In recent decades, China has made a roaring success of its economy and has quickly emerged as the world’s second-largest economy (based on GDP). However, due to the sharp increase in land and labor costs associated with a fast-growing economy, thousands of factories have moved from the traditional industrial areas of the coastal cities to inland provinces in Central and West China, such as Jiangxi Province, Anhui Province, Hubei Province, and Sichuan Province; some have even moved out of China altogether to parts of Southeast Asia.
Along with significant economic benefits to the local region, the new and relocated factories have brought a series of environmental problems, including air quality deterioration. In 2013, the number of national average haze days was 4.7, 2.3 more than the long-term average (2.4 days), and the highest level since 1961. In northern Jiangsu and central Henan, there were up to 15 more haze days than the long-term average. Furthermore, in 2014, a wide range of long-time haze appeared for the first time in Central China. Composite regional air pollution has now become the prominent environmental problem in China.

**Fugitive Emissions**

Volatile organic compounds (VOCs) are defined as organic compounds that with high volatility and can easily participate in photochemical reactions. VOCs also play a prominent role in the formation of ozone and secondary organic aerosol (SOA), which are considered to have strong correlation with the composite-regional air pollution. Recent studies have shown that chemical industries are a major source of VOCs in urban areas, such as Guangzhou, Houston, and Hong Kong. Zheng et al. found that solvent use-related industrial sources accounted for more than 80% of the total VOC emission in the Pearl River Delta region in 2011. Chen et al. suggested that a chemical industrial park was an odorous source that affected the population near the industrial district.

Fugitive emissions can generally be described as unintentional and uncontrolled emissions from equipment leaks and may arise due to the normal wear and tear, improper or incomplete assembly.

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*Figures 1. Sampling at the chemical industrial park.*

(a) Sampling inside manufacturing workshop and warehouse of raw materials (fugitive emission).

(b) Sampling at stack emission and ambient air.

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of components, corrosion, manufacturing defects, damage, fouling, and environmental effects. Recent studies have shown that a significant proportion of VOC emissions are fugitive emissions. In 2010, the United Nations Framework Convention on Climate Change (UNFCCC) reported that fugitive emissions contributed an estimated 4%–18% of total greenhouse gases (GHGs) and VOCs in the European Union, United States, and Canada. While according to the U.S. Environmental Protection Agency’s (EPA) Method 21, approximately 20% of potential leaks are not regularly checked due to a lack of resources, difficulty of access, and/or safety concerns.

It is our belief that investigating VOC emission characteristics in a chemical industrial park in the Jiangxi Province is critical for understanding the formation of composite-regional air pollution and devising effective control policies. In our study, the fugitive emissions ratios are even as higher as approximately 34%–48% of total VOC concentrations. Leaking valves are considered to account for approximately 50%–60% of fugitive emissions. Many countries are now focusing on how to control fugitive emissions, through the development of standards for the installation, operation, maintenance, and inspection of the valves.

The chemical industrial park is located east of a major city in the middle-east of Jiangxi Province with a total planning area of 10 km². The park was built in 2001 and was regarded as one of the largest in central southern China. The leading industries include fine chemistry and pharmaceutical chemistry. The location has a humid subtropical climate with four distinct seasons. Winters are short and fairly mild (i.e., the average low in January is 2°/35.6°F), but occasional frosts and snow is not unheard of. Summers are long and humid, with among the highest temperatures in China (i.e., the average temperature in July is 34°/93°F).

VOC Sampling

As shown in Figure 1, stack emission and fugitive emission samples were collected from three selected plants in the chemical industrial park in winter (January 1–8, 2014) and summer (July 16–20, 2014). Ambient air sampling measurements were carried out at the core of each selected plant. Manufacturing workshops, warehouses of raw materials and goods, and stack emissions were also selected for the sampling sites. VOC sampling was collected by using a leak-free, two-liter, stainless steel canister (UCI, USA) equipped with a restricted sampler operating at 38 mL/min (Entech Instrument Inc., California, USA). Other parameters (e.g., ozone concentration and emissions of sulfur dioxide [SO₂], total suspended particles [TSP], nitrogen dioxide [NO₂], ammonia [NH₃], hydrogen chloride [HCl], and chlorine [Cl₂]) were also monitored at the same time of each sampling using portable equipment.

