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REVOLUTIONISING LEAK MANAGEMENT

Leveraging State-of-the-Art Technology

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Background

Company Overview

Pacific Gas and Electric Company (PG&E), incorporated in California in 1905, is currently one of the largest combination natural gas and electric utilities in the United States (U.S.).

The company provides natural gas and electric service to approximately 15 million people throughout a 70,000 square-mile service area (an area larger than 33 of the 50 U.S. states) in northern and central California as shown in Figure 1 below. PG&E owns and operates 6,750 miles of gas transmission pipeline and approximately 42,000 miles of gas distribution pipe (60 psig or less). PG&E serves 4.3 million natural gas customer accounts (one in 20 U.S. gas consumers[1]) and delivers 970 BCF[2]/year (a daily average of 2.6 BCF).

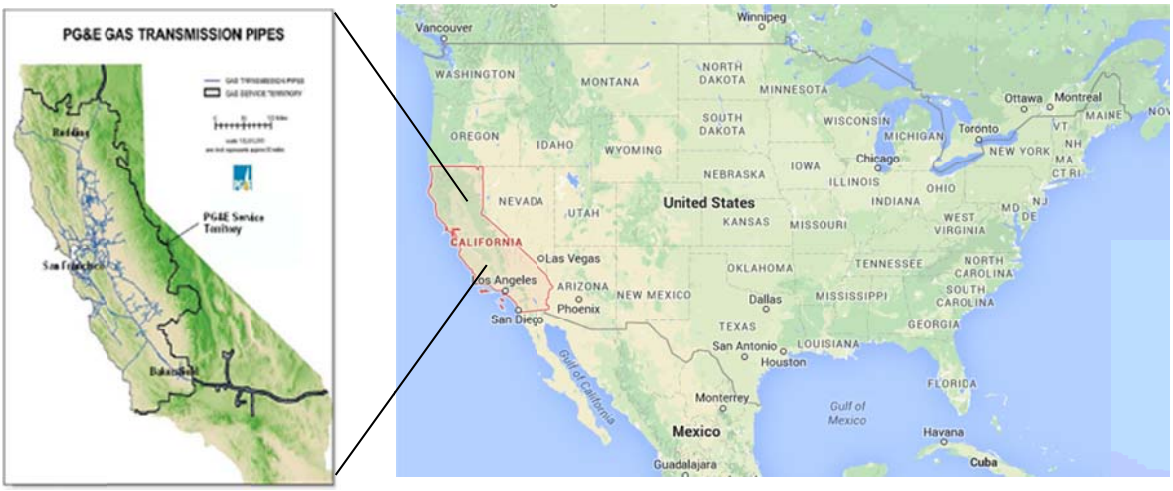

Figure 1–PG&E's gas service area

Approximately 67 percent of PG&E's gas transmission system's pipelines were installed before 1970 and 30 percent of the pipeline miles are within highly populated areas (designated under U.S. rules as Class Location 3 and 4 and High Consequence areas in Class Location 1 and 2).

[1] Based on total US Gas Consumers compiled by the US Energy Information Administration (http://38.96.246.204/dnav/ng/ng_cons_num_dcu_nus_a.htm).

[2] Billion cubic feet.

Situation

In the U.S., the annual incidence of death or injury as a result of catastrophic pipeline infrastructure failures has declined more than half over the past 20 years. However, recent incidents in San Bruno, California, (2010) and East Harlem, New York, (2014) that resulted in 16 fatalities, numerous injuries and substantial property damage have raised questions in the public's mind about the safety of older pipelines. The former chairperson of the National Transportation Safety Board (NTSB)—the federal agency responsible for investigating accidents of such nature—Deborah Hersman, stated in 2011, "accident investigations highlight the need for a new perspective on safety culture, record-keeping and aging infrastructure."

Accidents with significant consequences can result from unintentional release of natural gas from a pipeline, which can lead to fires or explosions close to population and property.

