Cause Analysis of the Large-Scale LPG Explosion Accident Based on Key Investigation Technology: A Case Study

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ABSTRACT: Blending dimethyl ether (DME) into liquefied petroleum gas (LPG) has become a common phenomenon. On December 3, 2019, an LPG/DME explosion occurred in Beijing, resulting in 4 deaths and 10 injuries. To deeply investigate the cause and explosion process of the explosion accident, the accident investigation method combining on-site inspection, material evidence analysis, experimental verification, and logical reasoning was used. In addition, the location of the ignition point, the explosive substances, the cause of the gas leakage, the process and the distribution characteristics of the gas leakage, and the ignition process were successively reasoned and analyzed in detail. The results show that the LPG/DME-blended gas can effectively corrode silicone flange gaskets, forming laminar fractures and radial cracks on the gasket. As a result, the tensile strength of the gasket decreased. Under the action of the gas pressure inside the pipeline, the gasket was torn and a leakage hole was formed. The leaked combustible gas formed at least 305 m^3 of the explosive gas mixture inside and outside the refrigerated storage. The investigation and research results have important scientific guiding significance for revealing the cause and preventing similar accidents.
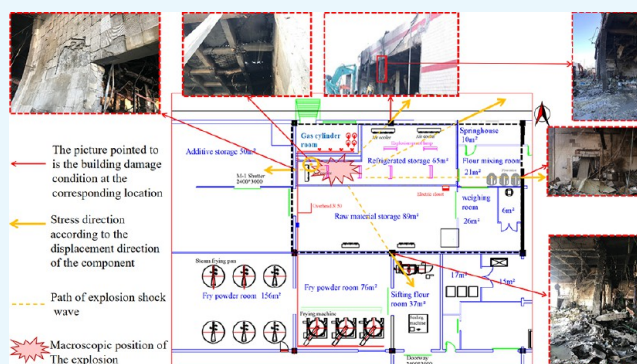
1. INTRODUCTION

China is a country rich in coal, poor in oil, and slight gas. Coal and oil account for over 70% of China's energy consumption.[1] Liquefied petroleum gas (LPG), as a companion of petroleum, is widely used in all walks of life in China because of its advantages of cleanness, safety, high calorific value, easy storage, and transportation.[2] With the increasing demand for LPG year by year in China, it has become a practice to mix LPG with substances of the same physical and chemical properties as LPG, of low price, and without reducing the fuel combustion calorific value and environmental safety.[3,4] Dimethyl ether (DME) has been widely used as the preferred blended fuel of LPG because of its low noise, low emission, smokeless combustion, high cetane number, and low price.[5–7]

Blending DME into LPG has become a common phenomenon in the LPG Industry in China, South Korea, Japan, India, and other countries.[8–13] In China, LPG/DME (<30%) blended gas has been widely used in home cooking and industrial combustion, so China has become the most potential market of DME alternative fuel in the world.[14] However, the addition of DME changed the reaction path and explosion mechanism of the original LPG fuel, resulting in a series of changes in the safety properties of the LPG fuel.[15,16] Until now, due to the lack of cognition and prevention research on the explosion mechanism of LPG and LPG/DME-blended gas, the explosion accidents of such substances occur

frequently. However, through mature technical methods and modern industrial analysis, researchers have carried out a series of research on the explosion characteristics and mechanism of gases and other substances, including LPG, and achieved fruitful results.[17–20] Table 1 lists the typical LPG and LPG/DME-blended gas explosion accidents in China since 2011.

In the gas explosion accident, the indoor explosion accident is particularly prominent.[21] According to statistics, in 2016, there were 909 gas explosion accidents in China, resulting in 127 deaths and 1096 injuries. Among them, 517 explosion accidents occurred in indoor places, accounting for 75%. In 2017, there were 702 gas explosion accidents, causing more than 1100 injuries and 126 deaths, including 465 indoor accidents, accounting for 66%.[22] Indoor gas explosion has become the main form of explosion that causes casualties and damage to buildings. The same problem also exists outside of China, and typical examples are (1) the gas explosion in London, U.K., in 1968 caused the collapse of Ronan Point
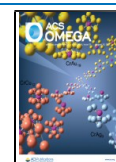
Table 1. Typical LPG and LPG/DME-Blended Gas Explosion Accidents in China Since 2011

