and emergency shutdown devices as leaks. However, releases from relief devices, emergency shutdown devices, vent stacks, and other similar devices are controlled and therefore should not be considered a leak. operators are required under the pipeline safety regulations to design certain pipeline components to safely release gas in a controlled manner without hazard. PHMSA should clarify use of this terminology to ensure that releases of gas through devices – in the manner that those devices were intended, designed, and constructed to safely release gas – are not to be considered "uncontrolled."

PHMSA Should Remove the Reference to 'Touch' to Identify a Leak.

NGA respectfully requests that PHMSA not refer to an unsafe practice of identifying leaks by touch. Placing a digit or a portion of the hand in the path of a leak is dangerous and is not a practice that operators use or condone.

Leak Grading Requirements

General Concerns

Using its definition of a leak, NGA proposes and encourages a distinction in the grading requirements between existing or probable hazards to public safety (Grade 1) and probable future hazards to public safety (Grade 2) while considering environmental emission risk criteria for driving repairs to non-hazardous Grades 3. NGA supports the Associations Grading proposals which are generally consistent with and address the intent of PHMSA's proposal. Further, NGA recommends considering the *proximity of leak indications to buildings or structures* as additional criteria similar to some existing state code requirements[16] which have proven to be effective in protecting the public and property. It's only logical that these criteria be included in distinguishing the potential for a leak to become a hazardous leak. NGA supports PHMSA's application of grading requirements as being limited to confirmed leaks (and not merely investigations of leak indications) for the following reasons.

Leak investigations are commonly triggered by one of three events: a customer odor call for a suspected gas leak, a gas alarm from a residential gas detector or methane indications from a scheduled leak survey that has been conducted. Odor calls are reports of gas odor by an individual (customer, member of the public, and occasionally an employee of the gas system). The operator or emergency services will respond to these calls and search for the source of the

[16] *See NYS Requirements in 16 NYCRR Part 255.*

gas odor. It is important to note that not all odor calls result in the discovery of a graded natural gas leak. Some reported natural gas odors may be attributed to other sources or factors unrelated to natural gas; others may be attributed to leaks on piping not jurisdictional to the operator. Nevertheless, odor calls are taken seriously and responded to urgently.
Upon arrival at the scene, existing operator specific procedures require responders to assess the situation (determine potential public safety risks) to ensure the safety of individuals and the surrounding area.

By contrast, scheduled leak surveys are proactively conducted by operators to search for potential leaks in their infrastructure. Methane detection instruments that are assessed fit-for-purpose by operators are used during these surveys to identify the presence or indication of methane, which can help locate potential leaks that may not be immediately recognized by human senses, such as smell, sight, or sound.

Leak pinpointing is a required precursor to accurately grading leaks and thus, determining appropriate responses from the operator. It involves precisely locating the source of a gas leak using fit-for-purpose specialized instruments and tools and a sampling process defined within an operator's specific procedure(s). Pinpointing the leak's location is essential to evaluating the impact of other variables like proximity to ignition sources, proximity to persons and property, ventilation conditions, migration potential, and other safety considerations. By taking these factors into account, the severity and urgency of a leak can be accurately assessed, allowing for appropriate actions and responses to be taken as defined within a leak grading process.

Additionally, the General requirements proposed for § 192.760 must provide flexibility for the operator to eliminate a leak through immediate and continuous action, without first grading the leak. As written, § 192.703(a)(3) requires an operator to determine a leak grade before a repair is made. The requirement to determine leak grade may unnecessarily delay repair of a leak and impede the mitigation of risk to public safety. Therefore, an exception should be made in § 192.703(a)(3) for those leaks which are eliminated through immediate and continuous action by operator personnel at the scene.

Grade 2 Leaks

NGA agrees with the Associations concerns regarding proposed Grade 2 leak criteria in the NPRM specifying operators to determine if actual leakage rates exceed 10 cubic feet per hour (cfh) is not practical when initially responding to a leak for several reasons:

a. Most of the industry does not have the resources to equip field personnel who respond to odor calls with instruments that can make these precise volumetric measurements of leaks. Where available, this type of equipment is usually only employed for mobile leak surveying.

b. Operators who have equipment that is purported to take these measurements note that the readings are clearly classified as estimates; the measurement precision is too limited to give confidence in the accuracy of individual readings.
c. The technology has not yet evolved to the point of accurately *and* consistently measuring flow rates from a leaking pipeline.
d. Direct measurement by field personnel of actual (not estimated) leakage rate for *all* non-Grade 1 leaks would be a practical impossibility given not only the number of leaks involved, but also the number that are below grade (thus requiring excavation, exposure, and measurement of the leakage). Furthermore, such direct measurement exercises would be burdensome and distracting to field personnel whose on-site priority is to evaluate and mitigate the immediate safety threat to persons and property.
e. Requiring operators to use leakage rate to discern between Grade 2 and Grade 3 leaks is in contradiction to PHMSA's proposal to define minimum sensitivity of leak detection equipment by parts-per-million gas alone (as proposed in § 192.763(a)(1)(ii)). Tying leak grading criteria to determination of volumetric leakage rate introduces a de facto secondary performance standard and nullifies the "flexibility for operators to choose from a baseline of high-quality equipment for their unique needs" that PHMSA has sought to establish in the ALDP requirements. Supplementing the criteria for grading leaks by environmental significance – including, but not limited to leak migration extent (as cited by PHMSA in the NPRM; see FR page 31941) – is necessary to provide operators the flexibility and technological wherewithal to perform this evaluation without the need to measure or estimate leakage rate. Establishing clear criteria that can be implemented effectively across the industry is crucial, particularly when operators are relying on the criteria to make decisions that impact public safety and environmental stewardship.

Criteria for grading leaks based on environmental significance should contain fit-for-purpose evaluation options operators could potentially apply, based on available technologies and the judgment of the operator. Because of the variability in available equipment and skills in operating such equipment, operators should only be required to apply <u>one</u> method under 192.760(c).
These must include, at a minimum, not only defined thresholds for estimated leakage rates, but also (consistent with precedent[17] in state pipeline safety regulations) options to assess and prioritize emissions estimates/risk based on leakage surface measurements that define impact and extent in square feet[18]. operators must be given latitude to define and utilize alternative

[17] 220 Mass. Reg. 114.07. *(a) Each Gas Company shall designate Grade 3 gas leaks as environmentally significant if during the initial identification or the most recent annual survey if: 1. the highest barhole reading shows a gas-in-air reading of 50% or higher or 2. the Leak Extent is 2,000 square feet or greater.*
[18] Appendix A - Final Report GTI Project Number 22509-3, 2019 Emission Factor Pilot Study, August 2020

methods for determining whether non-hazardous leaks should be classified as Grade 2 leaks based on the potential for environmental risk, according to the operator's unique judgment, skills, system knowledge, and available leak detection technologies.
Beyond the leak grading criteria, the proposed 6-month repair timeframe for Grade 2 leaks presents significant challenges to operators. Many cities have moratoriums on any non-emergency work on public right aways (streets, sidewalks, parkways) during special events, the winter period and holiday seasons. Seasonal disruptions due to weather, resource variability, and other constraints means that the 6-month repair interval could be artificially shortened and/or impractical to meet. A 12-month repair interval for Grade 2 leaks is appropriate, with additional provisions allowing for delay due to permitting restrictions beyond the control of the operator. Delays in permit issuance often occur, making it challenging to complete repairs within the designated timeframe. Paving moratoriums, highway and railroad permits, and environmental matters can also affect the timing of repairs. These factors must be considered to ensure realistic and achievable repair timeframes.

Additionally, extending the repair interval for Grade 2 leaks will allow operators to leverage project bundling more fully. Many operators already bundle work (when practicable) to prevent the need to excavate, blow down, and purge the same pipeline multiple times. Project bundling is already recognized[19] as an effective method of, and best practice for, reducing vented emissions. It also necessarily builds efficiencies in maintenance and construction activities and lowers associated costs. However, as leak repair intervals are compressed, project bundling becomes less and less feasible.

Also, as proposed, there is no provision for requesting an extension to repair Grade 2 leaks in § 192.760(c), unlike associated provisions for Grade 3 leaks in § 192.760(d). The industry believes that operators should have the opportunity to request extensions for both Grade 2 and Grade 3 leaks to accommodate various circumstances and challenges. This flexibility would ensure a more practical and effective approach to scheduling and performing leak repairs.

Grading Criteria Considerations

NGA respectfully requests PHMSA considers the following enhancements to proposed grading criteria. This criteria is based on a strategic combination of grading fundamental principles found in Gas Piping Technology Committee ("GPTC"), recommendations proposed in the Associations comments and those found within the NPRM proposal as well as existing state regulations.

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[19] al-Mukdad, et al., California Public Utilities Commission, "Natural Gas Leakage Abatement Summary of Best Practices, Working Group Activities, And Revised Staff Recommendations" (Jan. 2017), *https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/safety-policy-division/documents/final-best-practices-revised-staff-recommendations-with-bp-matrix-january2017.pdf*

Additionally, NGA requests that PHMSA acknowledge and consider that existing state leak grading programs do not all align with the measurement criteria PHMSA is proposing.
Even in as simple of a measurement as %LEL versus % gas in air, operators with extensive procedure, software, training and qualification material would be forced to modify their existing practices. Further, in some state jurisdictions, leak grading is addressed by state law, outside of pipeline safety regulation requirements, compounding the complexity of overlapping compliance and reporting requirements.

NGA feels the following recommendations address both public safety concerns, primarily of *ignition risk* in balance with considerations addressing *emissions risk*.

- **Grade 1 Leak** - A leak in which in the judgment of operating personnel at the scene is as an existing or probable hazard to public safety, property, or a significant environmental emission risk or meets the definition of an incident in § 191.3.

  (1) A Grade 1 Leak includes:
  a. A hazardous leak, as defined in § 192.3
  b. Damage by third party resulting in leakage;
  c. Escaping gas that has unintentionally ignited;
  d. Any indication that gas has migrated into a building, under a building, or into a tunnel as indicated using a combustible gas indicator (CGI);
  e. Any reading of gas using a CGI underground within five feet (1.5 meters) of a building wall;
  f. Any reading of 80% or greater of the LEL (60% for LPG systems) using a CGI in an enclosed space or substructure including manholes, vaults, catch basins;

  (2) A Grade 1 leak requires an immediate effort to protect life and property.
  (3) Continuous action[20] shall be thereafter taken until the condition is no longer hazardous.
  (4) Completion of repairs shall be scheduled on a regular day-after-day basis, or the condition kept under daily surveillance until the source of the leak has been corrected.

- **Grade 2 Leak** - A leak that does not meet the Grade 1 criteria but is in the judgment of operating personnel at the scene a probable future hazard to public safety, property, or significant environmental emission risk.

[20] Continuous action includes on-going mitigation measures as defined in an operators O&M plan to minimize public safety and emissions risk.

(1) A Grade 2 Leak includes:

a. Any reading less than 10 percent gas-in-air between the building and the curbline in any area continuously paved which is more than five feet (1.5 meters) but within 30 feet (9.1 meters) of the building and inside the curbline or shoulder of the road; or
b. Any reading less than 20 percent gas-in-air in any unpaved area which is more than five feet (1.5 meters) from but within 20 feet (6.1 meters) of a building and inside the curbline or shoulder of the road; or
c. Any reading of 30 percent or greater gas-in-air in an unpaved area which is more than 20 feet (6.1 meters) from but within 50 feet (15.2 meters) of a building and inside the curbline or shoulder of the road; or
d. Any reading of 30 percent or greater gas-in-air in a paved area which is more than 30 feet (9.1 meters) from but within 50 feet (15.2 meters) of a building and inside the curbline or shoulder of the road; or
e. Any reading above one percent but below four percent gas-in-air, within manholes, vaults or catch basins (sampling will be conducted with the structure in its normal condition as nearly as is physically possible).

(2) Grade 2 leaks shall be repaired within a period not to exceed one year.
(3) Grade 2 leaks shall be maintained under surveillance with a frequency not to exceed two months, except that leaks classified under paragraph (e) above shall be surveilled every two weeks unless extreme weather conditions warrant additional surveys as defined in an operator's integrity management and/or O&M plan.

- **Grade 3 Leak** – Any leak that does not meet the grade 1 or 2 criteria. Grade 3 Leaks shall be further characterized as an actionable emissions risk if:

(1) Is of sufficient magnitude to pose a significant emissions risk to the environment, applying one of the following criteria as determined by the operator:

(i) estimated leakage rate of 10 cubic feet per hour (CFH) or more; or
(ii) estimated ''leak extent'' (land area affected by gas migration) of 2,000 square feet or greater; or
(iii) an alternative method for determining environmental significance (such as the sum of bar hole leak indication readings % gas-in-air using a CGI) as identified in an operators' integrity management and/or O&M plan.

Leak Repair Requirements – Consideration of an Emissions Risk-Based Approach to Addressing Nonhazardous Grade 3 Leaks

Utility commissions across the country have reviewed and continue to review infrastructure modernization programs to replace aging natural gas delivery infrastructure.

In certain states, the programs are a result of regulatory filings, whereas in others, modernization and replacement policies were developed pursuant to legislative action[21].

The goal of each of these programs is the same: to ensure that the infrastructure upgrades and/or replacements necessary for the safe, efficient, reliable, and environmentally responsible delivery of natural gas are completed. There is no definitive best regulatory approach to addressing infrastructure replacement and modernization. In considering local distribution company (LDC) proposals to improve and replace infrastructure, commission's take into consideration the age of the infrastructure, factors affecting the ability of the LDCs to recover associated costs (e.g., changes to customer rates or bills in the broader context of socio-economic conditions), reliability, safety, environmental benefits, and the interests of the consumers themselves, including for rate continuity.

While Grade 3 leaks are recognized as nonhazardous to persons or property at the time of detection and can reasonably be expected to remain nonhazardous, NGA also recognizes the emissions risk component of Grade 3 Leaks. Grade 3 leaks are generally associated with legacy materials of construction (leak prone pipe (LPP) and are addressed within state approved infrastructure replacement programs. These programs are underpinned by risk-based assessments that take a balanced approach to prioritizing pipe segment replacement to extract the greatest degree of safety value including emissions reductions. The effectiveness of this balanced approach to managing emissions risk as a component of DIMP is evidenced by the fact methane emissions from natural gas distribution systems across the country have declined by 70 percent from 1990 – 2021[22] however NGA also recognizes there is more to do.

NGA is proposing a practical, fit-for-purpose alternative approach to further addressing Grade 3 Leak mitigation and enhancements to DIMP risk-based pipe replacement algorithms which includes assessing and addressing emissions risk in the spirit of the Pipes Act by assessing and implementing mitigation options for *actionable emitters*. Indeed, some states have already mandated a similar approach to address emissions risk on an otherwise nonhazardous leak awaiting mitigation through infrastructure replacement programs[23]. Each operator would be required to revise their DIMP and include assessment of Grade 3 actionable emitters and associated mitigation criteria. Proposed mitigation criteria for Grade 3 Leaks includes:

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[21] National Association of Regulatory Utility Commissioners (NARUC) Report January 2020
[22] *See* 2023 Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020 (April 15, 2023) (2022 GHGI).
[23] 220 CMR 114 Massachusetts Department of Public Utilities

(1) A Grade 3 Leak must be repaired within 5 years of the date of discovery except as described below:
  (i) A Grade 3 Leak actionable emissions risk shall be repaired within 24 months.
  (ii) A Grade 3 Leak non-actionable emissions risk on a leak prone pipe segment must be repaired or the pipe segment replaced within 10 years provided the leak is evaluated in accordance with (2) below.
(2) An operator must re-evaluate each Grade 3 leak at least once every 12 months not to exceed 15 months until the repair of the leak is complete.

Extension of Leak Repair/Remediation Grade 2 and Grade 3 Leaks

NGA supports a provision that allows an operator to request an extension of the leak repair deadline requirements for an individual grade 2 leak or grade 3 leak with advance notification to and no objection from PHMSA pursuant to § 192.18 or in the case of an intrastate pipeline facility regulated by the State, the appropriate State agency.

The operator's notification must show that the delayed repair timeline would not result in an increased risk to public safety, as well as that either the required repair deadline is impracticable, ~~or~~ that remediation within the specified time frame would result in the release of more gas to the environment than would occur with continued monitoring, or that a replacement project is pending and would negate the need to make any repair. The notification must include the following:

(1) A description of the leaking facility including the location, material properties, the type of equipment that is leaking, and the operating pressure;
(2) A description of the leak and the leak environment, including gas concentration readings, leak rate if known, class location, nearby buildings, weather conditions, soil conditions, and other conditions that could affect gas migration, such as pavement;
(3) A description of the alternative Repair/remediation schedule and a justification for the same; and
(4) Proposed emissions mitigation methods, monitoring, and repair schedule.

Effective Date for Regrading Existing Leak Inventory

The proposed criteria for Grade 1, 2, and 3 leaks in the NPRM differ from what many operators currently use or required to comply with from a state jurisdictional perspective. Once the rule is finalized, operators will need sufficient time to re-evaluate their existing leaks and determine if any changes in classification are necessary.

In addition, a management of change plan must be developed to ensure sustainable compliance conformance including addressing analysis of new federal requirements relative to state jurisdictional requirements, adjust operating procedures, assess impacts to contractual requirements and labor agreements, assess and update training and operator Qualification (OQ) requirements. This process can be particularly time-consuming for operators with a significant inventory of leaks.

Assessing and re-grading leaks according to the new criteria will require careful review and analysis of each individual leak. It is important to allocate adequate time for this evaluation process to ensure accurate and appropriate classification of leaks. The timeframe should account for the scale of the operator's leak inventory and allow for thorough assessments to be conducted. No less than 36 months are required from the time of the Final Rule's effective date to ensure that existing leaks are re-graded appropriately, and management of change plans are appropriately implemented. procedures and training are administered adequately.

By allowing operators the necessary time to reassess their existing leaks and management of change plans, the industry can ensure that the reclassification process is carried out effectively and in compliance with the new criteria established by the rule. This approach supports the goal of accurately categorizing leaks and implementing appropriate response measures based on the revised classification system.

Impacts of Accelerated Leak Repair Timelines on Pipe Replacement Programs & Maximizing Public Safety Value

Expedited leak repair requirements are likely to have unintended deleterious effects to operators' long-term pipeline replacement and infrastructure modernization initiatives. Pipeline replacement programs span several years and typically require submittal to, and approval from, state regulatory bodies, and require considerable planning and prioritization. Identified projects are not readily interchangeable (e.g., swapped in and out) on a year-to-year or month-to-month basis.

The proposed accelerated leak repair requirements compel operators to allocate funds and resources toward fixing leaks in pipelines that are (or may soon be) scheduled for replacement as part of a strategic pipeline replacement project. Repairing these leaks slightly sooner diverts resources from planned infrastructure upgrades, wastes resources, and hinders operators' ability to execute strategic replacement plans effectively. Like pipeline replacement, leak repair work has an impact on the individuals living near the pipelines. Crews fixing leaks utilize equipment that impact road travel, emit noise, and can at times be disruptive. The compounding impact of visiting a street or neighborhood to repair a leak on a pipeline that will soon be replaced is considerable and should not be discounted.

The expedited leak repair requirements can also impact operators' ability to carry out other essential projects related to pipeline safety and reliability. For instance, initiatives such as converting low-pressure systems or relocating inside meters may be delayed or hindered due to resources being shifted to focus on leak re-grading and repair activities with compressed timelines. The rule, as proposed, will incentivize operators to move towards more reactive leak mitigation and away from proactive replacement programs.

Operators need flexibility in allocating resources wisely, considering the best interests of customers. The rule should allow for prudent balancing of critical leak repairs with strategic long-term pipeline replacement projects.
This ensures effective resource utilization, system reliability, and responsible financial decision-making by operators, while minimizing impacts to the public living and working near critical energy infrastructure. NGA supports PHMSA's proposal concept to provide an exception to Grade 3 leak repair timelines if the segment containing the leak is scheduled for replacement and is replaced (§ 192.760(d)(2)(ii)). This concept is a prudent acknowledgment of the importance of safely and efficiently eliminating and preventing leaks by prioritizing long-term, risk-based strategic replacement programs.

Successful execution of replacement projects can furthermore help operators achieve reduction of leak backlogs and successfully move toward a sustainable "find and fix" regime for other leaks. However, in recognition of the need to fully realize these safety and efficiency benefits and the time horizons of the strategic replacement programs (e.g., those funded through the Natural Gas Distribution Infrastructure Safety and Modernization grants), the exemption for Grade 3 leak repairs scheduled for replacement should be revised from five (5) years to ten (10) years. Accordingly, a similar provision should be available for Grade 2 leaks scheduled for replacement within five (5) years. "Chasing" the repair of non-hazardous leaks on pipe that will be replaced, removed, or abandoned in the medium term is a clear waste of resources and a distraction from risk mitigation through strategic replacement and retirement of leaking pipelines. Any "heightened potential hazards" posed by Grade 2 leaks (relative to Grade 3) are mitigated by the stringent requirements in this NPRM to re-evaluate Grade 2 leaks on a periodic basis.

Leakage Survey Frequencies – Consideration of a Risk-Based Frequency of Inspection

A fundamental premise of risk management is reallocation of resources from activities that have a lesser effect on risk to activities that can have a greater impact. The current intervals specified for required inspections in Part 192 are not risk based and the proposal as written further propagates this non-risk-based approach to regulation.

The industries approach and understanding of risk-based inspection frequencies has advanced significantly with the introduction of sound engineering practices prescribed in the American Petroleum Institute Recommended Practice RP 580[24] for assessing Risk Based Inspections.

§192.723 for gas distribution operators requires leakage surveys be performed every 5-years not to exceed 63 months in non-business districts. A reasonable test for whether the current leak survey frequency is appropriate, relative to annual (not to exceed 15 months) leakage survey inside business districts, is whether *leaks found-per mile-per year* (i.e., normalized by survey interval) is substantially the same across leakage survey types. If this number is significantly higher for pipelines outside of business districts, it would suggest that the difference in leak proneness between piping inside and outside of business districts is not reflective of a 5:1 ratio, and that 5 years is therefore too infrequent for leakage surveys outside of business districts. However, available data does not support this scenario. In a small convenience sample of nine gas distribution pipeline operators, the Associations in their comments found no instance in which *leaks found-per mile-per year* was higher outside of business districts than it was inside of business districts. If anything, the available data suggests that a 5-year survey is an aggressive frequency relative to the typical rate of leaks found during annual leakage survey inside business districts. Therefore, NGA, believes the proposed amendments in the NPRM to increase distribution leakage survey frequency outside of business districts from 5 years (not to exceed 63 months) to 3 years (not to exceed 39 months) is not justified by leak reduction projections, nor an improvement in pipeline safety.

Risk reduction through leak survey frequency adjustment is better achieved through a less-prescriptive, more risk-based approach (e.g., DIMP and applying fundamental principles in API 580), since operators know their system, geography, conditions, and operational idiosyncrasies. Frequency of leakage surveys can be (and often are) accelerated by operators based on risk and performance of their systems. The successful utilization of DIMP to appropriately increase leak surveys based upon risk is discussed in further detail in these comments.

In addition, the current 5-year frequency facilitates synchronization of other pipeline safety risk assessments such as atmospheric corrosion inspections which was recently updated, appropriately, to a 5-year frequency based on overwhelming risk-based inspection evidence. Yet another factor to consider in assessing a risk-based approach to frequency of inspection is the introduction, and operators advocating use, of residential methane detectors. Literally hundreds of thousands of these devices have been installed in New York State alone supported by gas safety regulators and policymakers with hundreds of thousands more planned throughout the state. This is another example of a “layers of protection” approach to maximizing public safety value that needs to be integrated into the overall risk assessment when considering leak survey inspection frequencies.

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[24] American Petroleum Institute API Recommended Practice (RP) 580-2016 Risk-based Inspection (RBI), 3rd edition, February 2016

3.2 Advance Leak Detection Programs

NGA supports codification of minimum performance capabilities of instruments and technologies for leakage surveys as part of an advanced leak detection program. This approach will help support a fit-for-purpose use of technologies and practices that ensure leakage surveys and other leak detection practices are performed with fit-for-purpose equipment, procedures, and competent personnel. NGA also supports PHMSA's understanding of the importance of affording operators the flexibility to select equipment and technology that is most appropriate for its operational needs and the uniqueness of its pipeline system. NGA believes simply mandating use of the "newest" or "most sensitive" technology available is inappropriate for an adaptable, practicable, and effective Advanced Leak Detection Program (ALDP). ALDP must not be overly focused on novel technologies over a more holistic *good science common sense approach* used in conducting leak surveys and other O&M related leak detection activities. NGA also believes that in assessing and repairing leaks that PHMSA considers the overall carbon footprint of mitigation strategies and potential impact on ratepayers and overall pipeline safety value.

However, NGA remains concerned with some of the proposed requirements in § 192.763. It is critical for PHMSA to promulgate a regulation that does not impose burdensome and arbitrary requirements on instrument sensitivity and measurement techniques. While operators should be encouraged to implement technologies that are proven to be effective and fit-for-purpose, there should not be an assumption that traditional leak survey methods have become ineffective at identifying leaks, particularly those that represent a risk to public safety. Leak surveys performed on foot and by vehicle with more traditional, yet state-of-the-art equipment with associated detection thresholds and procedures have proven effective in helping the industry achieve a largely favorable safety performance based on the significant incident data collected annually by PHMSA.

NGA is also concerned regarding the apparent presumption that all leak detection processes and activities are similar in nature regardless of origin. Investigative techniques vary depending on the specific leak assessment activity being performed. For example, conducting leak surveys for interior jurisdictional piping versus exterior subsurface piping may require different instrument sensitivity capabilities, measurement techniques and investigative procedures. It is critical that the appropriate instruments, investigative procedures, training, and qualifications are fit-for-purpose considering the variables in performing these functionally specific activities. Instruments for leak surveys versus other leak detection activities may incorporate different sensor technologies and detection thresholds depending on the application of the equipment and site-specific conditions. The most sensitive technologies are used for leak surveys of buried outdoor piping. Low sensitivity thresholds (ppmv) are required to compensate for a variety of environmental variables resulting in diluted gas concentrations outdoors and/or reaction with the soil and other subsurface variables affecting gas migration patterns. In contrast, other O&M related leak detection activities, beyond mandated regulatory leak surveys, may incorporate instruments, equipment and procedures that are fit-for-purpose as identified in an operators O&M manual.

As a result, the sensitivity capability for performing these functions is typically effective in the % LEL range. An example of fit-for-purpose detection threshold application in the % LEL range are instruments and investigative techniques for conducting indoor jurisdictional piping leak surveys, where the survey environment is not affected by variables such as wind/soil diffusion and gas migration patterns.

While it may seem counter intuitive, if the instrument threshold detection limit is not aligned for the leak detection activity being performed, it may impede leak detection in the presence of a background combustible gas concentration at the parts per million level. The device may trigger a false alarm when the conditions are only slightly above background. Using leak survey equipment with a 5 ppm detection threshold for indoor piping may hinder an effective and efficient leak survey process.

One margin of safety calculation is a measurement of the difference between an instrument's detection threshold, and the Lower Explosive Limit (LEL) of methane in air (5% methane in air). If a combustible gas indicator ("CGI") threshold detection value is 0.1% gas in air (one part per thousand), the difference between the threshold detection limit and the LEL value is 50 times. The margins of safety for engineering design range from 1.5 to 20 times, depending on the application. The 50 times margin of safety is at least 2½ times greater. Instrument sensitivity requirements should consider a fit-for-service approach which includes allowing use of conventional CGI's and other methods such as the soap bubble test for conducting O&M related leak detection activities and interior and exterior above ground exposed piping leak and surveys. The current proposal would have significant unintended consequences of having to potentially replace tens of thousands of fit-for-purpose CGI instruments with little or no public safety value.

A comprehensive White Paper developed by GTI Energy is included as part of this submittal in Appendix B which highlights a fit-for-purpose approach not applying leak detection technology solutions. This White Paper served as a reference tool when New York State was developing a technology approval approach for instruments utilized in meeting regulatory requirements associated with gas leak detection[25].

In addition, some operators are currently deploying advanced fixed-sensor technologies integrated with smart metering systems that can provide continuous monitoring surveys of interior building jurisdictional piping. These devices/systems can monitor for leaks on interior building jurisdictional piping and if strategically placed, also monitor the potential for gas migration into a building from subsurface exterior jurisdictional piping through penetrations in basement walls.

[25] Appendix B - Leak Survey Equipment Considerations for NY Operations Development of a Regulatory Conformance and Technology Applicability White Paper, Gas Technology Institute, May 12, 2016,

These devices and systems are designed and installed to current industry standards specified by the National Fire Protection Agency[26] and Underwriters Laboratory Standards for Safety[27] and are designated as fit-for-service to alarm at 10% LEL detection threshold and lower, with a low-end sensitivity of 1% LEL (i.e. 500 ppm).

PHMSA is also reminded that several requirements being proposed for an ALDP have been applied on some scale, voluntarily by operators in the detection and investigation of leaks for years. This includes utilizing advanced technologies, enhancing procedures for performing leak surveys, and accelerating leak survey frequencies based on material type and geographic location. These activities have frequently been incorporated in an operator's Integrity Management and O&M plans.

NGA's commitment to exploring fit-for-service applications of ALDP is demonstrated by recent work of its research & development organization, NYSEARCH. A field study conducted by NYSEARCH and a large group of natural gas utilities in 2015, with additional validation tests in late 2017 and 2018 compared the results of three Advanced Mobile Leak Detection ("AMLD") technologies (including two types of cavity ring down spectrometers technologies[28] (one of which was used in the Weller Study coupled with modeling) with direct measurements of over 300 leaks using a high-volume sampler[29]. The goal of the NYSEARCH Study, co-funded by PHMSA, "was to define a process for independent validation of mobile methane emissions measurement technologies."[30] The results showed AMLD – could quantify leaks within very broad ranges, which is useful as a general tool for prioritizing leak mitigation, but for example, not to provide accurate emissions measurements for reporting or inventory purposes to develop emission factors for different pipe materials. One of the conclusions was that the technologies evaluated had a wide range of accuracy and precision and data analysis showed that accuracy of the predicted vs. actual flow rate indicated a 77% accuracy shown to within one order of magnitude."[31]

Stated simply, the NYSEARCH Study demonstrates that the AMLD methodology is not as accurate as using high volume samplers to measure the flow rate of specific leaks from specific types of pipe materials.

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[26] National Fire Protection Agency, NFPA 715 Installation of Fuel Gases Detection and Warning Equipment
[27] Underwriters Laboratories, UL 1484 Standard for Residential Gas Detectors and UL 2075 Standard for Gas and Vapor Detectors and Sensors.
[28] The AMLD technologies evaluated in the NYSEARCH Study are described in D'Zurko and Mallia, "Measurement Technologies Look to Improve Methane Emissions," Pipeline & Gas Journal (Feb. 2018) at 55, https://pgjonline.com/magazine/2018/february-2018-vol-245-no-2/features/measurement-technologies-look-to-improve-methane-emissions
[29] https://www.nysearch.org/white-papers/Validation-Methods-for-Methane-Emissions-Quantification-Technologies-Final.pdf (Oct. 2020) (hereinafter NYSEARCH Study).
[30] Id. p. 2.
[31] NYSEARCH Study, p. 1 referencing Figure 1.

While AMLD is not the best tool for developing population- based emission factors for different types of pipelines, the NYSEARCH Study noted that a previous report indicated that with repeated passes, mobile technologies such as AMDL can be useful in quantifying overall system emissions.

Instrument Sensitivity

Minimum sensitivity of leak survey equipment is specified in § 192.763(a)(1)(ii) as 5 parts per million (ppm) for each gas being surveyed.[32] The Proposed Rule would adopt this threshold based on the notion that unidentified handheld or mobile equipment can detect methane emissions less than 5 ppm. This 5 ppm sensitivity is also adopted as one of the variables defined in the minimum performance standard proposed in § 192.763(a)(1)(iii).

While the rulemaking docket contains vendor promotional materials and records of vendor meetings with PHMSA where the vendors made claims about the capabilities of their equipment, there is no documentation indicating that PHMSA has tested or otherwise verified these claims in order to establish a comprehensive technical basis for the 5 ppm threshold. The docket does include a "Technical Report" by Highwood Emissions Management, PHMSA-2021-0039-0011, purporting to provide a literature review of methane detection equipment. However, nothing in that report discusses detection limitations for any particular technology or provides a basis for the proposed minimum sensitivity criteria.

Inconsistency with EPA Requirements

The 5 ppm sensitivity that PHMSA has proposed is inconsistent with prescribed EPA requirements and state jurisdictional regulatory requirements. EPA defines a leak from a "fugitive emission component" (i.e., valve, connector, pressure relief device, open-ended line, flange, cover, and closed vent system) at a compressor station as "an instrument reading of 500 parts per million (ppm) or greater" using EPA's reference method for instrument LDAR monitoring.[33] Leaks from equipment within process units at onshore natural gas process plants are defined differently and range from 500 to 10,000 ppm.[34]

PHMSA notes that it chose 5 ppm because it is a "protective threshold of detection sensitivity" compared to EPA's standard of 500 ppm and that 500 ppm represents 1% of the lower explosive limit of methane gas.[35] PHMSA provided no technical basis for the 0.01% threshold and is not clear why PHMSA chose the threshold.

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[32] 88 Fed. Reg. at 31,932.
[33] 40 CFR § 60.5397a(a)(1).
[34] 40 CFR §§ 60.482-2a-60.482-11a.
[35] 88 Fed. Reg. at 31,933. PHMSA also acknowledged that EPA's 500 ppm standard is "1% of the lower explosive limit of methane gas" which calls into question why 5 ppm is necessary to be a protective threshold.

Congress directed PHMSA "to conduct leak detection and repair programs . . . to protect the environment."[36] EPA's most stringent regulatory definition of a leak is two orders of magnitude higher than PHMSA's proposed minimum sensitivity. PHMSA's blanket 5 ppm proposal exceeds the statutory mandate and would impose significant burdens on pipeline operators with little to no associated environmental or pipeline safety benefit.

False Positives May Result from Inappropriate Sensitivity Requirements

When selecting a performance standard for leak survey of transmission pipelines, the agency should account for the fact that too restrictive of a performance standard may lead to numerous false positives. The agency has not accounted for the resources that are typically spent on responding to indications of a leak to determine if it is truly a natural gas leak or alternatively, decayed matter from natural sources. As reported in the Association's comments, an interstate pipeline operator deployed the 5 ppm sensitivity level for leak survey of certain areas of its pipeline system. It found 39 leaks indications with this sensitivity level; upon further investigation, 36 were determined to be false. Operators will need to extend resources to investigate each and every leak indication, and PHMSA should acknowledge that (particularly for mobile, aerial, and satellite platforms) prescribing a minimum instrument sensitivity that is too restrictive is not beneficial and may even be detrimental.

Use of EPA-Approved Methods for Above-Ground Sources

EPA and state programs have robust requirements to regulate methane leaks on equipment in areas within the fence line of a facility. As PHMSA acknowledges in the NPRM, EPA requires the "repair of all leaks visible with an OGI (optical gas imaging) device or that produce an instrument reading of 500 ppm or greater."[37] PHMSA also confirms that "OGI cameras…are commonly used for fugitive emissions monitoring at LNG plants, compressor stations, and other facilities."[38] However, PHMSA proposes to require leakage surveys on valves, flanges, pipeline tie-ins, and ILI launcher and receiver facilities using the equipment that can meet a minimum sensitivity of 5 ppm.[39] This sensitivity requirement may preclude the use of OGI cameras. PHMSA should capitalize on the benefit of existing EPA regulations and allow operators to use OGI devices or an equivalent for a consistent and efficient regulatory program.
To resolve its concerns, NGA supports the Associations proposal incorporating fit-for-purpose detection threshold criteria for mandated regulatory leak surveys that considers variables associated with leak detection equipment applications such as buried piping, exposed piping, piping exposed within buildings or structures etc. in § 192.763:

[36] 49 U.S.C. § 60102(q)(1)(B).
[37] 88 Fed. Reg, at 31,932.
[38] 88 Fed. Reg, at 31,933.
[39] Proposed Section 192.763(a)(1)(iii)(A)-C).

§ 192.763 Advanced Leak Detection Program

(a) Advanced Leak Detection Program (ALDP) elements. Each operator must have and follow a written ALDP that includes the following elements:

(1) Leak detection equipment.
(i) The ALDP must identify operator approved leak detection equipment used to perform leakage surveys and other leak detection activities.
(ii) Leak detection equipment used in conducting leakage surveys must have a minimum sensitivity capability of one of the following:

(A) 5 parts per million for each gas being leakage surveyed using handheld or mobile leak detection survey equipment for leakage surveys of subsurface piping and piping components, unless described in § 192.763(a)(1)(ii)(C);
(B) 500 parts per million (or 10 kg/hr mass flow equivalent) for each gas being surveyed or investigated using optical, infrared, or laser-based leak detection equipment; mobile, aerial, or satellite-based platforms; or using fixed continuous monitoring sensors for jurisdictional piping within buildings;
(C) 500 parts per million for handheld leak detection equipment used within buildings; or
(D) sensitivity otherwise meeting the requirements of 40 C.F.R. Part 60, subpart OOOO for optical gas imaging or equivalent.

The operator must validate the sensitivity of this equipment periodically in accordance with manufacturer's instructions.

Additional Performance Standards

Incorporation of additional performance standards for evaluating technology effectiveness, as proposed in § 192.763(a)(1)(iii), is redundant and impractical. PHMSA imagines a standard leak, recognized by industry, "of 5 parts per million or more when measured within 5 feet of the pipeline," – something akin to the international prototype meter[40] – against which all leak detection equipment must be evaluated for acceptability.

[40] National Institute of Standards and Technology, *"Meter"*, nist.gov, https://www.nist.gov/si-redefinition/meter

However, defining such a "universal leak" by gas concentration *and* distance alone fails to consider other critical real-world leak characteristics, such as soil conditions, atmospheric conditions, plume behavior, and margin of uncertainty in the equipment being used. Even if operators attempted to apply this proposed standard within a controlled environment, it could not be practically or consistently repeated across industry. PHMSA's proposal in § 192.763(a)(2)(iii) to "have procedures for validating the sensitivity of the equipment before initial use by testing with a known concentration of gas and at the required offset conditions of 5 feet" neither makes reference to the 5 ppm minimum concentration that the equipment is expected to detect, nor controls for the variables discussed previously.

Outside of a controlled environment, application of the standard is even less practicable, particularly as it relates to the stipulation that some leaks must be measured within 5 feet of the pipeline (i.e., if they are of a sufficiently low concentration that they cannot be detected from further away than 5 feet). Wide variability in gas migration and venting patterns, depths-of-cover regularly more than 5 feet, as well as other potential factors make it extremely unlikely that operators can reasonably evaluate the performance of equipment based on prescribing gas concentration and distance from pipe wall alone. Furthermore, the 5 parts per million minimum sensitivity requirement represents a concentration of 0.01% of the lower explosive limit of methane gas. Imposing additional mandates to "use locating equipment to verify the tools are sampling the area within 5 feet of the buried pipeline" (as proposed in 192.763(a)(1)(iii)(A)) is at odds with such a conservatively low sensitivity threshold and imposes burdensome prework to handheld leak survey activities.

In order for an instrument performance standard to be applicable, practical, and repeatable under ALDP, it should be made synonymous with minimum sensitivity requirements for leak detection equipment established within the operator's ALDP.

3.3 Distribution Leakage Survey Frequency

Given the minimum leakage survey frequencies prescribed in §§ 192.706 and 192.723, as well as accelerated or supplemental leakage surveys dictated within an operator's DIMP (based on the risk of materials such as bare steel or cast-iron piping, as well as the threat of certain natural force threats, such as frost, earthquakes, or hurricanes), imposing additional mandates related to survey frequency within the ALDP requirements is redundant and inappropriate. Furthermore, the proposed requirements in § 192.763(a)(3) suggest that every leak should be detected through leakage survey, and therefore any leak found outside of a scheduled leak survey is evidence of insufficiently frequent survey practices. This is unreasonable and completely at odds with an approach involving a limited set of prescribed minimum survey frequencies, in combination with risk-based alternatives defined by DIMP.

Consideration of the concerns raised above and additional edits to § 192.763 provide clarity and flexibility necessary to create and implement a technically feasible, fit-for-purpose and practicable ALDP program that will enhance the leak detection and mitigation activities that operators are currently undertaking through DIMP and other pipeline safety efforts.

These considerations will ensure that the equipment, practices, frequencies, and program evaluations of ALDP will address both public safety and environmental protection effectively.

3.4 Liquefied Natural Gas Facilities—§ 193.2624

Liquefied natural gas facility operations play a vital role in providing energy supply security in the northeast region. Collectively, NGA members own/operate the largest number of LNG peakshaving facilities in the country and as such may have significant impacts by the proposed additional monitoring requirements.
It is important to distinguish these facility operations from larger import/export terminal operations as they have a different potential emissions profile, however far too often these facilities are inappropriately aggregated for purposes of emissions assessments.
As part of conducting the required risk assessment, PHMSA should consider whether to apply the proposed leakage survey requirements in 49 C.F.R. § 193.2624 to LNG facilities that are already subject to leak detection and repair (LDAR) requirements under statutes or regulations administered, or pursuant to permits or authorizations issued, by the U.S. Environmental Protection Agency (EPA) or another federal or state agency. If an LNG facility is already subject to LDAR requirements that provide adequate protection to public safety and the environment, there is no reason for PHMSA to add duplicative, and potentially inconsistent, regulations on that same topic in Part 193. PHMSA should also consider the unique nature of operations of peak shaving facilities when considering this proposal including emissions and public safety risk.

PHMSA's proposal to include an exemption for compressor stations on gas gathering and transmission lines that are subject to EPA's LDAR regulations supports the conclusion that regulations in Part 193 are unnecessary for LNG facilities that are subject to comparable provisions under statutes or regulations administered, or pursuant to permits or authorizations issued, by EPA or another federal or state agency.

In addition, PHMSA should consider other approaches in developing any proposed leakage survey requirement for LNG facilities under Part 193. For example:

- Applying the leakage survey requirements to mobile or temporary LNG facilities is unnecessary. Mobile and temporary LNG facilities are often relocated, reconnected, and repressurized, and there is no indication in the record that these non-stationary LNG facilities are a significant source of methane emissions. The Proposed Rule also appears to overlook the exception from Part 193 applicability for mobile and temporary LNG facilities that comply with the standards in 2001 NFPA 59A, which would not be subject to the proposed leakage survey requirements in any event.[41]

[41] 49 C.F.R. § 193.2019(a) (stating, in relevant part, that "mobile and temporary LNG facilities for peakshaving application, for service maintenance during gas pipeline systems repair/alteration, or for other short term applications need not meet the requirements of this part if the facilities are in compliance with applicable sections of NFPA–59A–2001")

- Certain components at LNG plants are inaccessible or unsafe to monitor and other components may be difficult to monitor for leakage survey purposes. PHMSA should either exempt components from the leakage survey requirements that are inaccessible or unsafe to monitor or allow LNG operators to make that designation in their leakage survey procedures. PHMSA should also allow LNG operators to designate alternative leakage survey intervals in their procedures for components that are difficult to monitor.

- The types of components that are subject to any leakage survey requirements should be clearly identified in any regulation. The definition of component in Part 193 is extremely broad, and there are certainly types of components—or even entire areas or portions of LNG plants—that are not susceptible to leaks.

  PHMSA should consider whether the leakage survey requirements need to apply to all components and areas within an LNG plant, and, if so, whether these components and areas should be surveyed at less frequent intervals.

- The proposed threshold for the capability of leak detection equipment of 5 parts per million (ppm) or more within 5 feet is unnecessary and unreasonable. Most LNG plants are continuously manned and monitored and have systems capable of detecting any leaks that present a hazard to the plant, personnel, and the public. The record does not justify requiring LNG operators to detect and remediate much smaller leaks at more frequent intervals, particularly at the 5-ppm-within-5-feet standard. That detectability standard is 10,000 times below the lower explosive limit for natural gas, and 100 times more conservative than the comparable requirement in EPA's LDAR regulations. The 5-ppm-within-5-feet standard also prohibits the use of a wide range of commercially available leak detection technologies. Adopting a one-size-that-fits-none approach for leak detection technology does nothing to promote public safety or protect the environment.

- Referring to both "equipment" and "components" in a leak survey requirement for LNG plants introduces uncertainty. The definition of "component" in 49 C.F.R. § 193.2007 already includes "equipment", and 49 C.F.R. § 193.2401, which delineates the applicability of Part 193 to equipment, is limited to "vaporization equipment, liquefaction equipment, and control systems". To avoid uncertainty, the types of components or equipment that are subject to any leakage survey requirements should be clearly specified by regulation.

- The proposed 6-month deadline for complying with the leak survey requirements for LNG facilities is impracticable. LNG operators will need additional time to obtain new permits, acquire new equipment, hire new personnel, and take other actions necessary to achieve compliance.

The following suggested revisions to the Proposed Rule are consistent with these comments:

§ 193.2624 Leakage surveys.

(a) Except as provided in paragraph (e) of this section, each operator of an LNG facility, including mobile, temporary, and satellite facilities must conduct periodic methane leakage surveys, on equipment and of designated components within their facilities containing methane gas or LNG, at least four times each calendar year, with a maximum interval between surveys not exceeding 4 ½ months, using leak detection equipment. Leak detection equipment must be capable of detecting and locating all methane leaks producing a reading of 5 parts per million or more of within 5 feet of the component or equipment surveyed.

(b) Operators must have written procedures providing for each of the following:

(1) Validating the leakage survey equipment and performing leakage surveys consistent with the equipment manufacturer's instructions for survey methods and allowable environmental and operational parameters;

(2) Validating the sensitivity of this equipment by the operator before initial use by testing with a known concentration of gas at a required offset condition of 5 feet; and

(3) Calibrating the equipment consistent with the equipment manufacturer's instructions for calibration and maintenance. Leak detection equipment must be recalibrated or replaced following any indication of malfunction; and.

(4) Designating the components subject to the periodic leakage survey requirements, not including any components that are inaccessible, unsafe to monitor, or difficult to monitor during one or more survey intervals.

(c) Each operator must maintain records of the leak survey and equipment sensitivity validation and calibration for five years after the leakage survey.

(d) Operators must review the results of the methane leakage surveys and address any methane leaks and abnormal operating conditions in accordance with their written maintenance procedures or abnormal operating procedures.

(e) The requirements in this section do not apply to:

(1) An LNG facility subject to a leak detection and repair program pursuant to a statute or regulation administered, or a permit or authorization issued, by the U.S. Environmental Protection Agency, another federal or state agency, or authority having jurisdiction ("AHJ"); or

(2) A mobile or temporary LNG facility.

Respectfully submitted,

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APPENDIX

Appendix A - Final Report GTI Project Number 22509-3, 2019 Emission Factor Pilot Study, August 2020

Appendix B - Leak Survey Equipment Considerations for NY Operations Development of a Regulatory Conformance and Technology Applicability White Paper, Gas Technology Institute, May 12, 2016,

FINAL REPORT
GTI PROJECT NUMBER 22509-3

2019 Emission Factor Pilot Study

Date Submitted

August 21, 2020

Prepared For

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The results within this report relate only to the items tested/reviewed.

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Executive Summary

Objective

Traditionally, inventories and reporting programs use emission factors based on leaks/emissions expected *per mile* of a specific *type* of pipe. This means that currently, the only way to show reductions is to reduce the number of miles of higher emitting types of pipe, such as cast iron and cathodically unprotected steel pipe. More recent regulations have included emission factors based solely on leaks.

The objective of this study was to develop a method for flagging large leaks for cost-effective measurement and repair to minimize systemwide methane leakage rates that further focuses on non-hazardous (grade 2 and 3) leaks. So, if a company can reduce its number of higher emitting non-hazardous leaks, it can reduce actual emissions *and* more accurately demonstrate the reduction.

The study conducted statistically sound sampling of non-hazardous pipeline leaks using well-proven field measurement techniques to provide data to calculate company-specific methane emission factors for Southern California Gas Company (SoCalGas) buried Distribution system leaks. State-of-the-art parametric and non-parametric statistical analysis, resampling, Monte Carlo, and Bayesian probabilistic analysis were used when appropriate.

The approach demonstrates that methane concentrations collected at designated types of locations, in the manner prescribed, and analyzed according to the Decision Tree process can be used to predict whether a leak flow rate is either above or below a specified target flow rate.

Background - Regulator, Industry Studies, and SoCalGas Process Development

Based on 2015 California state rulemaking, the research team at SoCalGas began the development of an approach for identifying and differentiating leaks on the buried distribution system that have relatively high flow rates, for the purpose of prioritizing repairs and reducing natural gas emissions from the distribution system. The approach was chosen with the objective of developing a "cost-effective" methodology as defined within the California State CPUC Rulemaking (R.) 15-01-008 [1]. Various prior industry studies, which include leak data from the SoCalGas system, were leveraged for this effort.

Initially, the work was based on the hypothesis that a small percentage (approximately 5%) of non-hazardous buried leaks in the SoCalGas distribution system had a flow rate of 10 scfh or larger, and that existing system data about the leaks obtained at the time the leaks are detected and graded could be leveraged to identify a sub-set of all system leaks that had the greatest probability of being high flow-rate leaks. Since leaks that are categorized as a safety hazard ("Code 1" or "Grade 1" leaks) are identified more readily and fixed immediately, studies have focused on the non-hazardous leaks ("Code 2 or 3" leaks) that are generally scheduled for later repair or monitored, and thus can continue emitting for a longer period of time. Prior industry studies suggested that the number of system non-hazardous leaks that have a high flow rate is a small percentage of total leaks. The goal was to verify the flow rate population distribution of non-hazardous leaks in the SoCalGas system and find an efficient way to identify large flow rate non-hazardous leaks, so they can be prioritized for repair.