Today across the U.S., more than 2.1 million miles of distribution pipelines are in service. Approximately 38 percent of these pipelines were installed before 1970. In comparison, approximately 42 percent of PG&E's distribution system was installed before 1970. Because distribution pipeline systems are in predominantly urban and suburban geographical areas, it is important operators know and understand the condition of their gas infrastructure so appropriate mitigation actions can be taken to minimise unintended releases.

A key indicator used to identify the condition of gas pipelines is the location and type of natural gas leaks detected through implementation of a periodic leak survey process.

PG&E's objective is to become the safest, most reliable gas utility in the nation. In the wake of the tragic San Bruno incident, the company has invested nearly $3 billion to improve its gas network and associated business processes. The company's leak management process now uses the world's most advanced leak detection technology and a new approach to finding and fixing leaks.

PG&E implemented a two-step leak management process many decades ago, similar to other gas operators in the U.S. The first step is to perform a "traditional" leak survey in which trained, qualified personnel use commercially available leak detection instruments[3] (predominately on foot using hand-held devices) to survey the transmission and distribution system for gas leaks on an established frequency[4]. Once identified, a leak is assigned a grade based on the amount of gas present, proximity to structures that define potential risk to public or property and the likelihood the leak will become more serious over time. The second step is leak repair, which is either performed immediately if the leak is deemed an immediate safety risk or scheduled and performed following the priority determined by the leak's assigned grade.

In an attempt to revolutionise historical, industry-wide leak management practices, PG&E is collaborating with a California-based technology innovator, Picarro Inc. The

[3] Leak survey instruments identify leaks by measuring methane concentrations in parts per million.

[4] Leak survey frequency depends on the type of facility, operating pressure and proximity of the facility to specific structures (e.g. school, hospital or other public building). The minimum frequency for a U.S. distribution system is every five years.

collaboration involves adaption of a mobile-based methane detection solution that combines a high-precision methane analyser with processing algorithms to locate natural gas leaks.

Picarro Surveyor™—Revolutionary Leak Management Solution

The Picarro Surveyor™ (Surveyor) is the industry's only commercially available leak detection solution today that can measure methane in parts-per-billion to survey gas pipelines at driving speeds and identify likely leak locations as well as leak-free areas.

Using the mobile-mounted Surveyor PG&E has found more hazardous and gradable leaks per leak survey area than using other commercially available leak detection technology. The Surveyor's biggest advancement is that it measures methane concentrations in parts-per-billion (PPB) as compared to parts-per-million (PPM) with other commercially available leak detection instruments. The technology can also distinguish natural gas from biogenic methane.

Figure 2–PG&E Picarro leak detection survey vehicle

The Surveyor is an integrated solution for mobile leak detection comprised of:

- A methane isotope analyser based on Cavity Ring Down Spectroscopy (CRDS)
- Peripheral equipment for providing 4G[5] mobile data connectivity
- Software for measuring Global Positioning System (GPS) location and atmospheric conditions
- Proprietary and patented embedded software that enables the collection, analysis and display of data—via several media—related to natural gas pipeline infrastructure

[5] **4G** refers to fourth generation mobile telecommunications technology that provides mobile broadband internet access.

Natural gas (primarily consisting of methane) emerging from a point source such as a natural gas pipeline leak is carried by the wind and dissipates into the atmosphere in the form of a plume. The Surveyor measures methane plume signatures and atmospheric and meteorological conditions and uses proprietary algorithms to compute the likely location of natural gas leaks while virtually eliminating false positive indications. These algorithms determine methane plume concentration and amplitude above ambient methane background, likely leak locations called Leak Indication Search Areas (LISA), the survey's Field of View (FOV) and methane plume isotope content.

Figure 3–Picarro analyser and computer onboard a PG&E survey vehicle

The Picarro Processing Platform, or P-Cubed™, provides secure, cloud-based data storage and processing, allowing the data and analysis to be available anytime, anywhere.

The reporting functionality of the Surveyor combines information from multiple measurement sessions run over the same region, taking advantage of varying atmospheric conditions, such as wind direction, wind speed and atmospheric stability, to produce aggregate survey results and to provide comprehensive territory coverage known as the FOV.