no.	occurrence time	explosive substance	occurrence locality	casualties	direct economic losses (million dollars)
1	November 14, 2011	LPG	Xi'an, Shaanxi Province, China	10 deaths and 36 injuries	1.39
2	November 23, 2012	LPG	Jinzhong, Shanxi Province, China	14 deaths and 47 injuries	2.26
3	June 11, 2013	LPG	Suzhou, Jiangsu Province, China	12 deaths and 8 injuries	1.96
4	October 10, 2015	LPG	Wuhu, Anhui Province, China	17 deaths	2.16
5	June 5, 2017	LPG	Linyi, Shandong Province, China	10 deaths and 9 injuries	6.32
6	July 19, 2019	LPG/DME	Changping District, Beijing, China	3 injuries	unknown
7	December 3, 2019	LPG/DME	Shunyi District, Beijing, China	4 deaths and 10 injuries	2.02
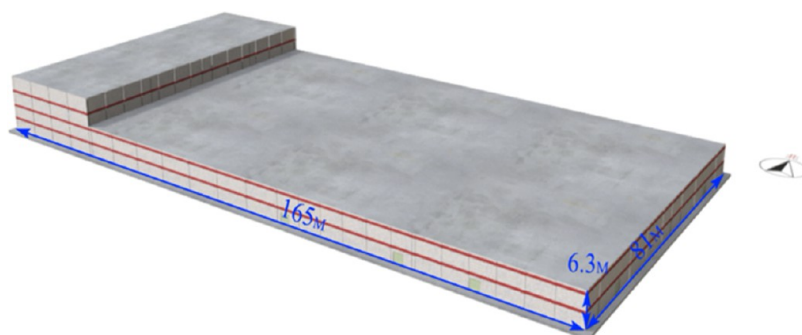
Figure 1. Overview of the production workshop where the explosion occurred.
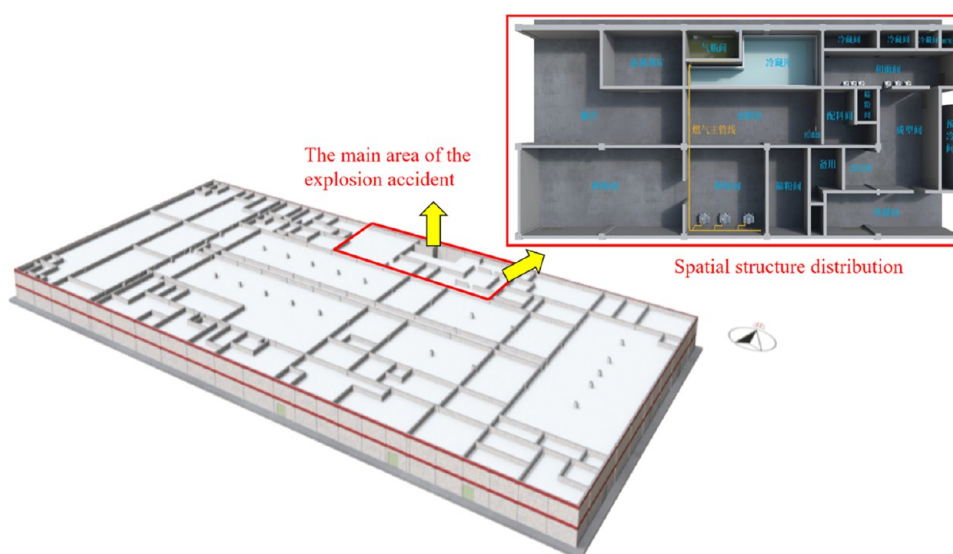
Figure 2. Relative location and the three-dimensional spatial structure distribution of the main explosion accident area.

apartment;[23] (2) the gas explosion in Izhevsk, Russia, in 2017 caused the collapse of a residential building;[24] and (3) the gas explosion in a unit house in Magnitogorsk, Russia, in 2019 caused the overall collapse of the whole unit building.[25] As the main place of human production and life, the prevention and control of explosion risk of indoor space is in urgent need of widespread attention.

At around 2:43 a.m. on December 3, 2019, an explosion occurred in the first-stage production workshop of Kyo-Nichi Todai Foods Co., Ltd. in Niulanshan Town, Shunyi District, Beijing, resulting in 4 deaths and 10 injuries, serious workshop damage, and direct economic losses of 2.02 million dollars. The production workshop where the explosion occurred is a brick and concrete structure building with one floor above ground and part of two floors above ground. It is 165 m long from east to west, 81 m wide from north to south, and 6.3 m high, as shown in Figure 1. Figure 2 shows the relative location

and the three-dimensional spatial structure distribution of the main explosion accident area.

