1. INTRODUCTION

The conventional method used to detect gas leaks involves positioning a detector in close proximity to the area to be checked. However, this can be a difficult operation and often entails lengthy inspection periods in elevated or narrow locations. To overcome these difficulties and thereby improve the operational efficiency and safety levels of gas distribution utilities, a growing requirement has emerged for remote sensing equipment.

Conventional gas detectors such as catalytic combustion detectors, flame ionization detectors (FID) and semiconductor-type detectors are not capable of remote sensing. Indeed, the only way to provide such remote sensing is by optical methods, and to obtain the most sensitive detection a laser, with monochromatic and rectilinear light, is required as the light source.

Laser spectroscopy has many advantages for gas sensing compared to the conventional gas detectors. In addition to the operational benefits of remote sensing, laser spectroscopy provides high sensitivity, fast response time and good molecular selectivity. Particularly, a tunable diode laser (TDL), which is an exceptionally compact and inexpensive laser device originally developed for telecommunications, can lead to a cost-effective remote gas detector. For these reasons, a number of scientists and engineers have studied the potential use of TDL to detect gas leaks [1-7].

Tokyo Gas Co., Ltd. and Anritsu Corporation have jointly developed a portable remote methane detector (PRMD) using a TDL [1, 5]. To the best of the authors' knowledge, this detector is the world's first portable device that enables detection of gas leaks from a distance. Figure 1 shows a PRMD outfit. Tokyo Gas Engineering Co., Ltd. has already introduced the PRMD into the Japanese market, and according to the operational results of Tokyo Gas, the PRMD was found to improve the operational efficiency of the emergency services and quality of surveillance activities. As of 1 January 1st, 2003, 39 PRMD units are in use at Tokyo Gas, along with other gas utilities and businesses.

Figure 1  An outfit of the Portable Remote Methane Detector (PRMD). — The detector consists of an electronic unit (left) and an optical unit (right). A laser beam is transmitted from a collimator on the central axis of the optical unit.
2. PRINCIPLE OF REMOTE DETECTION

Figure 2 shows a schematic diagram of the remote detection method. The PRMD detects the infrared (IR) absorption of methane, the principal component of natural gas, using a TDL device. The device transmits an IR laser beam with the wavelength set at one of the absorption wavelengths of methane. The optical unit then receives a fraction of the backscatter reflected from the target. The detector thereby measures the path-integrated concentration of methane between the detector and the target, which is termed the methane column density, rather than the concentration at a local point. The column density has the dimensions of the product of the concentration (ppm) and length (m) and is described in units of ppm-m. For example, if the laser light propagates in a methane cloud with a concentration of 100 ppm and a thickness of 1 meter, the detector output would be 100 ppm-m. Similarly, in the case of a methane cloud with a concentration of 10000 ppm and a thickness of 0.01 meters, the detector output would also be 100 ppm-m.

The operator can easily check a gas leak at a distance by hand-scanning the laser beam. During operation a red laser pointer shows the point being checked, and the time history of the methane column density is then shown on a liquid-crystal display (LCD) on the electronic unit, which issues an alarm if the methane column density exceeds a preset threshold (typically 100 ppm-m).

3. TECHNICAL BACKGROUND

3.1 Absorption Line Selection

To achieve high detection sensitivity in absorption spectroscopy, it is desirable to use as strong an absorption line as possible. Methane has two strong absorption bands, or groups of lines, centered at 3.3 \(\mu\text{m}\) (\(\nu_3\) band) and 7.6 \(\mu\text{m}\) (\(\nu_4\) band). However, it is difficult to make a TDL with a wavelength of over 2.2 \(\mu\text{m}\) operating at room temperature. The strongest absorption band
of methane below 2.2 μm is located at 1.64 to 1.70 μm (2ν₃ band). Detection of methane using a TDL with a wavelength of an absorption line in the 2ν₃ band has previously been reported [1, 8].

To design the PRMD, the authors selected the R(3) line (λ = 1.6537 μm) in the 2ν₃ band and developed a special TDL (InGaAsP distributed-feedback laser) with a wavelength for this line. This line is suitable for gas leak detection since it is one of the strongest absorption lines in the 2ν₃ band and is free of interference from atmospheric gases.

### 3.2 Principle of Highly Sensitive Detection

The PRMD must be able to measure very little power since it collects limited diffused reflections from the target. In a typical case, for example, the PRMD will receive as little as 100 nW light power from an initial laser of 10 mW. In addition, the detector must detect very weak absorptions. For example, 100 ppm-m methane corresponds to an absorption factor of less than 10⁻⁴. These are significant technical challenges of remote methane detection using TDL and to overcome them, the PRMD employs the second harmonic detection [9] of wavelength modulation spectroscopy (WMS).