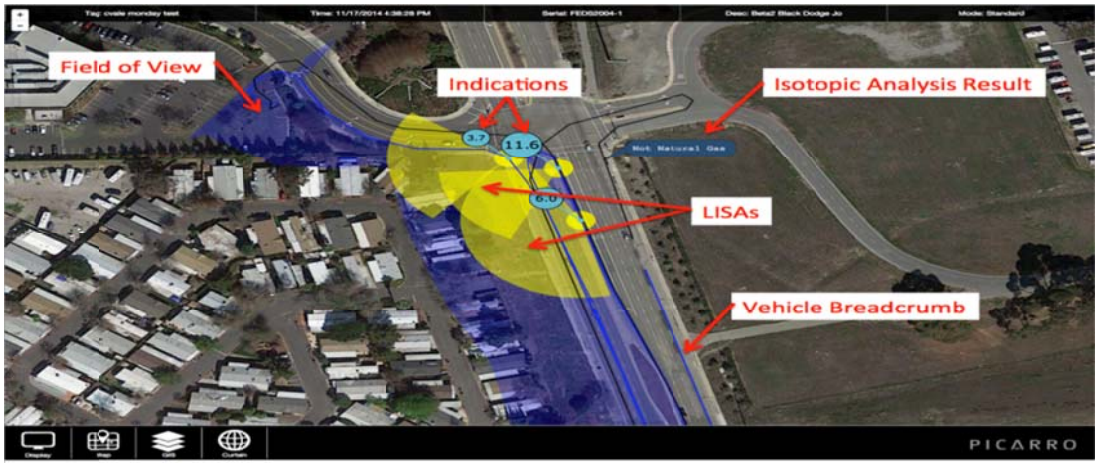

Figure 4–Example of Picarro Field of View and Leak Indication Search Areas

Aim

Develop a new, dynamic end-to-end leak management process that:

- Improves safety by finding and repairing more leaks faster than ever before
- Uses parts-per-billion advanced leak detection technology
- Obtains more data to migrate reactive integrity management strategies to proactive strategies—better informing the allocation of resources to focus on highest risk assets
- Improves quality of workmanship by reducing multiple hand-offs and rework
- Captures operating efficiencies using a work-bundling and routing approach
- Strengthens public confidence in the safety and integrity of PG&E's natural gas system
- Further reduces the impact on the environment by accelerating the leak repair process and minimising greenhouse gas emissions

Methods

PG&E took several steps to determine the viability and likelihood of integrating the Picarro Surveyor™ into its leak management program. It first completed *Proof of Concept* tests followed by two field studies that focused on technology viability and a third field study that focused on the end-to-end leak management process. Finally, PG&E conducted a series of pilots to develop a sustainable, enhanced leak management process that would be scalable over time.

Field Tests and Studies

PG&E, in collaboration with Picarro and Pipeline Research Council International (PRCI)[6], proved the Surveyor was a viable instrument for conducting natural gas system surveys in two controlled field tests at training facilities where leak fields exist and natural gas release could be controlled.

These controlled tests were extremely helpful because they not only established *Proof of Concept* but also supported the design of additional enhancements, such as refined algorithms to locate natural gas leaks and a documented, auditable record of the Surveyor FOV survey coverage of gas facilities. Picarro quickly embraced these requirements and provided an improved system that would be tested in an expanded study.

Field studies were then conducted at three PG&E division[7] service areas. The first two field studies directed by PG&E, PRCI and Picarro were designed to analyse side-by-side performance between the mobile Picarro Surveyor platform and traditional survey methods using commercially available leak detection instruments.

[6] **Pipeline Research Council International** (**PRCI**) is a global collaborative research development organisation of, by and for the energy pipeline industry.

[7] A division is a geographical subset of the overall service area.

A third field study was performed to test the effectiveness of PG&E's business processes established during and resulting from the first two side-by-side studies. Additionally, the third field study was designed to further investigate how to integrate and operationalise the Surveyor into PG&E's leak management process.