SoCalGas mined existing system data but found that there was no discernable relationship between available data and the flow rate of the leak. After much research, it was determined that surface expression measurements across the entire spread of the leak were needed to determine the flow rate. As more surface expression leak flow rate data was collected, some relationships to methane concentration measurements began to emerge.

Extensive surface expression method leak flow rate data was then collected along with methane concentration data at the corresponding prescribed surface measurement locations. Subsequent groupings of that data based on similar location descriptions yielded promising correlations to the leak flow measurements.

Starting in 2016, surface expression measurements were analyzed against site-specific characteristics of ground-level methane concentration measurements, and concentration thresholds were developed for each surface category to identify the leaks with the potential for a high flow rate. A process and workflow were then developed where surface expression measurements to calculate leak flow rate are performed whenever one or more of the concentration threshold values are met or exceeded, so repairs can be prioritized. This methodology was termed the "Decision Tree" (DT) approach.

In order to validate and achieve high statistical confidence in the DT model output a statistical and probabilistic data analysis study commenced, with the results presented in this report. This work led to the collection of leak flow data based on a geographically diverse random sample of the entire SoCalGas distribution system which established a technically sound foundational leak flow rate dataset. The data set used for the emission factor calculations in this report included 291 such samples.

Approach - Field Sampling, Measurement Techniques, and Decision Tree

System-Wide Random Field Sample (Leak Site) Design

For this pilot effort, SoCalGas stratified its sample population by district, and then randomly drew the corresponding number of leak site samples (per district or district grouping) to preserve the correct proportion of the districts in the total population of leaks.

Concentration Measurements

The operator utilizes either the Heath DP-IR (Detecto Pak Infrared) or GMI Gasurveyor along with the survey probe attachment to survey the leak site. The spread of the leak is determined by probing the ground surface and identifying the extent at which any methane concentration is present. Once the spread is determined the operator then identifies and records the highest sustained ground-level reading within the spread of the leak for each of the four surface conditions where gas indications are found.

Decision Tree Process

A process was then developed where surface expression measurements to calculate leak flow rate are performed whenever one or more of the leak concentration threshold values are met or exceeded, so repairs can be prioritized.

This methodology was termed the "Decision Tree" (DT) approach. The applicable concentration measurements are compared to the threshold values, and any one (or more) of the concentration measurements taken from the four prescribed surface conditions, that meets or exceeds the threshold concentration value will then result in that leak being classified as a potential large, non-hazardous leak with a possible leak flow rate of 10 scfh or higher.

The threshold values for concentration measurements by surface condition type are:

- 20% Gas: Crack (or seam) In Pavement - CIP
- 5% Gas: Unpaved Surface - US
- 80% Gas: Bar Hole (leak survey type) - BH
- 60% Gas: Small Sub-Structure (not gas system related) - SSS

Leak/Emission Flow Rate Measurements

The leakage flow rates were measured using the well-established and published surface expression methodology. These leak rate measurements provide an approximation of 'in-air' methane emission rates without the need to excavate the leak source.

Methodology - Data Collection and Statistical/Probabilistic Analysis

Non-hazardous leak survey data, including methane concentration measurements at defined types of surface condition locations, were collected as part of this study. The specific numbers of the various sampling efforts are listed in the Background section. Leakage flow rates were measured from selected underground distribution pipeline leaks, triggered based on the Decision Tree concentration thresholds, and based on a random sample across the entire SoCalGas distribution system.

Standard descriptive statistical analysis was conducted including calculation of sample means, medians, percentiles, inner quartile ranges, and other statistics. Various analysis and plotting techniques were used to confirm sampling bias and draw high-level conclusions on the different individual and grouped sample leak rate distribution center tendencies, uncertainties, and shape.

Data transforms were used to ensure that any regression model utilized had a sound basis. Monte Carlo Markov Chain (MCMC) with Metropolis-Hastings Sampling (MHS) and Gibbs Sampling (GS), Linear Regression (LR), and Analysis of Variance (ANOVA) were used to quality check sample set data, spot outliers, confirm assumptions, assess regression, and check probabilistic residuals and diagnostic measures.

A purely probabilistic Bayesian analysis was used to measure the Decision Tree performance by grouping leaks into two categories. By using this approach and analysis, there is no model "form" that needed to be "informed" or "trained". The analysis incorporated and related the leak concentration levels with the Decision Tree threshold point at 10 scfh between “Large” and “Not Large” leak groups. The DT performance metrics included developing a False/True Negative/Positive (Type I and II) error table.

Resampling with replacement (bootstrap) analysis of field leak rate data and Monte Carlo sampling of a fitted data distribution of leak rates were both used to infer the population mean leak rates with upper and lower confidence limits from the sample data. The SoCalGas emission factors were derived using a combination of the appropriate bootstrap population leak rate means and the Bayesian Decision Tree error table percentiles.

Summary of Results, Emission Factor Development, and Application

The national studies compared well with the SoCalGas studies. The mean, median, and upper and lower 95% percentiles for leak rate of these two groups are similar.

Two of five SoCalGas sample sets were known to contain sample bias, as well as being an order of magnitude in size smaller than the other three. These were analyzed in this report to show how bias might appear during analysis, and they were not included in the ultimate combined data set.

The non-hazardous leak rate values from the SoCalGas combined data set was analyzed for unexplainable outliers or extreme values and was log transformed, resulting in a normally distributed data set. Upon review of the extreme values, all of them were deemed as sound data points and not errors or anomalous values. The log-normal transformation of the leak rate data permitted a variety of statistical regression tools to be appropriately leveraged.

A series of regression and probabilistic analysis were conducted on the data set. Two key findings were that when the samples sizes supported categorical analysis that there was no significant sensitivity of the leak rate means to geographic operating districts where the leak was found, or the time interval from when the leak was detected.

An analysis of the field methane concentration vs. measured leak rates was done by Decision Tree methane concentration threshold category. The regression analysis of the mean leak flow rate vs. methane concentration showed the expected upward trend for the average values. The concentration threshold intersection with the established 10 scfh “Large” vs. “Not Large” flow rates were within the 95% confidence interval of the regression model or above and to the left (a conservative situation) of the predictive margin plots.

A Bayesian probabilistic analysis was conducted of the Decision Tree threshold performance. This resulted in a true/false-positive/negative Error Table. The Decision Tree thresholds correctly assigned low leak situations 98.9% of the time, i.e. true negatives with a 95% prediction interval of 98.9% to 99.5%. Likewise, the Decision Tree had a false negative (Type II error) of only 1.1% with a 95% prediction interval of 0.47% to 3.6%.

The leak rate data was bootstrapped 10,000 times with replacement and a re-sample size equal to the field data sample size. This analysis provided the overall mean leak rate, as well as the mean leak rates for less than (<) 10 scfh leakers and greater than or equal to (≥) 10 scfh leakers - all from the empirical data. The bootstrap analysis provided a full set of percentiles for the actual mean leak rates which allows one to establish confidence intervals for the mean values at any desired confidence level.

The leak rate data was fit to a log-normal distribution as well, and this fit was used to conduct a Monte Carlo analysis of the mean leak rates as was conducted with the bootstrap analysis using the actual field leak rate data. The same re-sample and over sample sizes were used as was done with the bootstrap analysis to properly propagate the uncertainty through the analysis. The result showed the two approaches were very similar, with the Monte Carlo of the log-normal distribution fit being conservative in the low- to mid- leak rate ranges and about the same in the high range of leak rates.

A set of emission factors based on the Decision Tree categorization were calculated by combining the mean leak rates with their corresponding expected percentiles (in a weighted manner) from the Decision Tree error table. It was noted that the Decision Tree derived emission factors were conservative (higher) than one would have obtained from a straight average of the empirical data from the All District Study of the SoCalGas system. This is due to the Bayesian analysis properly accounting for false negatives in the Decision Tree process.

A calculation of the efficiency of the process was done using the 2019 3-District Pilot study which had a total number of 356 screened leaks with surface concentration measurements. Of these, the DT was triggered for flow rate measurement 44 times. This therefore relates to a flow rate measurement ratio of 44 / 356 or 12.4%, meaning that when considering leak sites visited and screened with surface concentration measurements that one would expect to be triggered by the DT process and criteria to have approximately 1 in 8 of them classified as potential non-hazardous large leak rates and be scheduled for leak rate measurement or prioritized for repair.

For this particular example, rather than measuring all 356 leaks to find all the large leaks; the DT process was used resulting in the requirement to measure only 1 in 8 leaks while maintaining a false negative error of 1.1%. In summary:

- Using the DT method, 4 of the expected 7 large leaks were found by measuring the leak flow rate from 44 out of 356 leak sites.
- Without the DT, to find the same ratio of 4 out of the 7 large leaks, 203 leak flow rates on average would need to be measured out of the 356 leak sites.
- This means the DT efficiency increase is 203/44 = 4.6x (460%) more efficient at finding the same number of large leaks when not using the DT process.
- The DT is therefore an efficient screening mechanism, with a high potential to continue to improve over the short-term full implementation period.

Conclusions

SoCalGas conducted a statistically sound study of pipeline leaks using random samples and well-proven field leak concentration and flow rate measurement techniques to provide data to calculate SoCalGas company-specific natural gas emission factors for buried distribution system non-hazardous leaks.

The developed Decision Tree approach of using concentration measurements with thresholds to establish large and not large non-hazardous leaks was successful as measured by a 98.9% true negative value associated with predicted leak and actual leak rates.

The inferred population mean leak rates were combined with the associated Decision Tree performance percentages to calculate appropriately weighted emission factors for large and not large non-hazardous leaks.

This allows the assignment of emission factors for the not large non-hazardous leaks that would not have leak rate flow measurements performed on them, as well as any Decision Tree classified large non-hazardous leaks that did not have leak rate flow measurements performed.

The approach will be further refined and improved by continuing to:

- Collect field data leading to lower uncertainty, i.e. tighter confidence intervals around leak and Decision Tree performance metrics;
- Perform random checks for false negatives to identify possible upset conditions in expected leak rates, e.g. from a change in system performance and/or environmental stressors; and
- Analyze and adjust the Decision Tree thresholds or even add new thresholds to further increase the method's predictive accuracy and/or increase process efficiency to continuously improve the cost-effectiveness of the approach, overall process for detection, and repair of large flow system leaks to minimize natural gas emissions.

1. Introduction - Report Layout

Below is a brief description of the major sections of this report.

1. **Introduction - Report Layout.** This section describes the major sections of the report and their content.

2. **Background - Regulator, Industry Studies, and SoCalGas Process Development.** This section discusses national and California rulemaking related to natural gas emissions. A table of the past industry emission studies and the data sets used as part of this study is provided, along with details on the current studies, sample sets, and emission factor calculations used in this report. A basic timeline is also provided showing the order of activities in developing the Decision Tree process in relation to the various sets of data.

3. **Approach for Field Sampling, Measurement Techniques, and Decision Tree Process.** This section contains the development progression and components of the Decision Tree process (method). It includes how and when surface concentration measurements are taken, how leak rate size is initially estimated, and how leak flow rates are measured. A precision and sample size analysis related to the desired confidence interval width for mean leak rate is presented, as well as a minimum sample size for Bayesian probabilistic analysis used to measure the performance of the Decision Tree method. A discussion on random sampling is also presented.

4. **Methodology Overview of Data Collection and Statistical / Probabilistic Analysis.** The analysis methods employed in the Analysis and Results section are listed, and details are provided. A quality assurance section lists the statistical checks, secondary analysis, significant figure management, and standard conditions of the data collection. The methods for distribution fitting and Monte Carlo sampling of the same are described. Details on the leak concentration and leak flow rate measurement uncertainties, as well as the inferential statistical and probabilistic analysis uncertainties are addressed.

5. **Analysis and Results.** This is the largest section of the report and documents the collection and analysis of the SoCalGas study data. The leak rate data from the SoCalGas data sets is analyzed and compared with the national industry studies listed in the Background section. Descriptive statistics are calculated, and data is plotted. The data is transformed and checked for normality in its distribution graphically and with non-parametric statistical tests. Analysis of variance and linear regression are used to compare the leak rates of various studies as well as look at the relationships of leak surface concentration values to leak rate values. The Decision Tree prediction performance is analyzed quantitatively with a Bayesian probabilistic analysis and the average leak rate and population distributions of the various studies are calculated through bootstrap resampling of the field data. The leak rate data sets

are also fit to a log-normal distribution to demonstrate the ability to "stretch" small data sets as stopgap measure until adequate sample sizes are achieved for bootstrap means analysis.

6. **Emission Factor Development and Application.** In this section the bootstrapped leak rate distributions are combined with the Decision Tree prediction performance metrics to calculate company specific emission factors.

7. **Summary of Results and Conclusions.** This section contains a high-level summary of the results and conclusions of the study and recommended next and ongoing steps.

Appendix A: Surface Measurements of Underground Leak Flow Rate. This section provides details on the well-established technique used in the study for surface measurements of underground leak flow rates.

Appendix B: Statistical and Probabilistic Analysis Details and Supplemental Analysis. This section lists the technical details, detailed output, diagnostics, and residual analysis of the Bayesian Monte Carlo Markov Chain (MCMC) models, select linear regression, and logistic regression analyses.

Appendix C: Log-normal Distribution Facts. The details on the log-normal distribution, as well as the goodness-of-fit measures for the fit of the SoCalGas study data set are listed in this section.

Appendix D: Leak Spread Comparison to Leak Rate. Additional details on attempts to correlate the spatial spread of leaks concentration measurements to leak rate are listed in this section.

Appendix E: Study Leak Rate and Concentration Data. The leak rate and concentration observations for the national and SoCalGas studies are listed in this section.

References. The references cited in the report are listed in this section.

2. Background - Regulator, Industry Studies, and SoCalGas Process Development

Since the Natural Gas industry first began studying distribution system leak rates in the early 1990's SoCalGas has been a leader in both funding the work as well as providing its resources and facilities to conduct and participate in the studies. Data obtained by independent researchers from SoCalGas system leaks have been used in the following industry studies: EDF/WSU – 2015[1], GTI/OTD – 2013[2], DOE/GTI – 2019[3], CARB/GTI – 2019[4].

2.1. California Rule Making

Historically, public safety has been the driver for California gas utilities policy and procedures for identifying and repairing distribution system leaks that are potentially hazardous as soon as reasonably possible. However, on January 22, 2015, the CPUC opened Rulemaking (R.) 15-01-008 [5] to implement the provisions of Senate Bill (SB) 1371 (Statutes 2014, Chapter 525) [6].

SB 1371 required the adoption of rules and procedures to minimize natural gas leakage from CPUC-regulated natural gas pipeline facilities as a means of reducing emissions of greenhouse gases. SB 1371 directs the Commission to consult with the California Air Resources Board (CARB) [7], to achieve the goals of the Rulemaking. California's statutory methane emissions reduction target is to lower 2030 levels to at least 40% below 2015 levels.

The SB 1371 Leakage abatement program uses Emission Factors for distribution mains and services from the 1996 GRI/EPA study, Methane Emissions from the Natural Gas Industry, GRI-94/0257.25, EPA-600/R-96-080, June 1996. Volume 9: Underground Pipelines[8]. These are leaker-based emission factors with engineering units of "Mscf NG/day/leak".

EPA Subpart W[9] uses GRI-GHGCalc[10] population emission factors to estimate emissions from distribution mains and services derived from the same report used for the SB 1371 leaker-based EFs. To convert from leaker EFs to population EFs, GRI-GHGCalc multiplied the 1996 GRI/EPA study Volume 9 leaker EFs by leaks per mile (for mains) and leaks per service (for services) data.

For example, for mains: scf CH_4/hour/leak * leaks/mile = scf CH_4/hour/mile

2.2. Leak Grading in California

The leak grading criteria used by the state of California[11] follows the GPTC guidelines[12] closely.

Grade 1 leaks require immediate repair or continuous action until the conditions are no longer hazardous. Grade 2 leaks should be repaired within one year, but no later than 15 months from the date the leak was reported. Grade 3 leaks should be reevaluated every 15 months from the date reported until the leak is regraded or no longer results in a reading. SoCalGas terms the

"Grade" of the leak as "Code" rather than "Grade". Leak grading in other states is similar, though not identical, and some states have additional subcategories.

Another difference is that some states say just to monitor grade 3 leaks, whereas California calls on utilities to prioritize fixing high flow Grade (Code) 2s and 3s as soon as possible.

2.3. Summary of Studies Referenced or Developed as Part of this Report

SoCalGas collected field leak concentration measurements and leak flow rate data based on a geographically diverse random sample of the entire SoCalGas distribution system, which established a technically sound foundational leak flow rate dataset. A summary of the past industry emission studies referenced, as well as the SoCalGas studies performed as related to this report are summarized in Table 1 below. Further details about the past industry emission studies and SoCalGas studies are shown below Figure 1.

Table 1: Summary of Studies Referenced and Performed as Part of this Report.

Study	Header/Legend Abbreviation(1)	Year(s) Performed	Report Year	Scale	Number of Samples(2)	Used for Report EFs(3)	Reference Number
WSU/EDF 2015	Natl_WSU_EDF	2013	2015	National Multi-Utility	212	No	[1]
CARB/GTI 2019	Natl_CARB_GTI	2014-2015	2019	California Multi-Utility	76	No	[4]
OTD/GTI 2013	Natl_OTD_GTI	2011-2012	2013	National Multi-Utility	62	No	[2]
SoCalGas All District Study	AllDisPilot	2019	2019	SoCalGas	78	Yes	This Report
SoCalGas All District Leak Inventory Reduction Program	AllDisLIRP	2019	2019	SoCalGas	10	No	This Report
SoCalGas Decision Tree 157 Pilot	DT157Pilot	2015-2019	2019	SoCalGas	157	Yes	This Report
SoCalGas 3-District Pilot	3DisPilot	2019	2019	SoCalGas	56	Yes	This Report
SoCalGas 3-District Pilot Low Specification	3DisPilotLowSpec	2019	2019	SoCalGas	8	No	This Report

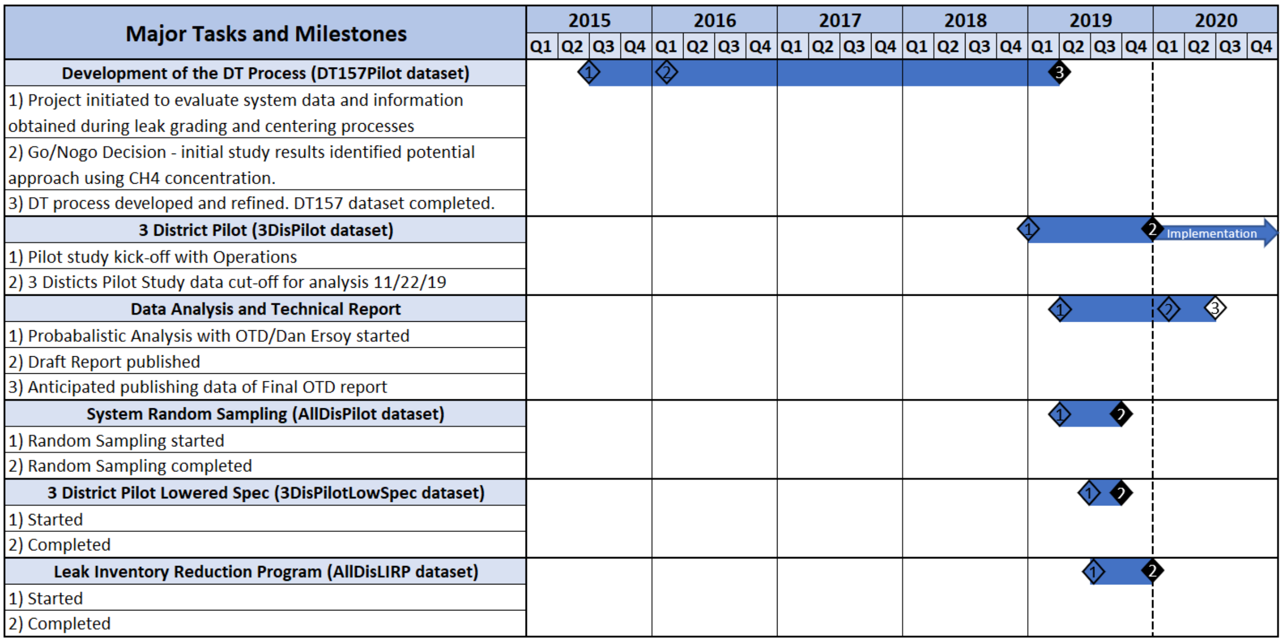
(1) The CARB study was conducted in the state of California, so the inclusion as a "national" study in the analysis is done to allow comparison of two groupings of studies (i.e., past industry studies and SoCalGas studies for this report) without multiple descriptors in table headings and plot legends. The industry studies are all multi-utility, and the SoCalGas studies are only with SoCalGas data. Therefore, in the summary plots and tables of this report, the CARB study is grouped with the two national studies (OTD and WSU below), and the term national studies is retained for this combined set.

(2) - In some cases, a very few (e.g., one or two) site observations were removed from the sample set for comparisons. These were done when upon future dig up of the sites the leak was found to be on a non-pipe item like a valve stem. The individual observations for all studies are in the Appendix section of this report.

(3) All the reports were referenced and statistically analyzed and compared; however, only the three SoCalGas large studies were used to develop the SoCalGas specific EF developed as part of this report. Only the SoCalGas studies included the set of surface concentration measurements as set up and collected using the Decision Tree process.

A basic timeline is provided in Figure 1 below showing the order of activities in developing the Decision Tree process in relation to the various sets of data referenced in the report.

Figure 1: Timeline of Major Tasks and Milestones.



Data Obtained from Past Industry Studies as Comparisons for this Report

California Air Resources Board. 2019 Study. (CA_CARB_GTI). California, multi-utility (including non-SoCalGas utilities in CA), multi-material, multi-facility study [4]. 76 samples.

National Operations Technology Development. 2013 Study. (Natl_OTD_GTI). National, multi-utility, multi-material, multi-facility study [2]. 62 samples.

National Washington State University Study. 2015 Study. (Natl_WSU_EDF). National, multi-utility, multi-material, multi-facility (e.g., service vs. main lines) study [1]. 212 samples.

SoCalGas Studies for this Report – Data and Study Terminology Definitions

All District Study (AllDisPilot). This study is distinct from the other pilot studies noted below. The study sample was stratified by district. A random sample was then drawn with the corresponding number of leak site samples (per district or district grouping) to preserve the correct proportion of the districts in the total SoCalGas population of leaks through all SoCalGas districts. The measurements were performed by GHD Corporation, Air Quality Services Group.

All District Leak Inventory Reduction Program (AllDisLIRP). This leak measurement data set consists of leak locations associated with the SoCalGas Leak Inventory Reduction Program (LIRP). The objective was to identify "large" leaks (greater than 10 scfh) within this leak population for prioritization. The leaks in this group are generally leaks detected many years ago. The locations in this study were system-wide and were measured by company crew or contractors: GHD Corporation & Gas Technology Institute (GTI). A subset of 10 LIRP leaks were provided for the current analysis because those were the only leaks for which concentration measurements and leak flow rate measurements were both obtained. The other LIRP leaks did not have this information and therefore were excluded from the analysis. As will be discussed later, this study was determined to have sample bias based on the sampling criteria because SoCalGas was specifically looking for the *largest* leaks. These 10 samples happened to have surface concentration measurements so they could be reviewed as part of this study.

Decision Tree 157 Pilot (DT157Pilot). This leak measurement data set was gathered by the SoCalGas research team to develop the Decision Tree methodology.

3-District Pilot (3DisPilot). Sample data from these leak locations were part of an implementation pilot study where the DT process plus subsequent leak flow measurements was deployed in 3 Operating Districts. This data contains the leaks that met the SoCalGas Decision Tree concentration thresholds. As part of the pilot study, all leaks were measured that met at least one of the four possible Decision Tree thresholds. Leaks were measured by company crew or contractors (GHD & GTI). The total screened number of leaks that had surface concentration measurements was 356. Of these 356 leaks, 56 samples had leak flow rate measurements. These three operating districts are considered a good representation of the overall SoCalGas service territory, and they are a geographical subset of the All District Study. The results of an overall sensitivity of leak rate to geographic operating district is presented later in this report.

3-District Pilot Low Specification (3DisPilotLowSpec). This includes eight leaks measured within a 3-District Pilot Study area that did not meet the SoCalGas Decision Tree Thresholds for surface concentration percent gas levels that would estimate leak flow rate to be greater than or equal to 10 scfh but were above 1% gas for unpaved surfaces (dirt or grass) or above 5% gas for cracks in paved surfaces. As will be discussed later, this small sample was determined to have sample bias based on the sampling criteria, since leak flow rates were measured at *lower* leak concentration levels for unpaved surfaces and cracks in pavement than the thresholds set by the Decision Tree for the same categories.

3. Approach for Field Sampling, Measurement Techniques, and Decision Tree Process

3.1. SoCalGas Process Development

SoCalGas began to search for a cost-effective means to identify and repair non-hazardous leaks as soon as reasonably possible to minimize the climate change impacts of methane emissions. In 2015, the Research team at SoCalGas began the development of a cost-effective approach of identifying and differentiating leaks on the buried distribution system that have high flow rates, for the purpose of prioritizing repairs.

Initial focus on Existing System Data and Leak Centering Process

Initially, the work was based on the hypothesis that existing system leak data obtained at the time buried non-hazardous distribution leaks are detected and graded could be leveraged to identify a sub-set of system leaks that had a greater probability of being high flow-rate leaks. Prior industry studies suggested that the number of system leaks that have a high flow rate is a small percentage of total leaks. The goal was to find an efficient way to identify these leaks, so they can be scheduled for repair. SoCalGas mined existing system data for "leak spread" but found that there was no discernable relationship between the available data and leak flow rate.

The spread of a leak is determined during traditional leak survey identifying the extent of the ground surface area where methane concentration indications are present. This is very useful from a safety evaluation standpoint as it may indicate the potential for hazard to nearby structures. However, as it relates to the flow rate of a leak no discernable relationship was found between the two data sets (see Appendix D).

Next, the concept of relating measurement of emissions from bar holes created during the leak centering process to the actual surface expression leak rate measurements of the leak site was investigated. Over thirty pending leak sites (Code 2s and 3s) were identified for an initial project within the Los Angeles basin area.

The surface expression measurements were completed and documented through detailed field notes indicating the associated concentrations found for each measurement as well as descriptive information of the ground characteristic of each measurement point. Once this was completed, distribution crews were dispatched to drill the bar holes required to center the leak on-site. Measurements of emissions were taken from the centering bar hole created by the crew prior to performing the repairs.

Unfortunately, the centering bar hole concentration data emission rates did not correlate well with the surface expression leak rate measurements of the site. However, some relationships were identified between the surface expression leak rate measurements and the concentration measurement data collected when the field notes indicated ground characteristics were similar.

Enhanced Leak Survey Practice

As more surface expression leak flow rate data was collected, some relationships of leak flow rate to methane concentration measurements began to emerge. Extensive surface expression method leak flow rate data was then collected along with methane concentration measurement data and corresponding types of ground surfaces and locations. Subsequent groupings of that data based on similar location descriptions yielded promising correlations to the leak flow measurements.

Given that the basis of traditional leak survey practice is to use methane *concentration* measurement data (e.g., % gas) as a means of determining when a leak is present, one should be able to leverage current leak survey practice to provide the additional leak concentration data needed to determine if a leak site has the potential to be a large leak with a higher *flow* rate (e.g., scfh). Another benefit of this approach is that the identification of potential large leaks occurs upon discovery of the leaks, which is in the most ideal timeframe possible.

3.2. Development of the Decision Tree Approach

Types of Surface Conditions

In 2015-2019, SoCalGas visited over three hundred code 2 and 3 leak sites to collect concentration screening value data. Based on the concentration data, 157 locations were selected for surface expression flow rate measurements (DT-157 SoCalGas Pilot).

The surface expression measurements were analyzed against site-specific characteristics (e.g., unpaved, crack in pavement, etc.) of ground-level methane concentration measurements. Next, concentration thresholds were developed for each surface category to identify the leaks with the potential for a high flow leak rate measurement.

A process was then developed where surface expression measurements to calculate leak flow rate are performed whenever one or more of the leak concentration threshold values are met or exceeded, so repairs can be prioritized.

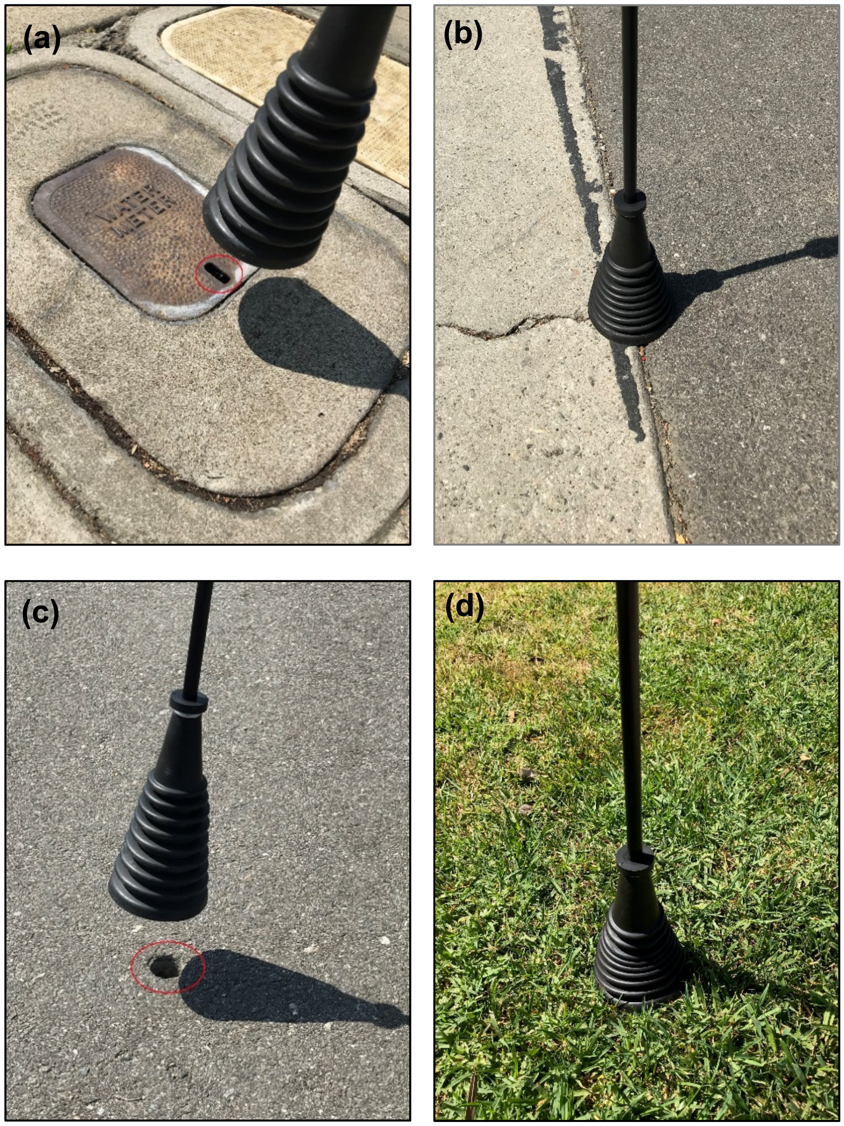
This methodology was termed the "Decision Tree" (DT) approach.

The DT approach collects the *maximum* methane concentration measurements at defined types of surface condition locations. The current process, which was also used to collect data as part of this study, uses four defined types of surface condition locations:

- Crack (or seam) In Pavement - CIP
- Unpaved Surface - US
- Bar Hole (leak survey type) - BH
- Small Sub-Structure (not gas system related) - SSS

The defined types of surface condition locations are shown in Figure 2 below.

Figure 2: Surface Condition Location Definitions.



(a) Sub-Structure-SSS, (b) Crack in Pavement-CIP, (c) Barhole-BH, and (d) Unpaved Surface-US

Methane Concentration Measurement Process

The operator utilizes the Heath DP-IR (Detecto Pak Infrared) or GMI Gasurveyor along with the survey probe attachment to survey the leak site by placing the conical end of the survey probe (as shown in Figure 2 above) directly onto the ground surface collecting drawn samples of methane in air.

This device contains a pump that draws the air samples from the cone-shaped probe at the ground surface to an analyzing chamber where infrared lasers are used to quantify the concentration of methane in the air and provide a methane concentration reading to the operator.

The spread of the leak is determined by probing the ground sub-surface and identifying the extent at which elevated methane concentrations are present.

Once the spread is determined the operator then identifies and records the highest sustained reading within the spread of the leak for each of the four surface conditions.

The required placement of the cone shaped probe for each of the 4 surface conditions is as follows:

- Crack (or seam) In Pavement - CIP: The probe is placed directly on top of the crack or seam and is in contact with the paved surface.
- Unpaved Surface – US: The probe is placed directly on top of and in contact with the unpaved surface whether it be soil, grass, or rocks.
- Bar Hole (leak survey type) – BH: The probe is placed directly on top of the bar hole with the cone shaped probe in contact with the ground surface and encompassing the bar hole.
- Small Sub-Structure (not gas system related) – SSS: The probe is placed directly on inside of or on top of the access hole(s) of a substructure (prior to venting or lifting the lid) with the cone shaped probe in contact with the ground surface and encompassing the access hole(s).

Training was provided to the operators in the pilot study to familiarize them with these additional requirements.

Decision Tree Concentration Threshold Values for Leak Flow Rate Measurement

The applicable *concentration* measurements are then compared to the threshold values, and any one (or more) of the up to four concentration measurements that meets or exceeds the threshold concentration value will then result (trigger) in that leak being classified as a potentially large, non-hazardous leak with a predicted leak flow rate of 10 scfh or higher.

The threshold values for concentration measurements by surface condition type are:

- 20% gas: Crack (or seam) In Pavement - CIP
- 5% gas: Unpaved Surface - US
- 80% gas: Bar Hole (leak survey type) - BH
- 60% gas: Small Sub-Structure (not gas system related) - SSS

These leak sites that trigger at least one of the defined types of surface conditions are then scheduled for leak flow rate testing using the process described below.

Leak Flow Rate Measurement Process

Leakage *flow* rates were measured from selected underground distribution pipeline leaks, chosen based on the Decision Tree methodology. The leakage flow rates were measured using the well-established and published Surface Expression methodology (detailed in Appendix A). Leak flow rates are reported in scfh of methane (CH_4).

These leak rate measurements provide an approximation of 'in-air' methane emission rates without the need to excavate the leak source. The study raw field data, including both concentration measurements and leakage flow rates, are in Appendix E.

3.3. Selection of Single vs. Facility/Material Specific EFs

SoCalGas also evaluated leakage spread data and "material" (e.g., plastic vs. steel, etc.) and "facility" (e.g., service vs. main) data to determine whether any of these system variables would help in predicting large leaks.

The discovery of the common mis-association of predicted material and facility data resulted from this effort and is demonstrated in the SoCalGas results of a collaborative study with CARB [4]. Based on this limitation, a single emission factor approach was selected.

3.4. Precision and Sample Size Analysis - Minimum Sample Size

A precision and sample size analysis (similar to a power and sample size analysis for hypothesis analysis) for desired confidence intervals was conducted ahead of the sampling[13, 14].

Precision and sample-size (PrSS) analysis is a key component in designing a statistical study that uses confidence intervals (CIs) for inference. It investigates the optimal allocation of study resources to increase the likelihood of the successful achievement of a study objective.

There is a strong correspondence between CIs and hypothesis tests. A $100(1-\alpha)\%$ CI can be obtained by inverting the acceptance region of the corresponding level α test. In other words, a $100(1-\alpha)\%$ CI provides the entire range of hypothetical values for a parameter of interest that cannot be rejected by the test at a significance level of α.

Despite the strong correspondence between PrSS used for CI analysis and Power and Sample Size (PSS) used for hypothesis tests, they will not necessarily lead to the same requirements for the sample size. A hypothesis test compares the parameter of interest with a single value, whereas a CI provides a range of plausible values. Thus, for the same significance level, the sample-size requirements for the CI will generally be larger than for the hypothesis test.

Sample Size for a One Mean Confidence Interval

Although SoCalGas used the bootstrap method to infer these population mean leak rates, the classical method of Precision and Sample Size is a useful tool while setting up a sampling plan. The selection of $1-\alpha$, probability of achieving the CI, and desired precision (i.e., the width of CI) are subjectively set; therefore, multiple values for these parameters are often selected for comparison. The same can be true of the estimated standard deviation of the measure of interest.

Using the typical/expected values from the national studies and the SoCalGas DT-157 studies, a set of inputs to the analysis was established:

- Confidence Level (level): 95%

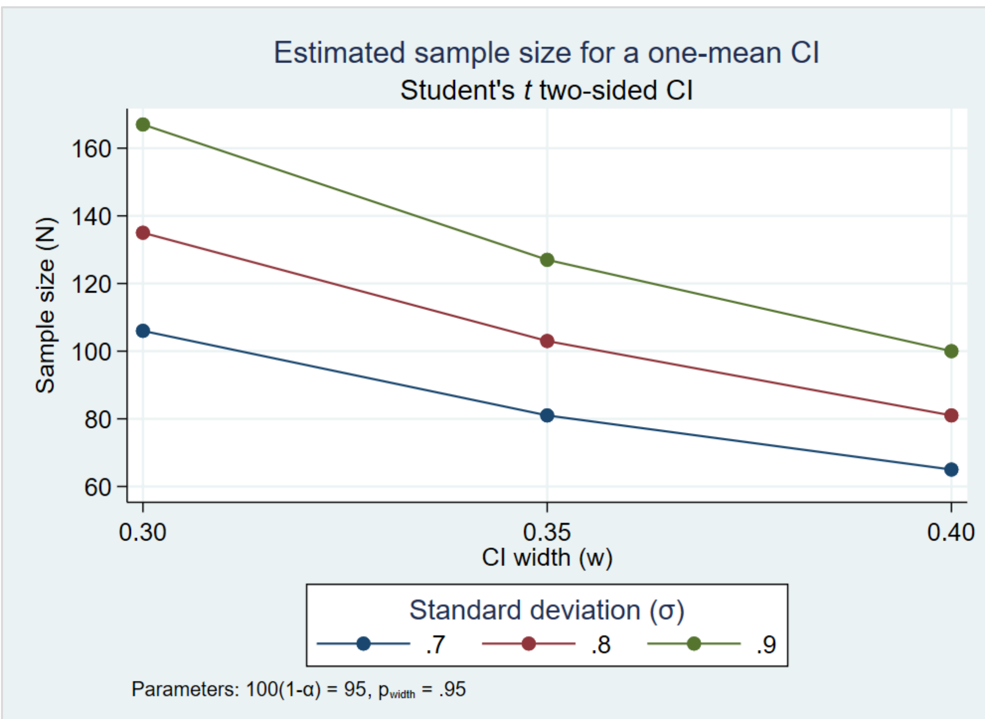
- Estimated standard deviation (SD) of log(10) of the Leak Rate in scfh: 0.7 - 0.9
- Desired precision (width) of log(10) of leak rate in scfh: 0.3 - 0.4
- Desired probability of achieving the CI width (Pr_width): 95%

With these input values, a sample size (N) calculation for a one mean CI of the log(10) of the leak rate was conducted and the results are presented in both Table 2 and Figure 3 below.

Table 2: Sample Size for a One Mean Confidence Interval of Log(10) Leak Rate.

level	N	Pr_width	width	sd
95	106	0.95	0.3	0.7
95	135	0.95	0.3	0.8
95	167	0.95	0.3	0.9
95	81	0.95	0.35	0.7
95	103	0.95	0.35	0.8
95	127	0.95	0.35	0.9
95	65	0.95	0.4	0.7
95	81	0.95	0.4	0.8
95	100	0.95	0.4	0.9

Figure 3: Sample Size for a One Mean Confidence Interval of Log(10) Leak Rate.



A centered value of 100 samples is shown in Table 2, which is a good target sample size to collect. This study resulted in 291 samples, which meets the one-mean sample size requirement for a standard deviation of 0.9 and CI width of 0.3 at 95% confidence.

Sample Size for a Bayesian Proportional Analysis

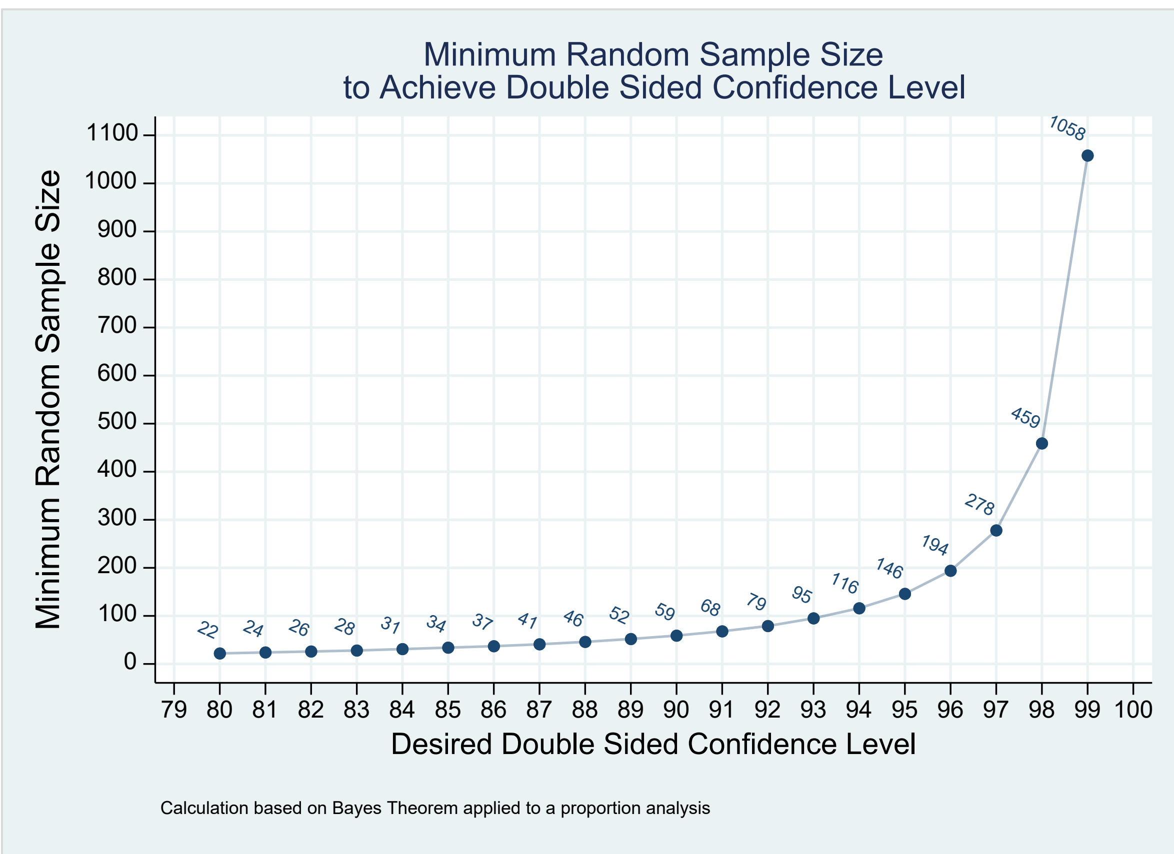
A similar analysis for minimum samples sizes was conducted but related to the Bayesian proportional analysis, which was done to create the Decision Tree performance error table.

The term proportional, as related to Bayesian analysis, refers to an analysis that is measuring the proportion (e.g., percentage) of a sample that falls in a certain category vs. calculating a variable of interest and its expected value and any other parameters. In this case, the Bayesian analysis is coherent and provides the expected value as well as the credible intervals at a 95% confidence level for the errors in the DT predictions.

Figure 4 below shows the minimum sample size required for a given two-sided (two tailed) confidence level. This is the sample size for any category of leak flow rate that will bring the Bayesian analysis Upper Prediction Limit (UPL) below the specified single sided confidence limits for the analysis when there is no occurrence in that category of a leaking sample.

The calculation for minimum sample size uses a conservative uniform (aka ignorant) prior for the Bayesian analysis to establish this significant sample size[15]. The sample size was established to ensure a better than 95% single sided credible band (aka, upper or lower prediction limit) was achievable for the proportion analysis.

Figure 4: Sample Size for a Bayesian Proportional Analysis by Confidence Level.



Ultimately, the error analysis had 117 (for Type I error calculation) and 174 (for Type II error calculation) respectfully, comfortably above the desired size. This established a conservative number of samples, since a uniform distribution is used for the proportion prior. This will be described in a later section of this report.

3.5. Physical Sampling Plan - Where to Sample

It is essential that a simple random or stratified random (for efficient, smaller sample sizes) sample be used vs. any other, potentially biased sample. A random sample is designed so each leak has the same likelihood of being chosen as part of the sample from the population of leaks. It will improve the accuracy of the results, helping ensure the statistics inferred from the sample are representative of the population. When such a proper random sample is taken then the analysis done from the sample such as bootstrap, Monte Carlo, regression, Bayesian proportions and the inferred results from the same are statistically sound.

For the SoCalGas *All District Study*, the non-hazardous leak population was stratified by operating district. A random sample was then drawn with the corresponding number of leak site samples (per district or district grouping) to preserve the correct proportion of leaks in each. This study contained 78 samples, which as discussed earlier and can be seen in Figure 4 is greater than the 65 samples required to achieve the desired 95% double-sided credible band with a CI width of 0.4 and standard deviation of 0.7.

As was done in this study, during the development of the Decision Tree process and its ongoing application for leak measurements, one should also take a random sample from the leaks that the Decision Tree estimates as *not* large leaks (i.e., less than 10 scfh) to confirm for true/false negatives. This is important to: (a) continually scan the population for situations that may have changed over time, and (b) continue to confirm and refine the Decision Tree performance metrics.

4. Methodology Overview of Data Collection and Statistical / Probabilistic Analysis

4.1. Descriptive Statistics of Study Samples

Standard descriptive statistical analysis was conducted including calculation of sample means, medians, percentiles, interquartile ranges, and other statistics. Various analysis and plotting techniques were used to confirm sampling bias and draw high-level conclusions on the different individual and grouped sample leak rate distribution center tendencies, uncertainties, and shape. An evaluation of SoCalGas data alongside recent Industry studies served as a baseline comparison.

4.2. Data Transformation, Regression, and MCMC Models

Data transforms were used to ensure that any regression utilized had a sound basis. Linear Regression (LR), and Analysis of Variance (ANOVA) were used to quality check sample set data, spot outliers, confirm assumptions, assess regression, and assess probabilistic residuals and diagnostic measures.

These steps led to the selection of a non-biased and robust SoCalGas sample set for further analysis. The highlights of these analysis methods are presented in the report body with additional, supporting regression details in Appendix B.

4.3. Decision Tree Predictive Performance

A purely probabilistic Bayesian analysis[15-17] was used to measure the Decision Tree performance that grouped detected leaks into two categories: "Large" leak rate (greater than or equal to 10 scfh) and "Not Large" leak rate (less than 10 scfh) predicted leak *rate category* based on site *concentration* measurements. A full false/true negative/positive error table (Type I and II error) was developed with Bayesian derived lower and upper prediction (credible) limits.

4.4. Population Mean Leak Rate Inferential Analysis

Resampling with replacement (Bootstrap) analysis[18-20] of field leak rate data and Monte Carlo sampling of a fitted data distribution of leak rates were both used to infer the population mean leak rates with upper and lower confidence limits from the sample data.

4.5. Emission Factor Determination

The SoCalGas emission factors were derived using the combination of the appropriate bootstrap population leak rate means and the Bayesian Decision Tree error table percentiles.

4.6. Method of Emission Factor Application

Several scenarios were developed to show how a utility could apply the emission factors based on operational considerations and if leak rate measurement and/or concentration measurements were taken.

4.7. Quality Assurance

Statistical Checks

The field data sample sets were reviewed from a data quality perspective through statistical quality checks, including:

- To establish if there were unexplainable outliers or extreme values, a set of statistical diagnostics was conducted, including: DFBETAs, Lowess, Leverage, and others.
- Normality of the response variable (leak rate) and the associated predictive residuals were checked, leading to applying a log transformation of the leak rate data which achieved a normal distribution of the transformed data.
- A combination of ANOVA, Regression, and non-parametric statistical tests (e.g., Kolmogorov-Smirnov) were conducted to test for normality of variable distributions, comparison of sample means, and other statistical parameters. These tests are noted in the report and/or documented in the appendices when appropriate.
- Since there is a danger in over relying on simple to use and quantitative statistical tests, this research also examined the normal quantile plot to determine normality rather than blindly relying on a few test statistics[21, 22]. For example, the Kolmogorov-Smirnov test[23] generally is not very powerful against differences in the tails of distributions. For these reasons, the Kolmogorov–Smirnov is not a particularly powerful test in testing for normality[24]. Hence, the quantile normal plots of the data were also carefully analyzed.

Probabilistic Regression Check

- As a secondary check on the traditional linear regression and analysis of variance (ANOVA), a Bayesian Monte Carlo Markov Chain (MCMC)[25] Metropolis-Hastings Sampling (MHS)[26, 27] random walk and Gibbs Sampling (GS)[28] non-frequentist and non-parametric analysis was also completed.

Significant Figures

- The values of leak flow rate measurements are reported to an extended number of digits in tables to allow comparison and prevent cumulative rounding errors when conducting calculations involving multiple variables and bootstrap analysis. These values are typically listed with three *digits* after the decimal place.
- The limiting significance values come from the precision of the flow rate measurement equipment (scfh), and the calculated emission factors (EF) are limited to two digits based on this precision.

- When the average leak flow rate data is combined with the Bayesian expected proportions for the Decision Tree assignments to calculate Emission Factors (EF), the total number of significant figures reported is three, which results in two digits after the decimal place.
- The output of regression analysis is automated and reported to many decimal places in the standard regression output table. These values were retained, and it should be noted that the precision of the analysis is not represented by these formats.