VOC Emission Characteristics

VOC concentrations were measured by analyzing the average results of samples from different industrial sectors or processes, such as manufacturing workshops, stack emissions, and ambient
levels. These sectors were divided into “fugitive emission (leakages),” “stack emissions,” and “ambient levels.” A total of 33 VOC species in winter samplers and 41 VOC species in summer samplers were detected in this study.

Figure 2 shows that the total VOC concentrations varied widely between different industrial sectors and processes. Among the three types of sectors, stack emissions showed the highest total VOC concentrations (43%) in winter. The total mean concentrations were in descending order from stack emissions to fugitive emissions to ambient levels, and the ratio of the three was 43%: 34%: 23% (Figure 2a). While in summer, fugitive emissions increased sharply and contributed more than 48% of the total VOC mean concentration, compared to 35% of stack emissions (Figure 2b).

The results suggest that fugitive emissions are one of the most important sources of VOC emissions in the chemical industrial park during summer, owing to the high temperatures that can accelerate the speed of VOCs leaking from valves, tank lids, and pumps. Furthermore, indoor air quality inside the manufacturing workshops and warehouses were important microenvironments for exposure to VOCs, especially in summer.

In China, the study of leak detection and repair (LDAR) is still in its infancy. To support improvements in this area, our investigation reviewed and compared LDAR programs from around the world. Currently, the most widely recognized standard for LDAR is EPA’s Method 21. Other standards related to LDAR are: ISA-93.00.01 Standard Method, International Standard ISO 15848 Industrial Valves, and Shell MESC SPE 77/312 Industrial Valves. Table 1 summarizes selected examples of applying the LDAR for monitoring the fugitive emissions of VOCs.

As shown in Table 1, LDAR programs based on EPA Method 21 are effective and have been extensively employed for the control of VOC fugitive emissions. The control effectiveness in
these LDAR programs ranges from 72.2% to 95%. Unfortunately, among the 110 plants in the chemical industrial park, only one plant has implemented an LDAR program (only 20% of the valves were involved in the Hongbo' LDAR program). In process plants, fugitive emissions are the main sources of VOC exposure to workers.\textsuperscript{18} Our study found that the total concentration of VOC fugitive emissions might be even higher than for stack emissions for some VOC species like acetone and ethane. Long-time exposure may threaten the health of plant workers. As a result, VOC fugitive emission control strategies are in urgent need.

<table>
<thead>
<tr>
<th>Location</th>
<th>Equipment Type and service</th>
<th>Initial Leak Rate (kg/hr)</th>
<th>Final Leak Rate (kg/hr)</th>
<th>Control Effectiveness (%)</th>
<th>Standards (LDAR program)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>RasGas Company, Qatar</td>
<td>Valves-gas</td>
<td>4.46</td>
<td>0.741</td>
<td>83.4</td>
<td>EPA Method 21 (RasGas' LDAR program)</td>
<td>9</td>
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<tr>
<td>RasGas Company, Qatar</td>
<td>Valves-Light Liquid</td>
<td>1.36</td>
<td>0.318</td>
<td>76.6</td>
<td>EPA Method 21 (RasGas' LDAR program)</td>
<td>9</td>
</tr>
<tr>
<td>Benzene plant, Malaysia</td>
<td>Valves</td>
<td>2.99\textsuperscript{a}</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>18</td>
</tr>
<tr>
<td>Benzene plant, Malaysia</td>
<td>Valves and Plumps</td>
<td>3.75\textsuperscript{a}</td>
<td>0.50\textsuperscript{a}</td>
<td>86.7</td>
<td>Piping and instrumentation diagram (PID) program</td>
<td>18</td>
</tr>
<tr>
<td>PETROL plant, USA</td>
<td>Valves, pumps and fl nges</td>
<td>89.6</td>
<td>4.45</td>
<td>95.0</td>
<td>EPA Method 21 (Smart LDAR program)</td>
<td>19</td>
</tr>
<tr>
<td>Cracker plant, Taiwan</td>
<td>Manufacturing process</td>
<td>129.3\textsuperscript{b}</td>
<td>25.6\textsuperscript{b}</td>
<td>80.2</td>
<td>EPA Method 21</td>
<td>20</td>
</tr>
<tr>
<td>SINOPEC, China</td>
<td>Valves</td>
<td>62.8</td>
<td>8.98</td>
<td>85.7</td>
<td>EPA Method 21 (SINOPEC' LDAR program)</td>
<td>21</td>
</tr>
<tr>
<td>SINOPEC, China</td>
<td>Plumps and Tanks</td>
<td>15.7</td>
<td>-</td>
<td>-</td>
<td>EPA Method 21 (SINOPEC' LDAR program)</td>
<td>21</td>
</tr>
<tr>
<td>Hongbo Chemical industrial plant, China</td>
<td>Valves</td>
<td>6.81</td>
<td>1.89</td>
<td>72.2</td>
<td>EPA Method 21 (Hongbo' LDAR program)</td>
<td>In this study</td>
</tr>
<tr>
<td>Other plants in the chemical industrial park</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>In this study</td>
</tr>
</tbody>
</table>