Various data were collected during field studies including but not limited to:

1. Total leaks by type and grade
2. System survey coverage
3. Time to complete leak survey
4. Average time to complete a LISA investigation
5. Number of false positives

The table below shows cumulated metrics from the field studies, which illustrate the effectiveness of the Surveyor.

	Total miles of main and number of services surveyed	Percentage of gas facilities covered by Picarro (FOV)	Gradable leaks ratio (Picarro/ traditional)	Productivity ratio (Picarro/ traditional)
Study #1	46 miles, 4195 services	89	4.8	2.9
Study #2	39 miles, 3545 services	88	1.9	3.4
Study #3	100 miles, 9073 services	81	1.8	2.6

Figure 5–Super Crew study metrics

Overall Study Results

All field studies (but not the controlled tests) and process enhancements in aggregate produced productivity and leak-find rate results that were used in planning future pilots. However, it is important to note that as PG&E progressed from the first through third field studies, not only were technology enhancements made by Picarro but PG&E also refined test protocols to more accurately determine Surveyor performance compared to traditional leak survey methods. Therefore, the third study's statistics were more accurate than studies one and two and provided primary data points as PG&E progressed from field studies to field pilots.

The studies provided valuable information for training development and change management requirements, new and revised standard operating procedures, operator qualifications, etc., all of which were developed prior to the first field pilot.

The studies also provided guidance on selecting and prioritising the most impactful enhancements to the Surveyor, with primary focus on increasing the accuracy of the leak search areas and further reducing the false positive rate.

Additionally, the field studies revealed the Surveyor significantly outperforms traditional surveyors using commercially available instruments by not only finding 80 percent more

leaks (including more hazardous leaks) but also surveying gas facilities more than two times faster than traditional methods.

Pilots

At this point, PG&E had proven the viability of the advanced leak detection technology and committed to leveraging it to develop an improved overall leak management process, including leak repair.

The next step was to engage a cross-functional team of 30 experts to design a comprehensive, end-to-end leak management process from leak survey schedule initiation to final documentation of all associated leak repairs.

Building the Leak Management Model with the Industry's First "Super Crew"

PG&E is the first gas utility in the world to test, study and integrate the advanced leak detection technology. The decades old leak management model was not sufficient to process the increased number of gas leaks the advanced technology and refined processes generated.

A paradigm shift was required to take advantage of the technology and develop a leak management program to fix all additional leaks in an accelerated timeframe. The goal was to find more leaks while reducing overall unit costs of leak survey and repair through a highly efficient, closely managed integrated approach throughout the entire end-to-end work stream.

In the first four weeks of 2014 a cross-functional team designed an initial process that was refined as feedback was received. Three iterative refinements, which are illustrated later in this document, culminated in the final process known as Super Crew.

Prior to the use of Picarro Surveyor for compliance survey activities, traditional survey was performed over 12 months and covered 20 percent of PG&E's gas facility assets. Leaks were inventoried and repaired based on their compliance dates. This several-decades-old leak management process was driven by these compliance dates and dictated multiple hand-offs between functions, such as mapping, engineering, estimating, scheduling, construction, etc.

The Super Crew process was built to find and fix all leaks in a specific deployment area within 30 days vs. over the course of a year with the previous process.

Super Crew is an end-to-end process executed by a cross-functional team that travels around the service area to survey and repair leaks. Key success factors have been involving people with a diverse set of skills and multi-function experience and acting on feedback received to drive continuous improvements.

	Old Model	New Super Crew Model
Leak Survey	Traditional surveyors walk the gas lines over 12 months	Using a mobile Surveyor, crews perform one year of a division survey in about four weeks
Work Readiness	Multiple processes of 15+ back-office systems produce work packages for crews	Tightly integrated process finds and fixes leaks with Super Crew in a three-week window
Leak Repair	Many handoffs result in continuous improvement opportunities	Vast economies of scale from fixing a year's worth of leaks in one area over several weeks

- Find 80% more leaks
- Repair within one month vs. one year
- Minimize handoffs
- Reduce unit costs

Figure 6–PG&E Super Crew vs. Traditional Survey

With each successive pilot, new, improved iterations of the process were implemented.