Standard Conditions

- The standard conditions related to the leak concentration and leak flow rate measurements in the report are to 1 atm of pressure and 60F for temperature.
- Additional details on temperature compensation of equipment is provided in the appendix.
- Leak flow rate measurements and the emission factors derived from the report are reported in scfh methane (CH_4).

Distribution Fitting and Monte Carlo Sampling

- A series of distribution fits was conducted on the log(10) of the leak rate for the SoCalGas sample set (291 samples). The results are described in Appendix C and include a few of the selected distributions that were fit and their goodness of fit measures.
- For illustrative purposes, the log-normal distribution fit was selected. The log-normal fit was sampled using a Monte Carlo method where the sample size of the distribution was set to the same sample size used to fit the distribution. This ensures that the average leak flow rates estimated from the Monte Carlo analysis contain the uncertainty associated with the limited sample size from which they were derived.
- As noted, the distribution fit was checked with multiple goodness of fit parameters, and the error associated with the fit done by the associated software was orders of magnitudes smaller than the uncertainty associated with the random sampling of the distribution (as noted below), so this fit error was not considered.
- The log-normal distribution fit was *not* used to calculate the emission factors, since a full bootstrap resampling with replacement analysis was done on the actual field leak flow rate sample measurements. However, the two were compared in the report to illustrate that if an operator does not have an adequate sample to run a bootstrap analysis of the average leak flow rate, then sampling from a fitted distribution could provide a "stop-gap" alternative until a large enough sample size from the field is obtained.

Leak Concentration and Flow Rate Measurement Error/Uncertainties

The concentration measurement and flow rate measurement uncertainty for the techniques used in this study have been laid out extensively in the referenced reports. In this study, the leak flow rate measurements are considered the baseline standard (i.e., an accurate indication of the true leak flow rate), and the concentration measurements are used to trigger the Decision Tree threshold points to determine if a leak is assigned to be a predicted *Large* or *Not Large* leak.

Therefore, the Bayesian analysis which calculates the true/false negatives and positives of the DT assignments inherently includes all measurement errors and uncertainty which is folded into those proportions. Further, the uncertainty from the population bootstrap resampling is many times larger than the measurement error, as is the uncertainty generated from the Bayesian proportional analysis and the associated upper and lower prediction limits.

Carrying Uncertainty Through to the Emission Factor Calculations

Additional steps are necessary to properly carry through the uncertainty related to the average (i.e., expected or baseline) emission factor and provide confidence limits at a selected confidence level for the EFs.

To do this, one would run Monte Carlo analysis by drawing from the bootstrap average leak rate population distributions of the appropriate data set and category of the leak rate (large and not large) and then weight those by the Bayesian proportions for those categories. This would be done thousands of times, picking the average leak flow rates and the associated Bayesian proportions from those distributions and then calculating the associated emission factors.

This would provide a full distribution of the emission factors for each category; one could then select the confidence level of choice (e.g., 95%) to generate the confidence interval around the average emission factors.

However, one would still use the expected (average) value of the emission factors in practice, but the confidence bands would help establish the level of uncertainty in those values.

SoCalGas plans to continue to implement the DT and leak flow measurement process system-wide and collect additional samples from ongoing leak surveys. This greatly increased data set will eventually be used to map the full uncertainty through the entire process to allow a set of confidence bands to be calculated for the emission factor's expected values, i.e. the base case. As of now, it should be noted that this information is not available to the emissions estimates currently being reported by the industry.

5. Analysis and Results

5.1. Descriptive Statistics

Comparison of SoCalGas Study to Industry Studies

The data obtained from the eight studies (described above) were quality checked and arranged into a single flat table.

Each of the studies used a Hi-Flow sampler and the dynamic flux chamber method. The main differences are likely the shape/material of the enclosure and the CGI used at the outlet of Hi-Flow. The minimum quantifiable leak rate, assuming a CGI accuracy of 5 ppm is approximately 0.002 scfh.

- WSU/EDF 2015: Hi-Flow + enclosure + CGI
- CARB/GTI 2019: Hi-Flow + enclosure + CGI
- GTI/OTD 2013: Hi-Flow + enclosure + CGI
- Five SoCalGas Studies: Hi-Flow + enclosure + CGI

As noted in a previous section, three Industry leak rate studies were used as baseline studies to which the SoCalGas pilot study were compared and contrasted.

Additionally, there were five SoCalGas studies. Three of these studies are considered "core" studies and are the focus of the emission factor calculation. These include the 3-District Pilot, the All District Study, and the Decision-Tree (DT) 157 study.

The remaining two SoCalGas studies (3DisPilotLowSpec and AllDisLIRP) contained very limited sample sizes of 8 and 10 samples respectively. In addition to being limited, these sample sets exhibited known sampling bias as will be demonstrated later in the report. That said, these data sets are still included in the analysis for comparison as well as to demonstrate how a biased sample could impact the statistical analysis and therefore bias the resulting emission factors.

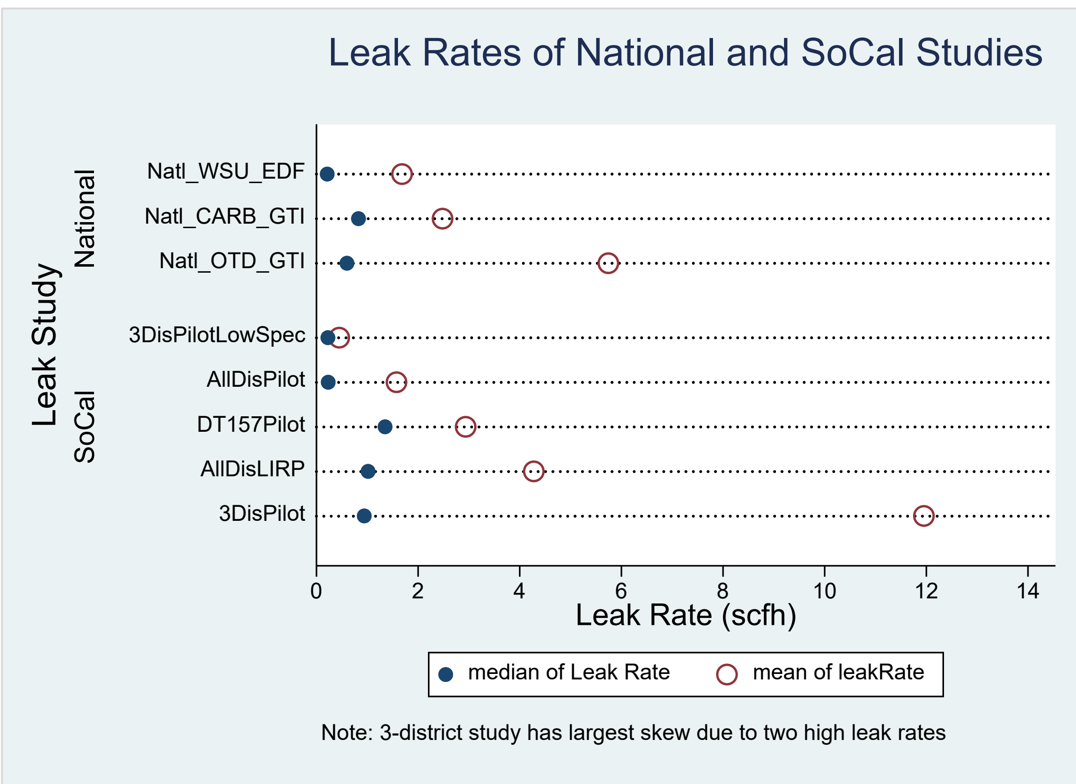
Sample counts as well as *methane* leak rate mean, minimum, and maximum for each of the eight studies are compiled in Table 3 below.

Table 3: Leak Rate Mean, Minimum, and Maximum by National and SoCalGas Study.

	National			
Study	**N(count)**	**mean(scfh)**	**min(scfh)**	**max(scfh)**
Natl_CARB_GTI	76	2.481	0.007	20.400
Natl_OTD_GTI	62	5.743	0.044	95.400
Natl_WSU_EDF	212	1.683	0.003	109.472
Total	**350**	**2.576**	**0.003**	**109.472**
	SoCalGas			
Study	**N(count)**	**mean(scfh)**	**min(scfh)**	**max(scfh)**
3DisPilot	56	11.952	0.020	373.000
3DisPilotLowSpec	8	0.448	0.060	1.640
AllDisLIRP	10	4.276	0.192	30.702
AllDisPilot	78	1.575	0.003	27.045
DT157Pilot	157	2.935	0.003	43.776
Total	**309**	**4.205**	**0.003**	**373.000**
Grand Total	**659**	**3.340**	**0.003**	**373.000**

The mean and median of the eight studies are plotted in Figure 5.

Figure 5: Leak Rate Median and Mean Plot by National and SoCalGas Study.



Data analysis using Dot Plots

The individual leak samples are plotted in a vertical dot plot and delineated by SoCalGas study (Figure 6). This type of plot is similar to a two-variable scatter plot, but, for the purposes of this analysis, the dot plots are used to visualize single variable trends of data. Most data for the three studies fall between 0.1 and 10 scfh except for the two smaller studies where 3-District Pilot Low Specification does not have leak rates *above* 1 scfh except for one point. Additionally, the All District LIRP data does not have leak rates *below* 0.1 scfh. The All District Study also has significantly more data on the lower end of the leak scale below 0.1 and 0.01 scfh.

In general, the various studies have a relatively large spread, but the 3-Distict Pilot Low Spec and the All District LIRP have a tighter spread, which may be a result of a smaller sample set as shown in Table 3 or another factor such as sampling bias. A further analysis of these two studies is presented later in this report.

A vertical dot plot of the three national studies is shown in Figure 7 below which reveals that the WSU study has significantly more data with leak rates less than 0.1 and 0.01 scfh. This may reflect the lower detectable leak rate in the WSU study (0.003 scfh) compared to the other national studies.

Figure 6: Leak Rate Plot by Sample for Five SoCalGas Studies.

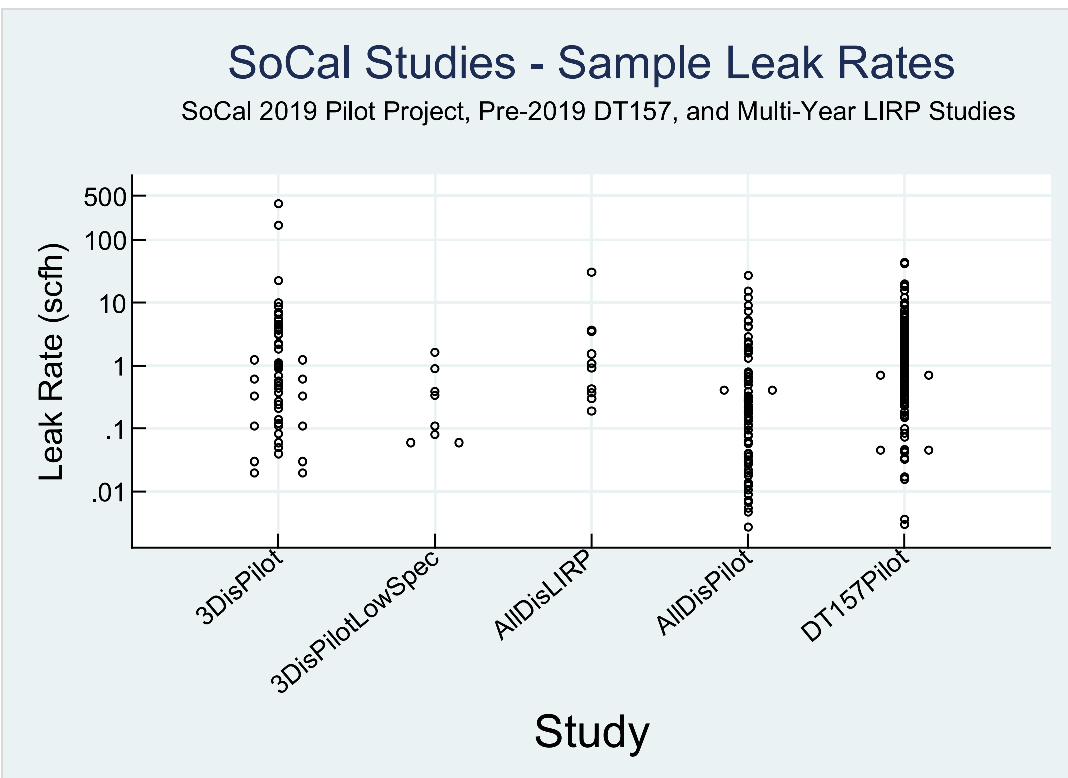
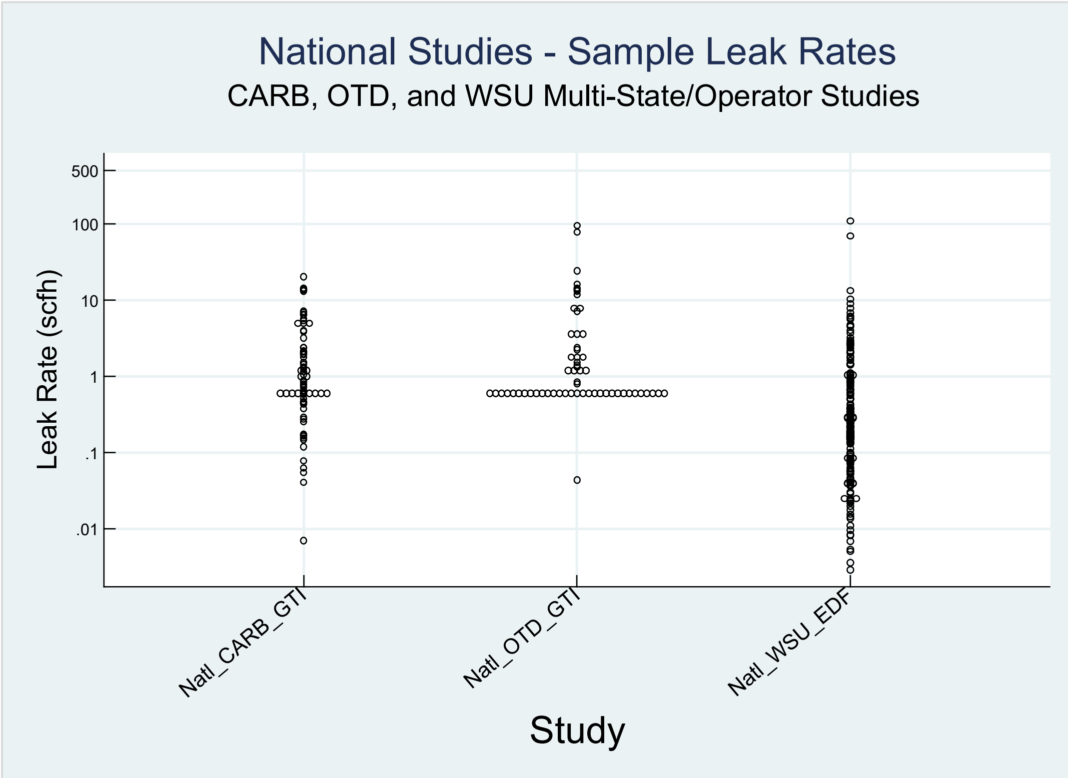


Figure 7: Leak Rate Plot by Sample for Three National Studies.



The leak rate means and 95% confidence interval limits (5% and 95%) (grouped by national and SoCalGas studies) are shown in Table 4 below. The confidence intervals show similar lower levels, but the combined data set for all five SoCalGas Pilots has a higher upper level as would be expected by the higher maximum values in the data set and their distribution. Focus will be placed on the bootstrap confidence intervals later in this report as they are more robust against issues with non-normally distributed variables.

Table 4: Leak Rate Mean and 95% C.I. National vs. SoCalGas Studies.

Study	Obs	Mean	[95% Conf.	Interval]
National	350	2.576	1.534	3.617
SoCal	309	4.205	1.551	6.860
Total	**659**	**3.340**	**1.980**	**4.699**

The sample count and sample percentiles 5%, 50% (median), and 95% are compiled in Table 5 below.

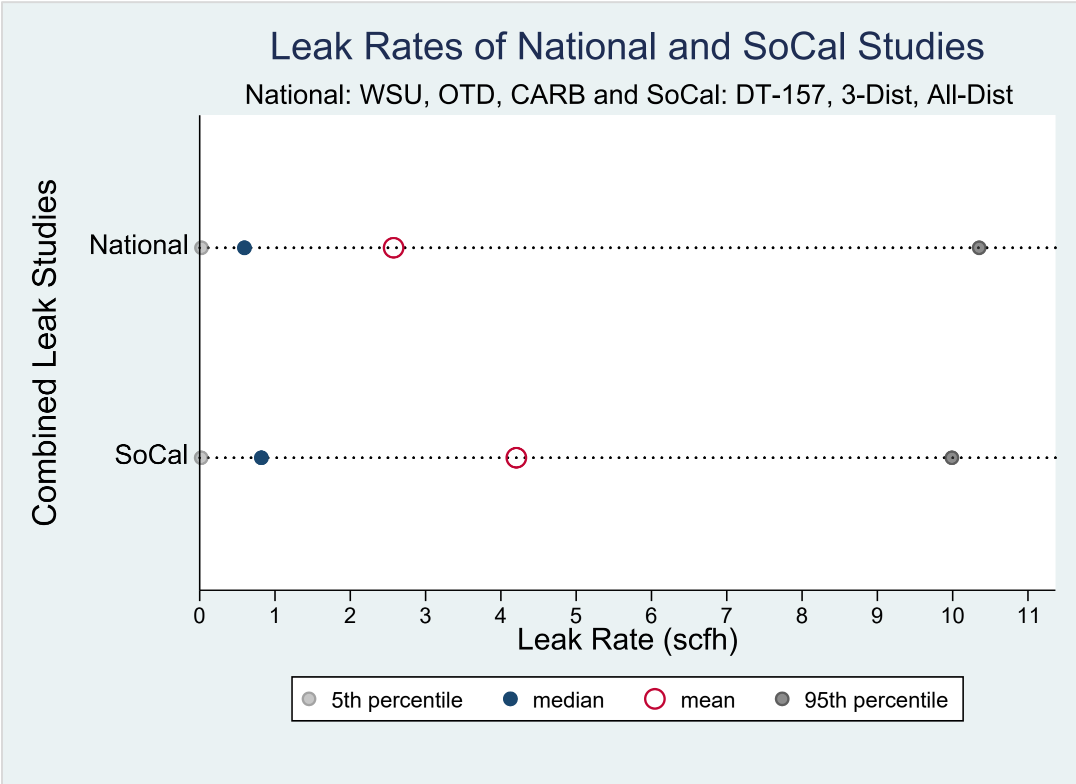
Table 5: Leak Rate Median, 5%, and 95% Percentiles by National and SoCalGas Study.

	National			
Study	**N(count)**	**p5(scfh)**	**med(scfh)**	**p95(scfh)**
Natl_CARB_GTI	76	0.063	0.827	13.800
Natl_OTD_GTI	62	0.600	0.600	16.200
Natl_WSU_EDF	212	0.014	0.211	4.753
Total	**350**	**0.024**	**0.594**	**10.352**
	SoCalGas			
Study	**N(count)**	**p5(scfh)**	**med(scfh)**	**p95(scfh)**
3DisPilot	56	0.030	0.940	22.290
3DisPilotLowSpec	8	0.060	0.225	1.640
AllDisLIRP	10	0.192	1.015	30.702
AllDisPilot	78	0.007	0.231	9.192
DT157Pilot	157	0.042	1.350	9.990
Total	**309**	**0.020**	**0.819**	**9.990**
Grand Total	**659**	**0.020**	**0.600**	**10.000**

A simple but compelling plot of the key points of the two tables above is shown in Figure 8 below. This plot shows the combined datasets from national and combined SoCalGas studies median, mean, 5th percentile, and 95th percentile of the samples sets.

There is especially strong similarity to the percentile (5%, 50%, and 95%) statistical measures between the two large combined data sets of 0.024 vs. 0.020, 0.594 vs. 0.819, and 10.352 vs. 9.990 respectively.

Figure 8: Leak Rate Lower/Upper Percentiles by Combined National and SoCalGas Studies.



A similar plot to Figure 8 above, but with all eight studies will be presented in an upcoming section on sample bias and will be discussed in association with identification of studies with sample related bias.

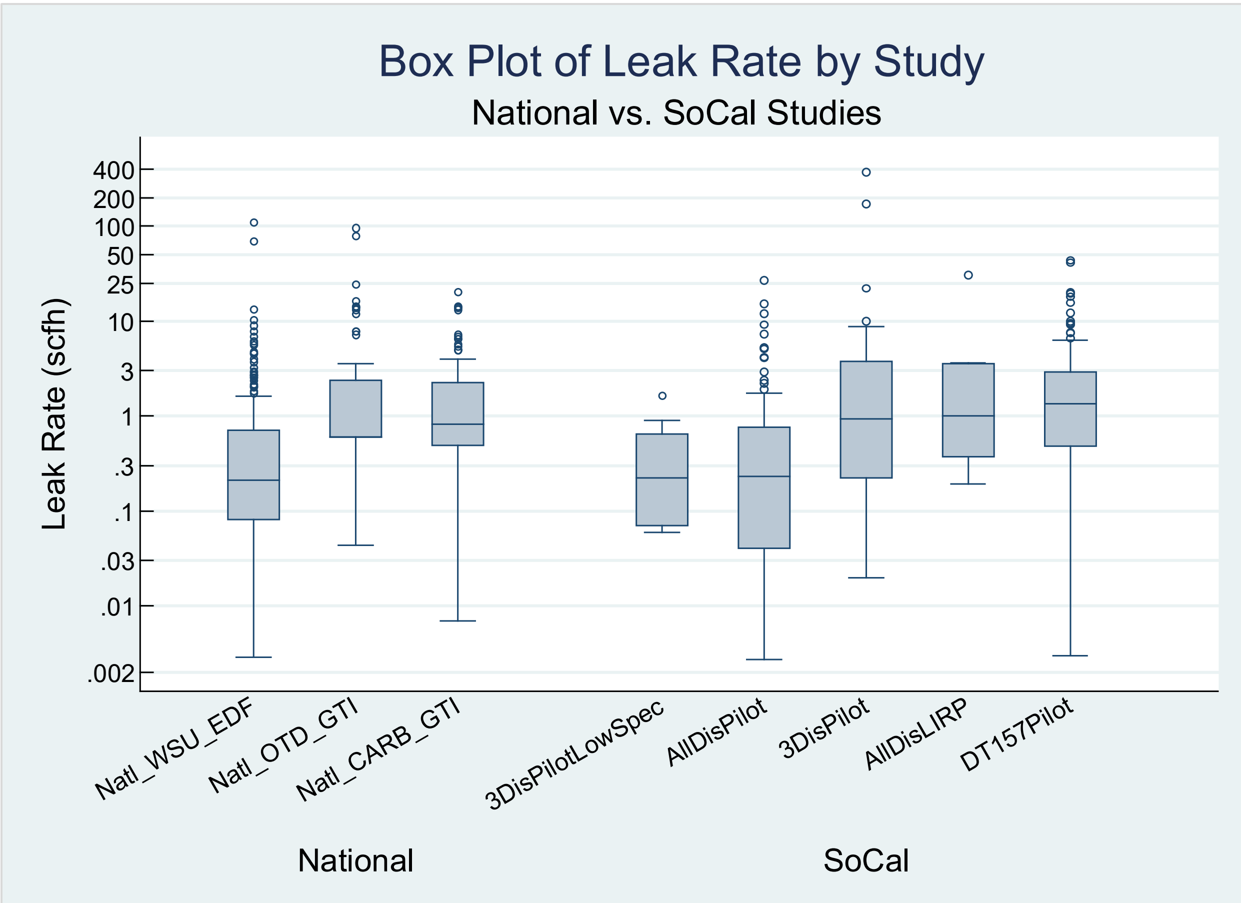
Data analysis using Box Plots

A box plot of the same leak data from the eight studies is shown in Figure 9. The box plot contains 50% of the data within the box, 25% above and 25% below the box. The median is drawn as a horizontal line within the box. Half the data is above and below the median. The box tails (whiskers) extend up to lesser of either the most extreme value or 1.5x the box height (also known as the inner quartile region, IQR). Values outside the tails are known as outliers or extreme values in general - but this should not infer that there is something wrong with the data, rather a close look should be taken of these points. As both the vertical dot and box plots are using logarithmic scales for the y-axis (leak rate), one can see that the distribution of the data appears to be log-normally distributed. This will be further analyzed in the Transformations section of this report.

The national OTD and CARB studies have similar distributions of data with nearly overlapping IQRs. However, the WSU study has nearly the entire IQR below the CARB and OTD studies. For the SoCalGas studies, the same trends (as explained in the vertical dot plot) are apparent with the 3-District Pilot Low Specification and All District Study. The studies have noticeably lower IQRs, with the 3-District Pilot having its highest value within the upper whiskers (or IQRs) of the other studies. This indicates low bias.

Additionally, the All District LIRP study shows its lowest value within the IQR's of the other studies, indicating high bias. This will be more quantifiably reviewed using frequency plots in the next section.

Figure 9: Leak Rate Box Plots by National and SoCalGas Studies.



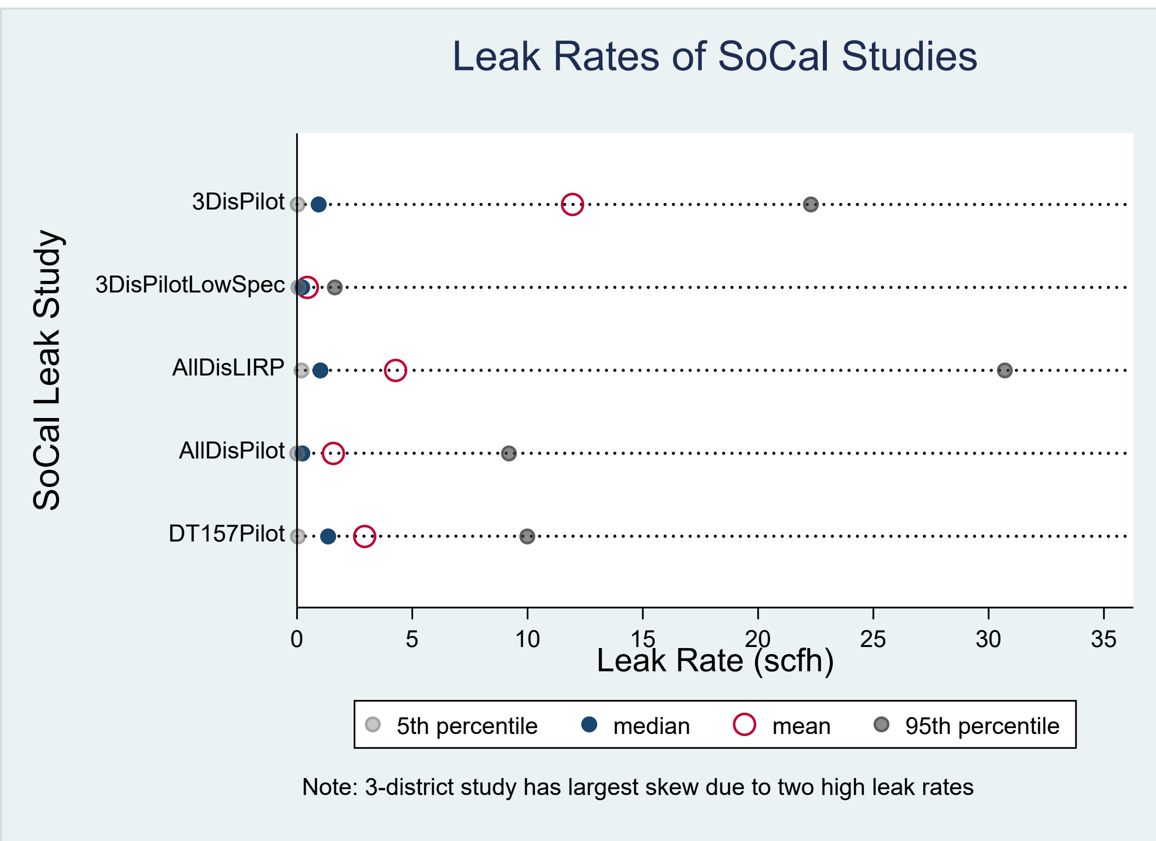
5.2. Removal of Studies with Sample Bias

Based on the analysis in the section above and more critically the knowledge of "confirmation bias" for the sampling of the 3-District Pilot Low Specification and the All District LIRP, these two studies will be removed from the three core studies prior to further analysis and incorporation into the emission factor calculations.

The five studies are plotted on a horizontal dot plot in Figure 10 below to allow comparison of study means, medians, and lower 5th and upper 95th percentiles. The 3-District Pilot Low Specification study has the lowest mean, median, and 95th percentile of the five SoCalGas studies. This study's sample selection used a lower Decision Tree concentration criterion (see Approach section for the criteria values) to check on the performance of the criteria and to look for additional false negatives by triggering a leak rate measurement at a lower threshold of leak concentration values. One would expect this to bias the sample to lower values than a purely random sample, which is the case.

The same is true of the All District LIRP study where this sample has the second highest mean and the highest 95th percentile. This study's sample selection was designed to pick higher rate leaks for the study. One would expect this to bias the sample to higher values than a random sample, which is the case. A look at the cumulative fraction plots will reinforce these observations.

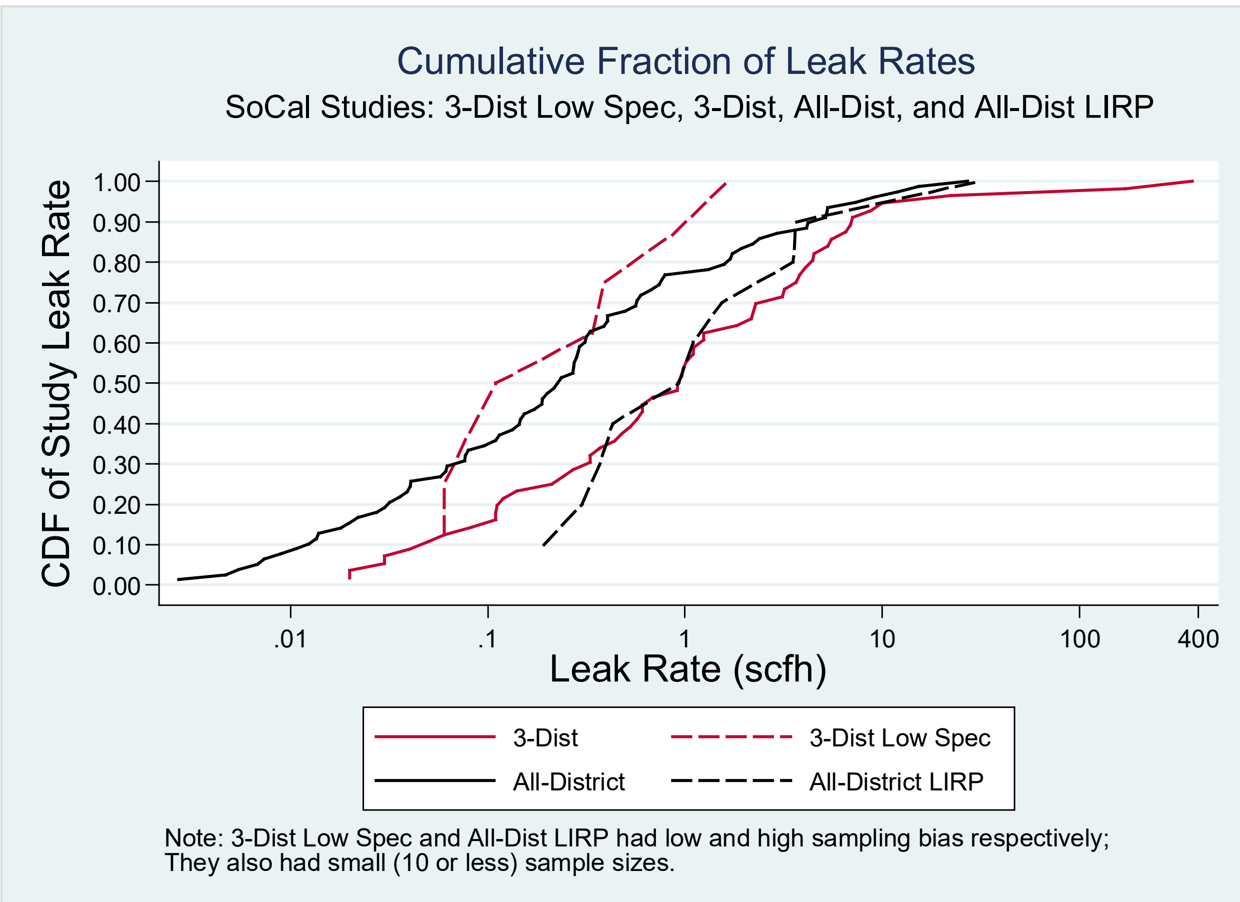
Figure 10: Leak Rate Lower and Upper Percentiles by SoCalGas Study.



The effect of sampling bias on the two smaller studies is shown below in Figure 11 where the biased studies (dashed lines) are shifted to the left (3-District) or right (All District) of their associated larger and randomly sampled studies.

The remainder of this report (with exception of one general ANOVA analysis) will focus on the three SoCalGas studies combined into an overall SoCalGas sample set for further analysis. This combined SoCalGas sample set then forms the foundation for the probabilistic-based emission factors associated with the Decision Tree groupings.

Figure 11: Leak Rate Cumulative Fraction of Two Sample-Biased SoCalGas Studies.

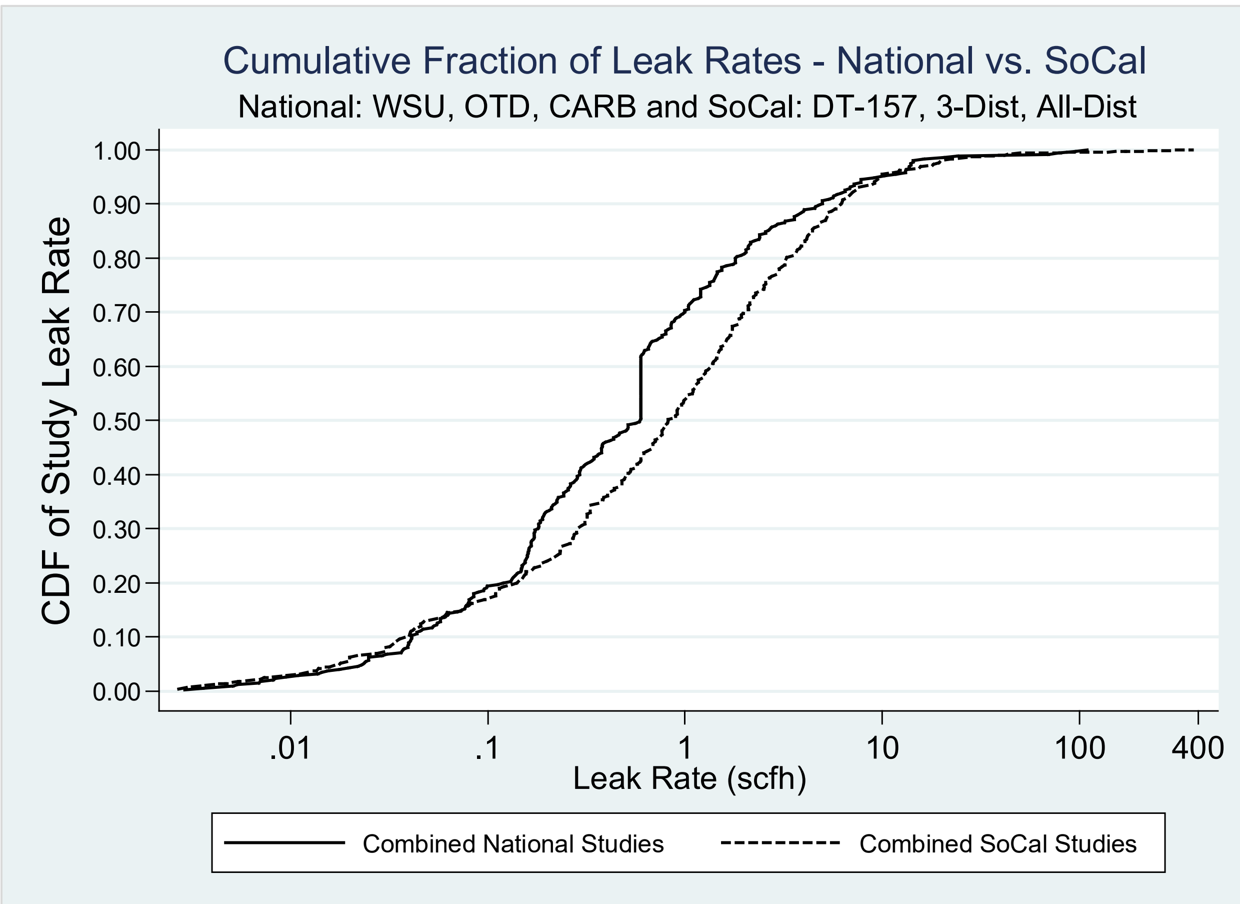


Data Analysis using Cumulative Fraction Plots

A more quantitative review of the leak rate distributions can be performed through cumulative fraction plots. These are sometimes referred to as frequency diagrams or cumulative distribution functions when discussing theoretical distributions. The cumulative fraction plots of the combined national and SoCalGas studies are shown in Figure 12 below.

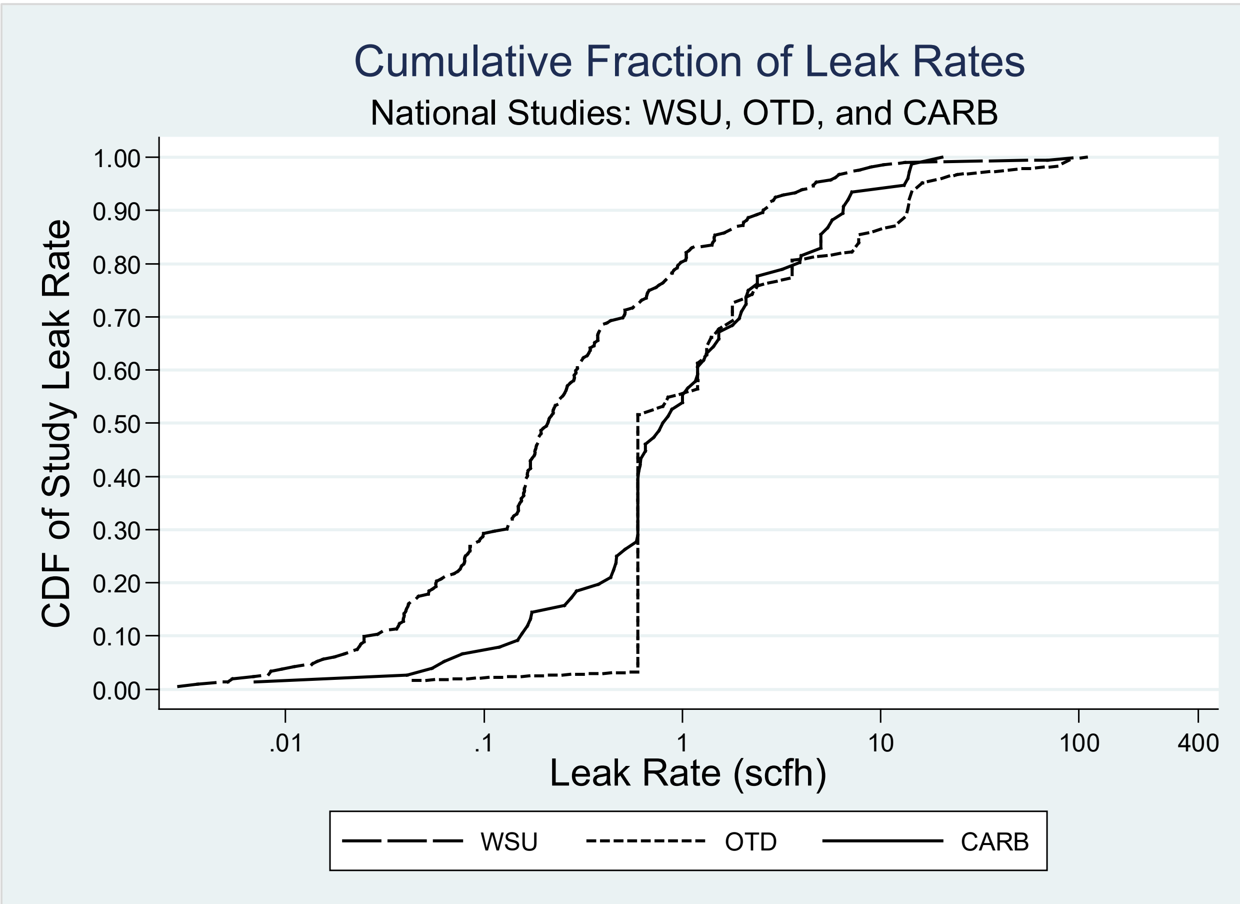
The distributions track on top of each other (on the ends) and diverge between approximately 0.20 and 0.90 fraction of the samples. The studies have effectively the same fractions (percentiles) of samples below 0.1 scfh and above 10 scfh. One could say they have the same fraction of "large" non-hazardous leaks, i.e. approximately 95% of the leaks are less than 10 scfh for both combined groups. Quantitative tests of sameness are presented later in this report.

Figure 12: Leak Rate Cumulative Fraction of Combined National and SoCalGas Studies.



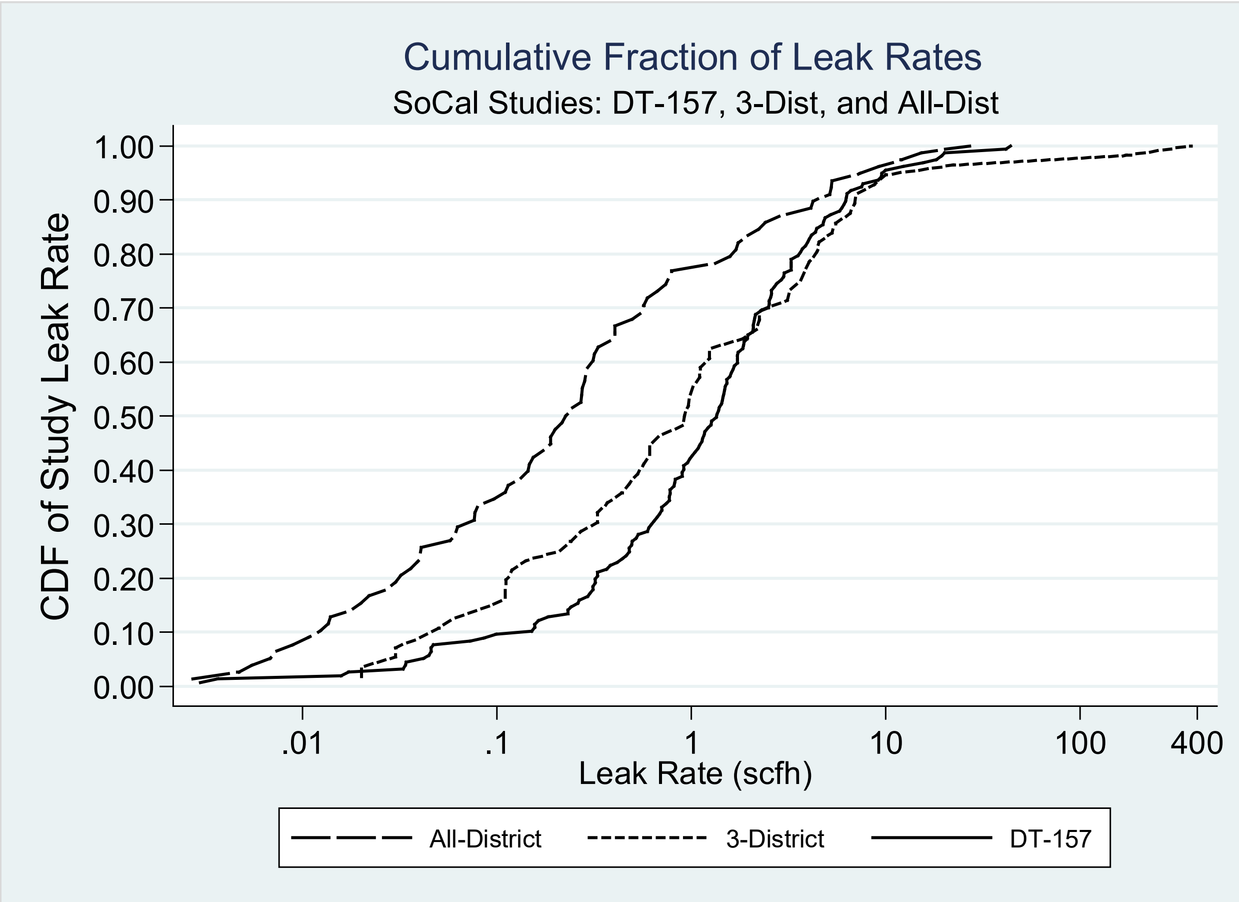
In Figure 13, the three national studies are plotted as cumulative fractions. The OTD and CARB studies are similar and intersect each other four separate times between 1 and 10 scfh, whereas the WSU study shows a lower overall distribution of leaks and is always to the left and above the other two study cumulative fraction plots. This is probably due to the lower detection limit in the WSU measurements compared to the other studies.

Figure 13: Leak Rate Cumulative Fraction of National Studies.



Finally, in Figure 14, the three SoCalGas studies are plotted as cumulative fractions. The 3-Distict and DT-157 studies are similar and intersect each other three separate times between 1 and 10 scfh, whereas the All-District study shows a lower overall distribution of leaks and is always to the left and above the other two study cumulative fraction plots.

Figure 14: Leak Rate Cumulative Fraction of Three SoCalGas Studies.



5.3. Data Transformation

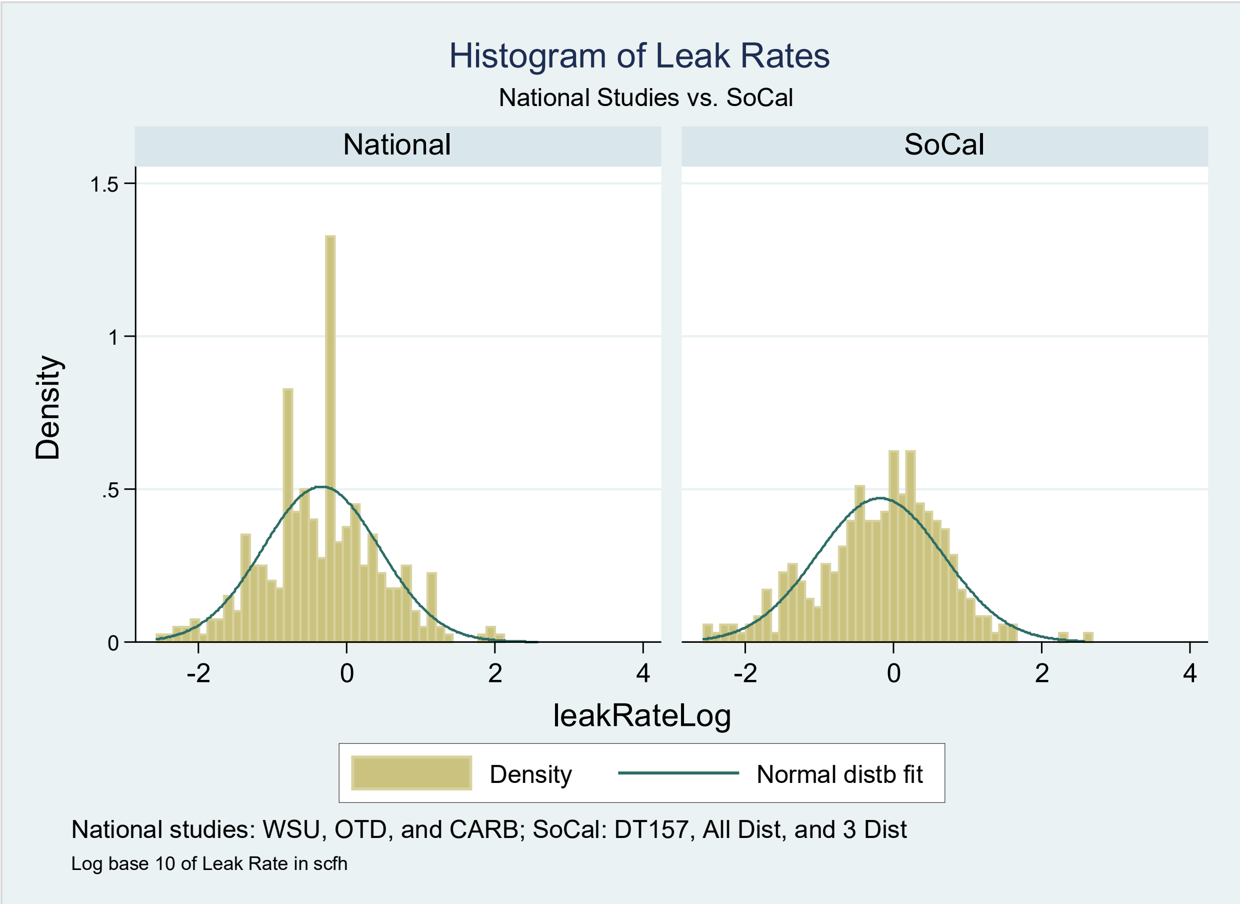
In prior sections, the national and SoCalGas data sets were presented, the data distributions were explained, and the studies with known (a priori) sampling bias (which were shown through the descriptive statistics) were removed.