In WMS the laser wavelength is modulated and the photodetector output is processed by phase sensitive detection with reference to the fundamental and harmonics of modulation. As shown in Figure 3, the laser wavelength of the PRMD is modulated by a sinusoidal injection current at a frequency of f = 10 kHz and the modulation center is locked at the absorption center of the 2ν₃ band R(3) line of methane (λ = 1.6537 μm). As a result, the second harmonic (2f) signal is proportional to the methane column density and the collection efficiency, while the fundamental (f) signal, due to wavelength modulation, should vanish. However, the sinusoidal injection current modulates the laser power as well as the laser wavelength, and therefore the f signal will be retained in proportion to the collection efficiency. Dividing the 2f signal by the f signal, the collection efficiency that changes as a function of target reflectance, distance and incident angle will be cancelled [1, 8, 10]. The PRMD therefore calculates the methane column density directly from the ratio between the 2f and f signals.

![Figure 3](image_url) **Figure 3 The Basic Concept of Second Harmonic Detection.** — The photodetector output has the second harmonic signal of the wavelength modulation in proportion to the absorption depth. The fundamental signal due to the power modulation is not shown in the figure.
4. PERFORMANCE

4.1 Features and Advantages of the Detector

The PRMD has the following advantages over conventional gas detectors:

• Remote sensing
• Good molecular selectivity
• Fast response time
• Maintenance free

Remote sensing is effective not only in locations that are elevated or narrow but also in other instances. This is due to the fact that the PRMD detects methane by line of sight and thereby enables the operator to, for example, survey indoor gas retention whilst standing outdoors by simply pointing the detector through a glass window. Considering the molecular selectivity, the PRMD has perfect selectivity to methane and will not respond to any other gases.

Since an IR absorption phenomenon is detected almost instantaneously, the PRMD is much faster than conventional gas detectors that utilizes some chemical reactions of the sensor element and specific gases. In addition, the PRMD is maintenance free, with no sensor elements requiring replacement at regular intervals.

4.2 Specifications

Table 1 lists of the specification for the current version of PRMD, which has a laser output power of 5 to 10 mW. This is established as Class 1, or eye-safe, by the international classification of the International Electrotechnical Commission (IEC), but the entire detector is classified as a Class 2 laser product due to the red laser pointer. In the United States, however, the PRMD is classified as a Class IIIb laser product by the Food and Drug Administration (FDA).

The collimator has a full angle divergence of 1.6 mrad. This corresponds to a detection area of 8 mm diameter at 5 m distance. A Fresnel lens was selected as the collection lens since it is lightweight and inexpensive. In the photodetector, an InGaAs PIN photodiode is packed with a pre-amplifier. The gain factor of the pre-amplifier can be switched three ways (“x 0.1”, “x 1” and “x 10”) depending on the level of received light power. In most cases, the gain setting of “x 1” (standard setting) is optimized the detection of gas leaks.

Regarding the response time, the PRMD is much faster than conventional gas detectors. As the time constant for phase sensitive detection of WMS (equivalent to the response time of the detector) gets shorter, the detector responds faster but in doing so noise level increases. To balance this, the time constant is set at 0.1 seconds.

Power consumption during operation is on average 10 W and is supplied by a special nickel-metal hydride battery which has battery life of more than 60 minutes at 25 ºC. The electronic unit weighs 2.6 kg (including the battery) and has a width of 195 mm, depth of 260 mm, and height of 88 mm. The soft case of the electronic unit weighs 0.6 kg. The optical unit weighs 0.9 kg and has a width of 114 mm, length of 244 mm and height of 206 mm as its maximum. The interconnecting tube weighs 0.3 kg and is 150 mm long. In total, the PRMD weighs 4.4 kg.

Regarding use in hazardous areas, the current version of PRMD has an operational limitation in that the detector is not explosion-proof. The operator must confirm in advance that the operating environment is not explosive.

The lower detection limit (LDL) increases with decreasing the received light power [1] and therefore, to avoid false alarms of gas leaks, the PRMD calculates the methane column density but displays "no measurement" alert if the received light power is smaller than preset thresholds. These thresholds are set to 200 nW, 20 nW and 2 nW with the gains settings of “x 0.1”, “x 1” and “x 10” respectively. The LDL is estimated experimentally to be below 1ppm-m, 5 ppm-m and 50 ppm-m with the gains settings of "x 0.1", "x 1" and "x 10" respectively [8]. With regards to the upper detection limit (UDL), the PRMD guarantees detection of methane up to an UDL of 6.0 x 10^3 ppm-m [8]. When the methane column density exceeds the UDL, the detector warns the operator by displaying the same "no measurement" alert.