The first pilot consisted of an 8-day cycle of continuous activity culminating in the repair of all gas leaks identified on day seven. Due to the sheer volume of work activities required in this model, the team stopped to review lessons learned and developed a revised model.

Figure 7–Super Crew initial process survey and repair coupled

The second iteration of the Super Crew operating model tested a de-coupled approach of first performing all survey and hazardous Grade 1[8] leak responses before subsequent execution of routine, non-hazardous leak repairs. In addition, improvements to auxiliary operations, such as welding, dump truck use and paving, were implemented to make crew-size lean and to maximise efficiencies. This model proved to be very effective and was well received by the team.

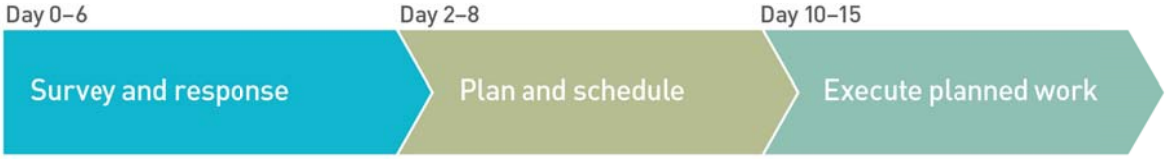

Figure 8–Super Crew decouple survey from repair process

The third pilot was designed to upscale the process in both size and complexity. Incremental changes to the de-coupled operating model were applied, such as centralised management of auxiliary operations, the utilisation of non-standard excavation techniques and a more robust back-office support system. This is the operating model PG&E used moving forward.

Figure 9–Current Super Crew process

[8] A Grade 1 gas leak, also referred to as a "hazardous leak," represents an existing or probable hazard to persons or property and requires immediate repair or continuous action until conditions are no longer hazardous.

Super Crew: Pilot Results

Following is the performance by work activity during the three phases of the pilot program compared to the traditional PG&E leak management model. Note the improvement of hours per unit from pilot one through pilot three.

	Pilot 1		Pilot 2		Pilot 3		Traditional Repair YTD	
Work description	Units	Hrs/Unit	Units	Hrs/Unit	Units	Hrs/Unit	Units	Hrs/Unit
Service replacement	38	46.50	95	20.92	43	16.65	919	35.05
Main repair	19	41.33	13	26.08	8	17.50	574	28.34
Above ground service repair	45	1.51	255	1.24	363	1.09	8,104	1.71
Below ground service repair	10	18.63	9	10.58	17	5.60	1,385	13.0

Figure 10–PG&E Super Crew pilot results

Key Take-Aways

The first Super Crew pilot was designed to test the process and no productivity gains were realised. However, pilots two and three showed an overall 40.1 percent fewer hours per repair unit. This productivity improvement represents 26,000 additional construction hours that can be applied to finding and fixing more leaks, thereby further reducing the overall system risk.

Super Crew: Critical Activities by Phase

PG&E learned through the pilots that specific activities must be performed in each critical phase to take advantage of the opportunity the new technology offers.

One-Time Planning Activities

1. **Optimise atmospheric conditions**[9]—Traditional leak survey methods and instruments are slower and find fewer gas leaks than the Picarro Surveyor, resulting in higher cost and a lower leak-find rate. If Picarro Surveyor is not used during optimal wind conditions, less FOV coverage is realised and higher incidence of foot survey (also known as "Gap"[10] survey) is required by traditional leak surveyors.
2. **Analyse leak-find rates to define the scope of work**—PG&E forecasts leak-find rates on gas facilities to develop daily work plans before arriving at the local division centre. This is a critical activity to ensure the availability of the right number of crews at the right time. For example, an expectation of 10 grade 1 leaks on a given day of survey requires enough crews in the area to respond immediately and concurrently.