Prior to running regression and probabilistic analysis to check for outliers and/or other issues with the data sets, this section analyzes the combined SoCalGas and combined national studies (as a baseline) to the leak rate distributions to determine if a transformation can be applied to make the rates normally distributed. The combined national studies are done for comparative purposes. Based off of the three analysis further described below, the log (base 10) of the leak rate is shown to be an appropriate transformation and will therefore be used in regression analysis, as well as for residual and diagnostic analysis.

Histogram of Log Transformed Leak Data

The national and SoCalGas combined sets were transformed to log(10) of the leak rate and plotted as histogram distributions. These are shown side-by-side in Figure 15 below. A normal distribution fit is overlaid on the density plots and shows good agreement. However, a more quantitative measure is needed.

Figure 15: Leak Rate Histogram of Log(10) of Combined National and SoCalGas Studies.



One-sample Kolmogorov-Smirnov Test for Lognormality

A Kolmogorov-Smirnov (KS) test for normality of the log(10) of leak rate was conducted on both the combined national studies, see Table 6, and for the combined SoCalGas studies, see Table 7. For the Kolmogorov-Smirnov (K-S) test, a combined K-S p-value of greater than 0.05 for a one sample test of normality indicates there is no support that the distribution is not normal distributed.

The K-S test is set up and reported in a manner opposite than most null hypotheses which are stated in a way that there is no relationship (i.e. the results are random) between two variables being studied. Both statistical tests result in supporting the possibility that the log transformed leak rate data is normally distributed as shown by their respective p-value being greater than 0.05.

Table 6: Kolmogorov-Smirnov test of Combined National Studies for Normality.

```
One-sample Kolmogorov-Smirnov test against theoretical distribution

normal((leakRateLog+.3443504)/.7850414)

Smaller group       D       P-value
 -----------------------------------
 leakRateLog:        0.0576    0.098
 Cumulative:        -0.0622    0.067
 Combined K-S:       0.0622    0.133
```

Table 7: Kolmogorov-Smirnov test of Combined SoCalGas Studies for Normality.

```
One-sample Kolmogorov-Smirnov test against theoretical distribution
normal((leakRateLog+.175378)/.857963)

 Smaller group       D       P-value
 -----------------------------------
 leakRateLog:        0.0407    0.382
 Cumulative:        -0.0574    0.147
 Combined K-S:       0.0574    0.292
```

Quantile-Normal Plot Analysis of Transformations

To visually check the transformation analysis, the quantile-normal plots of the log(10) transformed data were plotted for the combined national studies, see Figure 16, and for the combined SoCalGas studies, see Figure 17. Both plots show that leak rate data from the combined data sets appears log-normal distributed.

Figure 16: Quantile-Normal Plot of Log-normal Transformed Combined National Studies.

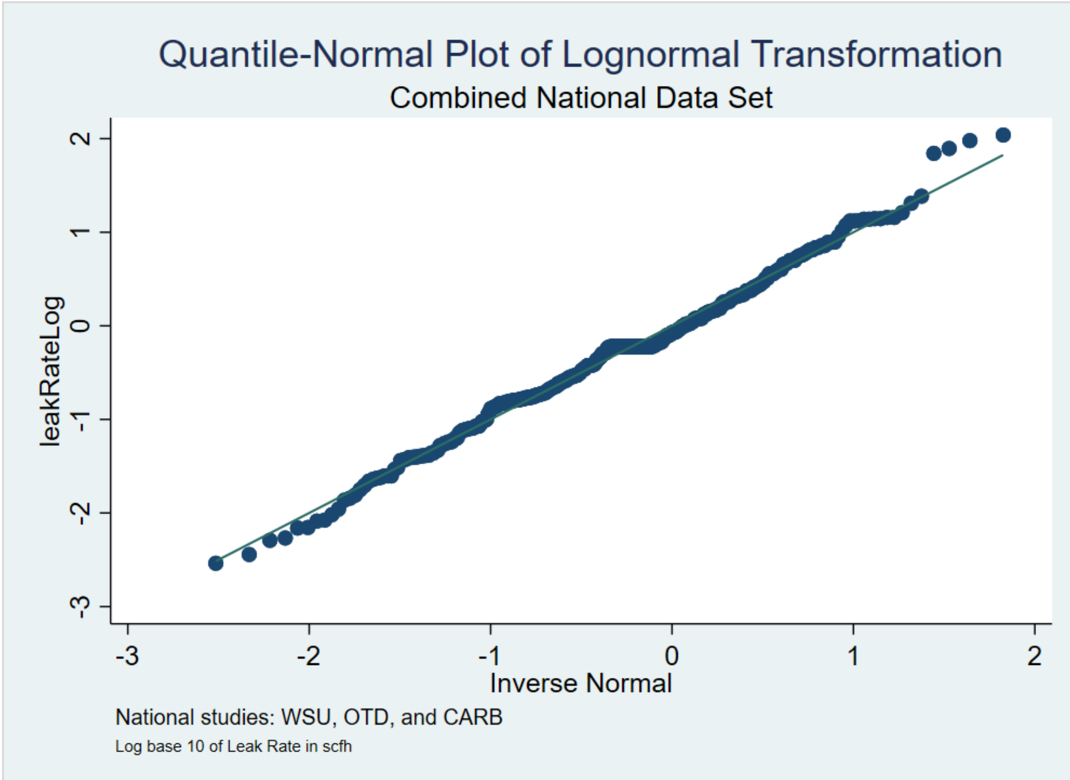
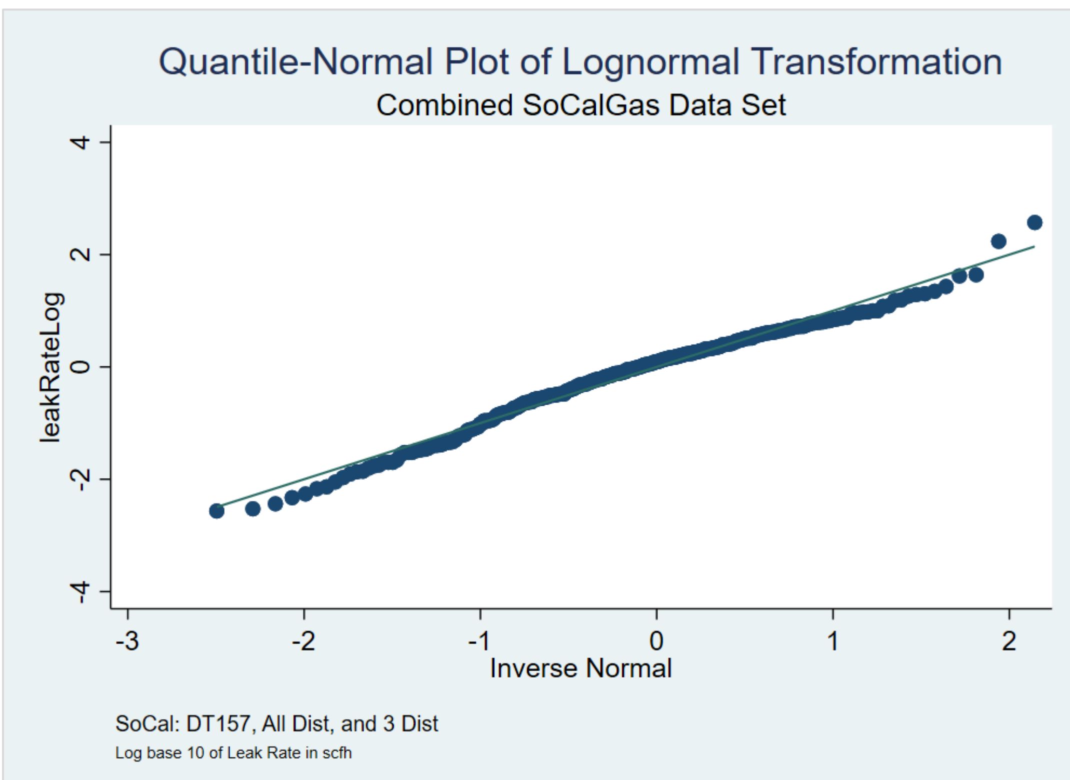


Figure 17: Quantile-Normal Plot of Log-normal Transformed Combined SoCalGas Studies.



5.4. Linear Regression Study Means Comparison

Combined National vs. Combined SoCalGas Study Means Analysis

The ANOVA analysis and output table for their first use are explained below. For the rest of this report, key conclusions from the ANOVA will be discussed with a detailed table included in the corresponding section or in the Appendix as noted.

Analysis of Variance (ANOVA)

Using the log transformation for leak rate, an ANOVA was completed between the combined national and all SoCalGas studies. The results are in Table 8 below. ANOVA is used to determine any difference in a metric variable (log(10) leak rate in this case), between two or more groups.

The upper part of the table shows the means for each group where one can observe the difference already noted in the descriptive statistics section of this report. However, note this is the mean of the log(10) of each measurement which is not the same as the log(10) of the mean of the leak measurements. The Prob > F or p-statistic is smaller (0.0099) than 0.05 and therefore indicates the result is *significant,* which means one would expect the same result (difference in means) if the entire *population* of the applicable studies were measured.

It is worth noting for completeness that the p-statistic for significance is derived from the F distribution - where F is the ratio of the two variance estimates (MS, or mean squares) listed in the ANOVA table for "between" vs. "within groups" respectively. The MS are calculated by the ratio of the sum of the squares (of deviation) for each source to the degrees of freedom.

Therefore, one can conclude that at least two groups exhibit a statistically significant difference in their means. Another way to interpret this would be to say that one would expect less than 1 time in 100 that these results would be obtained if there were no difference between the national and SoCalGas combined studies.

Bartlett's test for equal variances indicates a non-significant result which is good; otherwise, one would have to conclude that the variance between the groups were unequal. Also note the standard deviations between the two combined groups is close (0.79 and 0.85 in round numbers), and the frequency are both large and similar (350 and 309).

Finally, *Bonferroni* compares between all possible groups. In this case, it is simply a one-to-one comparison, so it is the same as the ANOVA. Additionally, the difference between log(10) means is shown with the same p-statistic as the overall ANOVA, but to only three vs. four significant figures (0.010).

Table 8: ANOVA of Combined National vs. Combined SoCalGas Leak Rate Means.

```
Summary of Log of Leak Rate (scfh)
study Scale          Mean   Std. Dev.       Freq.
------------------------------------------------
National       -.3443504   .78504136         350
SoCal         -.17955489   .84894047         309
------------------------------------------------
Total         -.26707906   .81914558         659

Analysis of Variance
Source               SS         df      MS            F     Prob > F
------------------------------------------------------------------------
Between groups     4.45688946      1   4.45688946    6.70     0.0099
Within groups      437.060768    657   .665237089
------------------------------------------------------------------------
Total           441.517657    658   .670999479

Bartlett's test for equal variances:  chi2(1) =   2.0052  Prob>chi2 = 0.157
             Comparison of Log of Leak Rate (scfh) by studyScale
                                (Bonferroni)
Row Mean-
Col Mean     National
---------------------
   SoCal      .164796
                0.010
```

The ANOVA includes several assumptions worth noting:

- The outcome variable is quantitative - true in this case.
- The errors or residuals are normally distributed. This could be problematic with small sample sets. It will be shown that the residuals are normally distributed in a later section of this report.
- The observations represent a random sample of the population. The two sample-biased studies which also contained ten or less samples were removed - which would be a problem to determine the above residual requirement as well, i.e. to quantify normality.
- The errors are independent. A good assumption in this study.
- The variance of each group is equal. This is the aforementioned Bartlett test which confirmed this assumption.

The ANOVA across the individual studies was run and confirmed that there was a difference between individual studies (not just the difference between the combined studies noted above). The results showed a $F(7, 651) = 17.79$ $p < 0.001$ meaning there is statistical difference between the study means. For those interested, the ANOVA table by study and a full pairwise comparison by study-to-study is presented in Appendix B. Instead of going into the individual study comparisons to one another with the ANOVA results, these will be discussed in the *regression* section below, which also allows the use of diagnostic tests to pinpoint outliers or extreme values in the data.

Linear Regression

Overview

The dependent (and continuous) variable for the linear regressions (LR) is the log(10) leak rate. The independent (and categorical) variable for the regression is the emission study for each leak observation (sample).

The linear regression results for the log(10) of leak rate by study is shown in Table 9 below. The first section of the regression output shows the model and residual (these are termed sources) sum of the squares of deviation, degrees of freedom, and mean square for the sources. The right side of the table provides the total number of sample observations, the F test score (7, 651) for the model and associated residual of 17.79, and the associated p-statistic which is less than 0.001. The number to focus on is the p-statistic which was explained earlier in the ANOVA section of the report. This means a significant model is observed, and the R-squared and adjusted R-squared values show a moderate level of accounting for variance.

The bottom section lists the regression coefficients (for all independent categorical variables) with the mean log(10) leak rates by study and associated error terms. These coefficients are used to calculate the t-value and the p-statistic. Again, placing focus on the p-statistic, it can be seen that for the non-biased studies, the differences in means for the All District Study and the WSU studies cannot be explained by random variation in the samples, i.e. the differences are significant since their p-statistic is less than 0.05 - as was discussed in the earlier sections of this report. Further, the All District Study and the WSU Study are statistically similar as noted in their pairwise large p-significance level of 0.678 (see Appendix B for regression details).

Table 9: Linear Regression of Individual National and SoCalGas Study Leak Rate Means.

Source	SS	df	MS			
Model	70.8808391	7	10.1258342	Number of obs	=	659
Residual	370.636818	651	.56933459	F(7, 651)	=	17.79
				Prob > F	=	0.0000
				R-squared	=	0.1605
				Adj R-squared	=	0.1515
Total	441.517657	658	.670999479	Root MSE	=	.75454

leakRateLog	Coef.	Std. Err.	t	P> t	[95% Conf.	Interval]
study						
3DisPilot	0	(base)				
3DisPilotLowSpec	-.5881559	.2851903	-2.06	0.040	-1.14816	-.028152
AllDisLIRP	.1388059	.259037	0.54	0.592	-.3698429	.6474547
AllDisPilot	-.5897834	.1321584	-4.46	0.000	-.8492916	-.3302752
DT157Pilot	.0843352	.1174437	0.72	0.473	-.146279	.3149494
Natl_CARB_GTI	.0444857	.1328832	0.33	0.738	-.2164457	.305417
Natl_OTD_GTI	.230709	.1391025	1.66	0.098	-.0424347	.5038527
Natl_WSU_EDF	-.5482558	.1133677	-4.84	0.000	-.7708662	-.3256454
_cons	-.0627922	.10083	-0.62	0.534	-.2607835	.135199

Three SoCalGas Study Means Analysis

In this section, the ANOVA technique is applied to the three SoCalGas studies that will provide the basis for the subsequent emission factor calculations.

Analysis of Variance (ANOVA)

In Table 10 below, there exists similar deviations between the studies and large sample sizes. The F test score (2, 288) = 18.72 and the p-statistic is less than 0.001. This result demonstrates evidence that statistical differences are present in the means of the log(10) leak rates between the studies in the population. The difference can be seen in the pairwise combinations at the bottom of the table. The AllDisPilot is different from the other two which are similar based on the p-statistic values.

Table 10: ANOVA of Leak Rate Means for Three SoCalGas Studies.

Summary of Log of Leak Rate (scfh)

study	Mean	Std. Dev.	Freq.
3DisPilot	-.06279222	.89898228	56
AllDisPil	-.65257563	.92139692	78
DT157Pilo	.02154301	.71202596	157
Total	-.17537804	.85796296	291

Analysis of Variance

Source	SS	df	MS	F	Prob > F
Between groups	24.5599302	2	12.2799651	18.72	0.0000
Within groups	188.909199	288	.655934719		
Total	213.469129	290	.736100446		

Bartlett's test for equal variances: chi2(2) = 8.7913 Prob>chi2 = 0.012

Comparison of Log of Leak Rate (scfh) by study
(Bonferroni)

Row Mean-Col Mean	3DisPilo	AllDisPi
AllDisPi	-.589783 0.000	
DT157Pil	.084335 1.000	.674119 0.000

Linear Regression

The dependent (and continuous) variable for the linear regressions is the log(10) leak rate. The independent (and categorical) variable for the regression is the emission study for each leak observation (sample).

The linear regression of the SoCalGas studies is shown in Table 11 below and further shows that the DT-157 and 3-District study means for log(10) leak rate are statistically the same, and that the All District study mean has a statistically significant difference (a lower value) from both of the other two studies. This was explained in an earlier section of this report when looking at the raw data and descriptive statistics and is not an anomaly that should be filtered out.

Table 11: LR and PW Comparison of Leak Rate Means for Three SoCalGas Studies.

Source	SS	df	MS			
				Number of obs	=	291
				F(2, 288)	=	18.72
Model	24.5599302	2	12.2799651	Prob > F	=	0.0000
Residual	188.909199	288	.655934719	R-squared	=	0.1151
				Adj R-squared	=	0.1089
Total	213.469129	290	.736100446	Root MSE	=	.8099

leakRateLog	Coef.	Std. Err.	t	P> t	[95% Conf.	Interval]
study						
3DisPilot	0	(base)				
AllDisPilot	-.5897834	.1418539	-4.16	0.000	-.8689853	-.3105815
DT157Pilot	.0843352	.1260597	0.67	0.504	-.1637799	.3324504
_cons	-.0627922	.1082272	-0.58	0.562	-.2758087	.1502243

Pairwise comparisons of marginal linear predictions

	Contrast	Std. Err.	Unadjusted t	Unadjusted P> t	[95% Conf.	Interval]
study						
AllDisPilot vs 3DisPilot	-.5897834	.1418539	-4.16	0.000	-.8689853	-.3105815
DT157Pilot vs 3DisPilot	.0843352	.1260597	0.67	0.504	-.1637799	.3324504
DT157Pilot vs AllDisPilot	.6741186	.1121933	6.01	0.000	.4532957	.8949415

Linear Regression Residual Analysis and Regression Diagnostics

A series of diagnostics were analyzed for the SoCalGas study regressions to confirm regression assumptions and to look for influential, outlier, or extreme values requiring further review and/or explanation or exclusion. All data points were retained after this detailed review of the diagnostics and residuals, including:

- Exogeneity
- Random Sampling
- Linearity in Parameters
- Multicollinearity
- Heteroscedasticity and Normal Distribution of Residuals
- Influential Observations - DFBETA
- Influential Observations - Cook's Distance
- Influential Observations - Leverage

The details and plots of all the diagnostics and residuals are presented in Appendix B.

5.5. Bayesian Monte Carlo Markov Chain (MCMC) Regression

A non-parametric Bayesian Monte Carlo Markov Chain (MCMC) [25] *regression* analysis was conducted. Two variations of random *sampling* were used, the random walk Metropolis-Hasting (MHS))[26, 27] method as well as the more robust Gibbs (GS)) [28] method. In both cases, 35,000 iterations were used with a 5,000 iteration burn-in run, resulting in an incorporated Monte Carlo sample size of 30,000. In both cases, the prior distribution for the log(10) leak rate distribution was "uniformed", i.e. a flat/uniform prior. The sigma prior was assumed as a conservative gamma function.

The results of these Bayesian-based regressions showed very similar results in output to the standard regression outputs already discussed. However, this is for convenience of comparison, since the methods are completely different, and this analysis uses Bayesian linear regression. This does not come as a surprise, since the regression assumptions were met, and the dependent variable (log(10) of leak rate) was normally distributed.

The detailed results of the Bayesian MCMC(MHS) and MCMC(GS) are presented in Appendix B.

5.6. Sensitivity of Leak Rate to Geographic District and Year of Detection Analysis

The sections below describe two sensitivity studies that were completed to determine if the SoCalGas studies demonstrated sensitivity in the log(10) leak rate values to *geographic* district (location of leak) and/or the *year* the leak was originally detected. The geographic districts and year of leak detection are not listed in the Appendix table. As shown below, the leak rate was not sensitive to either the geographic districts or the year the leak was originally detected.

Geographic District of Leak

The ANOVA analysis for geographic sensitivity is shown in Table 12 below. The p-statistic of 0.1087 shows that the difference between groups (districts) is not statistically significant; hence, there is no evidence of a difference in the log(10) leak rate values between different geographic districts. Note that for the analysis, several districts had to be dropped out of this particular ANOVA analysis due to only one sample with leak rates present. These were not dropped out of the overall study.

Table 12: ANOVA of Leak Rate Means Across Districts for Three SoCalGas Studies.

```
                        Analysis of Variance
    Source              SS         df      MS            F     Prob > F
------------------------------------------------------------------------
Between groups      69.7037636     83   .839804381      1.24     0.1087
 Within groups      152.271814    225   .676763619
------------------------------------------------------------------------
    Total           221.975578    308   .720699928

Bartlett's test for equal variances:  chi2(47) =  69.4664  Prob>chi2 = 0.018

note: Bartlett's test performed on cells with positive variance:
      36 single-observation cells not used
```

Year of Leak Detection

To get an understanding for the distribution of leak rates by year of detection, two plots were generated. The first is a box plot of leak rate by year detected (Figure 18). A scatter plot of the same data (Figure 19) shows the median, mean, and maximum leak rates detected by year.

Datasets from 2006, 2007, 2009, and 2012 were removed from this regression analysis since they only have 1, 3, 1, and 5 observations respectively. They were not removed from the study overall.

From the plots, one can see that 2019 has the most data, accounting for over 1/3 of all observations. It also has the smallest and highest single values of leak rates and the lowest median.

The medians of leak rate by year detected are very consistent, all between 0.5 and 2.0 scfh, except for 2019 which is below 0.50 scfh. The highest median leak rate occurred in 2015 after which the median leaks continue to decrease by year.

Figure 18: Leak Rate Box Plots by Year Leak Detected for Three Combined SoCalGas Studies.

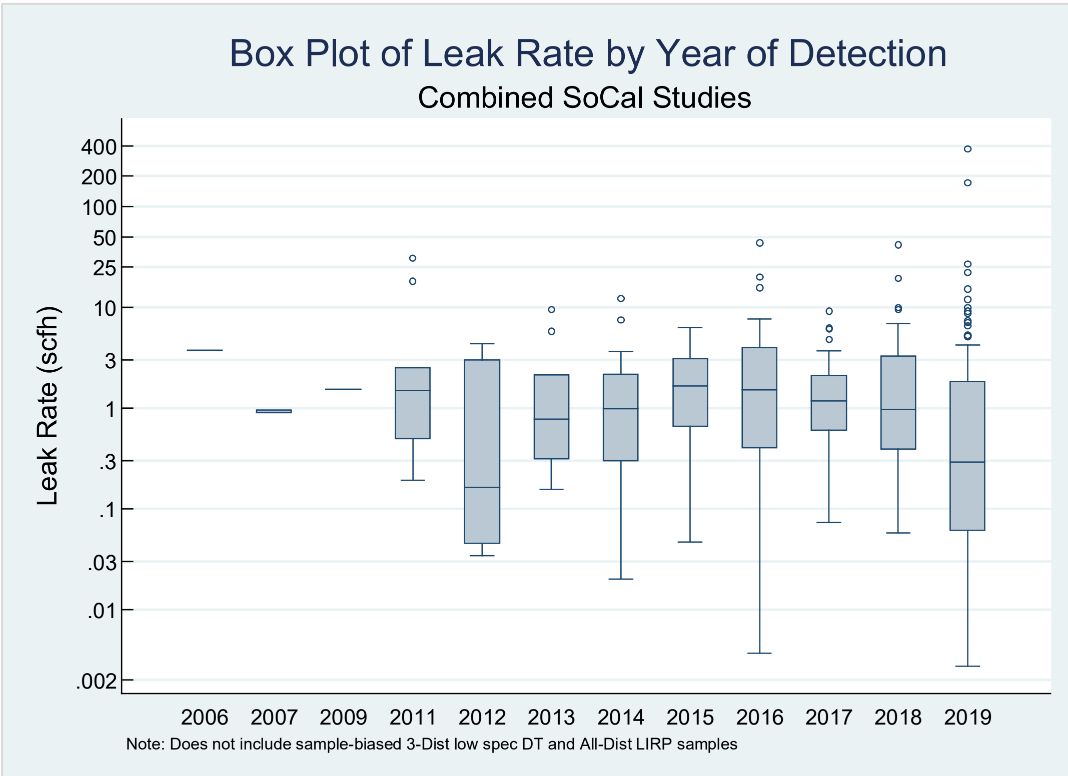
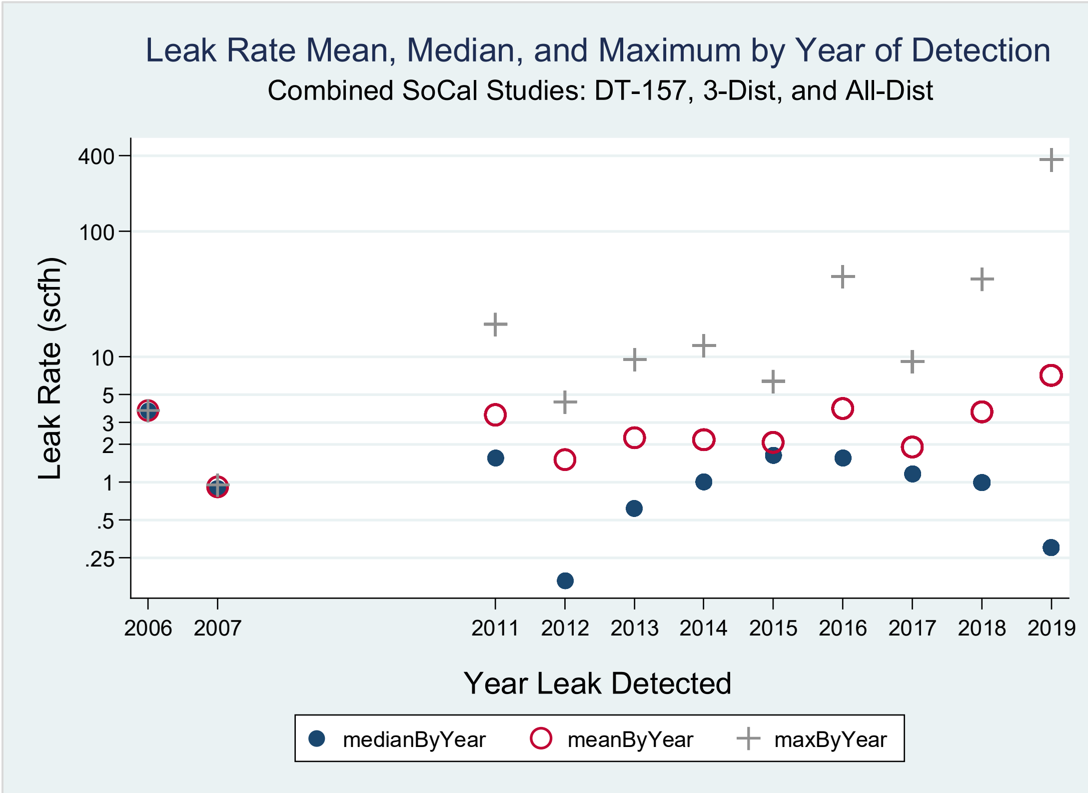


Figure 19: Leak Rate Median, Mean, and Maximum by Year SoCalGas Leaks Detected.



The ANOVA analysis is shown in Table 13 and the pairwise comparison in Table 14. Both of these results, show a quantitative measure of sameness or lack thereof.

In summary, the log(10) leak rate is insensitive to geographic district or year of detection based on the field data analyzed to date.

Table 13: ANOVA of Leak Rate Means Across Year Detected for Three SoCalGas Studies.

Year Leak Detected	Summary of Log of Leak Rate (scfh) Mean	Std. Dev.	Freq.
2006	.57175308	0	1
2007	-.03804038	.01594704	3
2009	.18752073	0	1
2011	.18185936	.67890395	11
2012	-.49550171	.99638628	5
2013	-.04097877	.59161147	10
2014	-.13138904	.74362153	19
2015	.08858402	.54923189	32
2016	.0052503	.84882588	39
2017	.00980475	.53934181	29
2018	.02103485	.67407974	38
2019	-.45726365	1.0032278	111

```
------------------------------------------------
      Total    -.16512119   .84288247         299

                        Analysis of Variance
    Source              SS         df      MS            F     Prob > F
------------------------------------------------------------------------
Between groups      17.6311516     11   1.60283196      2.37     0.0081
 Within groups      194.083206    287   .676248105
------------------------------------------------------------------------
    Total           211.714358    298   .710450864

Bartlett's test for equal variances:  chi2(9) =  43.0070  Prob>chi2 = 0.000
note: Bartlett's test performed on cells with positive variance:
      2 single-observation cells not used
```

Table 14: PW Comparison of Leak Rate Means by Year Detected for Three SoCalGas Studies.

Comparison of Log of Leak Rate (scfh) by yearDetected
(Bonferroni)

Row Mean-Col Mean	2006	2007	2009	2011	2012	2013
2007	-.609793					
	1.000					
2009	-.384232	.225561				
	1.000	1.000				
2011	-.389894	.2199	-.005661			
	1.000	1.000	1.000			
2012	-1.06725	-.457461	-.683022	-.677361		
	1.000	1.000	1.000	1.000		
2013	-.612732	-.002938	-.2285	-.222838	.454523	
	1.000	1.000	1.000	1.000	1.000	
2014	-.703142	-.093349	-.31891	-.313248	.364113	-.09041
	1.000	1.000	1.000	1.000	1.000	1.000
2015	-.483169	.126624	-.098937	-.093275	.584086	.129563
	1.000	1.000	1.000	1.000	1.000	1.000
2016	-.566503	.043291	-.18227	-.176609	.500752	.046229
	1.000	1.000	1.000	1.000	1.000	1.000
2017	-.561948	.047845	-.177716	-.172055	.505306	.050784
	1.000	1.000	1.000	1.000	1.000	1.000
2018	-.550718	.059075	-.166486	-.160825	.516537	.062014
	1.000	1.000	1.000	1.000	1.000	1.000
2019	-1.02902	-.419223	-.644784	-.639123	.038238	-.416285
	1.000	1.000	1.000	0.959	1.000	1.000

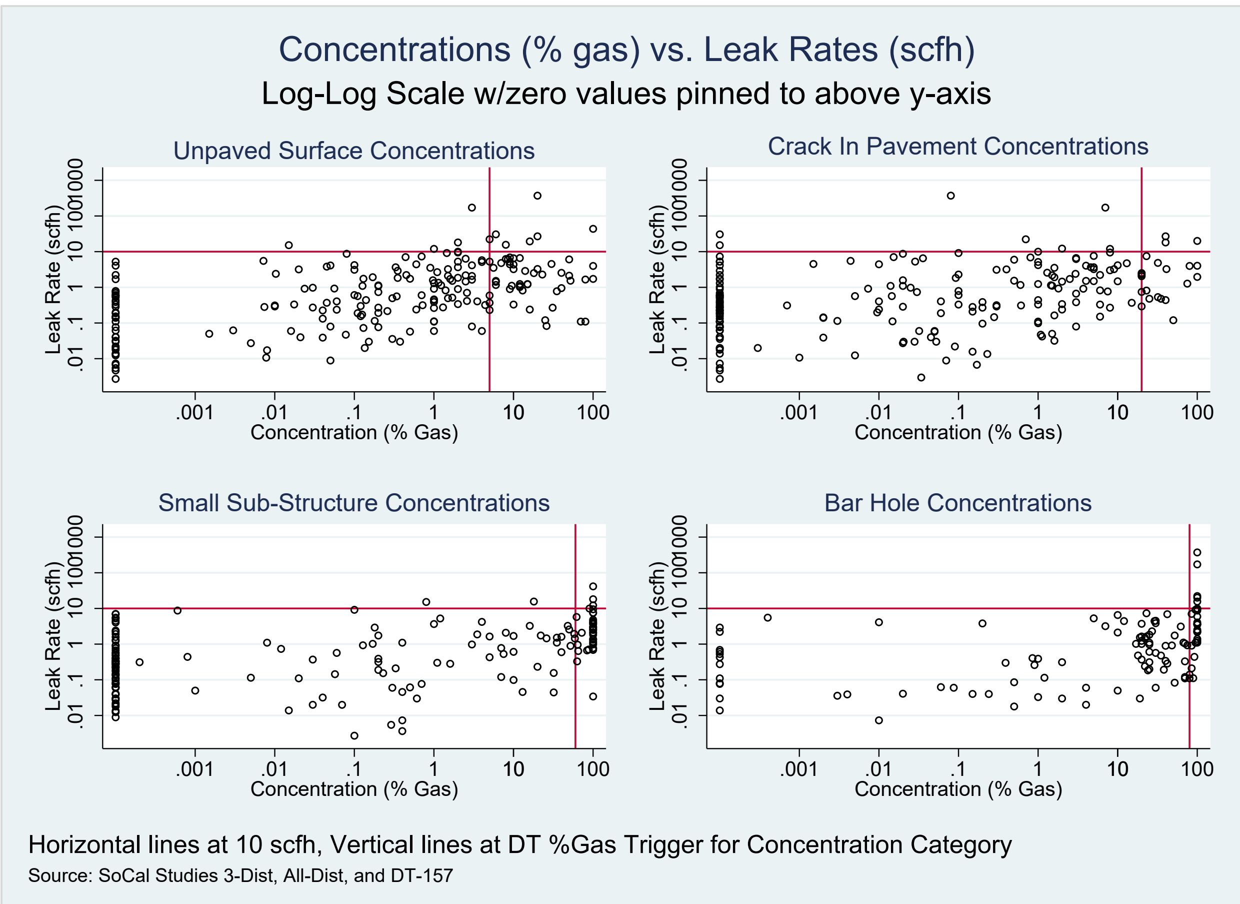
Row Mean-Col Mean	2014	2015	2016	2017	2018
2015	.219973				
	1.000				
2016	.136639	-.083334			
	1.000	1.000			
2017	.141194	-.078779	.004554		
	1.000	1.000	1.000		
2018	.152424	-.067549	.015785	.01123	
	1.000	1.000	1.000	1.000	
2019	-.325875	-.545848	-.462514	-.467068	-.478298
	1.000	0.070	0.181	0.452	0.143

5.7. Concentration vs. Leak Rate Analysis

General Trends

The four leak concentration measurement categories are plotted separately, but side-by-side in Figure 20. The Decision Tree 10 scfh leak rate value that separates "Not Large" from "Large" non-hazardous leak levels is plotted as a horizontal line, and each of the concentration levels that trigger a positive Decision Tree categorization are plotted as a vertical line at 80%, 20%, 60%, and 5% gas respectively. The zero values for concentration were set to 0.0001% gas which is less than the minimum value, appearing on the left-hand side of the plots.

Figure 20: Separate Plots of Leak Concentrations vs. Rates by DT Category.



One can see the general upward trend between the methane concentration measurements with increasing leakage flow rate. The scatterplots of maximum surface concentration vs. leak rate do support the thresholds. The upper left quadrants of the leak rate vs. concentration plots are the areas of false negatives for the DT process if each surface category was evaluated individually. One can visually see the very low number of false negatives (the measure of importance for the entire DT program) in these zones even when evaluated individually. In practice however, because the DT is an 'OR' gated process (i.e., the DT will be triggered if *any* one of the four category thresholds are met) this substantially reduces the number of false negatives in actuality from what is shown individually. These observations are also fully supported by the Bayesian probabilistic analysis later described in this report.

A regression analysis was done for general trend review. The regression analysis was *not* used for subsequent quantitative calculations related to the Decision Tree predictive capability, which is covered in the next section using Bayesian probabilistic analysis. The analysis demonstrated that any individual concentration measurement in any category is *not* a good predictor of leakage flow rate. The regression analysis is presented in Appendix B of this report as supplemental information.

5.8. Decision Tree Leak Prediction Quantitative Performance

Next, the Decision Tree performance measures were developed as related to its ability to properly predict a greater or equal to 10 scfh leak rate given any combination from one to all four measurement concentration measurement categories for any individual leak.

Leak Rate Statistics of Empirical Data by Decision Tree Groupings

Overall Results from Empirical Data

The combined SoCalGas study mean leak flow rate is presented again for the 291 samples in Table 15 with the associated 95% confidence intervals. As noted earlier in the report, the assumption of normality for leak rate data is violated, since we have a highly skewed distribution. The mean values and associated 95% confidence intervals presented in Table 15, Table 20, and Table 23 below are from the non-parametric bootstrap analysis conducted in Section 5.10 of the report.

Table 15: Combined Bootstrap Mean and C.I. for Three SoCalGas Studies (Baseline).

SoCal Studies	Obs	Mean	[95% Conf.	Interval]
Combined	291	4.303	1.635	12.013

For comparison, Table 16 presents the mean, minimum, and maximum in two groups: when the DT was not met and when the DT was met from the concentration value(s).

Excellent separation of the mean values is observed which are 1.168 scfh and 8.973 scfh respectively. This is plotted in Figure 21, and the median and 5th and 95th percentiles are shown in Table 17.

Table 16: Leak Rate Mean, Min., and Max. of by DT Grouping.

DT Met	N(count)	mean(scfh)	min(scfh)	max(scfh)
no	174	1.168	0.003	15.252
yes	117	8.973	0.034	373.000
Total	**291**	**4.306**	**0.003**	**373.000**

Figure 21: Mean Leak Rate for DT Categories.

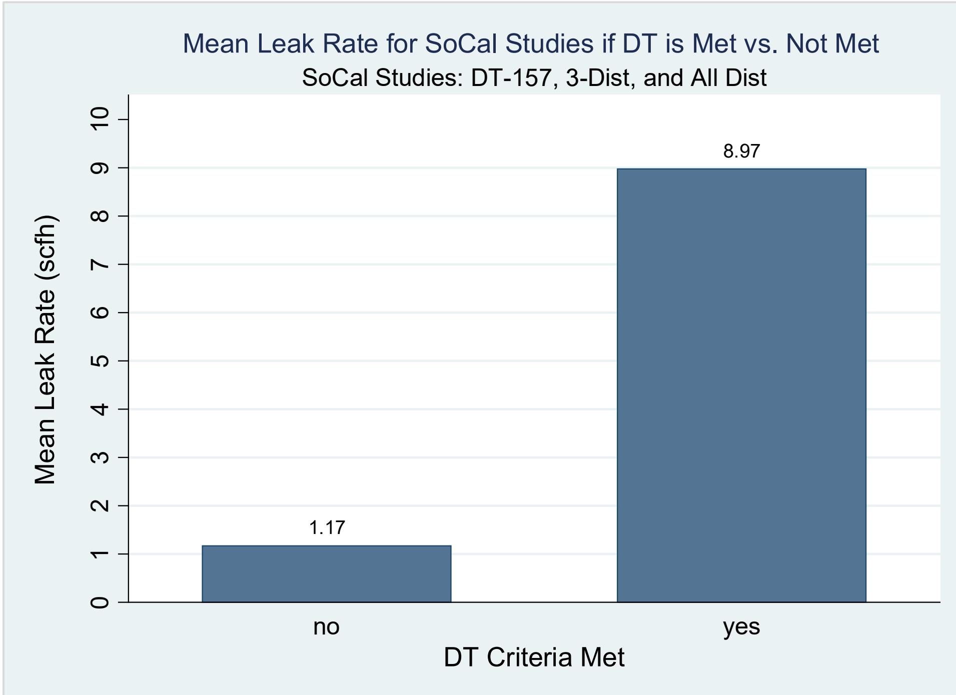


Table 17: Leak Rate Median, 5%, and 95% Percentiles by DT Grouping.

DT Met	N(count)	p5(scfh)	med(scfh)	p95(scfh)
no	174	0.011	0.376	5.156
yes	117	0.120	2.125	22.290
Total	**291**	**0.018**	**0.824**	**9.990**

Leak Rate Statistics of Empirical Data by Confirmed Leak Rate Groupings

In this section, *actual* leak rates are grouped into those less than 10 scfh and those greater than or equal to 10 scfh and then by whether or not the DT criteria was not met and was met.

Actual Leak Rate less than 10 scfh and True and False Negatives

When the DT is not met (i.e., predicting leak rate will be less than 10 scfh), we will refer to this as a "negative" prediction by the DT, and it is either true or false as determined by the subsequent leak rate measurement. In Table 18, the mean leak rate for these DT-related true and false negative situations are determined to be 1.023 scfh and 2.608 scfh respectively. These are plotted in Figure 22. The median and 5^{th} and 95^{th} percentiles are shown in Table 19.

Table 18: Leak Rate Mean, Min., and Max. of Confirmed <10 scfh by DT Grouping.

DT Met	N(count)	mean(scfh)	min(scfh)	max(scfh)
no	172	1.023	0.003	9.192
yes	105	2.608	0.034	9.990
Total	**277**	**1.624**	**0.003**	**9.990**

Figure 22: Mean Leak Rate for DT Categories when Actually < 10 scfh.

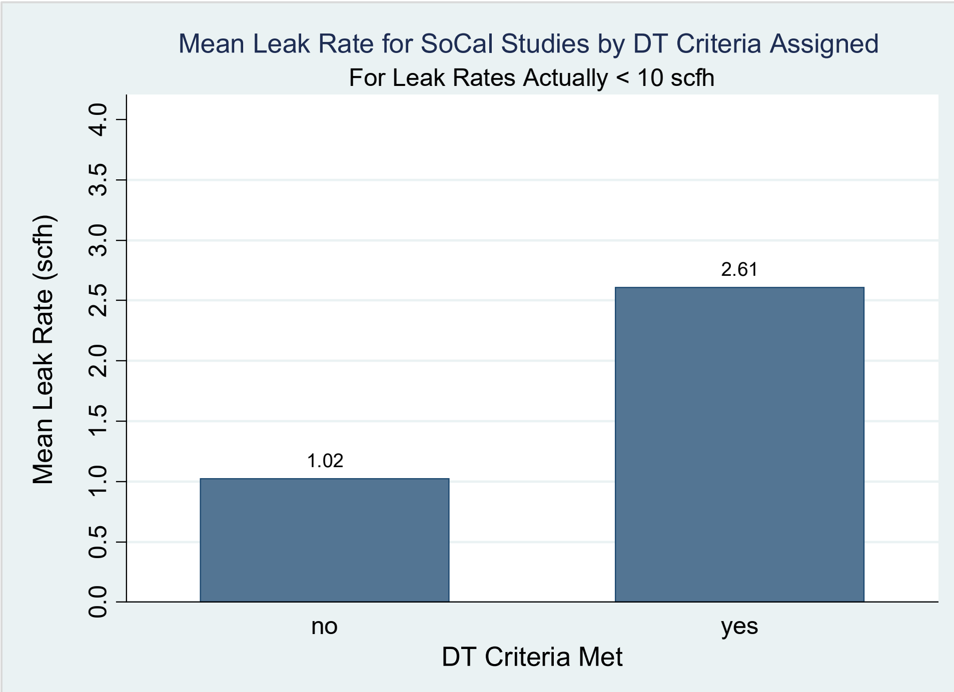


Table 19: Leak Rate Med., 5%, and 95% Percentiles of Confirmed <10 scfh by DT Grouping.

dt_met	N(count)	p5(scfh)	med(scfh)	p95(scfh)
no	172	0.011	0.350	4.434
yes	105	0.120	1.663	7.615
Total	**277**	**0.017**	**0.769**	**6.348**

The bootstrap mean leak rate of 1.623 scfh and confidence interval for the *actual* negatives, i.e. leaks with a flow rate less than 10 scfh, are listed in Table 20.

Table 20: Bootstrap Leak Rate Mean and C.I. for Confirmed < 10 scfh (Actual Negatives).

SoCal Studies	Obs	Mean	[95% Conf.	Interval]
<10 scfh	277	1.623	1.141	2.153

Actual Leak Rate greater than or equal to 10 scfh

When the DT is met (predicting leak rate will be greater than or equal to 10 scfh), we will refer to this as a "positive" prediction by the DT, and it is either true or false as determined by the subsequent leak rate measurement. In Table 21, the mean leak rate for these DT-related true and false positive situations are shown. These are plotted in Figure 23. The median and 5th and 95th percentiles are shown in Table 22.

Table 21: Leak Rate Mean, Min., and Max. of Confirmed ≥10 scfh by DT Grouping.

DT Met	N(count)	mean(scfh)	min(scfh)	max(scfh)
no	2	13.638	12.024	15.252
yes	12	64.662	10.000	373.000
Total	**14**	**57.373**	**10.000**	**373.000**

Figure 23: Mean Leak Rate for DT Categories when Actually ≥ 10 scfh.

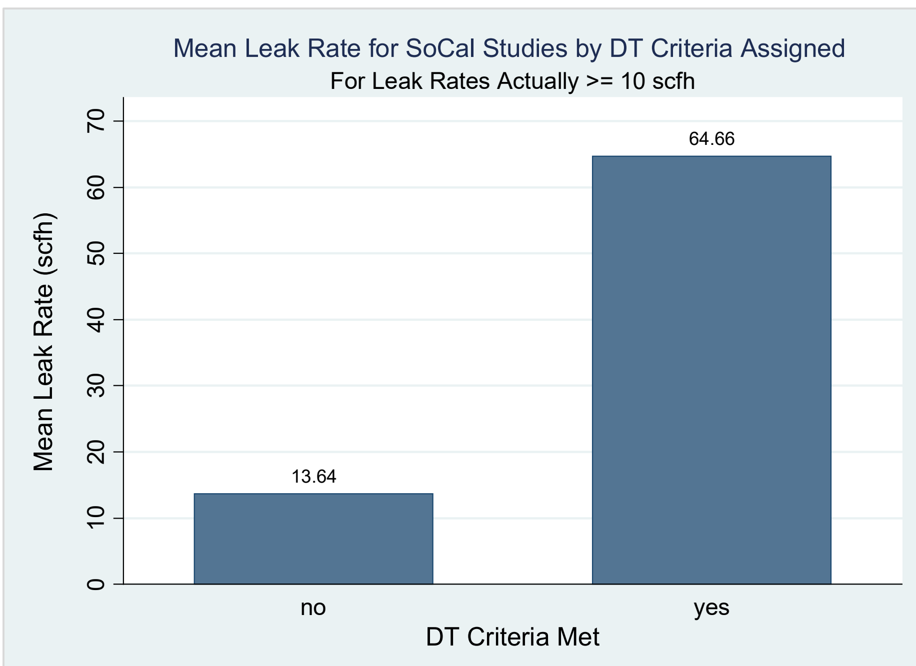


Table 22: Leak Rate Med., 5%, and 95% Percentiles of Confirmed ≥10 scfh by DT Grouping.

dt_met	N(count)	p5(scfh)	med(scfh)	p95(scfh)
no	2	12.024	13.638	15.252
yes	12	10.000	21.189	373.000
Total	**14**	**10.000**	**19.779**	**373.000**

The bootstrap mean leak rate of 57.667 and confidence interval for the *actual* positives, i.e. leaks with a flow rate greater than or equal to 10 scfh, are listed in Table 23.

Table 23: Bootstrap Leak Rate Mean and C.I. for Confirmed ≥ 10 scfh (Actual Positives).

SoCal Studies	Obs	Mean	[95% Conf.	Interval]
>=10	14	57.667	14.230	194.943

5.9. Bayesian Probabilistic Decision Tree Error-Type Analysis

A non-parametric Bayesian probabilistic analysis [15-17, 29] was conducted on the Decision Tree predictive power. The output includes the expected fraction (or percent) of sites that have true/false negative/positive outcomes. The Bayesian proportional analysis provides the most likely value of the errors in a coherent manner but also provides the upper and lower prediction limits around these values.

The results of the analysis are presented in Table 24 to Table 26 below, then plotted in Figure 24 and Figure 25. Table 24 and Figure 24 show the errors if one did not have prior knowledge of the leak concentration levels required for DT categorization as a likely large versus not large non-hazardous leak. In other words, it provides the likelihoods of any leak being in one of the four categories when concentration measurements were not available to input into the DT model. Normally, this would not be the case, since one will typically start with the informed knowledge of the DT category being met (positive) or not met (negative); however, it does provide a way to estimate the likely leak rate even without a concentration measurement available based on pure probability analysis.

Table 25 and Table 26 are of interest for this study since they provide the errors of a DT positive classification being true or false (Type I error) or of a DT negative classification being true or false (Type II error). These are plotted in Figure 25.

The DT has a low expected Type II error (false negative) of 1.1% and high, but conservative from an emissions standpoint, Type I error (false positive) of 89.7%. The lower and upper prediction (credible) limits are also tight, exhibiting a strong degree of belief and relatively low level of uncertainty.

Joint False/True Positive (Type I) and Negative (Type II) Errors

Table 24: Type I & II Uninformed (DT Cat. Unknown) Errors with 5% and 95% Pred. Limits.

Error Type	Count	LPL%	MLV%	UPL%
False Neg	2	0.281	0.687	2.140
False Pos	105	31.621	36.082	40.841
True Neg	172	54.291	59.107	63.727
True Pos	12	2.653	4.124	6.573

Independent False/True Positive Error Type I

Table 25: Type I Errors with 5% and 95% Prediction Limits for DT Positive Group.

Error Type	Count	LPL%	MLV%	UPL%
False Pos	105.000	84.044	89.744	93.359
True Pos	12.000	6.641	10.256	15.956

Independent False/True Negative Error Type II

Table 26: Type II Errors with 5% and 95% Prediction Limits for DT Negative Group.

Error Type	Count	LPL%	MLV%	UPL%
False Neg	2.000	0.469	1.149	3.554
True Neg	172.000	96.446	98.851	99.531

Figure 24: Expected Decision Tree Output with No Concentration Data.