The detection range, or maximum target distance, depends on the target reflectance. Using typical targets and setting the pre-amplifier gain to “x 1”, the detection range is up to 10 meters with a LDL of less than 5 ppm-m. In these instances, the minimum detectable flow rate is less than 10 ml-min^-1 for a gas leak from an indoor exposed pipe. The detection range can be extended up to 30 meters by a gain setting of “x 10” which will however increase the LDL by tenfold. If a retro reflector is used, the detection range can be extended much further.
In a laboratory of Tokyo Gas, the sensitivity of the PRMD to methane was measured and the performance of the PRMD as a practical gas leak detector was demonstrated. In the experiments a concrete block was selected as the target, its distance from the detector set to 5 meters and the incident angle set at 60 deg. In this instance, the received light power was 100 nW.

Firstly, the sensitivity of the PRMD to standard gases was measured. In this experiment, an absorption cell with a length of 0.1 meters was set in front of the concrete target and standard gases of 0, 98, 298 and 988 ppm methane, balanced by standard air, were introduced into the cell sequentially. Figure 4 shows the ratios between the $2f$ and $f$ signals for 0, 9.8, 29.8 and 98.8 ppm-m methane, respectively. With the LDL defined as the methane column density at which the signal-to-noise ratio (SNR) equals unity, the LDL is estimated to be 1.3 ppm-m.

Thereafter, the performance of the PRMD as a practical gas leak detector was demonstrated. In this experiment, a leak point was prepared using city gas (containing about 80 vol % methane) in front of the concrete target and a flow rate of 10 ml-min$^{-1}$. Figure 5 shows the time history of the detector output as the operator checked the leak point by hand-scanning the laser beam. As shown in Figure 5, signals over 100 ppm-m were measured when the laser light passed through the leak point.

### Table 1: Specification of the Current Version of PRMD.

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection principle</td>
<td>Second harmonic detection of WMS for IR absorption using target backscatter return</td>
</tr>
<tr>
<td>Detection object</td>
<td>Methane</td>
</tr>
<tr>
<td>Light source</td>
<td>InGaAsP distributed- feedback laser (Wavelength: 1.6537 µm, Output: 5 to 10 mW)</td>
</tr>
<tr>
<td>Laser Safety</td>
<td>Class 2 laser product (by IEC), Class IIIb laser product (by FDA)</td>
</tr>
<tr>
<td>Beam divergence</td>
<td>1.6 mrad</td>
</tr>
<tr>
<td></td>
<td>(Corresponds to an 8 mm diameter detection area at 5 m distance)</td>
</tr>
<tr>
<td>Collection lens</td>
<td>Fresnel lens (diameter: 84 mm)</td>
</tr>
<tr>
<td>Photodetector</td>
<td>InGaAs PIN photodiode (packaged with a pre-amplifier)</td>
</tr>
<tr>
<td>Response time</td>
<td>0.1 seconds</td>
</tr>
<tr>
<td>Weight</td>
<td>4.4 kg in total</td>
</tr>
<tr>
<td></td>
<td>Electronic Unit: 2.6 kg (including a battery), Soft case: 0.6 kg</td>
</tr>
<tr>
<td></td>
<td>Optical Unit: 0.9 kg, Interconnecting tube: 0.3 kg</td>
</tr>
<tr>
<td>Dimensions</td>
<td>Electronic Unit: W 195 mm x D 260 mm x H 88 mm</td>
</tr>
<tr>
<td></td>
<td>Optical Unit: W 114 mm x L 244 mm x H 206 mm</td>
</tr>
<tr>
<td>Power consumption</td>
<td>10 W</td>
</tr>
<tr>
<td>Battery</td>
<td>Nickel-metal hydrate battery (Battery life: &gt; 60 min @25°C)</td>
</tr>
<tr>
<td>Explosion-Proof</td>
<td>None</td>
</tr>
<tr>
<td>Lower detection limit</td>
<td>&lt; 5 ppm-m (&lt;50 ppm-m$^*$)</td>
</tr>
<tr>
<td>Minimum detectable</td>
<td>&lt;10 ml-min$^{-1}$ (in case of indoor exposed pipes)</td>
</tr>
<tr>
<td>Upper detection limit</td>
<td>&gt; 6000 ppm-m</td>
</tr>
<tr>
<td>Accuracy</td>
<td>within 10 % (100-1000 ppm-m)</td>
</tr>
<tr>
<td>Detection range</td>
<td>up to 10 meters (30 meters$^*$)</td>
</tr>
</tbody>
</table>

* when setting the gain of the pre-amplifier to “x 10”
passed through the leak point. These results show that the PRMD can detect a 10 ml-min$^{-1}$ gas leak from an indoor exposed pipe by setting the alarm threshold at 100 ppm-m.