[9] Pacific Gas & Electric Picarro Wind Study: A Review of Wind Climatology across the PG&E Service Area for Super Crew Picarro Leak Survey; Jan. 8, 2015 p.1

[10] Gap survey is defined as the geographical area where gas assets are not surveyed within the FOV of the Picarro Surveyor. These gas assets must be surveyed by leak surveyors on foot using traditional leak survey instruments.

Before Super Crew Arrives and Picarro Survey is initiated

1. **Engage municipalities early**—Advanced engagement with all municipal partners is critical to obtain expedited permitting and authorisations to enable timely completion of work. Early engagement promotes collaboration and improves relationships with city officials.
2. **Engage division personnel early**—Specific roles and responsibilities remain with each division when Super Crew arrives. Those personnel need to be engaged early because they are the extended Super Crew team; success is unlikely without them. They can explain important information unique to the division only those who work there know.
3. **Coordinate logistics centrally—**Moving a mobile workforce around the service territory requires advanced logistic planning and operations. Having a central role to address logistics, e.g. making lodging accommodations, is crucial to the team's success.
4. **Create a leak tracker—**A leak tracker that documents each leak from cradle to grave is important to identify and eliminate bottlenecks along the path towards completion. Data should include leak number and status, address and location, grade, etc. Leaks found before Super Crew arrives should be documented in the leak tracker to help coordinate work activities starting day one of Super Crew deployment.

During Survey

Survey the assets effectively and efficiently. Address Grade 1 emergency work so the entire body of non-emergency repair work can be analysed to make holistic decisions about pipe repair or replacement.

1. **Decouple leak survey from bundled repair**—To achieve the lowest unit cost possible, decouple the leak survey and grade 1 leak-response activities from the bundled repair portion of the process.
2. **Validate immediate-response gas leaks**—All possible immediate-response gas leaks are validated by a Leak Survey Supervisor prior to mobilising resources. This validation to PG&E standard operating procedures ensures crews are mobilised only when necessary. It also allows supervisors to coach employees around emergency response.
3. **Investigate leaks rather than just survey**—Traditional leak surveyors need to become leak investigators and need to be trained to follow a defined LISA investigation protocol to find all gas leaks. This was a paradigm shift for traditional leak surveyors who no longer walk all assets to determine where leaks are because the Surveyor now distinguishes between leak-free gas facilities and leak search areas.
4. **Implement a five-foot rule to cover all possible facility conditions**—Inspecting facilities for abnormal operating conditions (such as structures built over gas facilities, atmospheric conditions of pipe, etc.) and inspecting inside meter sets must be done by a traditional foot surveyor because the Picarro Surveyor is not currently optimised to

identify these conditions. This area comprises the last five feet of the service line up to and including the gas meter set assembly.

Preparation for Leak Repair or Pipe Replacement

1. **Pre-inspect all scheduled work locations**—This removes obstacles and prevents multiple visits during bundled repair. A single visit to a location before repairing/ replacing pipe produces superior customer experience and satisfaction.
2. **Review all planned work by engineering and estimate functions**—High-risk pipe must be identified and replaced, not repaired. PG&E applies decision-tree criteria to determine when and where pipe will be replaced. For example, any leaking pipe installed prior to 1985, regardless of pipe type, is replaced.
3. **Centralise the management of auxiliary operations**—Centralise management of auxiliary operations such as welding, paving, and the need for dump trucks or traffic control. Dependent upon the work type, the team realised significant benefits by leveraging these resources within multiple repair/replace locations, which led to greater efficiencies during bundled repair activities.
4. **Bundle work geographically**—All work including existing repairs must be analysed, bundled and routed to the appropriate execution team so operations are deployed once rather than multiple times. What follows is an example of repair work by crew.

Figure 11–Super Crew bundled work by crew

Summary of 2014 Super Crew Performance

PG&E conducted several pilots before defining a Super Crew leak management model that effectively uses Picarro's advanced leak detection solution to accelerate both leak survey and repairs. The redefined, streamlined leak management model has six process steps and 12 critical activities that, when performed correctly, significantly improve operating performance throughout the leak management work stream.