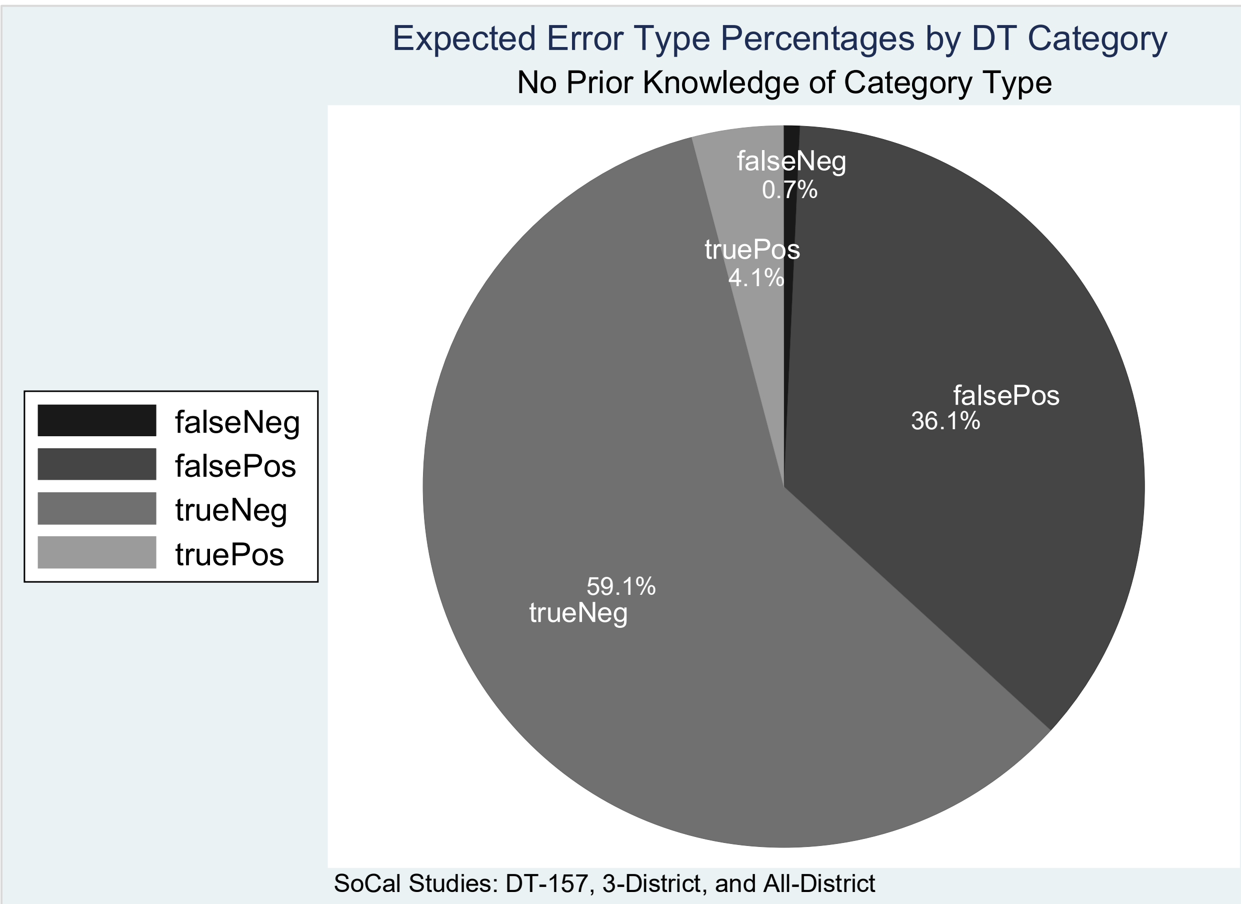
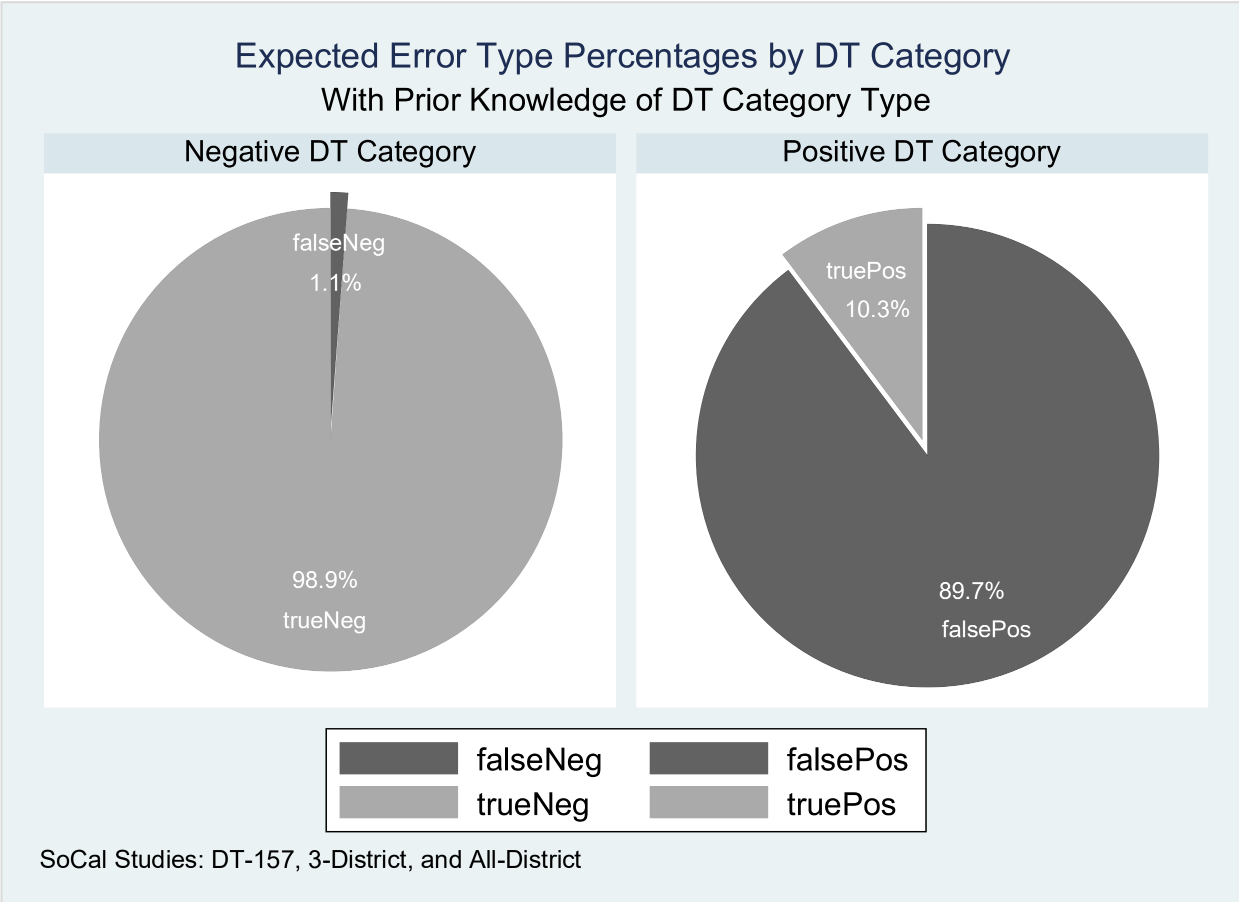


Figure 25: Expected Decision Tree Output with Known DT Category.



Overall Efficiency of Decision Tree Process

The last section used Bayesian analysis to calculate the likelihoods of Type I and II errors associated with the Decision Tree criteria at establishing if a leak would be a non-hazardous large or not large leak. There was 100% leak rate testing of the 291 sample set.

Expanding this discussion outside of the sample used to characterize the DT error and output levels, another operational consideration not discussed to this point is the *efficiency* of the DT approach as to what percentage of totally screened leaks would likely result in the DT criteria being met, thereby triggering a recommendation for leak rate measurement testing.

2019 3-District Pilot Data Example

With the DT threshold is set at the 10 scfh level, the 2019 Pilot study had a total number of 356 leaks with surface concentration measurements. Of these, the DT was triggered for measurement 44 times. Therefore, this relates to a flow rate measurement ratio of 44 / 356 or 12.4%. In other words, when considering leak sites visited and screened with surface concentration measurements that one would expect leaks triggered by the DT process and criteria to have approximately a 1 in 8 chance of being classified as potential non-hazardous large leak, scheduled for leak rate measurement, or prioritized for repair.

For this particular example, rather than measuring all 356 leaks to find all the large leaks; the DT process was used resulting in the requirement to measure only 1 in 8 leaks while maintaining a false negative rate of 1.1%. In summary:

- Using the DT method, 4 of the expected 7 large leaks were found by measuring the leak flow rate from 44 out of 356 leak sites. The value of 7 came from the 4 large leaks discovered from direct flow rate measurements of predicted large leaks, plus the 3 calculated from the DT false negative percent applied to the samples not predicted to be large leaks by the DT process.
- Without the DT, to find the same ratio of 4 out of the 7 large leaks, 203 leak flow rates on average would need to be measured out of the 356 leak sites.
- This means the DT efficiency increase is 203/44 = 4.6x (460%) more efficient at finding the same number of large leaks when not using the DT process.
- The DT *is* therefore an efficient screening mechanism, with a high potential to continue to improve over the short-term full implementation period.

Additional Ongoing False Negative Validation Sampling

In order to continually confirm and refine the false negative error rate of the DT, the leak investigation process will measure an additional 59 sites (for a 90% confidence level) that the DT predicts to not be a large leak. This amounts to 1-2% of the annually encountered leaks in the field (e.g., a total of about 3,000 to 6,000 leaks per year).

5.10. Population Mean Leak Rate Analysis

In this and subsequent sections of this report, the emphasis will be utilizing the leak flow measurement data to create a leak emission factor based on the Decision Tree analysis process.

Bootstrap Analysis of Field Leak Rate Data

A non-parametric bootstrap analysis [18-20] using resampling with replacement was conducted to establish the mean leak rates and a full set of mean percentiles of each of the studies as well as the combined SoCalGas studies.

The combined SoCalGas study included the overall mean leak rate and the mean leak rates for actual leak situations less than 10 scfh and greater than or equal to 10 scfh. The resample size was set to the same size as the field sample size, and the number of resamples was set to 10,000.

Monte Carlo Analysis of Fitted Distribution (for illustrative purposes only)

Additionally, the combined SoCalGas study samples were fit to a log-normal distribution as discussed in an earlier section of this report. This was then analyzed with a Monte Carlo analysis with samples from the distribution fit set to the original field sample size to extract out mean leak rates for the same three categories as was done with the bootstrap analysis.

This limited sample size for the Monte Carlo sample increases the uncertainty in the average, since you do not leverage the central limit theorem with huge sample sizes. You have huge numbers of overall samples, but each has only the limited number of individual observations per sample. This leads to more uncertainty vs. less.

Mean Leak Rate Analysis Results

The bootstrap mean leak rates and minimum and maximum *mean* leak rates from the bootstrap analysis are presented in Table 27.

The last three rows of the table also include the Monte Carlo analysis of the log-normal distribution fit of the sample leak rate distribution (details are in the next section and Appendix C). The bootstrap leak rates will be used as part of the emission rate calculations and are robust against non-normally distributed data.

Table 27: Leak Rate Bootstrap Means by Study Group.

Bootstrap Leak Rate Means (10,000 Resamples)			
Study	**mean(scfh)**	**min(scfh)**	**max(scfh)**
Natl CARB	2.484	1.098	4.756
Natl OTD	5.767	1.375	16.397
Natl WSU	1.682	0.506	4.462
SoCal DT-157	2.926	1.644	5.280
SoCal All-Dist	1.569	0.383	3.647
SoCal 3-Dist	12.043	0.826	54.358
SoCal All	4.303	1.635	12.013
SoCal LT10	1.623	1.141	2.153
SoCal GE10	57.667	14.230	194.943
SoCal L-N Fit All	4.960	2.483	26.049
SoCal L-N Fit L10	2.871	1.452	25.009
SoCal L-N Fit GE10	46.294	15.409	188.861

L-N: Log-normal fit to SoCalGas combined study is explained later in this section.
L10: Leak rate is less than 10 scfh
GE10: Leak rate is greater than or equal to 10 scfh

The 5th through 95th percentiles for the mean leak rates are presented in Table 28 for the bootstrap analysis.

Table 28: Leak Rate (scfh) Percentiles of the Bootstrap Mean.

Pct	CARB	OTD	WSU	DT157	All-Dist	3-Dist	SoCal	SoCalL10	SoCal GE10
5	1.783	2.838	0.803	2.247	0.909	2.124	2.331	1.421	20.786
10	1.921	3.331	0.915	2.376	1.031	2.679	2.574	1.463	24.487
15	2.020	3.721	1.050	2.463	1.114	4.824	2.790	1.493	30.401
20	2.100	4.011	1.150	2.535	1.187	5.347	3.015	1.517	33.143
25	2.166	4.284	1.225	2.604	1.249	6.058	3.246	1.537	39.146
30	2.229	4.551	1.303	2.667	1.309	8.253	3.433	1.555	43.303
35	2.294	4.808	1.377	2.729	1.365	8.625	3.606	1.573	45.360
40	2.350	5.073	1.457	2.785	1.416	8.986	3.781	1.590	47.597
45	2.410	5.325	1.539	2.838	1.475	9.588	3.945	1.605	51.525
50	2.460	5.570	1.613	2.894	1.529	11.469	4.121	1.622	55.236
55	2.512	5.810	1.694	2.951	1.587	11.876	4.289	1.637	57.394
60	2.572	6.058	1.769	3.007	1.644	12.363	4.488	1.652	60.164
65	2.632	6.369	1.858	3.068	1.707	14.587	4.697	1.669	66.590
70	2.697	6.689	1.952	3.136	1.779	15.173	4.924	1.687	69.620
75	2.776	7.026	2.058	3.207	1.849	15.766	5.167	1.706	72.679
80	2.856	7.411	2.186	3.288	1.931	18.171	5.452	1.727	79.532
85	2.963	7.841	2.327	3.394	2.026	19.000	5.793	1.752	83.776
90	3.072	8.444	2.499	3.523	2.152	21.846	6.197	1.785	93.578
95	3.259	9.397	2.786	3.719	2.358	25.268	6.894	1.834	105.665

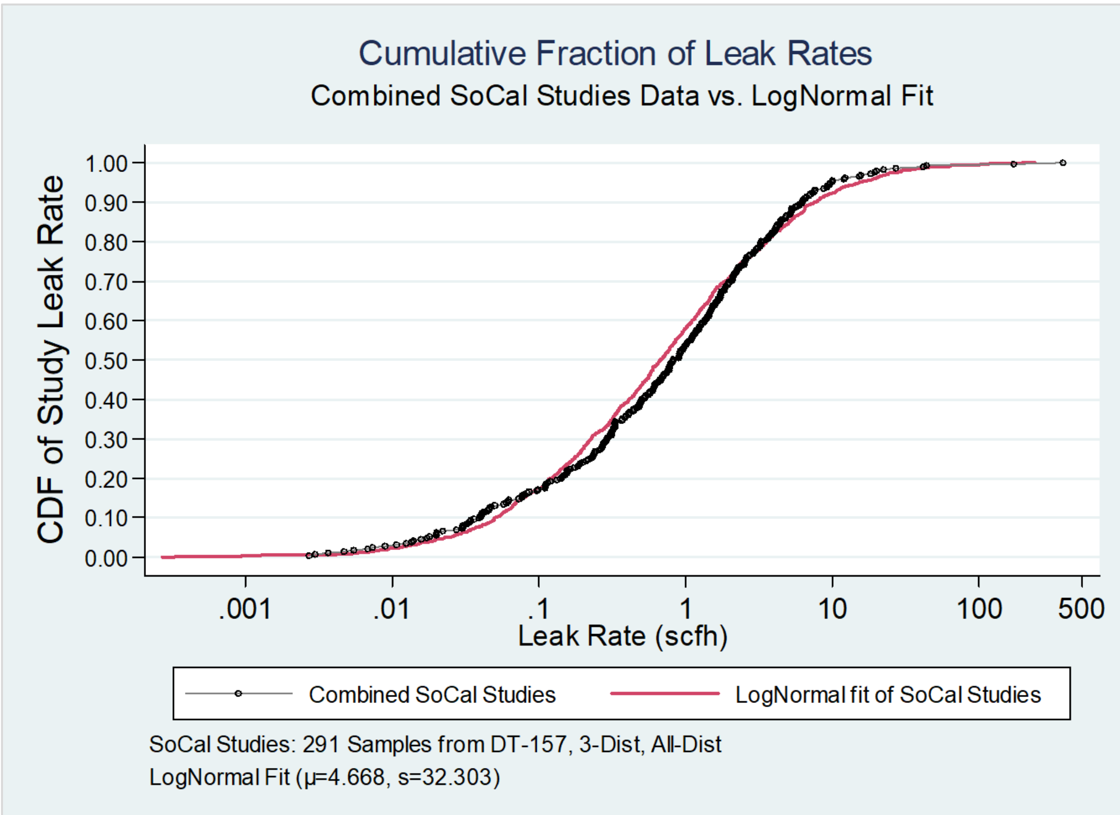
Log-Normal Distribution Fit and Monte Carlo Analysis

The log-normal distribution fit of the SoCalGas combined study leak rates is shown in Figure 26.

The black points are the 291 empirical data points from the field. The red line is the fit of a log-normal distribution with the two parameters noted on the plot.

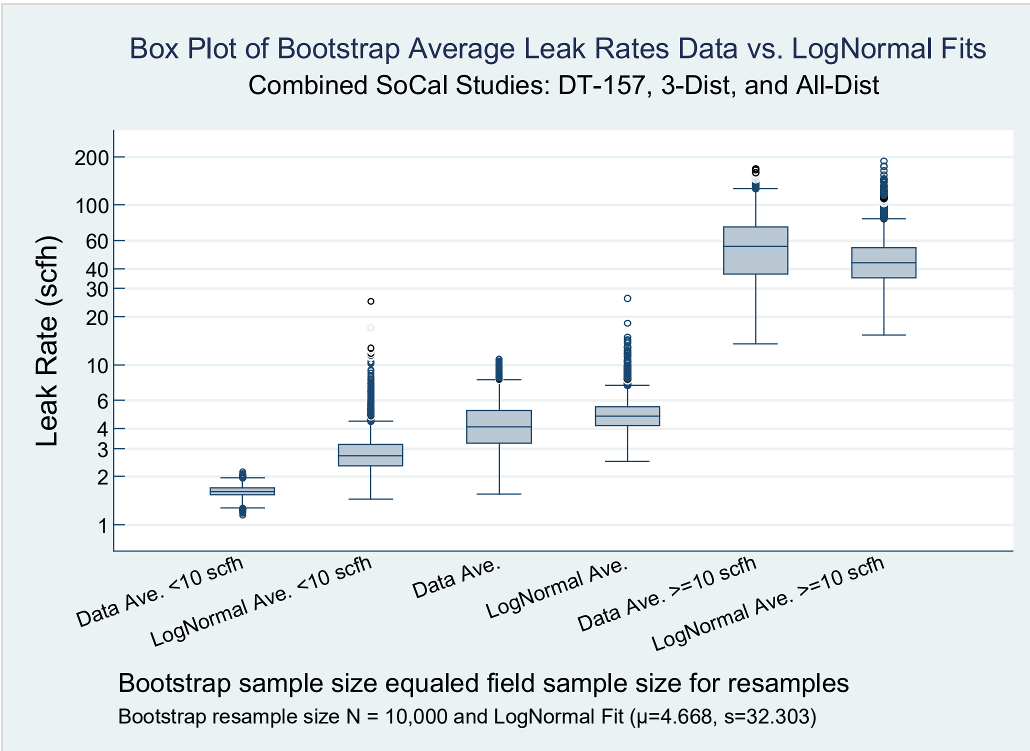
The fit is very strong with three relatively tight intersections between 0.01 and 100 scfh. A summary of the log-normal distribution is in Appendix C.

Figure 26: Leak Rate Cumulative Fractions of Combined SoCalGas Studies and L-N Fit.



A summary box plot of the bootstrap 10,000 resamples (at the original sample sizes) from the field leak rate data and the separate Monte Carlo simulations (also sampled at the original field sample size) from the fitted distribution is shown in Figure 27.

Figure 27: Bootstrap Mean Leak Rate Box Plots of Field Data and Log-Normal Fit.



One can see that the log-normal data is conservative in the low and mid-range, and about the same as the bootstrapped field data in the high range.

The log-normal (or other appropriate fit such as log-gamma) fit with a Monte Carlo analysis can therefore provide an alternative to the bootstrap resampling of the actual field leak rate data until a large enough sample size is available from the field to run the bootstrap analysis.

Once a significant bootstrap sample size is established one could then shift to the results of that analysis vs. fitting the distribution and running a Monte Carlo analysis.

6. Emission Factor Development and Application

6.1 Development of a Company Specific Emission Factor

As stated earlier, the objective of this study was to develop a method for flagging large leaks for cost-effective measurement and repair to minimize system-wide methane leakage rates. So, if a company can reduce its number of higher emitting non-hazardous leaks, it can reduce actual emissions *and* more accurately estimate the reduction.

With the information assembled in the previous sections, a SoCalGas-specific non-hazardous leak emission factor can be reliably developed based on sound statistical and probabilistic sampling and analysis.

Input Information

To construct an accurate emission factor, the following steps were taken (three decimal places are listed to prevent round-off errors in calculations):

1. From Table 27, use three specific bootstraps (log-normal fits if there is not enough samples to execute a bootstrap analysis, e.g. 30 random samples) of the mean leak rates from the SoCalGas studies, for the:
    1. Entire sample set (**ALL**): 4.303 scfh
    2. Samples < 10 scfh (**L10**): 1.623 scfh
    3. Samples ≥ 10 scfh (**GE10**): 57.667 scfh
2. Use the Bayesian Error Table most likely value (MLV) proportions for true and false negatives and positives from Table 25 and Table 26:
    1. False Positives (**FP**): 89.744%
    2. True Positives (**TP**): 10.256%
    3. False Negatives (**FN**): 1.149%
    4. True Negatives (**TN**): 98.851%

Calculation of Distinct Emission Factors

The emission factors are calculated by properly combining the information above for two situations, when the Decision Tree criteria is met (predicting greater than or equal to 10 scfh leak rates) and when it is not met (predicting less than 10 scfh leak rates) as follows:

1. For DT met **(≥ 10 scfh** prediction):
   - = [True Positive MLV% (**TP**)] x [Mean Leak Rate for ≥ 10 scfh (**GE10**)] + [False Positive MLV% (**FP**)] x [Mean Leak Rate for < 10 scfh) (**L10**)]
   - = 10.256/100 x 57.667 scfh + 89.744/100 x 1.623 scfh
   - = **7.37 scfh**
2. For DT not met (**< 10 scfh** prediction):
   - = [True Negative MLV% (**TN**)] x [Mean Leak Rate for < 10 scfh (**L10**)] + [False Negative MLV% (**FN**)] x [Mean Leak Rate for ≥ 10 scfh) (**GE10**)]
   - = 98.851 /100 x 1.623 scfh + 1.149/100 x 57.667 scfh
   - = **2.27 scfh**

   Note that the bootstrap mean of the leak rate for samples greater than or equal to 10 scfh was used conservatively in the above calculation. One can shift from this value to a bootstrap mean of the leak rate of the False Negatives of the sample data when enough of these values are obtained. There are currently only two occurrences of False Negatives, so a population mean cannot be obtained.
3. If no concentration measurements were taken, i.e. no application of Decision Tree or leak rate measurements, then one should use the entire sample set bootstrap mean:
   - = **4.30 scfh**
4. If one has an actual leak rate measurement, then use that measurement.

6.2. Table of Emission Factors

The SoCalGas-specific emission factors calculated above are summarized in Table 29 below.

Table 29: Table of SoCalGas Company Specific Emission Factors by DT Grouping.

EF Category	EF (scfh)
Combined All Case Ave EF	4.30
DT Not Triggered Ave EF	2.27
DT Triggered Ave EF	7.37

It is worth noting that these DT related emission factors are conservative due to the nature of properly accounting for false negatives. For example, if one were to take the straight average of the All District Study from the 78 samples, the single emission factor would be 1.58 scfh.

6.3. Carrying Uncertainty Through to the Emission Factor Calculations

Additional steps are necessary to properly carry through the uncertainty related to the average (i.e., expected or baseline) emission factor and provide confidence limits at a selected confidence level for the EF's.

To do this, one would run Monte Carlo analysis by drawing from the bootstrap average leak rate population distributions of the appropriate data set and category of leak rate (large and not large) and then weight those by the Bayesian proportions for those categories. This would be done thousands of times, picking the average leak flow rates and the associated Bayesian proportions from those distributions and calculating (thousands of times) the associated emission factors.

This would provide a full distribution of the emission factors for each category and then one could select the confidence level of choice (e.g., 95%) to generate the confidence interval around the average emission factors.

However, one would still use the expected (average) value of the emission factors in practice, but the confidence bands would help establish the level of uncertainty in those values.

This will be the next step once SoCalGas collects additional samples from the ongoing implementation of this approach. As was shown in an earlier section, it is desired to get a statistically significant sample for false negatives, so that data can be used for the associated average leak flow rate vs. the much more conservative measure currently being used, which is the average of actual leak flow rates above the 10 scfh threshold point.

6.4. Scenarios of EF Application

The scenarios that could be encountered in the field for leak repair are listed below with the guidance on what emission factor to use and when to use them.

Table 30: Table of Emission Factors to use for Field Situations.

Situation Number	Field Situation Description	Emission Factor
1	Measured concentration triggers DT < 10 scfh category & leak rate is not measured (which would be the typical situation) - Use DT Not Triggered Ave EF	**2.27 scfh**
2	Measured concentration DT ≥ 10 category & leak rate is not measured (used when leak rate cannot be measured, such as leaks quickly repaired or when leak is in a remote location) - Use DT Triggered Ave EF	**7.37 scfh**
3	Leak repaired and no concentration or leak rate measurements - Use Combined All Case Ave EF	**4.30 scfh**
4	Measured concentration(s) trigger DT >10 category & then leak rate measured and actual leak rate is < 10 scfh - Use the actual leak rate measurement for the emission factor	**Use actual leak rate measurement**
5	Measured concentration(s) trigger DT >10 category & then measure and actual leak rate is ≥ 10 scfh - Use the actual leak rate measurement for the emission factor	**Use actual leak rate measurement**

7. Summary of Results and Conclusions

Summary of Results

The national studies compared well with the SoCalGas studies. The upper and lower 95% percentiles for leak rate and the median and means of these two groups are similar.

Two of five SoCalGas sample sets were known to contain sample bias as well as being an order of magnitude in size smaller than the other three. These were analyzed in this report to show how bias might appear during analysis, and they were not included in the ultimate combined data set.

The non-hazardous leak rate values from the SoCalGas combined data set was analyzed for unexplainable outliers or extreme values and was log transformed, resulting in a normally distributed data set. Upon review of the extreme values, all of them were deemed as sound data points and not errors or anomalous values. The log-normal transformation of the leak rate data permitted a variety of statistical regression tools to be appropriately leveraged.

A series of regression and probabilistic analysis were conducted on the data set. A key finding was that when the samples sizes would support categorical analysis that there was no significant sensitivity of the leak rate means to geographic districts of the leak or the year that the leak was detected.

An analysis of the field methane concentration vs. measured leak rates was done by Decision Tree methane concentration threshold category. The regression analysis of the mean leak flow rate vs. methane concentration showed the expected upward trend for the average values. The concentration threshold intersection with the established 10 scfh "Large" vs. "Not Large" flow rate threshold was within the 95% confidence interval of the regression model or above and to the left (a conservative situation) of the predictive margin plots.

A Bayesian probabilistic analysis was conducted of the Decision Tree threshold performance. This resulted in a true/false positive/negative error table. The Decision Tree thresholds correctly assigned not large leak situations 98.9% of the time, i.e. true negatives with a 95% prediction interval of 98.9% to 99.5%. Likewise, the Decision Tree had a false negative (Type II error) of only 1.1% with a 95% prediction interval of 0.47% to 3.6%.

The leak rate data was bootstrapped 10,000 times with replacement with a re-sample size equal to the field data sample size. This analysis provided the overall mean leak rate, as well as the mean leak rates for less than 10 scfh leakers and greater than or equal to 10 scfh leakers - all from the empirical data. The bootstrap analysis provided a full set of percentiles for the actual mean leak rates which allows one to establish confidence intervals for the mean values at any desired confidence level.

The leak rate data was fit to a log-normal distribution as well, and this fit was used to conduct a Monte Carlo analysis of the mean leak rates as was performed with the bootstrap analysis using the actual field leak rate data. The same re-sample and sample sizes were used as was done with the bootstrap analysis to properly propagate the uncertainty through the analysis. The result showed the two approaches were very similar, with the Monte Carlo of the log-normal distribution fit being conservative in the low- to mid- leak rate ranges and about the same in the high-leak rates.

A set of emission factors based on the Decision Tree categorization were calculated by combining the mean leak rates with their corresponding expected percentiles (in a weighted manner) from the Decision Tree error table. It was noted that the Decision Tree derived emission factors were conservative (higher) than one would have obtained from a straight average of the empirical data from the All District Study of the SoCalGas system. This is due to the Bayesian analysis properly accounting for false negatives in the Decision Tree process.

A calculation of the efficiency of the process was done using the 2019 3-District Pilot study which had a total number of 356 screened leaks with surface concentration measurements. Of these, the DT was triggered for measurement 44 times. Therefore, this relates to a flow rate measurement ratio of 44 / 356 or 12.4%. In other words, when considering leak sites visited and screened with surface concentration measurements that one would expect leaks triggered by the DT process and criteria to have approximately a 1 in 8 chance being classified as potential non-hazardous large leak, scheduled for leak rate measurement, or prioritized for repair.

For this particular example, rather than measuring all 356 leaks to find all the large leaks; we used the DT process resulting in the requirement to measure only 1 in 8 leaks while maintaining a false negative rate of 1.1%. In summary:

- Using the DT method, 4 of the expected 7 large leaks were found by measuring the leak flow rate from 44 out of 356 leak sites.
- Without the DT, to find the same ratio of 4 out of the 7 large leaks, 203 leak flow rates on average would need to be measured out of the 356 leak sites.
- This means the DT efficiency increase is 203/44 = 4.6x (460%) more efficient at finding the same number of large leaks when not using the DT process.
- The DT is therefore an efficient screening mechanism, with a high potential to continue to improve over the short-term full implementation period.

Conclusions

SoCalGas conducted a statistically sound study of underground pipeline leaks using random samples as well as well-proven field leak concentration and flow rate measurement techniques to calculate SoCalGas company-specific natural gas emission factors for buried distribution system non-hazardous leaks.

The developed Decision Tree approach of using concentration measurements with thresholds to establish large and not large non-hazardous leaks was successful as shown by a 98.9% true negative value associated with predicted leak and actual leak rates.

The inferred population mean leak rates were combined with the associated Decision Tree performance percentages to calculate appropriately weighted emission factors for large and not large non-hazardous leaks.

This allows the assignment of emission factors for the not large non-hazardous leaks that would not have leak rate flow measurements performed on them as well as any Decision Tree classified large non-hazardous leaks that did not have leak rate flow measurements performed.

The approach will be further refined and improved by continuing to:

- Collect field data leading to lower uncertainty, i.e. tighter confidence intervals around leak and Decision Tree performance metrics;
- Perform random checks for false negatives to identify possible upset conditions in expected leak rates, e.g. from a change in system performance and/or environmental stressors; and
- Analyze and adjust the Decision Tree thresholds or even add new thresholds to further increase the method's predictive accuracy and/or increase process efficiency to continuously improve the cost-effectiveness of the approach, overall process for detection, and repair of large flow system leaks to minimize natural gas emissions.

Appendix A: Surface Measurements of Underground Leak Flow Rate

The approach employed a dynamic surface enclosure where ambient air is drawn through a well-mixed chamber at a constant measured rate. Methane emitted from the surface and mixed into the chamber air is sampled in the exhaust. The methane emission rate is calculated from the measured air flow rate through the chamber, measured inlet, and exhaust methane concentrations. This surface measurement technique for underground leaks have been validated and used extensively by many research teams, including GTI, in past research efforts [1, 4, 30].

The equipment required for this method includes an enclosure, a high-volume sampler (such as Bacharach's Hi Flow Sampler), and a combustible gas indicator (CGI), see Figure 28.

The Hi Flow sampler is a portable, battery-powered instrument designed to quantify methane emission rates from leaking components common to natural gas operations. When using the Hi Flow sampler, a robust validation procedure was followed to eliminate measurement issues as suggested by prior studies [31, 32]. In addition, the methane measurement instrument used in conjunction with the high-flow sampler was calibrated according to manufacturer requirements.

The use of the surface measurement method is suitable when leak locations are known and are accessible on foot. The underground leak first has to be identified using a screening instrument such as a handheld leak survey instrument (e.g. the DP-IR) that can be used to map out the area on the surface with elevated methane concentrations.

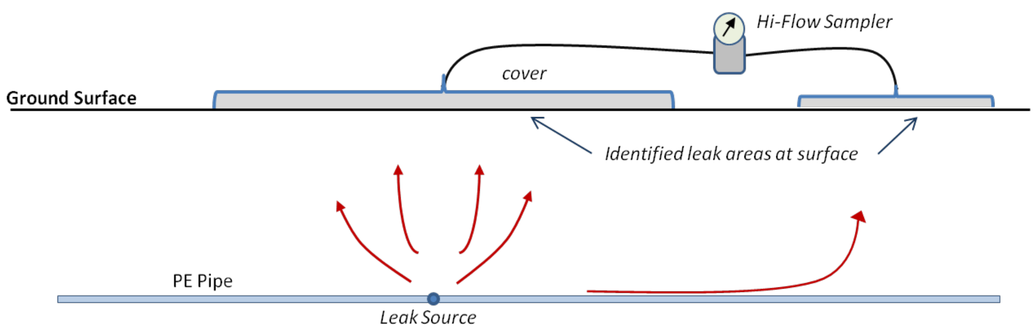
Figure 28: Quantifying surface flux rate of an underground emission.

Using the "enclosure/chamber method. The high-flow device is housed in the backpack.

Once the leak area is demarcated, if it is larger than the footprint of the enclosure, then it is segmented into a grid and each square segment is then measured with the enclosure to capture the surface expression of the area. A picture and schematic of this measurement method is shown in Figure 29 below. The total leak rate is the sum of the individual grid measurements.

During measurement, the top of the enclosure is attached to a high-volume sampler that pulls in air from the enclosed volume at a high flow rate. To calculate the leak flux rate under the enclosure, the sampling rate is multiplied with methane concentration of the sampled air; this is measured by a built-in methane sensor or by a separate combustible gas indicator (CGI). The built-in methane sensor has an accuracy of 0.02% methane which gives the device a sensitivity to detect natural gas at a leak rate of 0.6 scfh [33]. The unit also corrects temperature compensates automatically to 60 F. In order to improve the sensitivity, a CGI with low parts-per-million (ppm) methane sensitivity is placed at the outlet of the high-flow device.

Figure 29: Schematic of surface chamber measurements with the Hi-Flow sampler.



Appendix B: Statistical and Probabilistic Analysis Details and Supplemental Analysis

This appendix contains supplemental statistical and probabilistic analysis details that are summarized in the body of the report.

Linear Regression Residual Analysis and Regression Diagnostics

The following diagnostics were analyzed for the SoCalGas study regressions to confirm regression assumptions and to look for influential, outlier, or extreme values requiring further review and/or explanation or exclusion.

The residuals were from the full linear regression where the dependent variable is the log(10) of the leak flow rate (scfh), and the independent, categorical variables are the three SoCalGas studies.

The plots of the analysis are customized. Instead of just listing table data of these diagnostic measures, the values were scatter plotted, and the ID labels (observations) were paired to the diagnostic results *after* the regression analysis and plotted with the ID as the x-axis in some of the cases. This was done to allow one to quickly identify observations that should be focused on for further review and spot trends. The regression was not tied to the observation (sample ID) in any way.

1. **Exogeneity**: Assumes that given an independent set of variables, one can account for any error in the linear regression model. Stated a different way, one must have a sound causal model with factors for each casual influence on the dependent variable. There is no statistical test, and it was therefore designed into the regression model through cause and effect analysis/modeling (causal analysis).

2. **Random Sampling**: This was confirmed and discussed prior to sampling or regression. Two sample-biased studies were not included primarily due to confirmation bias and for small sample sizes. There is no statistical test for this, and it was therefore designed into the study.

3. **Linearity in Parameters**: Since the independent variables within this study are not metric, linearity in parameters were not compared within this report.

4. **Multicollinearity:** When a large number of independent (control) variables exists, there should not be strong correlations between them, which can inflate standard errors of estimated coefficients. This is not an issue with this analysis, since the datasets are from studies that are mutually independent of each other.

5. **Heteroscedasticity and Normal Distribution of Residuals**: Assumes that variance of the residuals is constant - if it is not, then this is known as heteroscedasticity. In this study, the residuals between the predicted and actual values were analyzed, demonstrated a symmetric

and normal distribution across zero (as plotted in Figure 30). Likewise, Figure 31 is a scatter plot comparing the residuals vs. the study (independent variable) with fitted values plotted as a line. In addition, a locally weighted (Lowess) line fit was conducted and appended onto Figure 31. The two lines are flat, nearly parallel to each other, and centered around zero. Note the values above and below these lines are nearly equally spread in numbers and density.

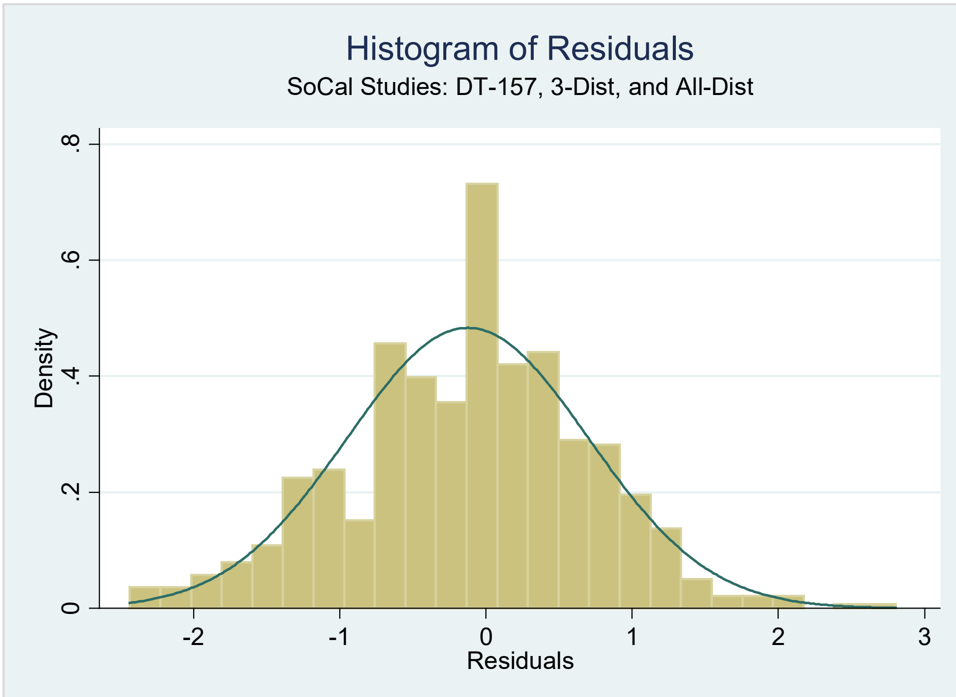
6. **Influential Observations - DFBETA**: This diagnostic is used to measure the influence of a single observation per each metric or categorical variable. A rule of thumb is that DFBETA might be a problem when an observation's absolute value of DFBETA is > 2/sqrt(N), where N is the total number of samples (observations). In this case, the value is 0.12. As can be seen from Figure 32, nearly all the cases are below this threshold number. To analyze values above the threshold number, Cook's distance and Leverage measures of influence were also utilized.

7. **Influential Observations - Cook's Distance**: This measure detects strange patterns and unusual variable combinations. Upon looking at DFBETA and Cook's distance, observation ID 97 and ID 121 are more influential than other observations (Figure 33). This makes sense, since these two observations are the two highest leak rates at 373 and 172 scfh (in round numbers). However, these are not problematic or erroneous outliers and *should* be considered influential, since they are in fact within the far-right tail of the expected leak rate distribution of the sample.

8. **Influential Observations - Leverage**: Finally, a dual plot of leverage vs. residuals is a very useful plot to analyze. If the *residual* of a case is high, this means that the regression would calculate a result that is quite off from the real outcome. Therefore, the residual is related to the *dependent* variable (leak rate in this case). A high *leverage* of a case means that the constellations of independent variables of a certain case are so extreme or uncommon that they influence the final result over proportionally. Therefore, the leverage is related to the independent variables of a case. The two red lines in the graph show the means for both residuals and leverages. Looking at the dual plot in Figure 34, one can see two observations in the upper right quadrant which are again the two highest leak rate samples as noted earlier. There are also three observations in the lower right quadrant which happen to be the three lowest leak rate readings. Since these observations are correct, it was decided to retain them in the analysis.

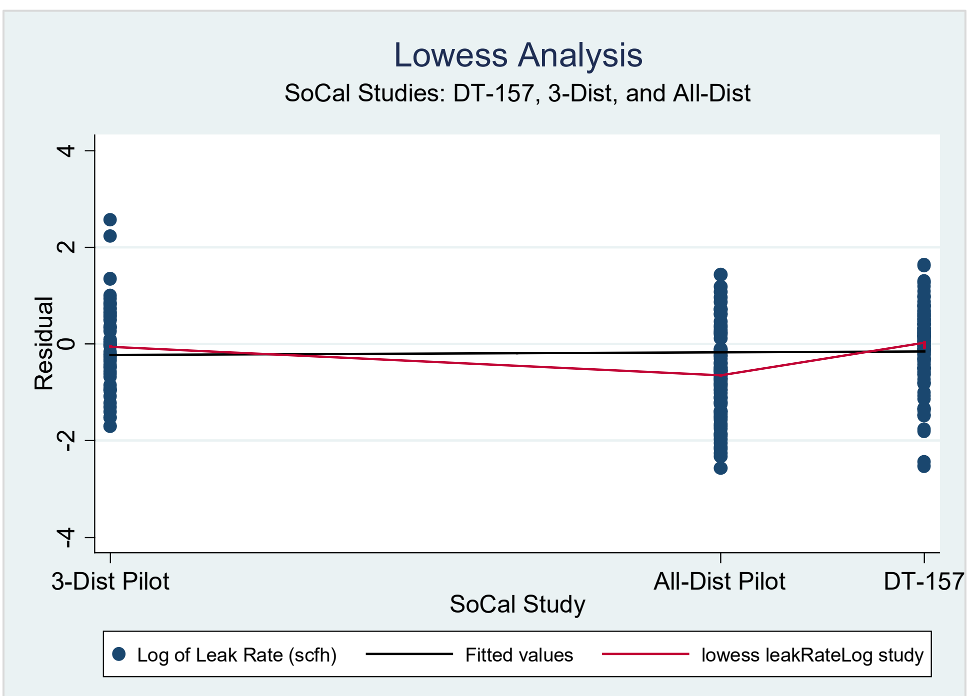
Residual Distribution

Figure 30: Histogram Diagnostic Plot of LR Leak Rate Residuals for Three SoCalGas Studies.



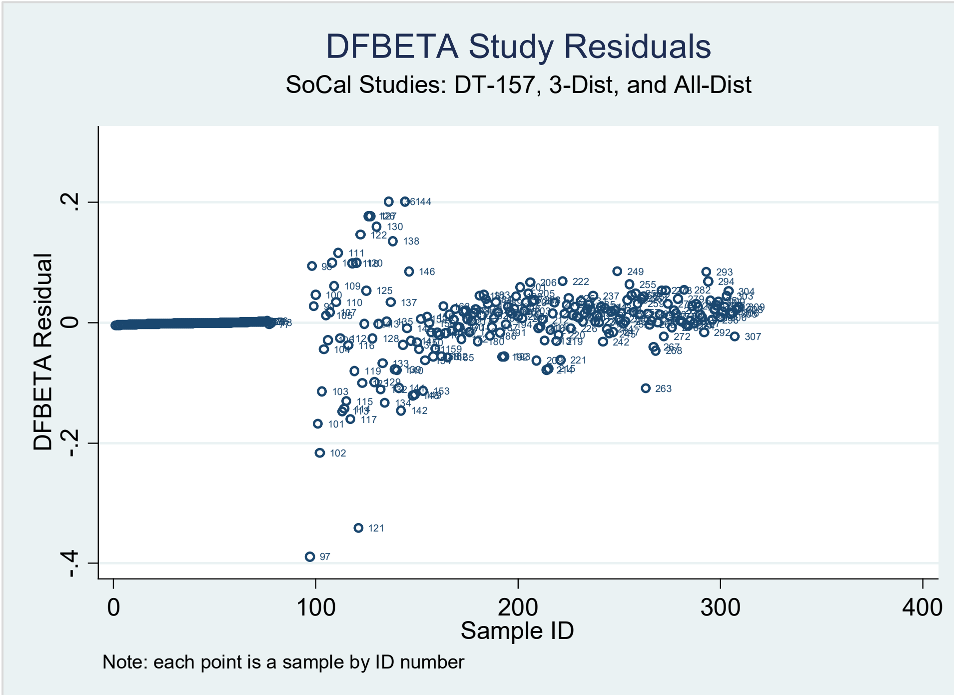
Lowess

Figure 31: Lowess LR Diagnostic of Leak Rate Residuals by SoCalGas Study.



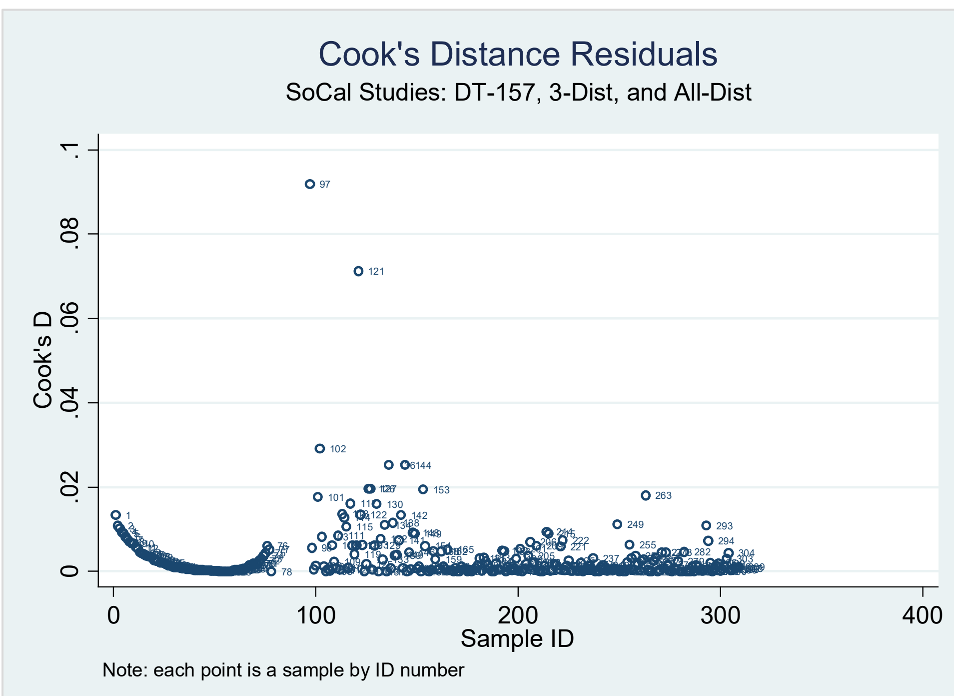
DFBETA

Figure 32: DFBETA LR Diagnostic of Leak Rate for Three SoCalGas Studies.



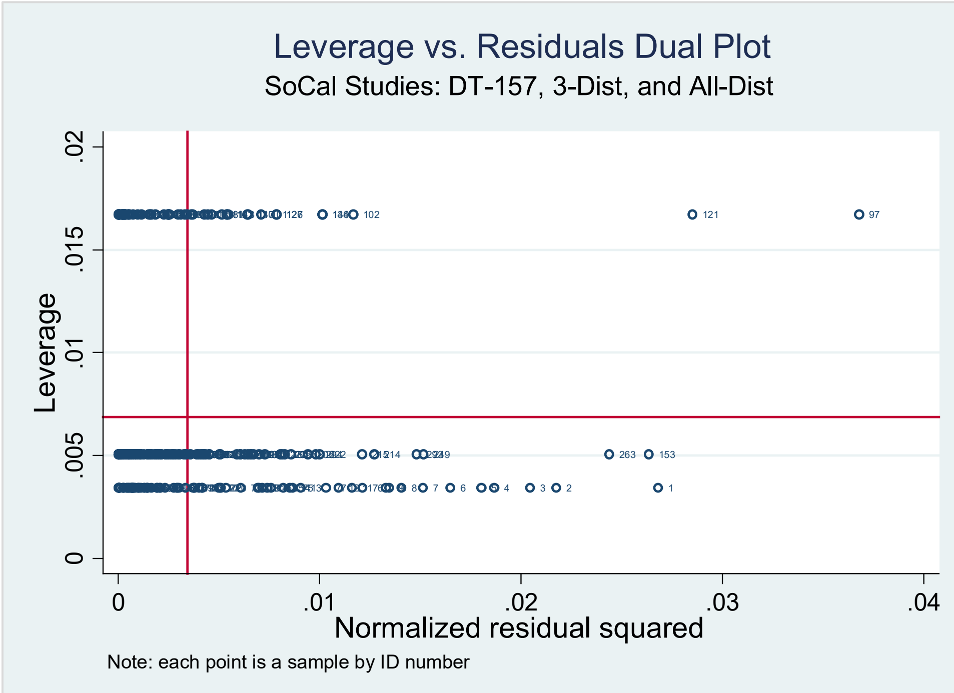
Cook's Distance

Figure 33: Cook's Distance LR Diagnostic of Leak Rate for Three SoCalGas Studies.



Leverage

Figure 34: Leverage LR Diagnostic of Leak Rate for Three SoCalGas Studies.