Table 1. Control Effectiveness of Implementing the LDAR Program for Monitoring VOC Fugitive Emissions.

Notes: \textsuperscript{a} mg/s was used in the original reference, and was converted to kg/hr in this study. \textsuperscript{b} ton/yr was used in the original reference, and was converted to kg/hr in this study (365 days/ year). N = Not LDAR program currently.

**LDAR Strategies for VOC Emission Control**

It is estimated that the LDAR costs for a typical refinery (with more than 20,000 connectors, valves, and pumps) in the United States may exceed one million dollars.\textsuperscript{19-22} Labor costs accounted for the vast majority of the total cost. The following list includes some LDAR strategies for improving the quality of program and reducing labor costs that emerged during our investigation:

- Using online technology for VOC data collection, storage, transmission, and management;
• Using the portable analytical instrument, if possible, using the infrared (IR) camera technology to detect gas leaks and measures the temperature (although the IR camera might be expensive, the detected efficiency would greatly improve the LDAR program, and thus, can save cost in the long run);
• Auditing LDAR program standards and staff to ensure the standardization of the LDAR program and prevent misoperation;
• Establishing an LDAR tracking plan to ensure complete LDAR program implementation;
• If the LDAR program performs well, try lowering the leak definition concentration to improve the quality of LDAR program and enhance the VOC control effectiveness; and
• Pay more attention to the high-leak valves and equipment (e.g., for valve seals, better containment would be achieved by using new sealing technologies and materials and by replacing the packing regularly).

Summary
A successful chemical industry is necessary for developing the economy. However, it is now widely recognized that the industry must decrease its environmental impacts to allow for sustainable development. A major contributing factor will be through controlling emissions. A combination of public pressure, environmental legislation, and the enterprises’ social responsibility will drive the expansion of the application of LDAR programs at more facilities. LDAR (or Smart LDAR) will play a vital role in the environmental performance of industrial plants. However, in China, industrial complexes still have a long way to go to implement their own LDAR programs. Apart from the increasing of awareness of environment and health issues, the facilities must be conscious of lowering VOC emissions and adopting LDAR programs and realize that effective LDAR programs can minimize the loss of valuable feed stocks and enhance overall productivity.

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16. DIS/SIS 15848 Industrial valves-fugitive emissions-measurement test and qualification procedures.
17. Shell MESC SPE 77/132 Industrial valves. Fugitive emission measurement, classification system, qualification procedure, and prototype and production tests of valves.

ACKNOWLEDGMENT:
This work was financially supported by the National Natural Science Foundation of China (Grants 41003057, 21467018 and 41203076), Natural Science Foundation of Jiangxi Province of China (20122BAB213017 and 20142BBG70005) and Foundation of Jiangxi Educational Committee (GJJ14511).