PG&E's Super Crew steady-state performance resulted in 44 percent lower survey cost and 30 percent lower repair and pipe replacement cost compared to the traditional leak management process.

The same body of work without applying the Super Crew process and Picarro technology would have cost an additional $4.6 million. Based on these significant accomplishments, PG&E formed a new organisation to launch Super Crew as its new standard operating model in 2015.

Conclusions

Integrating new technology into utility processes takes clear vision, support, sponsorship and investment from every level within the utility. A robust workforce engagement effort and strong leadership are critical success factors.

PG&E established the Super Crew process, a leak-management operating model, to integrate the Picarro advanced leak detection solution. This proactive, integrity management strategy has detected more leaks while improving efficiencies. By bundling and routing leak repair work, both operating costs and leak-completion cycle time are drastically reduced. As a result, PG&E is providing safer, more reliable gas service than ever before. With the drastic reduction in gas leaks and leak repair cycle time, PG&E has also reduced the environmental impact caused by methane emissions.

PG&E is continuing to improve this enhanced process by entering into a strategic partnership with Picarro to:

1. Further enhance the leak management cycle through greater automation of the end-to-end work stream
2. Provide more data to better inform integrity management processes to allocate resources to highest risk work and move from reactive to proactive practices to further minimise risk
3. Refine methane emission monitoring precision to reduce PG&E's impact to the environment

Super Crew performance and the Picarro solution are dependent on each other. The Surveyor needs a robust process to realise the overall potential operational benefits. The superior synergies from the combination of a redefined process and the Surveyor have revolutionised PG&E's leak management model.

Glossary of Terms

Term	Definition
Breadcrumb Trail	Electronic footprint of where a person, vehicle or device has travelled
Cavity Ring Down Spectroscopy (CRDS)	A highly-sensitive, laser-based, optical gas detection technology engineered by Picarro and used in the Picarro Surveyor to measure the concentration and stable isotopes of the methane molecule to a precision of less than one part-per-billion.
Distribution Main	For purposes of leak survey, a gas main operated at less than or equal to 60 pounds per square inch gauge (psig)
Field of View (FOV)	The coverage area of the Picarro Surveyor
Foot Survey	A search on foot for possible gas leakage in any area where PG&E facilities exist or where a gas leak is reported or suspected
Isotopic	An isotope can be many variations of the same chemical element. In this application the carbon in CH4 is analysed at the isotopic level looking at the carbon's C13:C12 ratio. This process can detect the difference between naturally occurring methane such as sewer gas vs. an actual pipeline source.
Leak	The unintentional escape of gas from containment
Leak Grade	A classification of a leak based on leak readings, public exposure and location
Leak Indication	A graphical indicator with associated values of the absolute peak concentration of the detected methane peak in parts-per-million (ppm)
Leak Indication Search Area (LISA)	The angular extension associated with each leak indication, which defines an area from which the methane plume is likely to have emanated as determined by wind variation and atmospheric conditions at the time of detection. The LISA sweeps out a cone-shaped area in which the potential leak is likely located.
Leak Repair	An action to restore a gas facility to sound condition by eliminating a gas leak
Leak Survey	A search for possible gas leakage in any area where PG&E facilities exist or where a gas leak is reported or suspected
Leak Surveyor	Qualified person that performs the follow-up traditional foot survey
P-Cubed™	Picarro's proprietary cloud-based software, data processing, storage and retrieval service that allows Picarro customers to access the data through the internet

Term	Definition
Picarro Surveyor™	Picarro's integrated solution for mobile leak detection comprised of hardware, embedded software and P-Cubed, Picarro's proprietary cloud-based, hosted software solution.
Picarro, Inc.	A technology company based in Santa Clara, Cal., USA
Service	A pipeline that serves as the common source of supply to an individual customer, to two adjacent or adjoining residential or small commercial customers or to multiple residential or small commercial customers served through a meter header or manifold
Traditional Survey	Leak survey conducted on foot using commercially available leak detection instruments that measure methane in parts per million (ppm)