Bayesian Monte Carlo Markov Chain (MCMC) Models of Sample Leak Rates

A non-parametric Bayesian Monte Carlo Markov Chain (MCMC) [25] regression analysis was conducted. Two variations of random *sampling* were used, the random walk Metropolis-Hasting (MHS))[26, 27] method as well as the more robust Gibbs (GS)) [28] method. In both cases, 35,000 iterations were used with a 5,000 iteration burn-in run, resulting in an incorporated Monte Carlo sample size of 30,000. In both cases, the prior distribution for the log(10) leak rate distribution was "uniformed", i.e. a flat/uniform prior. The sigma prior was assumed as a conservative gamma function. The same set up of dependent and independent variables was used as with the traditional linear regression and ANOVA analysis discussed in this appendix and the body of the report.

Metropolis-Hastings Sampling (MHS)

The results of the MCMC-MHS are shown in Table 31 below. The form is very similar in output to the standard regression outputs already explained. However, this is for convenience of comparison, since the methods are completely different, and this analysis uses Bayesian linear regression. The MHS method is about 33% efficient. Therefore, approximately 10,000 of the samples were utilized with the others being rejected.

From the table, the MCMC-MHS produces very similar coefficients and associated 95% credible interval as compared to the LR coefficients (means) and 95% confidence interval. This does not come as a surprise, since the regression assumptions were met, and the dependent variable (log(10) of leak rate) was normally distributed.

Table 31: Bayesian MCMC(MHS) of Leak Rate Means - Three SoCalGas Studies.

```
Model summary
----------------------------------------------------------------------------------
Likelihood:
  leakRateLogSoCal ~ regress xb_leakRateLogSoCal,sigma2)
Priors:
  leakRateLo~l:i.study _cons ~ 1 (flat)                                        (1)
                      sigma2 ~ igamma(.01,.01)
----------------------------------------------------------------------------------
(1) Parameters are elements of the linear form xb_leakRateLogSoCal.

Bayesian linear regression                             MCMC iterations  =     35,000
Random-walk Metropolis-Hastings sampling               Burn-in          =      5,000
                                                       MCMC sample size =     30,000
                                                       Number of obs    =        291
                                                       Acceptance rate  =      .3335
                                                       Efficiency:  min =     .06429
                                                                    avg =      .1081
Log marginal-likelihood = -360.84393                                max =      .2204
 ----------------------------------------------------------------------------------
                                                                  Equal-tailed
                         Mean   Std. Dev.     MCSE     Median  [95% Cred. Interval]
----------------------------------------------------------------------------------
leakRateLogSoCal
            study
       3DisPilot     (base)
3DisPilotLowSpec     (omitted)
       AllDisLIRP    (omitted)
      AllDisPilot   -.5893627   .1408558   .002931  -.5869901  -.8674918  -.3101206
       DT157Pilot    .0853107   .1241679   .002827   .0824296  -.1555874   .3314519
     Natl_CARB_GTI   (omitted)
      Natl_OTD_GTI   (omitted)
      Natl_WSU_EDF   (omitted)

            _cons    -.063096   .1081477   .002349  -.0618196  -.2803022   .1406578
----------------------------------------------------------------------------------
           sigma2     .659823   .0556692   .000685    .657526   .5587767   .7786351
```

Gibbs Sampling (GS)

A very similar analysis was repeated with the only difference being that Gibbs sampling was used instead of Metropolis-Hastings Sampling. Gibbs sampling is even more efficient (note a 99% efficiency), but it does take more computing power and time to complete. The results are in Table 32 below.

Table 32: Bayesian MCMC(GS) of Leak Rate Means for Three SoCalGas Studies.

```
Model summary
------------------------------------------------------------------------------------
Likelihood:
  leakRateLogSoCal ~ normal(xb_leakRateLogSoCal,sigma2)
Priors:
  leakRateLo~l:i.study _cons ~ normal(0,10000)                              (1)
                      sigma2 ~ igamma(.01,.01)
------------------------------------------------------------------------------------
(1) Parameters are elements of the linear form xb_leakRateLogSoCal.

Bayesian linear regression                             MCMC iterations  =     35,000
Gibbs sampling                                         Burn-in          =      5,000
                                                       MCMC sample size =     30,000
                                                       Number of obs    =        291
                                                       Acceptance rate  =          1
                                                       Efficiency:  min =      .9682
                                                                    avg =      .9854
Log marginal-likelihood = -377.39597                                max =          1
------------------------------------------------------------------------------------
                                                                    Equal-tailed
                         Mean   Std. Dev.     MCSE     Median  [95% Cred. Interval]
------------------------------------------------------------------------------------
leakRateLogSoCal
            study
       3DisPilot     (base)
3DisPilotLowSpec     (omitted)
      AllDisLIRP     (omitted)
     AllDisPilot   -.5896894   .1425934   .000834  -.5907453  -.8732188  -.3109355
      DT157Pilot     .083985   .1267482   .000732   .0830794  -.1636278   .3327636
   Natl_CARB_GTI     (omitted)
    Natl_OTD_GTI     (omitted)
    Natl_WSU_EDF     (omitted)

           _cons   -.0621054   .1084323   .000626  -.0618162  -.2748983   .1485988
------------------------------------------------------------------------------------
          sigma2     .661009   .0557936   .000327   .6578556   .5605393   .7781685
```

Diagnostics for one of the coefficients were selected for inclusion in the report, see Figure 35 for the MCMC(MHS) model and Figure 36 for the MCMC(GS) model. In both cases, the traces are flat and well spread out, the histogram and densities are symmetric and consistent, and autocorrelation decreases quickly or is non-existent; these are all excellent attributes of the residuals.

Figure 35: Diagnostics for Bayesian MCMC(MHS) of Leak Rate Means - SoCalGas Studies.

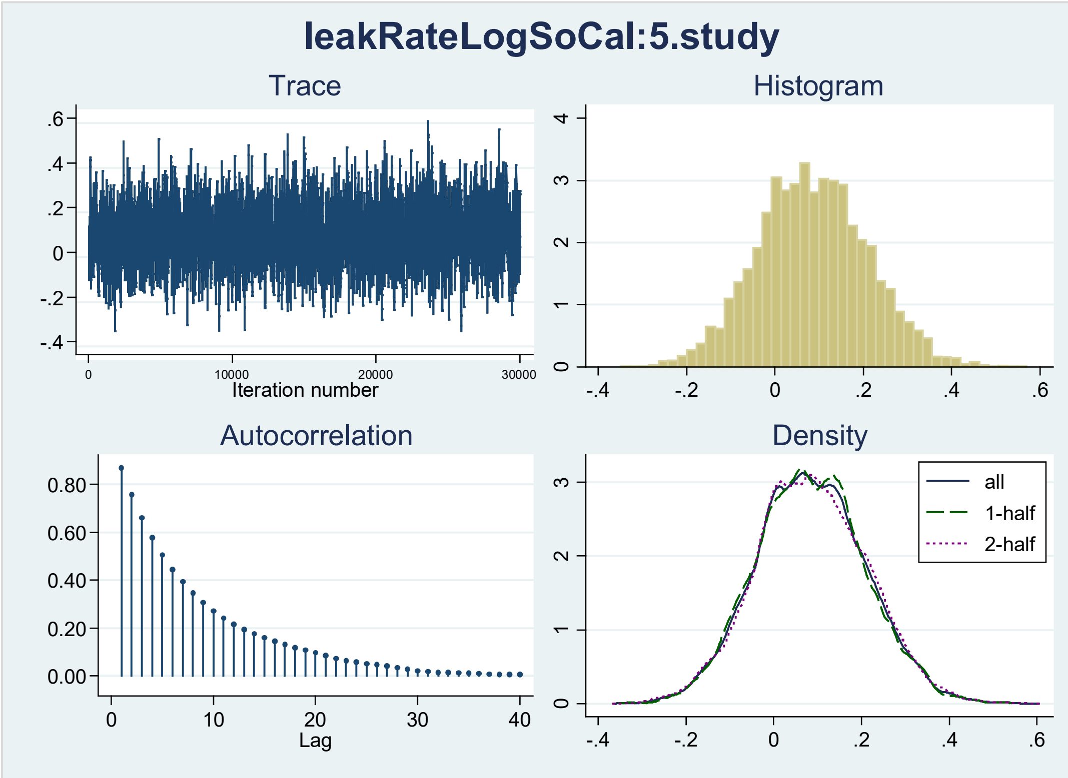
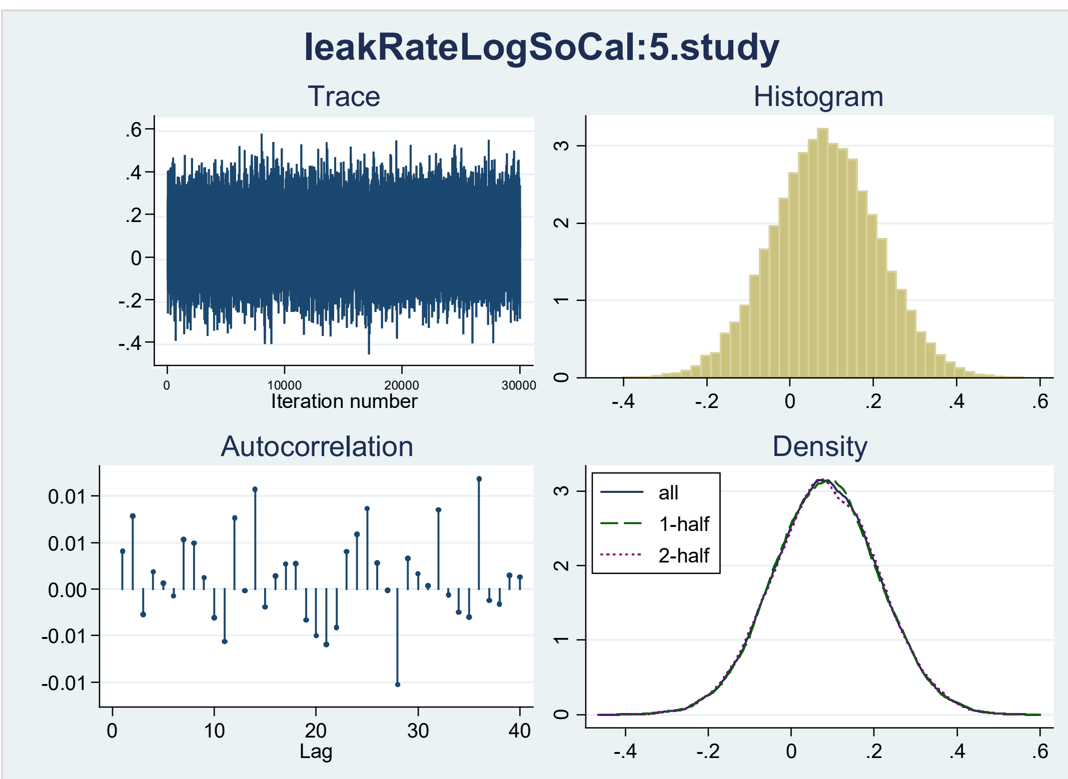


Figure 36: Diagnostics for Bayesian MCMC(GS) of Leak Rate Means - SoCalGas Studies.



ANOVA and Pairwise comparison of National and SoCalGas Studies

The ANOVA results of a log(10) means analysis by individual study is shown in Table 33 below. The analysis was done across national industry and SoCalGas studies.

Table 33: ANOVA of Individual National and SoCalGas Study Leak Rate Means.

```
               Summary of Log of Leak Rate (scfh)
      study          Mean    Std. Dev.       Freq.
-------------------------------------------------
  3DisPilot    -.06279222   .89898228          56
3DisPilotLS    -.65094811   .55460313           8
  AllDisLIR     .07601364   .65975028          10
  AllDisPil    -.65257563   .92139692          78
  DT157Pilo     .02154301   .71202596         157
  Natl_CARB    -.01830655   .64701923          76
  Natl_OTD_     .16791675   .61032353          62
  Natl_WSU_    -.61104802   .75895091         212
-------------------------------------------------
      Total    -.26707906   .81914558         659

                        Analysis of Variance
    Source              SS         df      MS            F     Prob > F
------------------------------------------------------------------------
Between groups      70.8808391      7   10.1258342     17.79     0.0000
 Within groups      370.636818    651    .56933459
------------------------------------------------------------------------
    Total           441.517657    658   .670999479

Bartlett's test for equal variances:  chi2(7) =  20.9465  Prob>chi2 = 0.004
```

The pairwise log(10) leak rate means comparison by individual study is shown in Table 34 below.

Table 34: PW Comparison by National/SoCalGas Study Pair for Leak Rate Means.

study	Contrast	Std. Err.	Unadjusted t	Unadjusted P> t	[95% Conf.	Interval]
3DisPilotLowSpec vs 3DisPilot	-.5881559	.2851903	-2.06	0.040	-1.14816	-.028152
AllDisLIRP vs 3DisPilot	.1388059	.259037	0.54	0.592	-.3698429	.6474547
AllDisPilot vs 3DisPilot	-.5897834	.1321584	-4.46	0.000	-.8492916	-.3302752
DT157Pilot vs 3DisPilot	.0843352	.1174437	0.72	0.473	-.146279	.3149494
Natl_CARB_GTI vs 3DisPilot	.0444857	.1328832	0.33	0.738	-.2164457	.305417
Natl_OTD_GTI vs 3DisPilot	.230709	.1391025	1.66	0.098	-.0424347	.5038527
Natl_WSU_EDF vs 3DisPilot	-.5482558	.1133677	-4.84	0.000	-.7708662	-.3256454
AllDisLIRP vs 3DisPilotLowSpec	.7269618	.357911	2.03	0.043	.0241625	1.429761
AllDisPilot vs 3DisPilotLowSpec	-.0016275	.2801178	-0.01	0.995	-.551671	.5484159
DT157Pilot vs 3DisPilotLowSpec	.6724911	.2734834	2.46	0.014	.1354751	1.209507
Natl_CARB_GTI vs 3DisPilotLowSpec	.6326416	.2804605	2.26	0.024	.0819253	1.183358
Natl_OTD_GTI vs 3DisPilotLowSpec	.8188649	.2834601	2.89	0.004	.2622584	1.375471
Natl_WSU_EDF vs 3DisPilotLowSpec	.0399001	.2717579	0.15	0.883	-.4937277	.5735279
AllDisPilot vs AllDisLIRP	-.7285893	.2534416	-2.87	0.004	-1.226251	-.2309277
DT157Pilot vs AllDisLIRP	-.0544706	.246089	-0.22	0.825	-.5376946	.4287533
Natl_CARB_GTI vs AllDisLIRP	-.0943202	.2538202	-0.37	0.710	-.5927253	.4040849
Natl_OTD_GTI vs AllDisLIRP	.0919031	.2571309	0.36	0.721	-.4130028	.596809
Natl_WSU_EDF vs AllDisLIRP	-.6870617	.24417	-2.81	0.005	-1.166518	-.2076058
DT157Pilot vs AllDisPilot	.6741186	.1045251	6.45	0.000	.4688716	.8793657
Natl_CARB_GTI vs AllDisPilot	.6342691	.1216158	5.22	0.000	.3954625	.8730757
Natl_OTD_GTI vs AllDisPilot	.8204924	.1283822	6.39	0.000	.5683993	1.072585
Natl_WSU_EDF vs AllDisPilot	.0415276	.0999235	0.42	0.678	-.1546836	.2377388
Natl_CARB_GTI vs DT157Pilot	-.0398496	.1054399	-0.38	0.706	-.246893	.1671938
Natl_OTD_GTI vs DT157Pilot	.1463737	.1131775	1.29	0.196	-.0758633	.3686108
Natl_WSU_EDF vs DT157Pilot	-.632591	.0794473	-7.96	0.000	-.7885949	-.4765871
Natl_OTD_GTI vs Natl_CARB_GTI	.1862233	.1291281	1.44	0.150	-.0673345	.4397811
Natl_WSU_EDF vs Natl_CARB_GTI	-.5927415	.1008801	-5.88	0.000	-.790831	-.3946519
Natl_WSU_EDF vs Natl_OTD_GTI	-.7789648	.108942	-7.15	0.000	-.9928849	-.5650447

Linear and Logistic Regression of Concentration vs. Leak Flow Rates

Linear Regressions

The linear and logistic regressions of maximum surface concentration vs. leak rate measurements were conducted to explore possible correlations, but were not used to inform the development of the Decision Tree process, including:

- The concentration thresholds,

- The average leak rate of the samples,
- The probability of the DT error type (i.e. the confusion/error matrix), and
- The calculation of the company-specific emission factors (EFs).

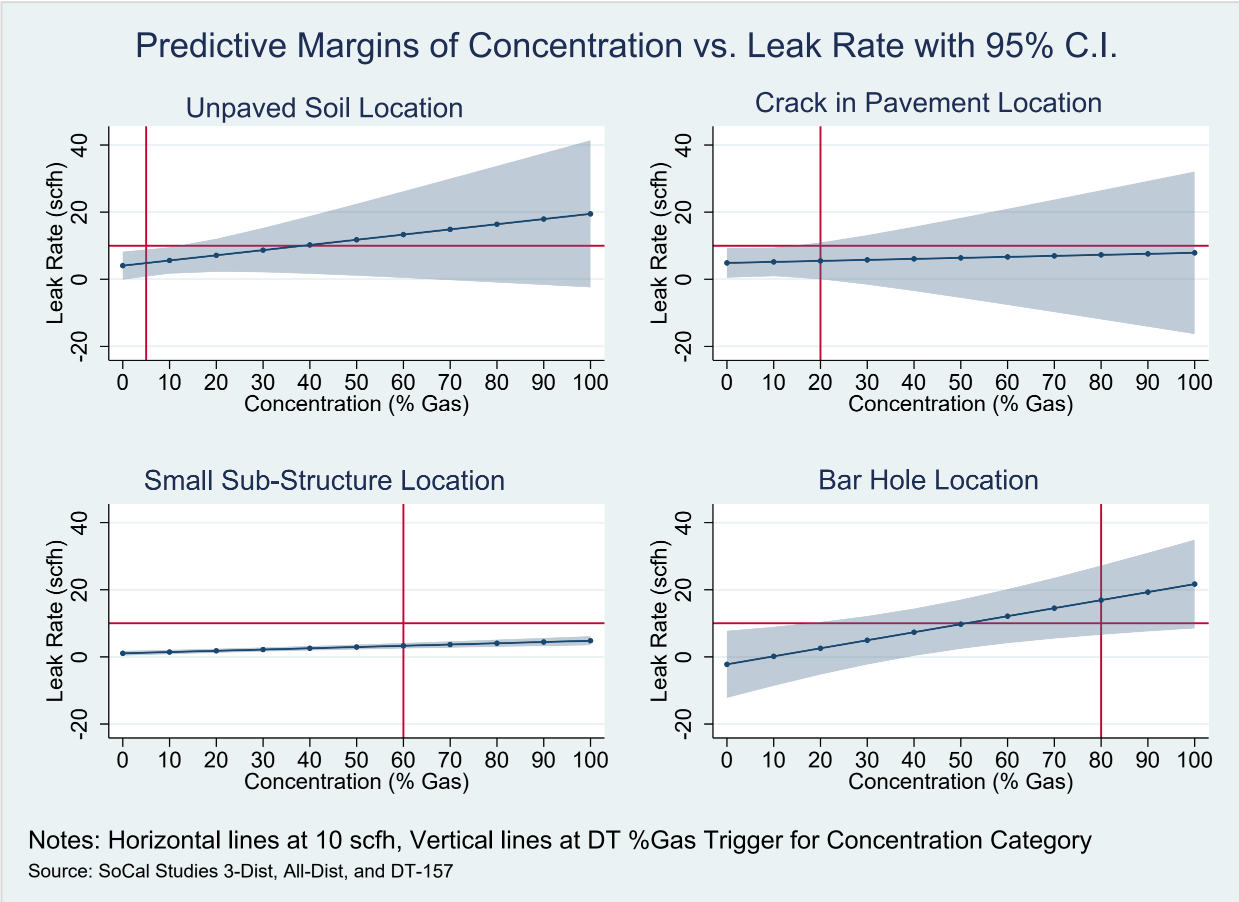
The two regression analyses of the relationship (or lack thereof) between the concentration and leak rate were in fact done post facto as a means of evaluating the empirical DT development. Since only the purely probabilistic Bayesian analysis was used to establish the important true and false negative and positive error values associated with the DT processes these regression sections are presented in the Appendix section of this report.

The regression margin plots in Figure 37 show average leak rate trend upward with increase in concentration, however, the 95% confidence intervals do cross zero in three of the cases and this would be expected from the regression results.

In the regression plot, the Decision Tree 10 scfh leak rate value that separates "Not Large" from "Large" non-hazardous leak levels is plotted as a *horizontal* line and each of the concentration levels that trigger a positive Decision Tree categorization are plotted as *vertical* lines at 80, 20, 60, and 5% gas respectively.

One can see that with the exception of the small sub-structure category, the intersection of the horizontal and vertical lines fall on or within the confidence intervals. The small sub-structure plot has tighter confidence intervals as well as a flatter regression slope for the average value. The trigger of 60% gas is conservatively set nonetheless, since the intersection of the lines is above the confidence interval bands. However, additional sampling and studies need to be conducted to increase the data set and improve the regression and associated confidence intervals.

Figure 37: Predictive Margins for Leak Rate by Concentration from Linear Model.



The linear regressions of concentration vs. leak rate are in Table 35 below. The regression was set up with the continuous (metric) independent variable as concentration and the dependent variable as leak flow rate. The regression was completed four times, once for each surface concentration category. The correlation is extremely poor, partly due to running the regression vs. the leak rate as opposed to the log(10) of the leak rate. However, the analysis was done more for an illustrative purpose; to plot the result margins and show the expected value of the leak rate (not log if the same) vs. each type of surface concentration measure.

Table 35: Linear Regression of DT Concentration and SoCalGas Study Leak Rates.

```
Regress leakRate conc_bh_80
      Source |       SS           df       MS      Number of obs   =       112
-------------+----------------------------------   F(1, 110)       =      6.72
       Model |  9515.73041         1  9515.73041   Prob > F        =    0.0108
    Residual |  155816.784       110  1416.51622   R-squared       =    0.0576
-------------+----------------------------------   Adj R-squared   =    0.0490
       Total |  165332.514       111  1489.48211   Root MSE        =    37.637
------------------------------------------------------------------------------
    leakRate |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
  conc_bh_80 |   .2391175   .0922574     2.59   0.011      .056285    .4219499
       _cons |   -2.20756   5.045601    -0.44   0.663    -12.20676    7.791637
```

```
Regress leakRate conc_cip_20
      Source |       SS           df       MS      Number of obs   =       196
-------------+----------------------------------   F(1, 194)       =      0.05
       Model |  47.3922424         1  47.3922424   Prob > F        =    0.8156
    Residual |  168596.222       194  869.052691   R-squared       =    0.0003
-------------+----------------------------------   Adj R-squared   =   -0.0049
       Total |  168643.614       195  864.839048   Root MSE        =     29.48
------------------------------------------------------------------------------
    leakRate |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
 conc_cip_20 |   .0300363   .1286223     0.23   0.816    -.2236413     .283714
       _cons |   4.863149    2.23957     2.17   0.031     .4461168    9.280181
```

```
Regress leakRate conc_sss_60
      Source |       SS           df       MS      Number of obs   =       166
-------------+----------------------------------   F(1, 164)       =     21.18
       Model |  348.668852         1  348.668852   Prob > F        =    0.0000
    Residual |  2700.05992       164    16.46378   R-squared       =    0.1144
-------------+----------------------------------   Adj R-squared   =    0.1090
       Total |  3048.72878       165  18.4771441   Root MSE        =    4.0576
------------------------------------------------------------------------------
    leakRate |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
 conc_sss_60 |   .0374123   .0081297     4.60   0.000       .02136    .0534647
       _cons |   1.077003   .3728651     2.89   0.004     .3407682    1.813238
```

```
Regress leakRate conc_us_5
      Source |       SS           df       MS      Number of obs   =       210
-------------+----------------------------------   F(1, 208)       =      1.73
       Model |  1403.11046         1  1403.11046   Prob > F        =    0.1901
    Residual |  168849.997       208  811.778832   R-squared       =    0.0082
-------------+----------------------------------   Adj R-squared   =    0.0035
       Total |  170253.108       209   814.60817   Root MSE        =    28.492

------------------------------------------------------------------------------
    leakRate |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
   conc_us_5 |    .154349   .1174023     1.31   0.190     -.077102    .3858001
       _cons |   4.044118   2.121006     1.91   0.058    -.1373072    8.225544
```

Logistic Regressions

This section presents logistic regressions of the probability of a large leak rate as a function of concentration measurements. This analysis was done post facto and did not contribute to the DT thresholds for concentrations in the report. The basic steps for the regression include:

1. Establish the leak rate scfh large leak threshold. This decision can be based on several criteria, including the distribution of leak rate values from published industry studies and/or the company-specific leak rate distributions encountered in the field. For this study the value of 10 scfh was already established.
2. Collect field concentration and leak rate data as discussed in early sections of this report.
3. Run Logistic Regression with the continuous independent variable set to the leak concentration in %gas and the dependent categorical (binary) variable set to large (greater than or equal to10 scfh) vs. not large (less than 10 scfh) leak rates. The logistic regression output margin plots for the SoCalGas DT concentration categories are presented in Figure 38 to Figure 40 below.

Figure 38: Sensitivity of SSS Concentration to Large Leak Detection (Logistic Regression).

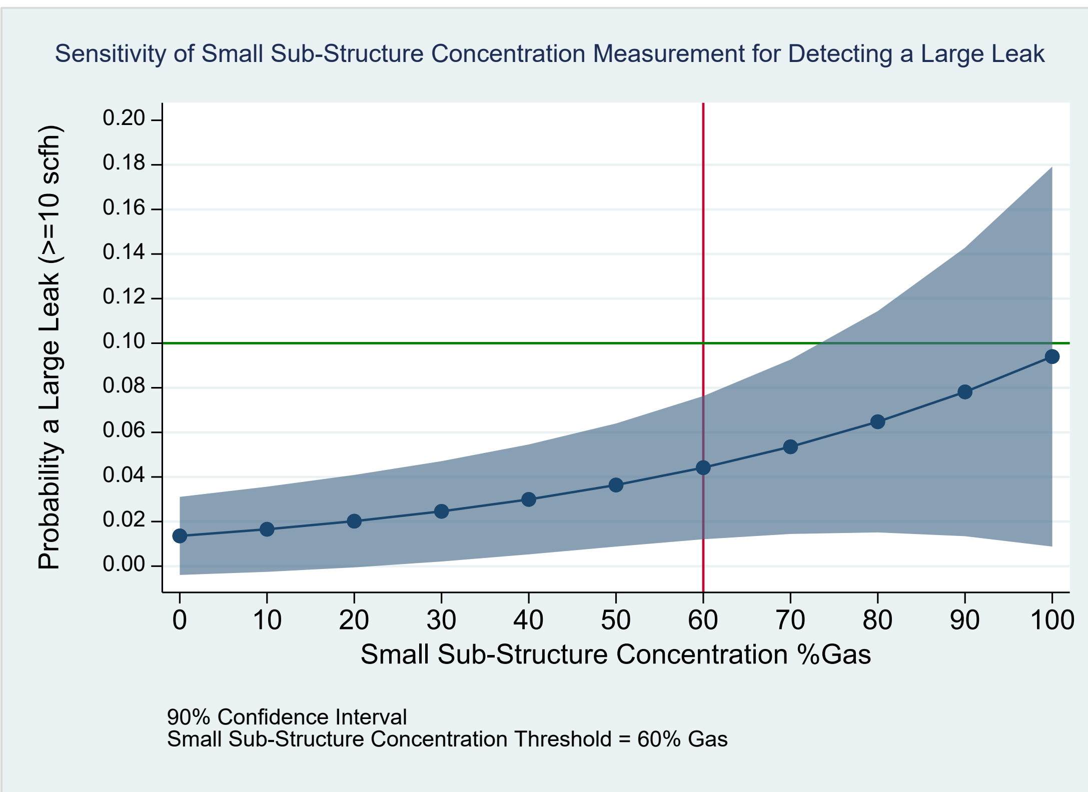


Figure 39: Sensitivity of CIP Concentration to Large Leak Detection (Logistic Regression).

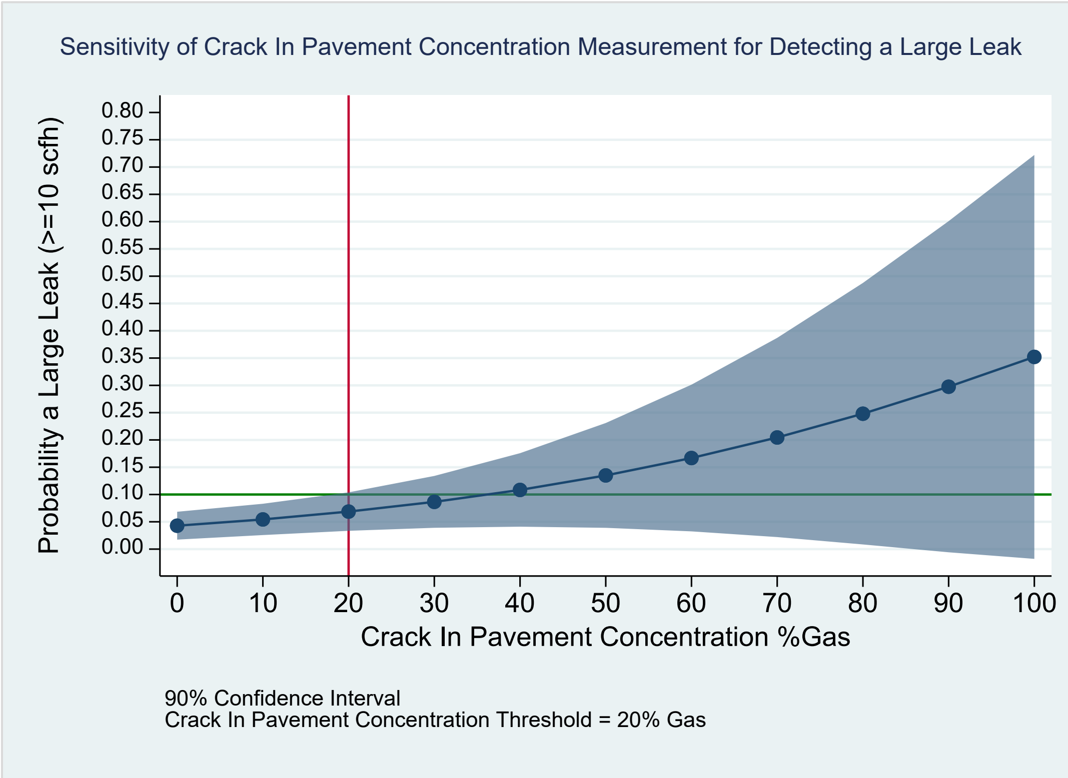
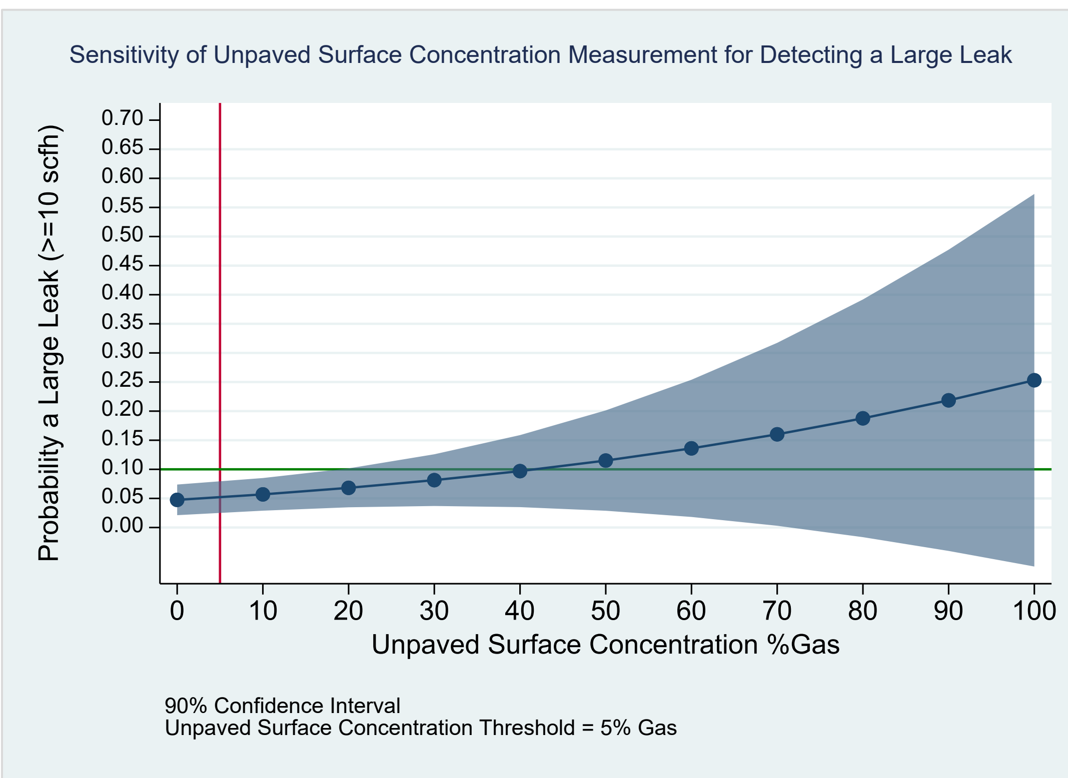


Figure 40: Sensitivity of US Concentration to Large Leak Detection (Logistic Regression).

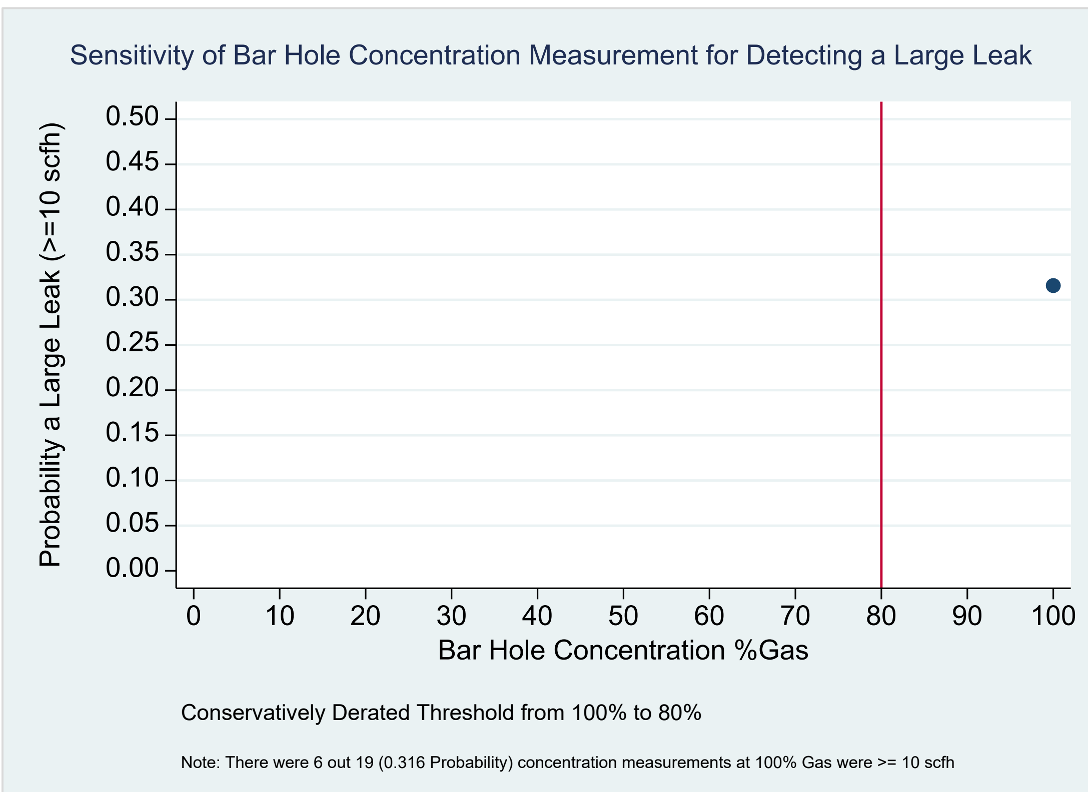


4. It is possible that the data will not support the *convergence* of a logistic (or other) regression. This was the case for the Bar Hole concentration vs. leak rate data as shown in Figure 41. To address these situations, and assign a concentration threshold, one should:

    a. First, take a straight ratio of the relationship (as noted in the plot note). In this case, there was a 31.6% probability of a large leak when the Bar Hole concentration was 100% gas. This value was de-rated (lowered) by 20% from 100% to 80% for the threshold as a conservative measure.

    b. Second, to establish the confidence in this measure, a Bayes analysis confirmed that if one has a gas concentration of less than or equal to 80% in a Bar Hole, then one should expect zero (0) probability of large leaks and will be 95% confident that the actual percent is no higher than 4.1%. This was based on having 71 data points (field samples) that had Bar Hole concentrations that were less than or equal to 80% gas and *all* 71 had less than or equal to 10 scfh measured leak rates.

Figure 41: Sensitivity of BH Concentration to Large Leak Detection (Logistic Regression).



5. Establish the concentration thresholds for each category by setting the confidence interval to 90%, so you have a single sided upper limit of 95%. Then make an initial threshold assignment to establish a 95% confidence of a 10% probability (subjective decision on this number) or less of a large leak at or below the concentration threshold.

6. Then, with the new thresholds set, run a second Logistic Regression with *interactions* this time to take credit for more than one threshold when it is triggered. See Figure 42 to Figure 44 below.

Figure 42: Sensitivity of SSS Concentration to Large Leak Detection - Multi-Thresholds.

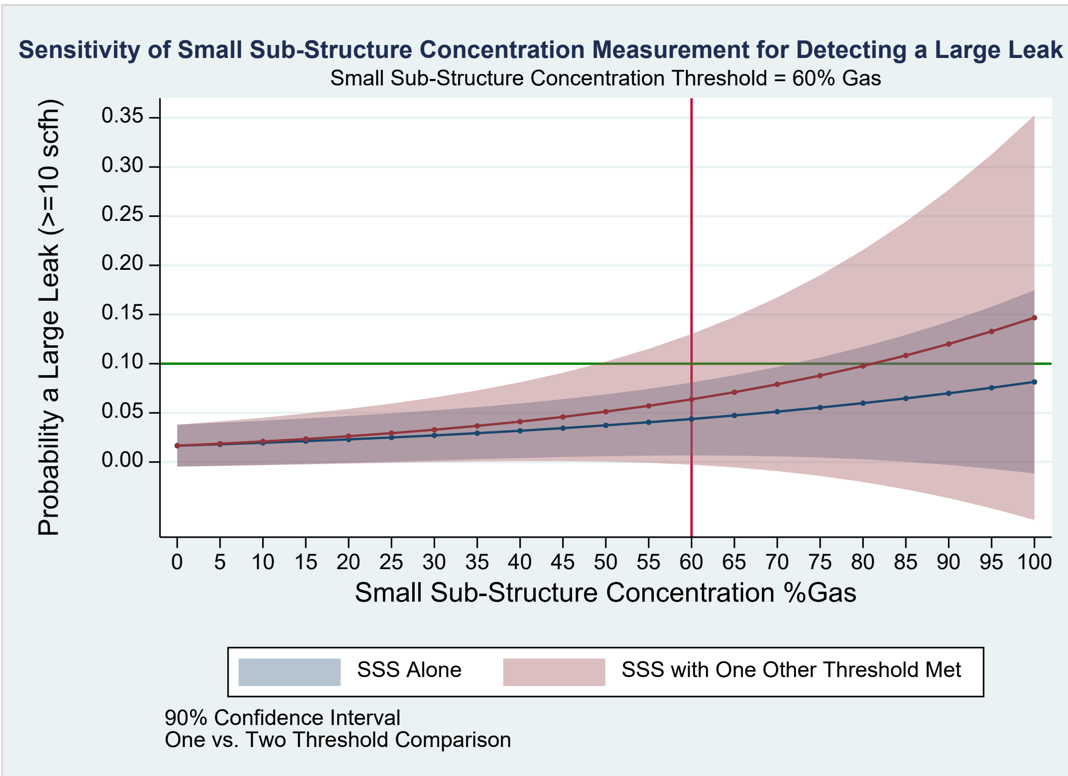


Figure 43: Sensitivity of CIP Concentration to Large Leak Detection - Multi-Thresholds.

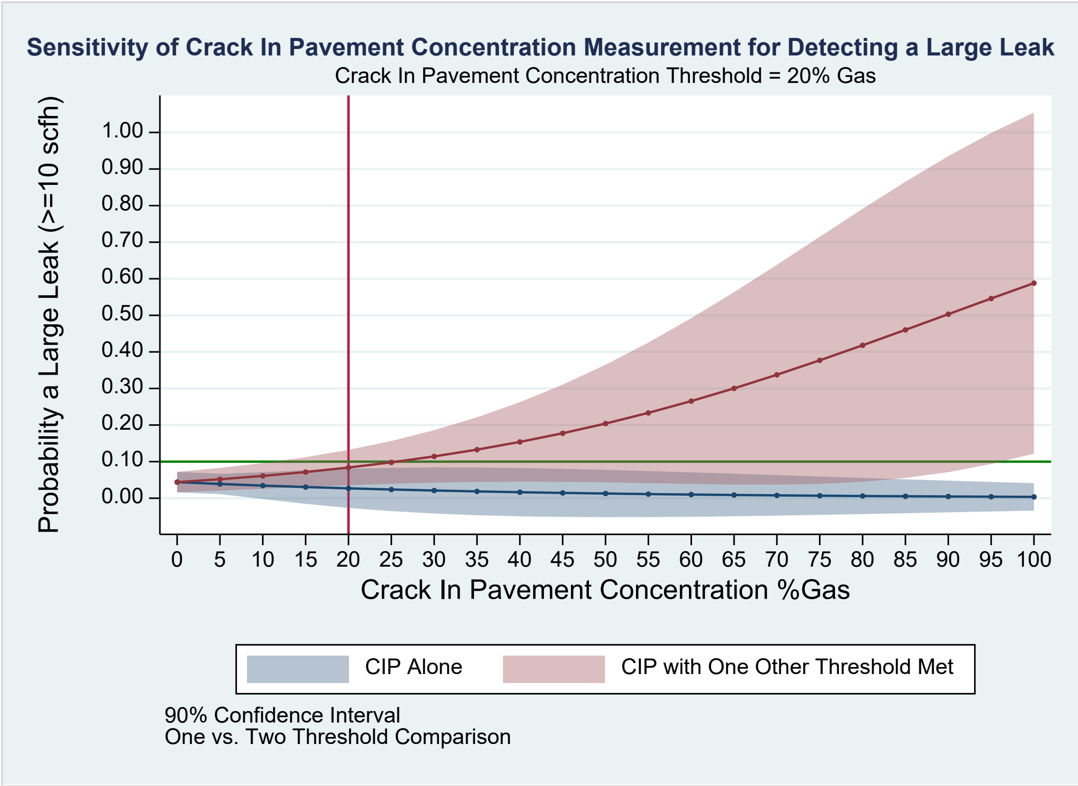
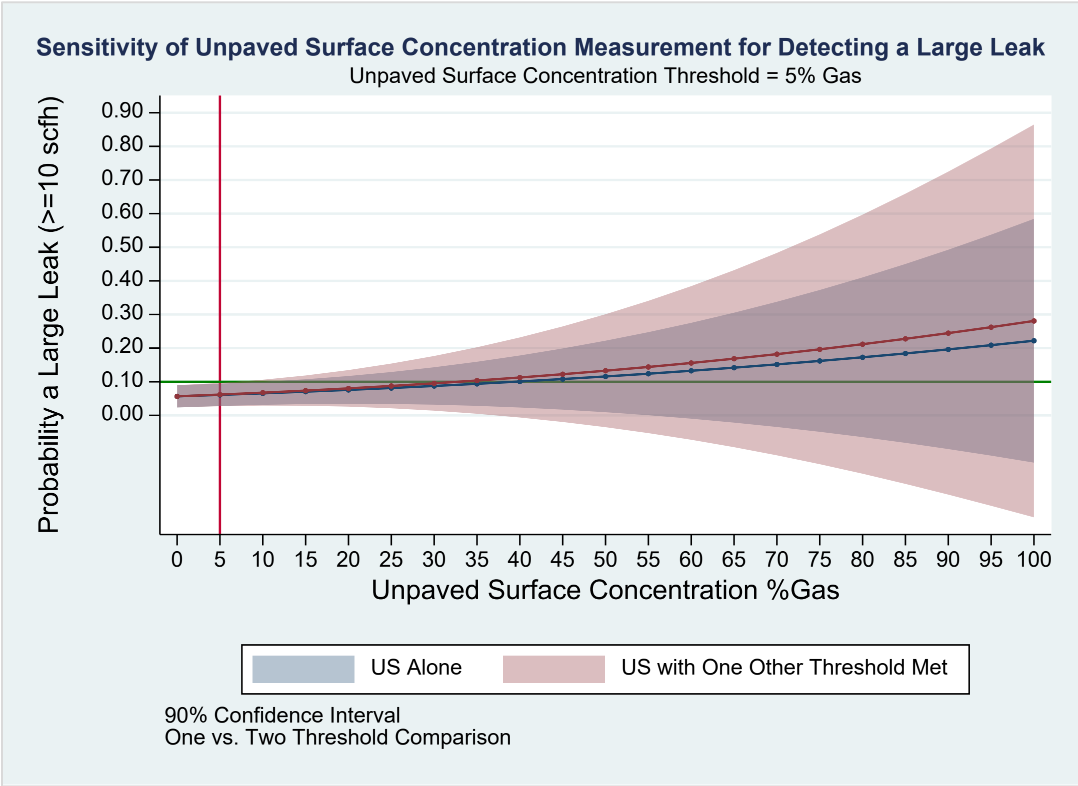


Figure 44: Sensitivity of US Concentration to Large Leak Detection - Multi-Thresholds.



7. Check that (a) the single thresholds *still* have the 95% confidence of no more than a 10% chance of large leak (which should be the case); but now you can (b) check that when you have two thresholds met, that the expected (mean) value for that is also below the 10% probability. The concentration threshold can be adjusted to meet both these objectives.
8. Based on this analysis, for the SoCalGas study, one could change the SSS threshold from 60% gas to 70% gas, the other three are set as noted in (7) above. The 60% gas SSS concentration threshold is more conservative than 70% gas and reflects that a 60% gas concentration is considered "hazardous" for this category in California.
9. If the SSS threshold was increased from 60% gas to 70% gas, it would have improved the DT results. There would be four (4) less false positives and no other changes, i.e. no increases in false negatives across the 291 sample data set.

Appendix C: Log-normal Distribution Facts

Log-normal Distribution Equations

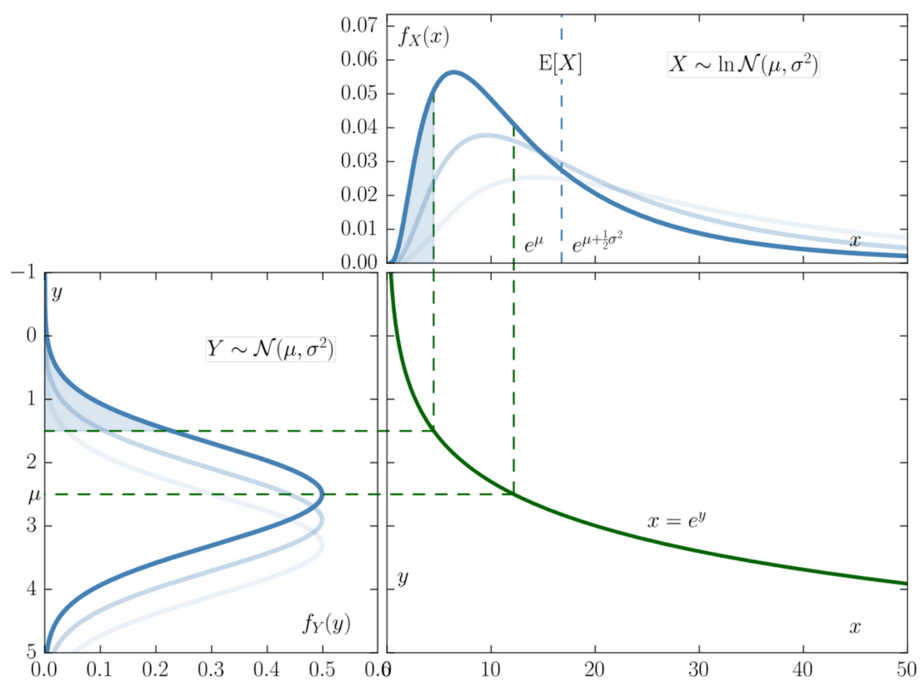
Table 36: Log-Normal Distribution Equations.

Probability density function :	$f(x)=\frac{1}{x\sqrt{2\pi\sigma_1^2}}\exp\left[-\frac{(\ln[x]-\mu_1^2)}{2\sigma_1^2}\right]$ where $\mu_1=\ln\left[\frac{\mu^2}{\sqrt{\sigma^2+\mu^2}}\right]$ and $\sigma_1=\sqrt{\ln\left[\frac{\sigma^2+\mu^2}{\mu^2}\right]}$
Cumulative distribution function :	No closed form
Parameter restriction :	$\sigma>0,\mu>0$
Domain :	$x\geq 0$
Mean :	μ
Mode :	$\exp(\mu_1-\sigma_1^2)$
Variance :	σ^2
Skewness :	$\left(\frac{\sigma}{\mu}\right)^3+3\left(\frac{\sigma}{\mu}\right)$
Kurtosis :	$z^4+2z^3+3z^2-3$ where $z=1+\frac{\sigma}{\mu}$

Source: [34]

Log-normal Plot and Comparison to Normal Distribution

Figure 45: Log-normal Distribution Theoretical Plot.