5. **OPERATION**

5.1 **Examples**

Figures 6(a) to (d) show examples where the PRMD has been clearly effective. In use, the operation of the PRMD is classified broadly into two categories. The first category of use regards the emergency services, where personnel are aware of gas leaks and need to pinpoint them. The second category relates to surveillance activities, where personnel need to confirm that there is no gas leak or retention.

In the case of the emergency services, the PRMD is used for both exposed and concealed pipes. For exact pinpointing of leaks, exposed pipes are necessary. When the pipes are hidden underneath floor-boards or above the ceiling-boards, the operator only has to pull up one piece of the board and point the laser beam at the pipe to check for the leak. If the pipes are totally concealed, however, the exact pinpointing is impossible, but the quantitative information on the LCD helps the operators trace the leaking point.

In the case of surveillance activities, the PRMD is used mainly for exposed pipes. Sometimes it is used to confirm there is no gas retention in high or narrow locations that are difficult to access. Although one might think a vehicle-mounted PRMD could be used for driving surveys of buried pipes, the current version of PRMD is not suitable for this operation. At the height of the laser beam, for example 10 cm above ground, the gas is extremely diluted and thus the sensitivity of the detector is not sufficient.

As already mentioned, the PRMD can detect a 10 ml-min$^{-1}$ gas leak from an indoor exposed pipe. In the case of outdoor use, the minimum detectable flow rate is case dependant, for example under windy circumstances it is much greater than 10 ml-min$^{-1}$.

5.2 **Operational Results of Tokyo Gas**

At Tokyo Gas, the PRMDs are used mainly for emergency services. To evaluate the benefits of the PRMD, 148 emergency service operations were recorded and classified into three categories.

Figure 7 shows the operational results. The PRMD was definitely effective in 15 % of the emergency service operations (category 1). In this category, the PRMD reduced inspection times
Figures 6  Examples in which the PRMD is clearly effective. — Leak in Elevated Place (a), Leak in Narrow Place (b), Retention in Closed Room with a Glass Window (c) and Retention in Elevated Place (d).
and the labor costs dramatically. In addition, it also sometimes reduced the construction costs. For example, when personnel pinpointed the leak to be in pipes in elevated places, no scaffolding was required to check the pipes and only a bare minimum of scaffolding was required to repair the leak. Without the PRMD, it would have taken much longer to pinpoint a leak in category 1 than in category 2. Therefore, the detector reduced the total inspection time of all emergency services by much more than 15%.

Although the PRMD was unable to pinpoint leaks in 23% of the emergency service operations (category 3), most of the leaks in this category were pinpointed by careful inspection with conventional detectors or leakage detecting liquid. Even if the leak could not be pinpointed, the pipes were repaired by lining methods or replaced with new ones.

Regarding the use for surveillance activities at Tokyo Gas, the PRMD is used as supplementary detectors.

According to the operational results of Tokyo Gas, the PRMD was found to improve the operational efficiency of the emergency services and the quality of surveillance activities.

6. CONCLUSION

Tokyo Gas Co., Ltd. and Anritsu Corporation have jointly developed a portable remote methane detector (PRMD) using a TDL. The detection principle is based on the second harmonic detection of WMS for IR absorption using target backscatter return. The detector has advantages over conventional gas detectors such as remote sensing, good molecular selectivity, fast response time and maintenance free. When used with typical targets at distances up to 10 meters, the PRMD has a lower detection limit of less than 5 ppm-m in methane column density and can pinpoint a detect a 10 ml-min⁻¹ gas leak from an indoor exposed pipe. The target distances can be extended up to 30 meters, if the operator accepts a lower detection limit of 50 ppm-m.

In Japan, Tokyo Gas Engineering Co., Ltd has already introduced the PRMD into the market and sales figures are rapidly growing. As of January 1st, 2003, 39 units of PRMD are in use at Tokyo Gas, some other gas utilities and businesses. According to the operational results of Tokyo Gas, the PRMD has been shown to significantly improve the operational efficiency of emergency services and the quality of surveillance activities.

Figure 7: Operational Results of Tokyo Gas in Case of Emergency Service.
REFERENCES