Source: [35]

Distribution Fitting Goodness of Fit

Although still popular today, the Chi-Squared, Kolmogorov-Smirnoff and Anderson-Darling goodness of fit statistics are technically all inappropriate as a method of comparing fits of distributions to data[36].

They are also limited to having precise observations and cannot incorporate censored, truncated or binned data. Realistically, most of the time we are fitting a continuous distribution to a set of precise observations and then the Anderson-Darling does a reasonable job.

For important work you should instead consider using statistical measures of fit called information criteria.

- **SIC** (Schwarz information criterion, aka Bayesian information criterion BIC)[37]
- **AIC** (Akaike information criterion)[38]
- **HQIC** (Hannan-Quinn information criterion)[39]+

The aim is to find the model with the lowest value of the selected information criterion.

We decided to illustrate the log-normal distribution, but as can be seen in Table 37 the log-gamma has an excellent fit. The log-normal was used for illustration due to its common application in these types of log distributions.

Table 37: Distribution Goodness of Fit to SoCalGas data set (291 samples).

Distributions fitted	Data	LogGamma	Dagum	Log-normal	LogLogistic	LogLaplace	Weibull
				Goodness of fit			
AIC		966.8	983.9	990.1	991.2	994.2	1014.7
AIC ranking		1	2	3	4	5	6
SIC		977.7	994.9	997.4	998.5	1005.1	1022.0
SIC ranking		1	2	3	4	5	6
HQIC		971.1	988.3	993.0	994.1	998.5	1017.6
HQIC ranking		1	2	3	4	5	6
				Comparison of data and fitted distribution statistics			
Minimum	0.00272	0.00272	0	0	0	0	0
Maximum	373	+Infinity	+Infinity	+Infinity	+Infinity	+Infinity	+Infinity
Mean	4.31	Undefined	4.99	4.67	Undefined	Undefined	3.14
St. Dev	24.37	Undefined	Undefined	32.30	Undefined	Undefined	6.50

Appendix D: Leak Spread Comparison to Leak Rate

As noted in the Background section of this report, early in the development of the program, system data were mined, and system leak flow rates were measured to evaluate the relationships between measured methane concentration and "leak spread" data against the flow rate of the leak. However, no correlation was found in this data, see Figure 46 to Figure 49.

A total of 68 leak sites at SoCalGas had measured methane concentration levels and the associated leak spread. The largest spread (distance in feet) across the leak site was recorded and placed into one of four categories by length range, see Table 38. These four categories were assigned a Numeric Code as shown in the table. The numeric code is used in the figures as well.

Table 38: Leak Spread Categories.

Category Length Range (feet)	Category Numeric Code
0 to 5	5
6 to 10	10
11 to 20	20
21 to 40	40
> 40 feet	50

Figure 46: Scatter Plot of Leak Concentration Spread vs. Leak Rate.

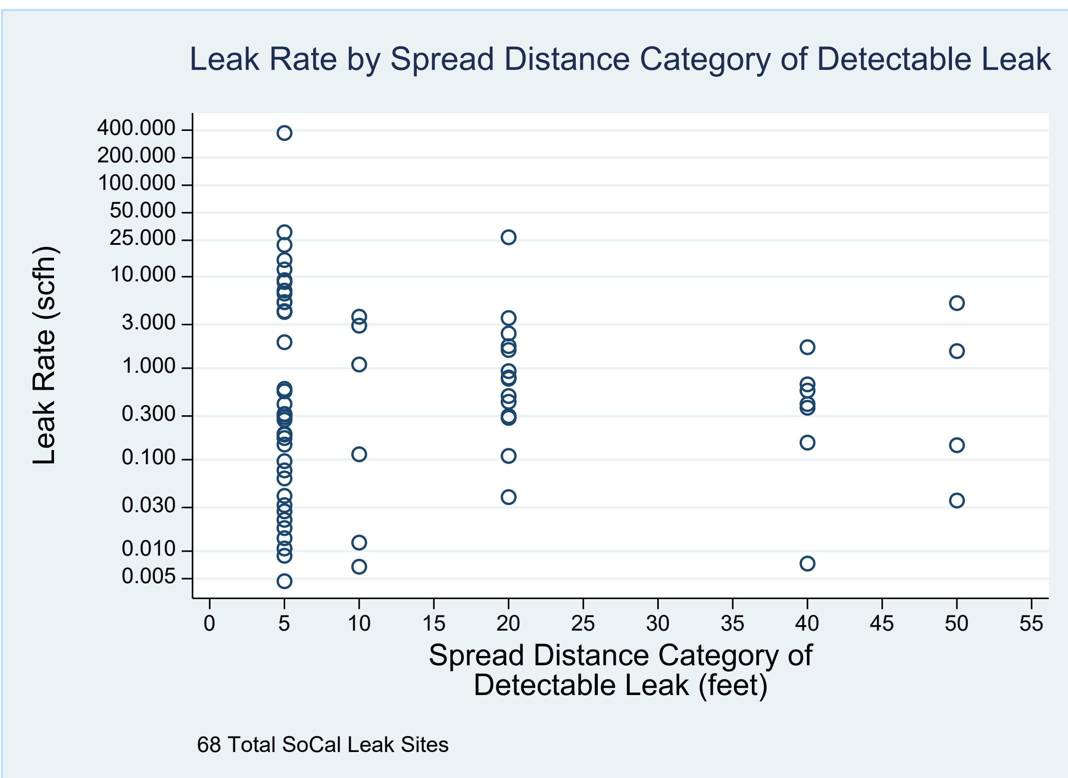


Figure 47: Histogram of Leak Rates by Leak Concentration Spread.

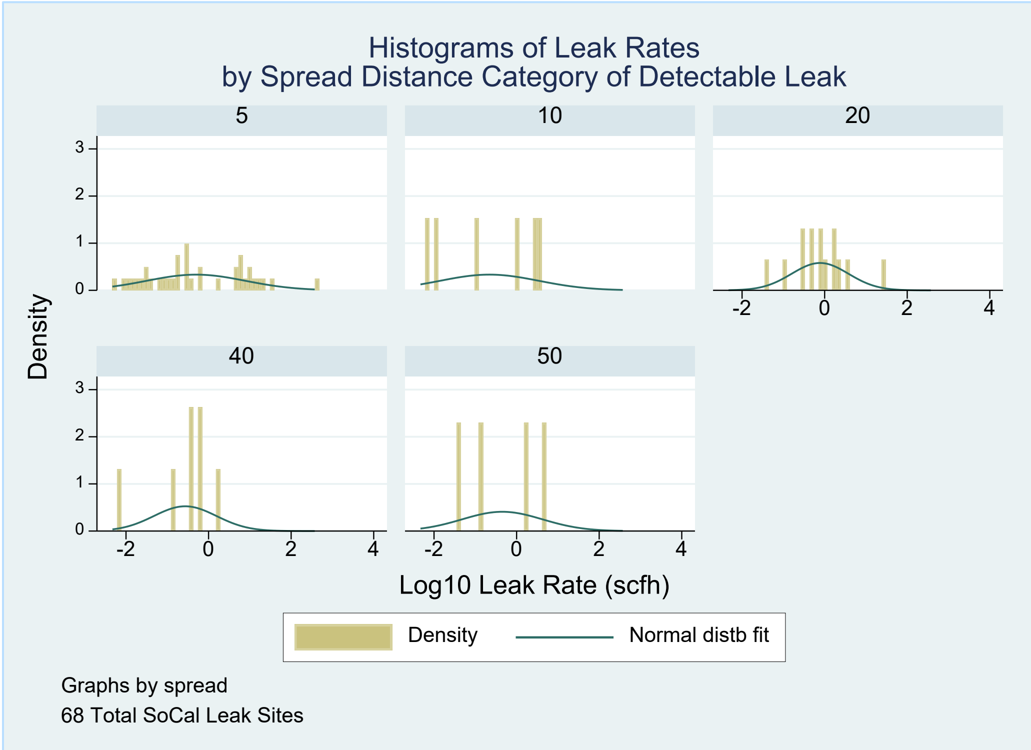


Figure 48: Box Plot of Leak Concentration Spread vs. Leak Rate.

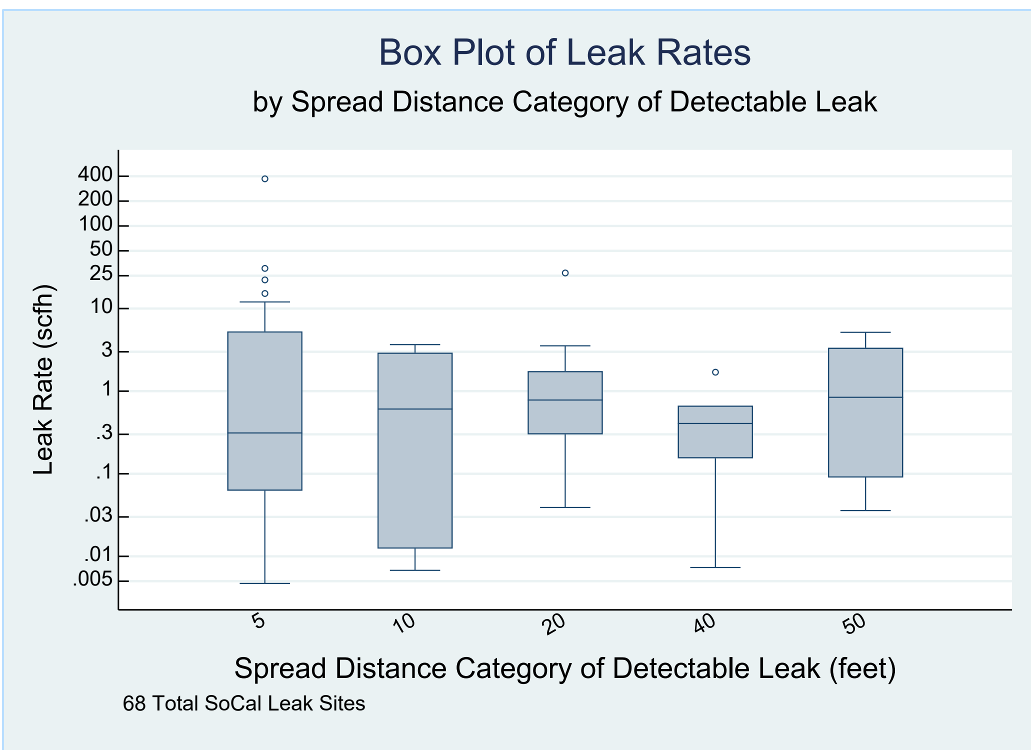
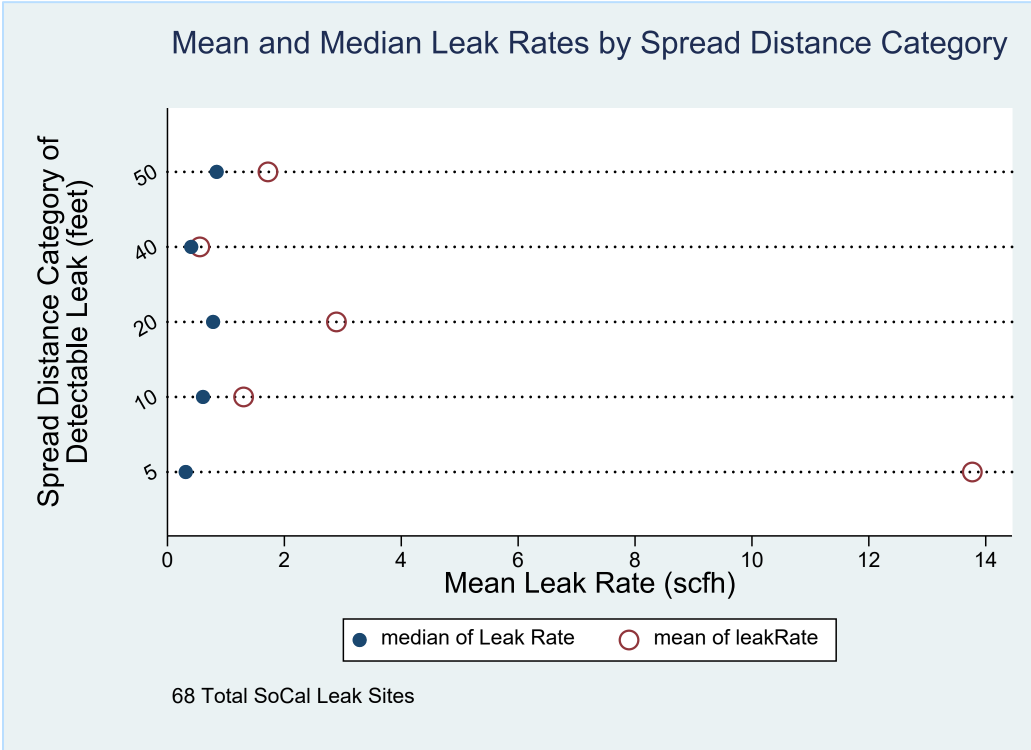


Figure 49: Mean and Median of Leak Rate by Leak Concentration Spread.



Appendix E: Study Leak Rate and Concentration Data

For the SoCalGas studies, the DT approach collected methane concentration measurements at defined types of surface condition locations. The four defined types of surface condition locations are listed in the Table 39 below and use the following abbreviations:

- Bar Hole (leak survey type) - BH
- Crack (or seam) In Pavement - CIP
- Small Sub-Structure (not gas system related) - SSS
- Unpaved Surface - US

Table 39: Leak Rate scfh Methane (CH_4) and Concentration (% gas) by Study.

	Study	Leak Rate (scfh)	Conc. BH (% gas)	Conc. CIP (% gas)	Conc. SSS (% gas)	Conc. US (% gas)
1.	AllDisPilot	0.0027	.	0.00	0.10	0.00
2.	AllDisPilot	0.0047	.	0.00	.	0.00
3.	AllDisPilot	0.0055	.	0.00	0.29	0.00
4.	AllDisPilot	0.0068	.	0.17	.	0.00
5.	AllDisPilot	0.0073	0.01	0.00	0.40	0.00
6.	AllDisPilot	0.0089	.	0.07	0.00	0.05
7.	AllDisPilot	0.0107	.	0.00	.	0.01
8.	AllDisPilot	0.0124	.	0.01	0.00	0.00
9.	AllDisPilot	0.0136	.	0.23	0.00	0.00
10.	AllDisPilot	0.0139	0.00	0.00	0.01	0.00
11.	AllDisPilot	0.0179	0.50	0.00	0.00	0.00
12.	AllDisPilot	0.0199	.	0.00	0.07	0.00
13.	AllDisPilot	0.0273	.	0.02	0.00	0.01
14.	AllDisPilot	0.0300	0.00	0.03	0.00	0.00
15.	AllDisPilot	0.0319	.	1.60	0.04	0.00
16.	AllDisPilot	0.0358	0.00	0.00	.	0.30
17.	AllDisPilot	0.0390	0.00	0.00	0.00	0.04
18.	AllDisPilot	0.0403	0.15	0.00	0.00	0.00
19.	AllDisPilot	0.0409	0.02	0.00	0.00	0.00
20.	AllDisPilot	0.0575	.	0.05	.	0.50
21.	AllDisPilot	0.0614	.	0.00	0.50	0.00
22.	AllDisPilot	0.0625	0.06	0.00	0.00	0.00
23.	AllDisPilot	0.0765	.	0.00	0.00	0.20
24.	AllDisPilot	0.0769	0.00	0.00	0.70	0.00
25.	AllDisPilot	0.0798	0.00	0.00	0.00	0.05
26.	AllDisPilot	0.0964	.	0.20	0.00	.
27.	AllDisPilot	0.1101	.	0.00	0.02	0.00
28.	AllDisPilot	0.1147	1.20	0.00	0.01	0.18
29.	AllDisPilot	0.1329	.	0.00	0.00	0.04
30.	AllDisPilot	0.1442	.	0.00	0.06	0.00
31.	AllDisPilot	0.1465	.	0.28	0.00	0.00
32.	AllDisPilot	0.1540	.	0.00	0.23	0.00
33.	AllDisPilot	0.1726	.	0.00	0.00	0.13
34.	AllDisPilot	0.1884	.	0.00	0.00	0.00
35.	AllDisPilot	0.1894	.	0.06	0.20	0.11
36.	AllDisPilot	0.1991	25.00	0.01	.	0.00
37.	AllDisPilot	0.2168	.	0.00	0.00	0.26
38.	AllDisPilot	0.2263	.	0.00	0.00	0.04
39.	AllDisPilot	0.2367	.	0.00	0.00	0.06

	Study	Leak Rate (scfh)	Conc. BH (% gas)	Conc. CIP (% gas)	Conc. SSS (% gas)	Conc. US (% gas)
40.	AllDisPilot	0.2710	.	0.20	0.00	0.20
41.	AllDisPilot	0.2730	.	0.00	.	0.03
42.	AllDisPilot	0.2749	0.00	0.00	0.00	1.30
43.	AllDisPilot	0.2823	.	0.15	1.60	0.01
44.	AllDisPilot	0.2867	42.00	0.02	0.00	0.00
45.	AllDisPilot	0.2920	.	0.30	0.00	0.01
46.	AllDisPilot	0.3120	2.00	0.00	0.00	0.01
47.	AllDisPilot	0.3168	.	0.30	0.20	0.72
48.	AllDisPilot	0.3319	.	1.00	0.00	0.02
49.	AllDisPilot	0.3879	.	0.20	0.00	0.00
50.	AllDisPilot	0.4060	.	0.01	0.00	3.50
51.	AllDisPilot	0.4060	0.85	0.06	0.00	0.06
52.	AllDisPilot	0.4975	.	0.00	0.00	0.30
53.	AllDisPilot	0.5600	.	0.00	0.00	0.34
54.	AllDisPilot	0.5698	.	0.01	0.06	0.00
55.	AllDisPilot	0.6676	.	3.00	0.00	.
56.	AllDisPilot	0.7387	.	0.03	0.01	0.20
57.	AllDisPilot	0.7688	.	7.50	0.00	0.00
58.	AllDisPilot	0.7927	.	0.10	.	0.00
59.	AllDisPilot	1.3139	.	0.00	0.00	1.00
60.	AllDisPilot	1.5844	.	0.02	0.00	0.97
61.	AllDisPilot	1.6990	.	0.00	10.00	0.00
62.	AllDisPilot	1.7470	.	0.00	0.20	0.13
63.	AllDisPilot	1.9275	.	1.60	0.00	0.17
64.	AllDisPilot	2.2184	0.00	0.00	0.00	0.45
65.	AllDisPilot	2.3995	.	2.95	0.00	0.01
66.	AllDisPilot	2.9205	0.00	0.00	0.18	0.35
67.	AllDisPilot	4.1216	0.01	0.00	.	0.05
68.	AllDisPilot	4.2127	.	1.00	4.00	0.10
69.	AllDisPilot	5.1560	.	1.00	.	4.00
70.	AllDisPilot	5.2590	.	0.00	1.20	0.00
71.	AllDisPilot	5.2750	.	0.00	0.00	2.00
72.	AllDisPilot	7.3507	23.00	0.00	.	0.70
73.	AllDisPilot	9.1915	.	0.10	0.10	1.45
74.	AllDisPilot	12.0244	.	8.00	.	1.00
75.	AllDisPilot	15.2524	.	0.00	0.80	0.01
76.	AllDisPilot	27.0447	.	40.00	.	20.00
77.	AllDisPilot	0.0220	.	0.09	0.00	0.00
78.	AllDisPilot	0.5958	.	0.00	40.00	0.00
79.	AllDisLIRP	0.4301	0.00	0.00	5.00	0.00
80.	AllDisLIRP	0.3704	.	0.00	.	0.04
81.	AllDisLIRP	30.7021	.	0.00	.	6.00
82.	AllDisLIRP	0.1922	38.00	0.00	.	0.20
83.	AllDisLIRP	3.6600	.	4.60	.	0.33
84.	AllDisLIRP	3.5400	100.00	1.60	.	0.90
85.	AllDisLIRP	1.5400	19.00	0.50	.	52.00
86.	AllDisLIRP	1.1000	95.00	0.01	0.01	0.13
87.	AllDisLIRP	0.9300	75.00	1.80	0.13	0.06
88.	AllDisLIRP	0.3000	0.39	0.00	0.00	0.12
89.	3DisPilotLowSpec	0.0800	.	3.00	.	3.00
90.	3DisPilotLowSpec	0.1100	70.00	1.00	.	1.00
91.	3DisPilotLowSpec	1.6400	20.00	.	5.00	3.00
92.	3DisPilotLowSpec	0.3900	1.00	0.00	0.20	1.00
93.	3DisPilotLowSpec	0.0600	30.00	.	0.30	1.00
94.	3DisPilotLowSpec	0.0600	4.00	0.05	0.00	4.00
95.	3DisPilotLowSpec	0.9000	40.00	0.00	0.00	2.00
96.	3DisPilotLowSpec	0.3400	40.00	2.00	0.00	2.00
97.	3DisPilot	373.0000	100.00	0.08	.	20.00
98.	3DisPilot	0.1200	70.00	50.00	7.00	25.00
99.	3DisPilot	0.3700	20.00	15.00	0.03	5.00

	Study	Leak Rate (scfh)	Conc. BH (% gas)	Conc. CIP (% gas)	Conc. SSS (% gas)	Conc. US (% gas)
100.	3DisPilot	0.2700	.	8.00	.	31.00
101.	3DisPilot	10.0000	100.00	1.00	.	2.00
102.	3DisPilot	22.2900	100.00	0.70	.	5.00
103.	3DisPilot	4.0600	100.00	4.00	0.00	0.00
104.	3DisPilot	1.2400	100.00	.	.	15.00
105.	3DisPilot	0.4800	35.00	35.00	0.00	.
106.	3DisPilot	0.9600	.	.	64.00	.
107.	3DisPilot	0.4400	92.00	1.00	0.00	1.00
108.	3DisPilot	0.1100	0.00	0.00	0.00	70.00
109.	3DisPilot	0.2100	85.00	0.15	0.33	.
110.	3DisPilot	0.3300	70.00	0.00	0.00	10.00
111.	3DisPilot	0.0830	52.00	0.00	0.00	26.00
112.	3DisPilot	0.9100	85.00	.	.	.
113.	3DisPilot	7.0600	85.00	0.02	0.00	0.44
114.	3DisPilot	6.5500	10.00	0.04	.	10.00
115.	3DisPilot	5.2900	5.00	0.03	.	5.00
116.	3DisPilot	1.1100	67.00	1.50	.	9.50
117.	3DisPilot	8.7500	100.00	0.02	0.00	0.08
118.	3DisPilot	0.1115	89.00	0.01	.	1.00
119.	3DisPilot	2.2960	27.00	0.10	.	23.00
120.	3DisPilot	0.1100	80.00	0.00	0.00	80.00
121.	3DisPilot	172.4400	100.00	7.00	.	3.00
122.	3DisPilot	0.0500	10.00	1.50	0.00	0.00
123.	3DisPilot	3.2000	7.00	0.40	.	0.02
124.	3DisPilot	0.6100	25.00	0.10	.	0.10
125.	3DisPilot	0.2400	22.00	0.01	.	0.60
126.	3DisPilot	0.0300	19.00	0.02	0.00	0.38
127.	3DisPilot	0.0300	2.00	0.05	0.61	0.15
128.	3DisPilot	0.9200	48.00	0.01	0.00	0.02
129.	3DisPilot	3.1200	62.00	0.30	.	0.10
130.	3DisPilot	0.0400	0.24	0.05	.	0.02
131.	3DisPilot	0.6100	0.00	0.00	10.00	0.00
132.	3DisPilot	3.8200	0.20	.	.	0.05
133.	3DisPilot	1.8400	25.00	0.09	.	0.35
134.	3DisPilot	5.5400	0.00	0.00	0.00	0.01
135.	3DisPilot	0.5700	30.00	0.01	0.00	0.11
136.	3DisPilot	0.0200	4.00	0.00	0.00	0.14
137.	3DisPilot	0.3300	.	0.10	0.00	0.00
138.	3DisPilot	0.0600	0.09	0.03	0.00	0.02
139.	3DisPilot	2.1800	100.00	1.50	.	2.50
140.	3DisPilot	2.2300	100.00	6.00	.	0.00
141.	3DisPilot	3.6700	100.00	5.00	1.00	2.00
142.	3DisPilot	6.9300	42.00	0.80	0.00	9.00
143.	3DisPilot	1.1000	25.00	0.02	0.40	12.00
144.	3DisPilot	0.0200	.	0.00	0.03	.
145.	3DisPilot	0.6900	0.00	0.00	100.00	0.00
146.	3DisPilot	0.1400	80.00	0.00	0.00	0.00
147.	3DisPilot	0.9800	25.00	0.03	3.00	0.03
148.	3DisPilot	4.5300	30.00	0.00	0.00	30.00
149.	3DisPilot	4.4400	12.00	0.01	.	9.00
150.	3DisPilot	1.0200	17.00	0.00	0.17	12.00
151.	3DisPilot	1.2400	20.00	1.00	0.00	12.00
152.	3DisPilot	0.5300	0.00	0.00	7.50	0.00
153.	DT157Pilot	0.0030	.	0.03	.	.
154.	DT157Pilot	0.0337	.	.	.	.
155.	DT157Pilot	1.1364	.	.	.	0.20
156.	DT157Pilot	0.6868	.	.	.	.
157.	DT157Pilot	0.3201	.	.	.	.
158.	DT157Pilot	0.0456	.	.	0.40	.
159.	DT157Pilot	0.0857	0.50	.	.	.

	Study	Leak Rate (scfh)	Conc. BH (% gas)	Conc. CIP (% gas)	Conc. SSS (% gas)	Conc. US (% gas)
160.	DT157Pilot	0.3121	.	0.61	.	.
161.	DT157Pilot	0.2598	0.90	.	.	.
162.	DT157Pilot	0.0471	.	1.08	.	0.08
163.	DT157Pilot	2.6745	.	.	.	1.10
164.	DT157Pilot	0.3009	.	.	1.10	.
165.	DT157Pilot	0.0420	.	1.12	.	.
166.	DT157Pilot	1.3500	.	.	.	1.14
167.	DT157Pilot	0.3674	.	.	.	.
168.	DT157Pilot	0.8960	.	.	52.00	.
169.	DT157Pilot	2.1040	.	.	.	1.50
170.	DT157Pilot	0.4980	.	.	.	1.50
171.	DT157Pilot	0.4934	.	.	.	.
172.	DT157Pilot	0.1844	24.00	.	.	.
173.	DT157Pilot	1.7206	.	2.50	.	.
174.	DT157Pilot	1.8764	.	.	3.50	.
175.	DT157Pilot	0.9169	.	3.70	.	.
176.	DT157Pilot	0.3302	.	6.00	.	.
177.	DT157Pilot	0.7801	.	.	7.00	.
178.	DT157Pilot	1.5748	.	.	.	.
179.	DT157Pilot	2.0911	.	.	8.00	.
180.	DT157Pilot	0.1558	.	.	32.00	.
181.	DT157Pilot	6.1970	.	.	.	8.50
182.	DT157Pilot	1.2619	.	.	.	.
183.	DT157Pilot	6.6519	.	3.00	.	12.00
184.	DT157Pilot	4.7489	.	13.00	.	.
185.	DT157Pilot	3.2550	.	5.00	16.00	1.50
186.	DT157Pilot	0.2394	.	2.00	.	16.00
187.	DT157Pilot	0.4809	18.00	.	.	.
188.	DT157Pilot	1.0130	20.00	.	.	.
189.	DT157Pilot	3.7304	20.00	.	.	.
190.	DT157Pilot	1.6414	23.00	.	.	.
191.	DT157Pilot	0.3124	25.00	.	.	.
192.	DT157Pilot	0.0444	.	.	32.00	.
193.	DT157Pilot	0.0456	.	.	13.00	.
194.	DT157Pilot	0.6210	.	.	.	.
195.	DT157Pilot	2.5850	.	.	50.00	.
196.	DT157Pilot	1.7481	52.00	.	22.00	0.50
197.	DT157Pilot	1.4472	.	.	59.00	.
198.	DT157Pilot	2.1470	.	.	100.00	.
199.	DT157Pilot	5.9664	100.00	0.50	.	.
200.	DT157Pilot	1.1704	.	.	100.00	.
201.	DT157Pilot	12.2475	.	2.00	100.00	.
202.	DT157Pilot	0.9859	.	.	100.00	.
203.	DT157Pilot	1.8368	.	.	100.00	.
204.	DT157Pilot	3.6167	100.00	.	100.00	.
205.	DT157Pilot	7.5300	.	23.00	100.00	.
206.	DT157Pilot	18.2144	.	40.00	100.00	2.00
207.	DT157Pilot	4.0392	.	100.00	100.00	.
208.	DT157Pilot	4.3662	.	.	100.00	10.00
209.	DT157Pilot	0.0329	1.00	.	.	.
210.	DT157Pilot	0.4608	.	.	.	1.00
211.	DT157Pilot	0.5173	.	.	.	1.70
212.	DT157Pilot	0.8978	.	.	.	9.00
213.	DT157Pilot	0.1640	.	1.60	.	.
214.	DT157Pilot	0.0158	.	0.15	.	.
215.	DT157Pilot	0.0173	.	.	.	0.01
216.	DT157Pilot	0.3845	.	3.00	.	.
217.	DT157Pilot	1.4855	.	10.00	.	.
218.	DT157Pilot	3.5326	.	.	.	5.60
219.	DT157Pilot	0.1560	.	.	.	0.12

	Study	Leak Rate (scfh)	Conc. BH (% gas)	Conc. CIP (% gas)	Conc. SSS (% gas)	Conc. US (% gas)
220.	DT157Pilot	0.2646	.	.	.	1.00
221.	DT157Pilot	0.0342	.	.	100.00	.
222.	DT157Pilot	20.0870	100.00	100.00	.	.
223.	DT157Pilot	1.4640	.	.	.	2.50
224.	DT157Pilot	2.9820	.	.	100.00	.
225.	DT157Pilot	5.1899	.	.	.	9.00
226.	DT157Pilot	0.4406	.	40.00	.	0.14
227.	DT157Pilot	1.2760	.	75.00	.	.
228.	DT157Pilot	2.5837	.	1.30	.	.
229.	DT157Pilot	1.1464	.	1.45	.	1.23
230.	DT157Pilot	1.0416	70.00	.	.	.
231.	DT157Pilot	3.9882	.	80.00	.	100.00
232.	DT157Pilot	0.7686	.	.	100.00	.
233.	DT157Pilot	1.5258	.	.	.	1.70
234.	DT157Pilot	2.0598	.	20.00	100.00	.
235.	DT157Pilot	3.0195	.	8.00	100.00	.
236.	DT157Pilot	1.9665	.	100.00	.	.
237.	DT157Pilot	6.2496	.	3.00	.	8.00
238.	DT157Pilot	0.7680	.	.	100.00	.
239.	DT157Pilot	1.2204	.	.	.	15.00
240.	DT157Pilot	0.7068	.	.	.	2.60
241.	DT157Pilot	2.5560	.	.	.	40.00
242.	DT157Pilot	0.1512	.	6.00	.	.
243.	DT157Pilot	2.2884	100.00	20.00	.	.
244.	DT157Pilot	0.4158	.	.	.	2.60
245.	DT157Pilot	0.2928	.	20.00	.	.
246.	DT157Pilot	1.7202	.	.	.	1.60
247.	DT157Pilot	0.3294	.	.	63.00	.
248.	DT157Pilot	1.9344	.	.	58.00	.
249.	DT157Pilot	43.7760	.	.	.	100.00
250.	DT157Pilot	0.9558	.	.	.	40.00
251.	DT157Pilot	1.5210	.	4.00	35.00	6.00
252.	DT157Pilot	0.6426	.	.	65.00	.
253.	DT157Pilot	0.7788	.	.	.	35.00
254.	DT157Pilot	4.4340	29.00	.	.	0.60
255.	DT157Pilot	15.6582	100.00	.	18.00	8.00
256.	DT157Pilot	6.3480	.	.	.	2.50
257.	DT157Pilot	1.6632	.	.	.	80.00
258.	DT157Pilot	7.6152	.	5.00	100.00	.
259.	DT157Pilot	3.2760	.	.	.	20.00
260.	DT157Pilot	1.3860	.	.	100.00	.
261.	DT157Pilot	4.8633	.	32.00	.	.
262.	DT157Pilot	5.7782	.	.	62.00	4.00
263.	DT157Pilot	0.0037	.	.	0.40	.
264.	DT157Pilot	1.4552	.	2.00	26.00	.
265.	DT157Pilot	0.6030	.	.	.	0.70
266.	DT157Pilot	0.8245	.	6.00	.	1.40
267.	DT157Pilot	0.0991	.	1.00	10.00	.
268.	DT157Pilot	0.0730	.	.	.	0.13
269.	DT157Pilot	0.7068	.	.	88.00	.
270.	DT157Pilot	1.3986	100.00	.	.	.
271.	DT157Pilot	9.5040	.	8.00	100.00	.
272.	DT157Pilot	0.2325	.	.	20.00	.
273.	DT157Pilot	9.5397	100.00	.	.	2.00
274.	DT157Pilot	3.2640	.	41.00	48.00	.
275.	DT157Pilot	1.1678	.	0.60	.	6.00
276.	DT157Pilot	0.4800	.	25.00	.	.
277.	DT157Pilot	1.8600	.	.	.	2.00
278.	DT157Pilot	1.4997	22.00	5.00	.	.
279.	DT157Pilot	4.8165	.	.	100.00	7.00

	Study	Leak Rate (scfh)	Conc. BH (% gas)	Conc. CIP (% gas)	Conc. SSS (% gas)	Conc. US (% gas)
280.	DT157Pilot	0.8160	.	23.00	.	.
281.	DT157Pilot	0.7466	.	20.00	.	.
282.	DT157Pilot	9.9900	.	.	90.00	.
283.	DT157Pilot	0.5940	.	.	.	5.00
284.	DT157Pilot	0.5346	.	32.00	.	.
285.	DT157Pilot	0.8190	.	.	.	13.00
286.	DT157Pilot	2.7444	.	.	100.00	.
287.	DT157Pilot	0.6696	.	.	84.00	.
288.	DT157Pilot	3.2484	.	9.00	.	10.00
289.	DT157Pilot	2.5164	.	20.00	.	18.00
290.	DT157Pilot	1.3392	.	.	100.00	.
291.	DT157Pilot	1.0860	.	.	100.00	0.20
292.	DT157Pilot	0.3206	.	.	.	4.40
293.	DT157Pilot	41.7180	.	.	100.00	.
294.	DT157Pilot	19.4700	.	.	.	16.00
295.	DT157Pilot	4.1681	.	10.00	.	3.00
296.	DT157Pilot	0.9130	.	.	.	1.00
297.	DT157Pilot	2.0910	.	.	72.00	3.00
298.	DT157Pilot	2.8928	.	.	.	14.00
299.	DT157Pilot	3.8766	30.00	.	100.00	.
300.	DT157Pilot	1.1046	100.00	.	35.00	.
301.	DT157Pilot	1.7305	.	.	.	100.00
302.	DT157Pilot	2.5212	100.00	.	100.00	.
303.	DT157Pilot	6.0848	.	.	.	50.00
304.	DT157Pilot	9.1800	95.00	.	.	.
305.	DT157Pilot	1.4310	.	.	.	6.00
306.	DT157Pilot	1.6083	.	.	40.00	.
307.	DT157Pilot	0.2317	.	.	.	5.00
308.	DT157Pilot	2.1249	10.00	.	.	50.00
309.	DT157Pilot	2.4960	.	.	100.00	.
310.	Natl_CARB_GTI	20.4000	.	.	.	.
311.	Natl_CARB_GTI	14.4000	.	.	.	.
312.	Natl_CARB_GTI	13.9850	.	.	.	.
313.	Natl_CARB_GTI	13.8000	.	.	.	.
314.	Natl_CARB_GTI	13.2000	.	.	.	.
315.	Natl_CARB_GTI	7.2000	.	.	.	.
316.	Natl_CARB_GTI	6.9000	.	.	.	.
317.	Natl_CARB_GTI	6.4950	.	.	.	.
318.	Natl_CARB_GTI	6.4750	.	.	.	.
319.	Natl_CARB_GTI	5.7000	.	.	.	.
320.	Natl_CARB_GTI	5.4000	.	.	.	.
321.	Natl_CARB_GTI	5.0000	.	.	.	.
322.	Natl_CARB_GTI	5.0000	.	.	.	.
323.	Natl_CARB_GTI	5.0000	.	.	.	.
324.	Natl_CARB_GTI	4.0000	.	.	.	.
325.	Natl_CARB_GTI	3.9000	.	.	.	.
326.	Natl_CARB_GTI	3.2000	.	.	.	.
327.	Natl_CARB_GTI	2.4000	.	.	.	.
328.	Natl_CARB_GTI	2.3860	.	.	.	.
329.	Natl_CARB_GTI	2.1540	.	.	.	.
330.	Natl_CARB_GTI	2.1000	.	.	.	.
331.	Natl_CARB_GTI	2.0970	.	.	.	.
332.	Natl_CARB_GTI	2.0000	.	.	.	.
333.	Natl_CARB_GTI	1.9440	.	.	.	.
334.	Natl_CARB_GTI	1.8000	.	.	.	.
335.	Natl_CARB_GTI	1.5340	.	.	.	.
336.	Natl_CARB_GTI	1.5320	.	.	.	.
337.	Natl_CARB_GTI	1.4360	.	.	.	.
338.	Natl_CARB_GTI	1.3310	.	.	.	.
339.	Natl_CARB_GTI	1.2840	.	.	.	.

	Study	Leak Rate (scfh)	Conc. BH (% gas)	Conc. CIP (% gas)	Conc. SSS (% gas)	Conc. US (% gas)
340.	Natl_CARB_GTI	1.2000	.	.	.	.
341.	Natl_CARB_GTI	1.2000	.	.	.	.
342.	Natl_CARB_GTI	1.1680	.	.	.	.
343.	Natl_CARB_GTI	1.0670	.	.	.	.
344.	Natl_CARB_GTI	1.0000	.	.	.	.
345.	Natl_CARB_GTI	1.0000	.	.	.	.
346.	Natl_CARB_GTI	0.8840	.	.	.	.
347.	Natl_CARB_GTI	0.8530	.	.	.	.
348.	Natl_CARB_GTI	0.8000	.	.	.	.
349.	Natl_CARB_GTI	0.7640	.	.	.	.
350.	Natl_CARB_GTI	0.7190	.	.	.	.
351.	Natl_CARB_GTI	0.6540	.	.	.	.
352.	Natl_CARB_GTI	0.6510	.	.	.	.
353.	Natl_CARB_GTI	0.6170	.	.	.	.
354.	Natl_CARB_GTI	0.6130	.	.	.	.
355.	Natl_CARB_GTI	0.6010	.	.	.	.
356.	Natl_CARB_GTI	0.6000	.	.	.	.
357.	Natl_CARB_GTI	0.6000	.	.	.	.
358.	Natl_CARB_GTI	0.6000	.	.	.	.
359.	Natl_CARB_GTI	0.6000	.	.	.	.
360.	Natl_CARB_GTI	0.6000	.	.	.	.
361.	Natl_CARB_GTI	0.6000	.	.	.	.
362.	Natl_CARB_GTI	0.6000	.	.	.	.
363.	Natl_CARB_GTI	0.6000	.	.	.	.
364.	Natl_CARB_GTI	0.6000	.	.	.	.
365.	Natl_CARB_GTI	0.5850	.	.	.	.
366.	Natl_CARB_GTI	0.5150	.	.	.	.
367.	Natl_CARB_GTI	0.4670	.	.	.	.
368.	Natl_CARB_GTI	0.4620	.	.	.	.
369.	Natl_CARB_GTI	0.4520	.	.	.	.
370.	Natl_CARB_GTI	0.4350	.	.	.	.
371.	Natl_CARB_GTI	0.3780	.	.	.	.
372.	Natl_CARB_GTI	0.2930	.	.	.	.
373.	Natl_CARB_GTI	0.2760	.	.	.	.
374.	Natl_CARB_GTI	0.2550	.	.	.	.
375.	Natl_CARB_GTI	0.1740	.	.	.	.
376.	Natl_CARB_GTI	0.1720	.	.	.	.
377.	Natl_CARB_GTI	0.1660	.	.	.	.
378.	Natl_CARB_GTI	0.1560	.	.	.	.
379.	Natl_CARB_GTI	0.1480	.	.	.	.
380.	Natl_CARB_GTI	0.1200	.	.	.	.
381.	Natl_CARB_GTI	0.0780	.	.	.	.
382.	Natl_CARB_GTI	0.0630	.	.	.	.
383.	Natl_CARB_GTI	0.0550	.	.	.	.
384.	Natl_CARB_GTI	0.0410	.	.	.	.
385.	Natl_CARB_GTI	0.0070	.	.	.	.
386.	Natl_OTD_GTI	95.4000	.	.	.	.
387.	Natl_OTD_GTI	78.6000	.	.	.	.
388.	Natl_OTD_GTI	24.3000	.	.	.	.
389.	Natl_OTD_GTI	16.2000	.	.	.	.
390.	Natl_OTD_GTI	14.4000	.	.	.	.
391.	Natl_OTD_GTI	13.9852	.	.	.	.
392.	Natl_OTD_GTI	13.8000	.	.	.	.
393.	Natl_OTD_GTI	13.2000	.	.	.	.
394.	Natl_OTD_GTI	11.8800	.	.	.	.
395.	Natl_OTD_GTI	7.8000	.	.	.	.
396.	Natl_OTD_GTI	7.8000	.	.	.	.
397.	Natl_OTD_GTI	7.2000	.	.	.	.
398.	Natl_OTD_GTI	3.6000	.	.	.	.
399.	Natl_OTD_GTI	3.6000	.	.	.	.

	Study	Leak Rate (scfh)	Conc. BH (% gas)	Conc. CIP (% gas)	Conc. SSS (% gas)	Conc. US (% gas)
400.	Natl_OTD_GTI	3.6000	.	.	.	.
401.	Natl_OTD_GTI	2.3864	.	.	.	.
402.	Natl_OTD_GTI	2.2500	.	.	.	.
403.	Natl_OTD_GTI	1.8000	.	.	.	.
404.	Natl_OTD_GTI	1.8000	.	.	.	.
405.	Natl_OTD_GTI	1.8000	.	.	.	.
406.	Natl_OTD_GTI	1.5317	.	.	.	.
407.	Natl_OTD_GTI	1.4000	.	.	.	.
408.	Natl_OTD_GTI	1.3310	.	.	.	.
409.	Natl_OTD_GTI	1.3307	.	.	.	.
410.	Natl_OTD_GTI	1.2000	.	.	.	.
411.	Natl_OTD_GTI	1.2000	.	.	.	.
412.	Natl_OTD_GTI	1.2000	.	.	.	.
413.	Natl_OTD_GTI	1.2000	.	.	.	.
414.	Natl_OTD_GTI	0.8526	.	.	.	.
415.	Natl_OTD_GTI	0.8000	.	.	.	.
416.	Natl_OTD_GTI	0.6000	.	.	.	.
417.	Natl_OTD_GTI	0.6000	.	.	.	.
418.	Natl_OTD_GTI	0.6000	.	.	.	.
419.	Natl_OTD_GTI	0.6000	.	.	.	.
420.	Natl_OTD_GTI	0.6000	.	.	.	.
421.	Natl_OTD_GTI	0.6000	.	.	.	.
422.	Natl_OTD_GTI	0.6000	.	.	.	.
423.	Natl_OTD_GTI	0.6000	.	.	.	.
424.	Natl_OTD_GTI	0.6000	.	.	.	.
425.	Natl_OTD_GTI	0.6000	.	.	.	.
426.	Natl_OTD_GTI	0.6000	.	.	.	.
427.	Natl_OTD_GTI	0.6000	.	.	.	.
428.	Natl_OTD_GTI	0.6000	.	.	.	.
429.	Natl_OTD_GTI	0.6000	.	.	.	.
430.	Natl_OTD_GTI	0.6000	.	.	.	.
431.	Natl_OTD_GTI	0.6000	.	.	.	.
432.	Natl_OTD_GTI	0.6000	.	.	.	.
433.	Natl_OTD_GTI	0.6000	.	.	.	.
434.	Natl_OTD_GTI	0.6000	.	.	.	.
435.	Natl_OTD_GTI	0.6000	.	.	.	.
436.	Natl_OTD_GTI	0.6000	.	.	.	.
437.	Natl_OTD_GTI	0.6000	.	.	.	.
438.	Natl_OTD_GTI	0.6000	.	.	.	.
439.	Natl_OTD_GTI	0.6000	.	.	.	.
440.	Natl_OTD_GTI	0.6000	.	.	.	.
441.	Natl_OTD_GTI	0.6000	.	.	.	.
442.	Natl_OTD_GTI	0.6000	.	.	.	.
443.	Natl_OTD_GTI	0.6000	.	.	.	.
444.	Natl_OTD_GTI	0.6000	.	.	.	.
445.	Natl_OTD_GTI	0.6000	.	.	.	.
446.	Natl_OTD_GTI	0.6000	.	.	.	.
447.	Natl_OTD_GTI	0.0439	.	.	.	.
448.	Natl_WSU_EDF	109.4722	.	.	.	.
449.	Natl_WSU_EDF	69.7000	.	.	.	.
450.	Natl_WSU_EDF	13.2912	.	.	.	.
451.	Natl_WSU_EDF	10.3518	.	.	.	.
452.	Natl_WSU_EDF	8.9751	.	.	.	.
453.	Natl_WSU_EDF	7.8412	.	.	.	.
454.	Natl_WSU_EDF	6.8595	.	.	.	.
455.	Natl_WSU_EDF	6.1869	.	.	.	.
456.	Natl_WSU_EDF	5.9035	.	.	.	.
457.	Natl_WSU_EDF	5.6127	.	.	.	.
458.	Natl_WSU_EDF	4.7525	.	.	.	.
459.	Natl_WSU_EDF	4.5909	.	.	.	.

	Study	Leak Rate (scfh)	Conc. BH (% gas)	Conc. CIP (% gas)	Conc. SSS (% gas)	Conc. US (% gas)
460.	Natl_WSU_EDF	4.5446	.	.	.	.
461.	Natl_WSU_EDF	4.0154	.	.	.	.
462.	Natl_WSU_EDF	3.7319	.	.	.	.
463.	Natl_WSU_EDF	3.2224	.	.	.	.
464.	Natl_WSU_EDF	2.9655	.	.	.	.
465.	Natl_WSU_EDF	2.8829	.	.	.	.
466.	Natl_WSU_EDF	2.7585	.	.	.	.
467.	Natl_WSU_EDF	2.7051	.	.	.	.
468.	Natl_WSU_EDF	2.6703	.	.	.	.
469.	Natl_WSU_EDF	2.5612	.	.	.	.
470.	Natl_WSU_EDF	2.5575	.	.	.	.
471.	Natl_WSU_EDF	2.3693	.	.	.	.
472.	Natl_WSU_EDF	2.1575	.	.	.	.
473.	Natl_WSU_EDF	2.1111	.	.	.	.
474.	Natl_WSU_EDF	2.0437	.	.	.	.
475.	Natl_WSU_EDF	2.0330	.	.	.	.
476.	Natl_WSU_EDF	1.8371	.	.	.	.
477.	Natl_WSU_EDF	1.7565	.	.	.	.
478.	Natl_WSU_EDF	1.6219	.	.	.	.
479.	Natl_WSU_EDF	1.4635	.	.	.	.
480.	Natl_WSU_EDF	1.4562	.	.	.	.
481.	Natl_WSU_EDF	1.4498	.	.	.	.
482.	Natl_WSU_EDF	1.4265	.	.	.	.
483.	Natl_WSU_EDF	1.4140	.	.	.	.
484.	Natl_WSU_EDF	1.1119	.	.	.	.
485.	Natl_WSU_EDF	1.0910	.	.	.	.
486.	Natl_WSU_EDF	1.0518	.	.	.	.
487.	Natl_WSU_EDF	1.0454	.	.	.	.
488.	Natl_WSU_EDF	1.0454	.	.	.	.
489.	Natl_WSU_EDF	1.0444	.	.	.	.
490.	Natl_WSU_EDF	0.9838	.	.	.	.
491.	Natl_WSU_EDF	0.9539	.	.	.	.
492.	Natl_WSU_EDF	0.9414	.	.	.	.
493.	Natl_WSU_EDF	0.9081	.	.	.	.
494.	Natl_WSU_EDF	0.8880	.	.	.	.
495.	Natl_WSU_EDF	0.8552	.	.	.	.
496.	Natl_WSU_EDF	0.8482	.	.	.	.
497.	Natl_WSU_EDF	0.8213	.	.	.	.
498.	Natl_WSU_EDF	0.7985	.	.	.	.
499.	Natl_WSU_EDF	0.7646	.	.	.	.
500.	Natl_WSU_EDF	0.7400	.	.	.	.
501.	Natl_WSU_EDF	0.6807	.	.	.	.
502.	Natl_WSU_EDF	0.6678	.	.	.	.
503.	Natl_WSU_EDF	0.6671	.	.	.	.
504.	Natl_WSU_EDF	0.6594	.	.	.	.
505.	Natl_WSU_EDF	0.6271	.	.	.	.
506.	Natl_WSU_EDF	0.5978	.	.	.	.
507.	Natl_WSU_EDF	0.5907	.	.	.	.
508.	Natl_WSU_EDF	0.5627	.	.	.	.
509.	Natl_WSU_EDF	0.5143	.	.	.	.
510.	Natl_WSU_EDF	0.5140	.	.	.	.
511.	Natl_WSU_EDF	0.5082	.	.	.	.
512.	Natl_WSU_EDF	0.4997	.	.	.	.
513.	Natl_WSU_EDF	0.4348	.	.	.	.
514.	Natl_WSU_EDF	0.4168	.	.	.	.
515.	Natl_WSU_EDF	0.3936	.	.	.	.
516.	Natl_WSU_EDF	0.3855	.	.	.	.
517.	Natl_WSU_EDF	0.3819	.	.	.	.
518.	Natl_WSU_EDF	0.3796	.	.	.	.
519.	Natl_WSU_EDF	0.3765	.	.	.	.

	Study	Leak Rate (scfh)	Conc. BH (% gas)	Conc. CIP (% gas)	Conc. SSS (% gas)	Conc. US (% gas)
520.	Natl_WSU_EDF	0.3763	.	.	.	.
521.	Natl_WSU_EDF	0.3762	.	.	.	.
522.	Natl_WSU_EDF	0.3631	.	.	.	.
523.	Natl_WSU_EDF	0.3582	.	.	.	.
524.	Natl_WSU_EDF	0.3447	.	.	.	.
525.	Natl_WSU_EDF	0.3445	.	.	.	.
526.	Natl_WSU_EDF	0.3392	.	.	.	.
527.	Natl_WSU_EDF	0.3311	.	.	.	.
528.	Natl_WSU_EDF	0.3188	.	.	.	.
529.	Natl_WSU_EDF	0.3097	.	.	.	.
530.	Natl_WSU_EDF	0.3056	.	.	.	.
531.	Natl_WSU_EDF	0.2970	.	.	.	.
532.	Natl_WSU_EDF	0.2948	.	.	.	.
533.	Natl_WSU_EDF	0.2916	.	.	.	.
534.	Natl_WSU_EDF	0.2916	.	.	.	.
535.	Natl_WSU_EDF	0.2847	.	.	.	.
536.	Natl_WSU_EDF	0.2847	.	.	.	.
537.	Natl_WSU_EDF	0.2826	.	.	.	.
538.	Natl_WSU_EDF	0.2736	.	.	.	.
539.	Natl_WSU_EDF	0.2632	.	.	.	.
540.	Natl_WSU_EDF	0.2619	.	.	.	.
541.	Natl_WSU_EDF	0.2602	.	.	.	.
542.	Natl_WSU_EDF	0.2552	.	.	.	.
543.	Natl_WSU_EDF	0.2494	.	.	.	.
544.	Natl_WSU_EDF	0.2429	.	.	.	.
545.	Natl_WSU_EDF	0.2428	.	.	.	.
546.	Natl_WSU_EDF	0.2424	.	.	.	.
547.	Natl_WSU_EDF	0.2290	.	.	.	.
548.	Natl_WSU_EDF	0.2263	.	.	.	.
549.	Natl_WSU_EDF	0.2234	.	.	.	.
550.	Natl_WSU_EDF	0.2233	.	.	.	.
551.	Natl_WSU_EDF	0.2196	.	.	.	.
552.	Natl_WSU_EDF	0.2147	.	.	.	.
553.	Natl_WSU_EDF	0.2112	.	.	.	.
554.	Natl_WSU_EDF	0.2108	.	.	.	.
555.	Natl_WSU_EDF	0.2059	.	.	.	.
556.	Natl_WSU_EDF	0.1987	.	.	.	.
557.	Natl_WSU_EDF	0.1945	.	.	.	.
558.	Natl_WSU_EDF	0.1934	.	.	.	.
559.	Natl_WSU_EDF	0.1905	.	.	.	.
560.	Natl_WSU_EDF	0.1892	.	.	.	.
561.	Natl_WSU_EDF	0.1890	.	.	.	.
562.	Natl_WSU_EDF	0.1854	.	.	.	.
563.	Natl_WSU_EDF	0.1848	.	.	.	.
564.	Natl_WSU_EDF	0.1822	.	.	.	.
565.	Natl_WSU_EDF	0.1812	.	.	.	.
566.	Natl_WSU_EDF	0.1808	.	.	.	.
567.	Natl_WSU_EDF	0.1798	.	.	.	.
568.	Natl_WSU_EDF	0.1742	.	.	.	.
569.	Natl_WSU_EDF	0.1716	.	.	.	.
570.	Natl_WSU_EDF	0.1714	.	.	.	.
571.	Natl_WSU_EDF	0.1713	.	.	.	.
572.	Natl_WSU_EDF	0.1712	.	.	.	.
573.	Natl_WSU_EDF	0.1676	.	.	.	.
574.	Natl_WSU_EDF	0.1662	.	.	.	.
575.	Natl_WSU_EDF	0.1658	.	.	.	.
576.	Natl_WSU_EDF	0.1628	.	.	.	.
577.	Natl_WSU_EDF	0.1623	.	.	.	.
578.	Natl_WSU_EDF	0.1614	.	.	.	.
579.	Natl_WSU_EDF	0.1610	.	.	.	.

	Study	Leak Rate (scfh)	Conc. BH (% gas)	Conc. CIP (% gas)	Conc. SSS (% gas)	Conc. US (% gas)
580.	Natl_WSU_EDF	0.1600	.	.	.	.
581.	Natl_WSU_EDF	0.1595	.	.	.	.
582.	Natl_WSU_EDF	0.1582	.	.	.	.
583.	Natl_WSU_EDF	0.1580	.	.	.	.
584.	Natl_WSU_EDF	0.1549	.	.	.	.
585.	Natl_WSU_EDF	0.1544	.	.	.	.
586.	Natl_WSU_EDF	0.1524	.	.	.	.
587.	Natl_WSU_EDF	0.1498	.	.	.	.
588.	Natl_WSU_EDF	0.1496	.	.	.	.
589.	Natl_WSU_EDF	0.1486	.	.	.	.
590.	Natl_WSU_EDF	0.1471	.	.	.	.
591.	Natl_WSU_EDF	0.1413	.	.	.	.
592.	Natl_WSU_EDF	0.1392	.	.	.	.
593.	Natl_WSU_EDF	0.1367	.	.	.	.
594.	Natl_WSU_EDF	0.1344	.	.	.	.
595.	Natl_WSU_EDF	0.1323	.	.	.	.
596.	Natl_WSU_EDF	0.1309	.	.	.	.
597.	Natl_WSU_EDF	0.1127	.	.	.	.
598.	Natl_WSU_EDF	0.0999	.	.	.	.
599.	Natl_WSU_EDF	0.0987	.	.	.	.
600.	Natl_WSU_EDF	0.0964	.	.	.	.
601.	Natl_WSU_EDF	0.0948	.	.	.	.
602.	Natl_WSU_EDF	0.0896	.	.	.	.
603.	Natl_WSU_EDF	0.0848	.	.	.	.
604.	Natl_WSU_EDF	0.0847	.	.	.	.
605.	Natl_WSU_EDF	0.0847	.	.	.	.
606.	Natl_WSU_EDF	0.0826	.	.	.	.
607.	Natl_WSU_EDF	0.0804	.	.	.	.
608.	Natl_WSU_EDF	0.0802	.	.	.	.
609.	Natl_WSU_EDF	0.0798	.	.	.	.
610.	Natl_WSU_EDF	0.0790	.	.	.	.
611.	Natl_WSU_EDF	0.0770	.	.	.	.
612.	Natl_WSU_EDF	0.0761	.	.	.	.
613.	Natl_WSU_EDF	0.0738	.	.	.	.
614.	Natl_WSU_EDF	0.0706	.	.	.	.
615.	Natl_WSU_EDF	0.0635	.	.	.	.
616.	Natl_WSU_EDF	0.0608	.	.	.	.
617.	Natl_WSU_EDF	0.0577	.	.	.	.
618.	Natl_WSU_EDF	0.0575	.	.	.	.
619.	Natl_WSU_EDF	0.0574	.	.	.	.
620.	Natl_WSU_EDF	0.0555	.	.	.	.
621.	Natl_WSU_EDF	0.0530	.	.	.	.
622.	Natl_WSU_EDF	0.0524	.	.	.	.
623.	Natl_WSU_EDF	0.0469	.	.	.	.
624.	Natl_WSU_EDF	0.0456	.	.	.	.
625.	Natl_WSU_EDF	0.0438	.	.	.	.
626.	Natl_WSU_EDF	0.0416	.	.	.	.
627.	Natl_WSU_EDF	0.0413	.	.	.	.
628.	Natl_WSU_EDF	0.0408	.	.	.	.
629.	Natl_WSU_EDF	0.0403	.	.	.	.
630.	Natl_WSU_EDF	0.0397	.	.	.	.
631.	Natl_WSU_EDF	0.0397	.	.	.	.
632.	Natl_WSU_EDF	0.0392	.	.	.	.
633.	Natl_WSU_EDF	0.0392	.	.	.	.
634.	Natl_WSU_EDF	0.0377	.	.	.	.
635.	Natl_WSU_EDF	0.0369	.	.	.	.
636.	Natl_WSU_EDF	0.0364	.	.	.	.
637.	Natl_WSU_EDF	0.0306	.	.	.	.
638.	Natl_WSU_EDF	0.0292	.	.	.	.
639.	Natl_WSU_EDF	0.0249	.	.	.	.

	Study	Leak Rate (scfh)	Conc. BH (% gas)	Conc. CIP (% gas)	Conc. SSS (% gas)	Conc. US (% gas)
640.	Natl_WSU_EDF	0.0249	.	.	.	.
641.	Natl_WSU_EDF	0.0249	.	.	.	.
642.	Natl_WSU_EDF	0.0240	.	.	.	.
643.	Natl_WSU_EDF	0.0236	.	.	.	.
644.	Natl_WSU_EDF	0.0229	.	.	.	.
645.	Natl_WSU_EDF	0.0219	.	.	.	.
646.	Natl_WSU_EDF	0.0197	.	.	.	.
647.	Natl_WSU_EDF	0.0177	.	.	.	.
648.	Natl_WSU_EDF	0.0155	.	.	.	.
649.	Natl_WSU_EDF	0.0144	.	.	.	.
650.	Natl_WSU_EDF	0.0137	.	.	.	.
651.	Natl_WSU_EDF	0.0110	.	.	.	.
652.	Natl_WSU_EDF	0.0096	.	.	.	.
653.	Natl_WSU_EDF	0.0084	.	.	.	.
654.	Natl_WSU_EDF	0.0082	.	.	.	.
655.	Natl_WSU_EDF	0.0069	.	.	.	.
656.	Natl_WSU_EDF	0.0054	.	.	.	.
657.	Natl_WSU_EDF	0.0051	.	.	.	.
658.	Natl_WSU_EDF	0.0036	.	.	.	.
659.	Natl_WSU_EDF	0.0029	.	.	.	.

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the Energy to Lead

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Leak Survey Equipment Considerations for NY Operations

Development of a Regulatory Conformance and Technology Applicability White Paper

Report Issued
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Prepared For
Northeast Gas Association (NGA)

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Executive Summary

The New York State Public Service Commission (NYSPSC) adopted a new definition of a gas service line effective April 2, 2015 (Case 14-G-0357) to align New York's "service line definition" with the federal definition in 49 CFR Part 192. Prior to adopting this change, the definition of a service line in New York ended at the first fitting inside the front wall of a building for inside meter locations. The change in New York extends jurisdictional piping to the outlet of the gas meter even when the meter is located inside a building and the piping was installed and historically maintained by building owner or where required by statute, by the building owners licensed plumber. Accordingly, LDCs are now obligated to perform periodic leak surveys and visual atmospheric corrosion inspections in accordance with federal and state code requirements. In response, Commission staff recently issued a Straw Proposal requesting comments from LDCs to substantiate the use of Combustible Gas Indicators (CGI) with a minimum gas detection threshold of 0.1% gas in air (parts per thousand) for leak survey of inside service lines. This white paper lays out the technical justification and fit-for-purpose nature for the use of CGI technology as applied to inside leak surveys.

Instruments for leak surveys and leak pinpointing/investigations are mature technology that have been on the market for many years. The instruments incorporate different sensor types depending on the practical application of the equipment and site specific conditions. The most sensitive technologies are used for leak surveys of buried outdoor piping. Low sensitivity thresholds (ppmv) are required to compensate for a variety of environmental variables resulting in diluted gas concentrations outdoors and/or reaction with the soil and other subsurface variables effecting gas migration patterns. In contrast, sensitivity detection thresholds for instruments typically used for indoor leak investigations and surveys, where the survey environment is not affected by variables such as wind/soil diffusion and gas migration patterns, are greater than instruments used for outdoor surveys.

While it may seem counter intuitive, if the instrument threshold detection limit is too low (i.e., too sensitive), it may impede leak detection in the presence of a background combustible gas concentration at the parts per million level. The device may trigger a false alarm when the conditions are only slightly above background. Using leak survey equipment with a parts per million detection threshold for indoor piping may hinder an effective and efficient leak survey process.

One margin of safety calculation is a measurement of the difference between an instrument's detection threshold, and the Lower Explosive Limit (LEL) of methane in air (5% methane in air). If a CGI threshold detection value is 0.1% gas in air (one part per thousand), the difference between the threshold detection limit and the LEL value is 50 times. Margins of safety for engineering design range from 1.5 to 20 times, depending on the application. The 50 times margin of safety is at least 2½ times greater.

NY State regulation 16 NYCRR-255.3(a)(12) defines the leakage survey process. This definition goes beyond the current federal definition by specifying detection thresholds rather than stating that an appropriate, properly calibrated instrument be used. With the change of the NY State service line definition, and the inclusion of indoor piping as part of this definition, NY State should broaden their leak survey requirements to parallel current federal code and allow the use of technically substantiated leak survey equipment at appropriate detection thresholds for use in indoor environments.

CGI use is a long accepted past practice that has a proven track record of safety. NY LDC leak investigation practices prescribe the use of CGIs at the parts per thousand detection threshold to investigate potential indoor leak claims. LDC leak survey technicians and emergency response personnel are already equipped and trained in the use of a CGI for leak investigation of inside piping systems. Because indoor gas leaks are in a controlled and contained space they are less affected by external environmental variables, and result in a situation that does not require as sensitive an instrument and associated low detection threshold set point. A typical CGI has a 50 times margin of safety based on the LEL concentration of methane. CGIs should be considered fit-for-purpose for indoor leak surveys.

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Background

The New York State Public Service Commission (NYSPSC) adopted a new definition of a gas service line effective April 2, 2015 (Case 14-G-0357) to align New York's "service line definition" with the federal definition in 49 CFR Part 192. This new service line definition extends jurisdictional piping to the outlet of the gas meter even when the meter is located inside a building. This effectively broadens the inspection purview of piping under the jurisdiction of the LDC to include natural gas piping inside of buildings up to and through the outlet of the gas meter. Accordingly, LDCs are now obligated to perform periodic leak surveys in accordance with federal and state code requirements.

In order to help meet this requirement, Commission staff recently issued "*Straw Proposal for The Adoption of Gas Service Line Leakage Survey and Corrosion Inspection Requirements*" as part of Case 15-G-0244. This Straw Proposal is requesting comments from LDCs to substantiate the use of Combustible Gas Indicators (CGI) for leak survey of inside service lines.

New York State regulation 16 CRR-NY-255.3(a)(12) stipulates "Leakage survey means a systematic survey made for the purpose of locating leaks in a gas piping system using an approved instrument which continuously analyzes atmospheric samples near ground level and is capable of detecting the presence of gas in parts per million air." It is surmised from the "…near ground level …"and the "… detection … in parts per million air" language, and from the fact that historic NYS definition of a service line ended at the first fitting inside the building wall, that this section of the NYS code was intended to apply to leakage surveys of <u>below ground outdoor</u> natural gas piping systems vs. exposed indoor piping systems. The NY LDCs and the GTI study propose to utilize combustible gas indicators (CGIs) with a minimum gas detection threshold of 0.1% gas in air (parts per thousand) as a means to meet the new requirement for indoor surveys.

A review of the use of CGIs with a parts per thousand detection threshold (0.1% gas in air) as an applicable technology option for inside leak surveys is therefore desirable. This review lays out the technical justification for use of these CGI instruments with fit-for-purpose detection thresholds.

This white paper is intended to be a regulatory conformance and technology applicability study. The objective is to weigh all considerations, and assess the fit-for-purpose nature of the CGI technology as applied to inside leak surveys - all viewed through the lens of public safety.

(1) Current and Proposed Survey and Use Case Requirements

New York State regulation 16 CRR-NY-255.3(a)(12) stipulates "Leakage survey means a systematic survey made for the purpose of locating leaks in a gas piping system using an approved instrument which continuously analyzes atmospheric samples near ground level and is capable of detecting the presence of gas in parts per million air." This definition goes beyond the current federal definition and associated requirements by specifying detection thresholds rather than broadly defining an appropriate, properly calibrated instrument for purposes of detecting gas-in-air concentrations indicative of a pipeline leak.

The NYS code requirement for leak survey instrumentation is consistent with the historic NYS definition of a service line, which terminated at the outlet of the meter or the first fitting inside the building wall, whichever came first. The types of approved equipment at the parts per million detection level are appropriate and consistent with the survey requirements for outdoor buried piping systems. With the change of the NY State service line definition to align with the federal code and the inclusion of indoor piping as part of this definition, NY State should consider broadening their leak survey requirements to parallel current federal code in this regard and allow the use of technically substantiated leak survey equipment at appropriate detection thresholds for use in these indoor environments.

Outdoor leak surveys of buried piping are affected by a number of variables relative to leak surveys of indoor piping systems. Most notable is the contained environment and direct access to the indoor exposed piping in contrast to inaccessibility of buried piping, leak diffusion, atmospheric conditions, and soil interaction affecting gas leak migration patterns. These issues are expanded upon in Section 2 of this White Paper. As a result, the leak survey equipment for these two applications are frequently different in terms of sensor technology, device features and detection levels.

The application under consideration within this White Paper is leak survey of visibly accessible indoor piping systems. We specifically note the difference between the leak survey and leak investigation processes. Leak survey of indoor piping is the process of sampling the atmosphere for combustible gas in the vicinity of the exposed pipe and fittings up through the outlet of the meter. If combustible gas is detected, the leak investigation process begins and the piping and appurtenances are further examined along the path of the pipe where the leak source is pinpointed. For inside piping, the same equipment (CGI) is often used for *both* the initial leak survey *and* the pinpointing investigation.

(2) Differences between Conventional Outdoor Leak Survey Instruments and CGIs

Outdoor leak survey equipment used for leakage surveys of buried piping is different from combustible gas indicators used for pinpointing below ground leaks, indoor leakage surveys, and worker safety.

Some differences could include:

- sensor configuration
- sensitivity thresholds
- measurement units
- alarm set points
- calibration requirements
- gases that are detected
- procedures & patterns of use

Some equipment can serve a dual purpose. These are usually air quality combustible gas monitors that can be outfitted with a sampling wand and pump to serve as leak detectors in addition to their original purpose. A description of the sensor detection technologies is found in Appendix B.

A survey of the marketplace found 25 individual manufacturers of leak survey equipment and CGIs available in the U.S. (This survey is not intended to be a complete list of equipment). A total of 69 devices were available for purchase. Twelve devices did not state their detection technology.

Table 1 lists the five sensor technologies found in the market search and their percentage of the 58 total with known detection technology. Two of the technologies (catalytic bead and flame ionization) require the presence of oxygen to properly operate and must not be used in areas with depleted oxygen levels. Some devices utilize two sensor technologies and therefore have multiple ranges; for ease of comparison we have normalized the percentages by individual detector technology in the table to add up to 100%.

Table 1. Common Leak Detector Technologies

Technology	Advantages	Disadvantages	%
Semiconductor	Inexpensive, long life	Sensor contamination	39
Catalytic bead	Inexpensive	Finite lifetime, contamination	27
Infrared (IR)	Selective, wide range	Humidity, interferences	13
Thermal conductivity	Good for high conc.	Less sensitivity	14
Flame ionization (FID)	Responsive to combustibles	Requires hydrogen fuel	7

Table 2contrasts the various detection technologies inclusive of detection level and typical use. Readout units can be % LEL (Lower Explosive Limit) or parts per million(ppm). Some instruments allow the user to select the display units. Threshold detection limits vary with detector technology.

Table 2. Comparison of Leak Detector Technologies

Technology	Device Use/Purpose	Typical Range	Gas Detected
Semiconductor	CGI, leak survey	50-50,000 ppm	Flammable
Catalytic bead	CGI, leak survey	500-50,000 ppm	Flammable
Infrared (IR)	Leak survey	1-50,000 ppm	Methane
Thermal conductivity	CGI	1-100 % gas	Flammable
Flame ionization (FID)	Leak survey	0.1-50,000 ppm	Flammable

Infrared (IR) and Flame Ionization Detector (FID) sensors are the most sensitive, followed by semiconductor and catalytic bead. The sensitivity range of thermal conductivity detectors are appropriate for detecting concentrations of gas generally in the 1-100% gas in air range and are used in applications where oxygen is not required for use (purging operations etc.).

FID instruments have historically been used for outdoor buried pipe leak surveys and are more typical in applications where the survey environment is affected by variables such as wind, soil diffusion, and gas migration patterns thus requiring sensitivity thresholds to address these variables. IR detectors are used in mobile leak survey equipment like the Optical Methane Detector (OMD). IR spectroscopy is the underlying technology behind the Remote Methane Leak Detector (RMLD). A newer technology that uses Cavity Ring Down Spectroscopy (CRDS) is also based on IR spectroscopy.

Most devices have a hazard class rating of at least Class 1 Division 1, which enable their use in areas where explosive or combustible gases, vapors, or liquids are likely to be present, or present due to repair, maintenance, or equipment/process breakdown.

In addition to the information in the Table, other distinctions should be made between the types of detectors. Less expensive models generally do not have data logging capabilities or do not have a sampling pump. Sampling with a pump is more representative than a passive sampler that relies on the diffusion of test gas to the sensor. All of the leak survey equipment and most of the CGIs will alert the operator of the presence of combustible gas through both a visual alarm on the device along with an audible indication.

Periodic calibration is recommended by most manufacturers. The frequency of calibration varies by manufacturer, however not all of the lower cost devices have the ability to be calibrated. Common practice is to verify instrument performance before each day's use by a "bump" test exposing the sensor to a burst of methane gas to insure the sensor will respond to methane. It is recommended to periodically calibrate and bump test all equipment used for gas industry leak survey detection, whether the activity is for programmatic leak survey operations or for leak investigations. Each individual LDC must ascertain their own periodicity and calibration requirements based on manufacturer's recommendations. In NYS, all gas leak survey and leak detection equipment must be calibrated in accordance with the manufacturers recommendations *or* every 3 months.

Outdoor Leak Survey, Investigation, and Pinpointing Process

A pipeline leak *survey* is the act of systematically surveying the atmosphere in the vicinity of a pipe or a defined geographic area that bounds the area in which a subsurface pipe is known to be present for the presence of natural gas. The pipe being surveyed can be above ground or buried. Current NY State code requires the use of an approved instrument which continuously analyzes atmospheric samples and is capable of detecting the presence of gas in parts per million in air. The NY Department of Public Service has approved flame ionization and certain IR technology for code mandated leak surveys. Leak survey equipment can be hand held devices with an appropriate sampling probe, a flexible wand allowing the operator to locate a leaking area, or can be mounted on a vehicle for extended surveys.

Once a leak has been identified, either through a survey or a report from the general public (odor call), the process of leak *investigation and pinpointing* begins. The leak investigation process for suspected leaks on buried piping includes taking leak readings below ground from bar holes or sample access points using appropriate sample probes and filters for below ground samples. This process also includes sampling general contained atmospheres from buried structures (sewer, catch basin, manholes, etc.) and at locations outside a building wall such that the leak can be classified. A leak is then *pinpointed* before an excavation is made to repair the leak, pinpointing a leak source is typically accomplished through progressive leak readings from below grade bar-holes such that the probable leak location is sufficiently bounded and identified prior to suspected piping being exposed and repaired.

A survey of 15 LDCs in the northeast conducted for this report found that FID and IR-based devices were used by 72% of the respondents for leak surveys. When the process moved to leak investigations and pinpointing, CGIs dominated at 87%. Figure 1 graphs the responses.

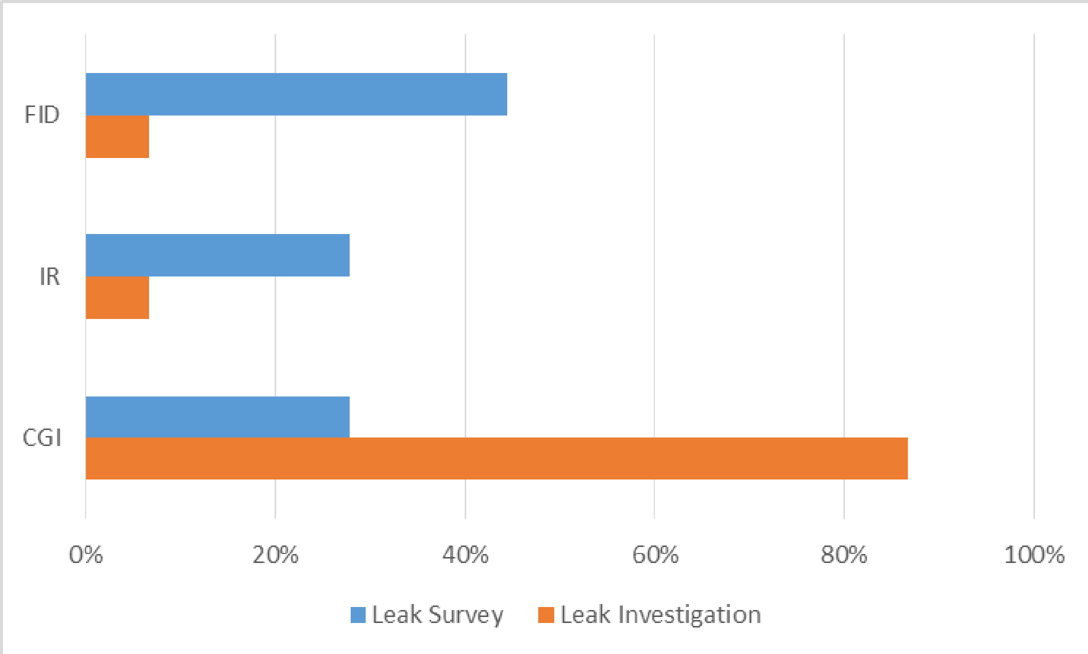

Figure 1. Equipment used for Leak Surveys vs. Leak Investigations

Indoor Leak Survey and Pinpointing/Investigation Process

On inside piping, fittings, or other equipment, a similar process is used as with outdoor leak surveys. The general area is first tested for the presence of combustible gas. The atmosphere in the area or along the path of the gas piping is then sampled for the presence of combustible gas. If combustible gas is found, the piping and appurtenances are further examined for a leak and the exact leak source is pinpointed. For inside piping, the same equipment (CGI) is often used for *both* the initial leak survey examination *and* the pinpointing investigation.

Air Quality and Personal Safety Monitors

Devices used for indoor leak survey and personal safety monitoring are usually smaller than the leak survey units, have similar detection thresholds and are intended to be clipped to a belt, hard hat, or other location on a person. Some have carrying straps and are worn over the shoulder. Many contain multiple sensors to check for oxygen, carbon monoxide (CO), and hydrogen sulfide in addition to combustible gas. Sensors for other gases are available from some manufacturers. Some companies use these devices as an initial survey tool followed by the same leak pinpointing process as described above.

A quick survey of the marketplace found 15 individual manufacturers available in the U.S. (as before, this survey is not intended to be a complete list of equipment.) A total of 43 devices were available for purchase.

Summary

Instruments for leak surveys and leak pinpointing/investigations are mature technology that have been on the market for many years. There are a variety of sensor technologies available depending on the practical application of the equipment and site specific conditions.

FIDs and IR-based technologies are used for leak surveys of buried piping because of the low threshold detection limit needed when the gas is diluted outdoors and/or reacts with the soil and buried environment.

CGIs are used for indoor leak surveys, outdoor and indoor leak investigations, and personal safety monitors. The majority of CGI detectors on the market rely on catalytic bead and/or metal oxide semiconductors. Each device type is used for a specific application and is considered fit-for-purpose for its intended use when coupled with an appropriate procedure.

(3) Leak Surveys - Outdoor Buried vs. Indoor Aboveground Situations

Outdoor aboveground surveys of buried piping systems are different from exposed indoor aboveground surveys. One obvious difference is the fact that the leaks from buried piping systems need to migrate from the leak site through soil or other dense material, to eventually diffuse into the atmosphere where they can be detected. The ability of natural gas to vent at the ground surface is critical for the success of an above ground survey of buried piping.

Outdoor Aboveground Leak Surveys of Buried Piping Systems

When measuring leaks outside, consideration must be made for gas migration, reaction mechanisms, and diffusion of gas into the atmosphere. Methane is lighter than air and will rise quicker than other gases, following the path of least resistance. Large leaks could generate a plume of methane that would rise with directional momentum. Smaller leaks will slowly diffuse through soil and gradually mix with air. In that instance, the density would be much closer to air and the methane concentration much lower due to dilution. Windy conditions will quickly dilute the gas further. Because of the inherent dilution potential due to atmospheric conditions and gas migration, it is critical to use equipment with an appropriate detection threshold and fit for purpose for the application. This threshold detection level is typically in the parts per million range.

Soil chemistry and makeup may also play a part. Volatile organics such as methane can be adsorbed by the clay matrix in soil, leading to false negative reports of small leaks. Methane may also be lost through oxidation by methanotrophic bacteria in the aerobic zones of soils. Methane loss appears to be positively correlated with temperature. Water content of the soil will collect in the voids between the soil particles and obstruct the rise of methane to the surface. In wet or frozen conditions, the gas may be restricted from venting. Other obstructions include ground surface treatments. If the leak is under concrete or asphalt it may travel a distance from the source, following the path of least resistance until it finds a point where it can vent to atmosphere.

Continuous sampling of the atmosphere within a defined geographic area that bounds the pipe of concern (pattern survey) or along the path of buried main and services should be made at close proximity to ground level, typically 2-6 inches above the ground surface. In areas where the gas piping is under pavement, samplings should also be at curb lines, available ground surface openings (such as manholes, catch basins, sewers, power, telephone duct openings, fire and traffic signal boxes, or cracks in the pavement or sidewalk), or other interfaces where the venting of gas is likely to occur. In the case of any exposed piping subject to similar environmental variables, sampling should be adjacent to the piping. The pace of the survey is dependent on the equipment used and is typically addressed in application procedures.

All these factors influence the selection of leak survey instruments with respect to the detection threshold. Again, and for the reasons note above, leak survey equipment used in outdoor *aboveground* surveys of *buried* piping systems must be capable of detecting gas in air at the parts per million level.

Indoor Leak Investigations

Leak investigations of exposed piping in aboveground, *indoor* environments are typically not significantly influenced by environmental variables similar to those for outdoor surveys of buried piping. However, indoor environments have their own specific considerations such as accessibility of the pipe, confined space, and leak diffusion. Some examples of above ground leaking components are worn/aged gaskets and seals such as leaks at pipe threads, valve packings, pressure regulator relief valves, atmospheric vents, etc. Inside a residential building, leaks may be from appliances, fittings, meters, regulators, and very importantly, migration of exterior buried piping leaks into a building structure.

Indoor environments have a distinct leak survey advantage over outdoor environments, in that the pipe is predominantly exposed within the building allowing the gas to be generally contained in the vicinity of the pipe. This enables direct gas sampling of the atmosphere in the vicinity of the pipe without influences from external variables affecting the presence and migration of gas relative to the pipe location. For pinpointing, this direct accessibility enables a continuous gas/air sample to be drawn in close proximity along the path of the pipe, typically 6" or less from the pipe itself. This means that the leaking gas does not have time and space to dilute in the surrounding air and provides a higher concentration vs. a similar size leak from a buried pipe outdoors that has to migrate to the surface and then is diluted with outdoor air. The lack of dilution enables the process of identification of hazardous leaks in indoor environments to be conducted at a different threshold of detection, typically parts per thousand, and enables the use of CGIs for this activity.

A significant difference between indoor vs. outdoor leak surveys is the limited ability of a gas leak to diffuse in an indoor environment. The physical constraints of the building confine the vast majority of the escaping gas to a limited area inside the building such as basements, attics and dead air spaces. Gas movement between rooms is obstructed by floors, walls, ceilings and closed doors.

The orientation of a gas source within a room will result in different gas-air distributions. Leaks at elevated pressure have a greater impact than leaks at residential/equipment utilization pressure because there is more driving force for the leak at higher pressure, and higher concentrations of gas in the surrounding environment. This limited ability of gas to diffuse and dilute within a building, by its very nature, creates an opportunity for a hazardous condition to develop because the gas can accumulate within the confines of the building or interior space.

The obvious limitation of indoor leak survey is the limited access to gas piping where it is concealed within building walls, ceilings and utility chases. In these cases, the survey operation extends along the gas pipe to the physical boundary imposed by the construction of the building. If access is available to the confined space where the gas pipe is present, then the survey probe is typically used to sample the air in those limited locations. Beyond this practice, the general public is warned of a potential gas leak through the use of odorant injected into the gas supply. Federal code stipulates that gas be readily detectable to the average person's olfactory sense at a concentration of 20% LEL. New York has a lower (more conservative) state code for odorant detection (10% LEL – parts per thousand) that supersedes the Federal code.

Summary

In general, outdoor environments require more sensitive instrumentation due to the dilution, migration, reaction, and diffusion of methane in that environment. Indoor gas leaks are in a controlled and contained space, where concentration can build easier over time, are less affected by external environmental variables, and result in a situation that does not require as sensitive an instrument and associated low detection threshold set point to achieve similar operational and public safety benefits. Instrumentation for both applications should be selected on a fit for purpose basis with an appropriate procedure for use.

(4) Sensitivity Considerations and False Positives and Negatives

While it may seem to be counter intuitive, if the set point or instrument threshold detection limit is too low (i.e., too sensitive), it may actually impede leak detection. Devices used for outdoor, aboveground leak surveys require much higher sensitivity and lower threshold detection limits to properly assess if a leak is present. This is fundamentally related to the potential for dilution and reaction as discussed earlier. These conditions are *not* present in indoor leak survey operations.

False Positives

The reason that leak detection instruments for indoor leak survey may be too sensitive is the concept of "false positives." A false positive is a situation in which a result improperly indicates the presence of a condition that is actually not present. In the presence of a background combustible gas concentration at the parts per million level, a leak investigation worker may not be able to accurately identify a leak using equipment that is too responsive to low levels of combustible gas that may result from background materials such as household chemicals. The device may trigger a false alarm when the conditions are only slightly above background for example when exposed to certain pipe joining compounds. As a result, the use of leak survey equipment for indoor piping at the parts per million detection threshold may hinder an effective and efficient leak survey process.

It should be noted that NY LDC leak investigation practices prescribe the use of CGIs at the parts per thousand detection threshold to investigate potential indoor leak claims. CGI use is a long accepted past practice that has a proven track record of safety. We specifically note here the difference between the leak survey process and the leak investigation process. This same approach is suggested within the GTI Atmospheric Corrosion Study and for broader use as a leak survey practice for NY LDCs. This does not prohibit the use of more sensitive leak detection equipment during the leak investigation process as warranted by the site-specific conditions.

False Negatives

The opposite of a false positive is a "false negative," which is a result that improperly indicates no presence of a condition (the result is negative), when in reality the condition is present. Catalytic bead and FID sensors require the presence of oxygen to work properly. If the oxygen level is low, they will not work and may give a false sense of security because the methane concentration display is low even when true methane levels are much higher.

There is potential for this situation to occur in an indoor leak survey. For example, if a leak was found in a utility chase, this smaller "confined" space could have a higher methane concentration with a resulting lower oxygen concentration. Using one of the detectors that require oxygen to operate, such as an FID, might give a falsely low reading for a combustible gas concentration. OSHA released a Hazard Information Bulletin discussing the use of combination oxygen and combustible gas detectors. Workers should understand the limitations of these detectors and correlate the oxygen content with less than LEL readings that may potentially be much higher.

(5) Margin of Safety to LEL and Threshold Detection Levels

The margin of safety is a measure of how well a design satisfies the design requirements for its intended application. For the application of monitoring combustible gas, the margin of safety is a measure of the difference between an instrument's detection threshold, and the intrinsic safety requirement of the measurement operation. Each individual LDC must determine their own margin of safety requirements.

Leak survey and investigation equipment commonly report data as % LEL, % gas in air, parts per million (ppm) by volume of gas, or parts per thousand. Table 3 shows how the different units compare for several concentration levels.

Table 3. Correlation of Different Units of Methane Concentration

% LEL	% Gas in Air	Methane, parts per million	Methane, parts per thousand
100%	5%	50,000 ppm	50 parts per thousand
10%	0.5%	5,000 ppm	5 parts per thousand
1%	0.05%	500 ppm	0.5 parts per thousand
0.1%	0.005%	50 ppm	0.05 parts per thousand
0.01%	0.0005%	5 ppm	0.005 parts per thousand

The following are example calculations for common threshold detection limits found with typical leak investigation (CGI) and leak survey (FID) equipment.

If the CGI set point (threshold detection value) is 0.1% gas in air (2% LEL) this equates to one part per thousand, or 1000 parts per million. Most CGIs are capable of reaching this threshold detection limit. Using the LEL value of methane (5% gas in air), the relative difference between the threshold detection limit and the LEL value is 50 times. This means that there would be a margin of safety of 50 times with the CGI use. The 0.1% gas in air is the level of detection for CGIs currently being used by some NY LDCs for inside leak investigation. This is also the level of detection proposed within the GTI Study for inside leak survey and the level of detection associated with "belt-clip" CGIs proposed for broader use in New York State within the Staff Straw Proposal as part of Case 15-G-0244.

The same calculation can be made for an FID instrument. An FID threshold detection value of 1 part per million is 0.0001% gas in air, or 0.002% LEL, or 0.001 parts per thousand. Comparing again to the LEL value for methane, the relative difference between the threshold detection limit and the LEL value is 50,000 times. The margin of safety for FID instruments used for inside leak survey is therefore 50,000.

Material margins of safety are often published in technical standards but there is no dedicated standard to this subject. One source (www.engineeringtoolbox.com) lists margins of safety for engineering design ranging from 1.5 to 20 times, depending on the application. The 50 times margin of safety of most commonly available CGIs is greater (more than two times) than this highest estimated margin of safety for engineering design.

Residential Methane Detectors (RMDs)

Residential methane detectors are small AC powered plug-in devices intended to detect natural gas (methane) which may be present in a residential building. These devices are intended to sound an alarm at or above 25% LEL of natural gas or LP-Gas. Japan is currently the only area that mandates the presence of an RMD in homes.

The 25% of LEL set point of RMDs translates to 1.25% gas in air, 12.5 parts per thousand, or 12,500 parts per million. Using the same LEL of methane logic as above (5% gas in air), the difference between the set point of RMDs and the LEL value is 4, giving a margin of safety of 4 times. Legislation is being considered in New York to require RMDs in residential areas. Recommendations are underway to reduce the RMD set point to 10% LEL (0.5% gas in air, 5,000 parts per million, or 5 parts per thousand), with a difference between the set point and the LEL of methane of 10, increasing the margin of safety to 10 times.

Table 4 summarizes the margin of safety information for typical leak investigation (CGI) and leak survey (FID) equipment, plus the existing and proposed RMD standards. The CGI devices have a greater margin of safety than RMDs and many common engineering designs. Their margin of safety is not so large to induce false positives from background methane levels.

Table 4. Margin of Safety for Various Devices

Common Device	Lower Threshold Detection Limit or Set Point	Margin of Safety, Compared to Methane LEL
CGI	0.1 % gas in air	50
FID	1 ppm	50,000
RMD	25% LEL	4
RMD proposed	10% LEL	10
Odorant Detection (NYS)	10% LEL	10

(6) Natural Gas Odorant Considerations

Because methane by itself is odorless, odorants have been added to natural gas streams in the United States ever since the 1937 Texas school explosion. The requirement that gas in certain classes of natural gas transmission and distribution pipelines be odorized (or contain a natural odorant) is prescribed in the Code of Federal Regulations (CFR) Title 49 Part 192.625. The purpose of the odorant is for people to quickly detect if a natural gas leak is present. Odorant serves as the primary means of leak detection for the general public. Odorant is considered by some as the, "last line of defense" for leak detection.

The text in 49 CFR 192.625 specifies an odorant concentration to be detected by a normal sense of smell at 20% LEL, while some states such as New York and Maryland are lower at 10% LEL, and Massachusetts is even lower. As these current codes and regulations stand today, a leak survey worker in New York would be more likely to smell gas in an indoor space prior to any residential methane detector activating an alarm. Using a CGI device with a threshold detection value of 0.1% gas in air (2% LEL) would enable the detection of gas even earlier as the CGI would detect gas at a detection threshold 5 times lower than the odorant detection threshold in New York.

Following the margin of safety reasoning in the previous section, the 10% LEL level of odorant detection in New York equates to a margin of safety of 10 compared to the LEL of methane.

(7) Having Greater Numbers of Leak Survey Instruments in the Field

The majority of NY LDC field technicians are already equipped with CGIs, all of which have the ability to be used for inside leak surveys. At least one NY LDC is already using belt clip leak detectors that are equivalent to traditional CGIs but in a more compact form.

The advantage of having many more CGIs (including belt clip detectors) in the field is clear. The public safety benefit of enabling these devices to be used for leak survey of indoor piping will enable significantly more surveys to be performed on an ongoing basis versus limiting leak surveys to more expensive and overly sensitive, specialized equipment (as it relates to indoor leak surveys). There are significant public safety benefits in enabling more surveys to be performed and this could be achieved by expanding the type of fit-for-purpose equipment approved within New York for indoor leak surveys.

In the situation where an abnormal combustible gas concentration is detected, a more sensitive instrument could be made available by the LDC to confirm the reading or assist in the leak investigation process.

Conclusions

The survey protocol proposed within the GTI Atmospheric Corrosion Study and attached here as Appendix A recommends the use of CGIs with a level of detection at the parts per thousand level for leakage survey of indoor piping systems. This approach, inclusive of both the type of equipment and threshold level of detection, is consistent with existing LDC practices for leak investigation inside buildings. The level of detection at the parts per thousand level is appropriate for this leak survey application since:

- Most of the inside gas piping is directly accessible for survey inside the building as opposed to buried piping systems where soil characteristics impede the leak migration to the ground level for detection.
- Leakage is contained and concentrations will build within the confines of the structure and does not quickly dissipate, as is the case in an outdoor environment.
- Detection thresholds at a parts per thousand level have historically enabled the identification of potentially hazardous leaks on inside piping systems.
- Use of leak survey equipment on indoor piping at the parts per million detection threshold frequently hinders the leak survey process as the background methane level may exceed this threshold when a leak is present.
- Once a leak is detected at the parts per thousand level during a leak survey, the LDC begins its leak investigation process. An instrument at the parts per million detection threshold can be utilized, if necessary, during this follow on process to accurately pinpoint the leak.
- The parts per thousand detection level is within the same order of magnitude (while being five times lower) for the level of detection of natural gas odorant in NY, which is the primary means for the general public to identify a natural gas leak.
- A CGI with a threshold detection value of 0.1% gas in air (one part per thousand) has a 50 times margin of safety as compared to the LEL value of methane.
- LDC leak survey technicians and emergency response personnel are already equipped and trained in the use of a CGI for leak investigation of inside piping systems. The use of this equipment at these levels will be more efficient and cost effective if the CGI is approved for use in this application.

CGIs should be considered fit-for-purpose for indoor leak surveys.

Appendix A – Leak Survey Protocol for the GTI Atmospheric Corrosion Study

The listed items below cover leak survey inspection of visibly accessible indoor natural gas piping, regulators, fittings, and meters; including the wall penetrations or point of entry (POE) to the interior of the building through the outlet of the meter.

1. The operator is responsible for satisfying all internal safety procedure requirements, training and operator qualification requirements. This procedure does not address such requirements.
2. All reasonable efforts shall be made to survey and inspect visibly accessible service piping.
3. Document any piping that was obstructed and any incomplete portions of the inspection.
4. Leak surveys will be conducted using a conventional portable combustible gas indicator[a] (CGI) with a 0.1% gas reporting threshold.
5. The leak survey is to be conducted by assessing the general atmosphere approximately 6" from the pipe/fitting/meter using an appropriate sample probe[a].
6. If multiple leaks are found during the leak inspection, record only the highest reading[b].
7. In an instance when an abnormal combustible gas concentration is detected, a more sensitive instrument can always be requested to confirm the reading.

Notes:

a. A component of the GTI Study will compare the results of the above indoor leak survey protocol with leak surveys performed with belt clip CGI leak detectors.
b. Item 6 applies only to data collection for the GTI Study and is not broadly applicable to LDC leak survey protocols.

Appendix B –Brief Discussion of Conventional Combustible Gas Sensor Technologies

Catalytic bead detectors (Figure 2) were the first combustible gas detectors in the market. They function by oxidizing (burning) the combustible gas at the hot surface of the bead and measuring the resultant change in resistance of the bead, which is directly proportional to concentration. They are relatively low-cost and well established. They have an approximate life span of five years because the oxidation process consumes the sensor material, and it eventually depletes and becomes unresponsive. Catalytic bead sensors respond to all combustible gases but they respond at different rates to each and so can be calibrated for particular gases in specific applications. The bead surface can be contaminated by certain gases and reduce sensitivity and lifetime.

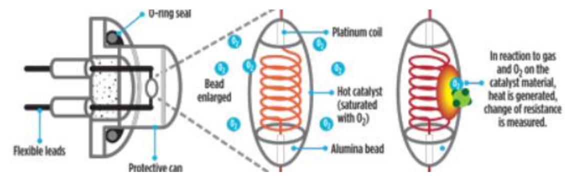

Figure 2. Catalytic Bead Sensor
Image from Reference 4

Semiconductor based combustible gas detectors (Figure 3) were introduced in the late sixties as an alternative to the catalytic bead. They are usually constructed from transition metal oxides. With these sensors, gas is adsorbed onto the sensor surface, changing the resistance of the metal oxide. Concentration of the combustible gas is proportional to the resistance. When the gas disappears, the sensor returns to its original condition. No sensor material is consumed in the process, and as a result, they can have a longer life expectancy. Like the catalytic bead sensor, they are susceptible to contamination. Sometimes the interferences from other gases are minimized by using appropriate filtering materials that absorb all other gases except the gas to be detected. This is a common application in semiconductor sensors used for the residential methane detector market.

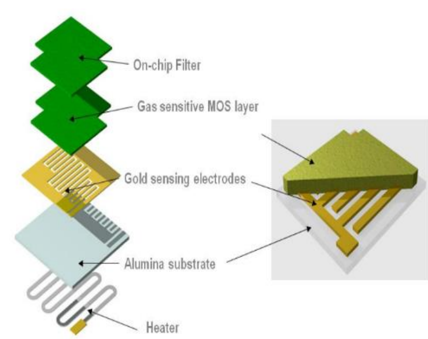

Figure 3. Semiconductor Sensor
Image from Reference 5

Infrared sensors (Figure 4) work on the principle that gases containing two or more dissimilar atoms absorb infrared radiation in a unique manner that can be easily detected. Each gas has a unique fingerprint spectrum and specific bands of the spectrum are targeted for analysis. As the gas concentration increases, the absorption band increases. Infrared sensors are highly selective and offer a wide range of sensitivities, from parts per million levels to 100 percent concentrations. The selection of the band for monitoring is important to eliminate interferences from other gases that might be present such as ambient humidity.

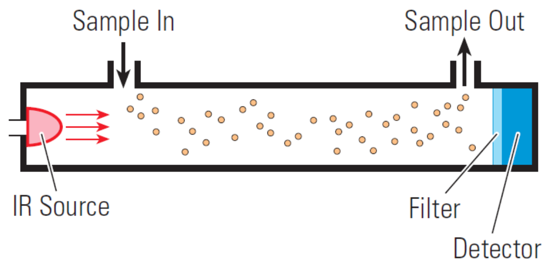

Figure 4. IR Sensor
Image from Reference 1

A **flame ionization** detector (FID, Figure 5) is a general-purpose detector used to determine the presence of volatile carbon-based compounds that are burned in a hydrogen-air flame. When the organic compounds burn, ions are generated that cause an increase in the flame's baseline ion current at a collection electrode in proximity to the flame. The more carbon atoms a molecule contains the greater the response. They are commonly used as detectors for gas chromatography but can also be used as standalone monitors for leak detection. Despite the hydrogen/oxygen flame, these devices are usually rated as intrinsically safe and can be used in Class 1 Division 1 locations.

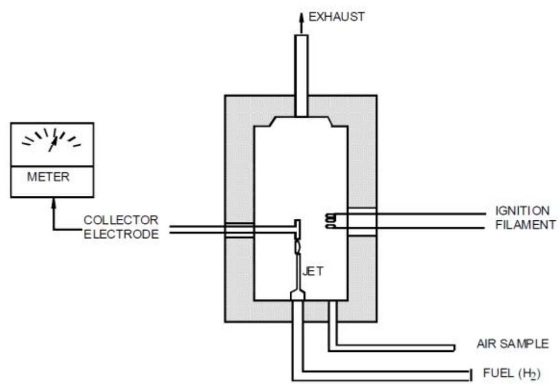

Figure 5. FID Sensor
Image from Reference 6

Thermal conductivity detectors (TCD, Figure 6) work on the principle that gaseous compounds possess different heat conduction characteristics (thermal conductivity). By comparison to a sealed reference gas cell containing one thermistor in air, a second thermistor will change temperature as gas composition changes. When tuned to respond to combustible gases, it can be used as a wide range detector for high concentration levels.

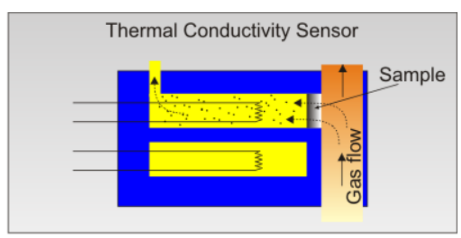

Figure 6. TCD Sensor
Image from Versaperm Ltd.

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