Explosion accidents are valuable learning cases for people to recognize large-scale space gas explosions in essence, and the investigation and analysis of explosion accidents have become an important means for people to understand the risk characteristics of gas explosion accidents and put forward effective prevention and control measures. The collection and analysis of explosion traces, material evidence, and relevant information in the site and surrounding environment are the main means for investigation and analysis of explosion accidents, and also the basic factors for judging the nature, causes, and process of explosion accidents.[26] In addition, numerical simulation has become an important technical means of industrial accident investigation and inversion.[11,27−29] In view of this, this combination method of onsite inspection, material evidence analysis, experimental
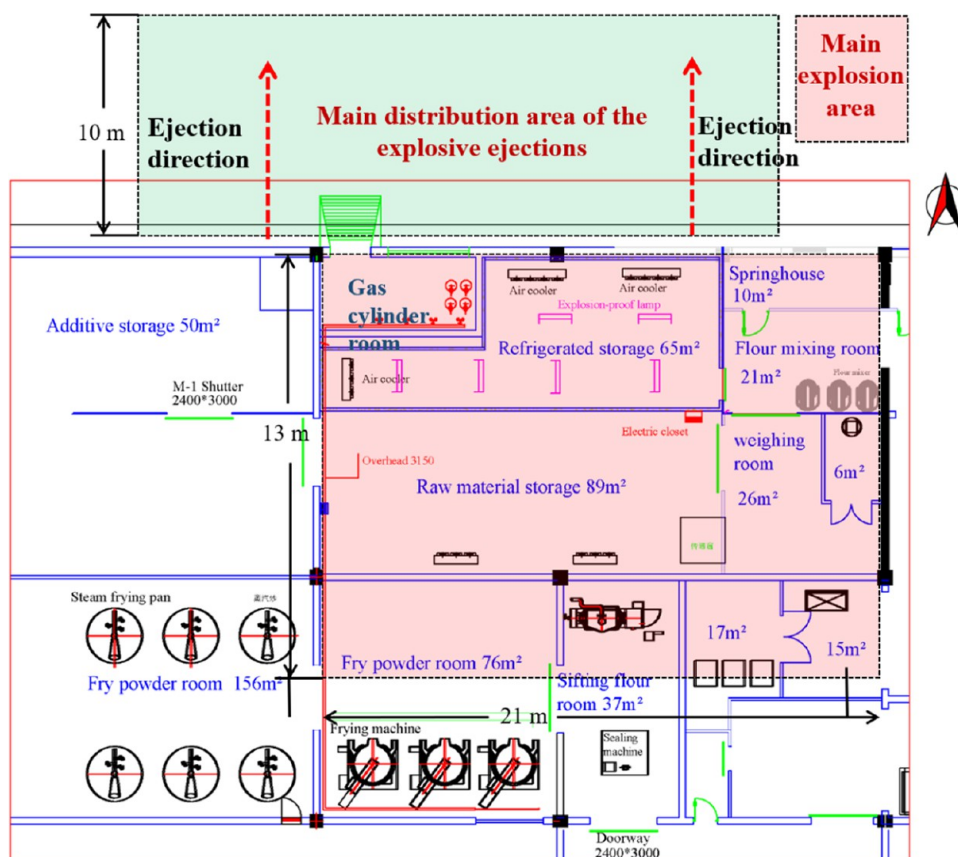
Figure 3. Explosion site plan.

verification, and logical reasoning to investigate and analyze the Kyo-Nichi Todai Foods Co., Ltd. gas explosion accident. The research results will have important scientific guiding significance for revealing the causes of this explosion accident and preventing similar accidents. At the same time, they can also improve the characteristics and mechanism of LPG/DME-blended gas explosions on a large scale and help to further improve the technical system of fire and explosion accident investigation and the safety production standard system.

2. INVESTIGATION AND ANALYSIS

2.1. Onsite Inspection and Results. In the middle of the driveway on the north side of the workshop where the explosion occurred, a large number of wall tiles and window and door ejections were found. The ejections are large and have no obvious smoke trace. The throwing range is about 10 m to the north. According to the workshop plan, as shown in Figure 3, the ejections are mainly northern external walls of refrigerated storage and gas cylinder room. The main explosion area is the area extending 21 and 13 m to the east and south of the gas cylinder room.

This area from north to south mainly involves the gas cylinder room, refrigerated storage, raw material storage, and stir-frying powder room. The whole building in this area was seriously damaged, as shown below.

(1) The 240 mm thick perforated brick partition wall used in the inner side of the gas cylinder room and south side of the raw material storage collapsed completely, as shown in Figure 4a.

(2) The 370 mm thick perforated brick external wall on the north side of the gas cylinder room, refrigerated storage, and cold springhouse collapsed completely.

(3) The refrigerated storage made of stainless steel polyurethane plate was the most seriously damaged, most of the polyurethane burnt out, as shown in Figure 4b.

(4) The reinforced concrete wall on the west side of the explosion site was blasted out with an obvious spherical concave, its center height was about 3 m, and some cracks larger than 2 mm appeared on this wall, as shown in Figure 4c.

(5) The reinforced concrete roof of the refrigerated storage was obviously damaged and cracks larger than 2 mm were found. The roof near the west wall suffered the most serious damage, specifically, the roof was blown through and a lot of steel bars were exposed, as shown in Figure 4d.

(6) Two reinforced concrete columns on the north side of the explosion site were blasted out with obvious damage displacement pointing to the northeast, and one reinforced concrete column on the south was blasted out with damage displacement pointing to the southeast, as shown in Figure 4e.

The ceiling partitions of the surrounding workshops and storages fell off after being affected by the explosion, and the damage degree gradually reduced along the surrounding areas. The combustibles stacked in the north of the workshop and around the explosion area have multiple discrete local combustion points.

From the aspect of the damage pattern and influence scope, the explosion site presents obvious volume explosion
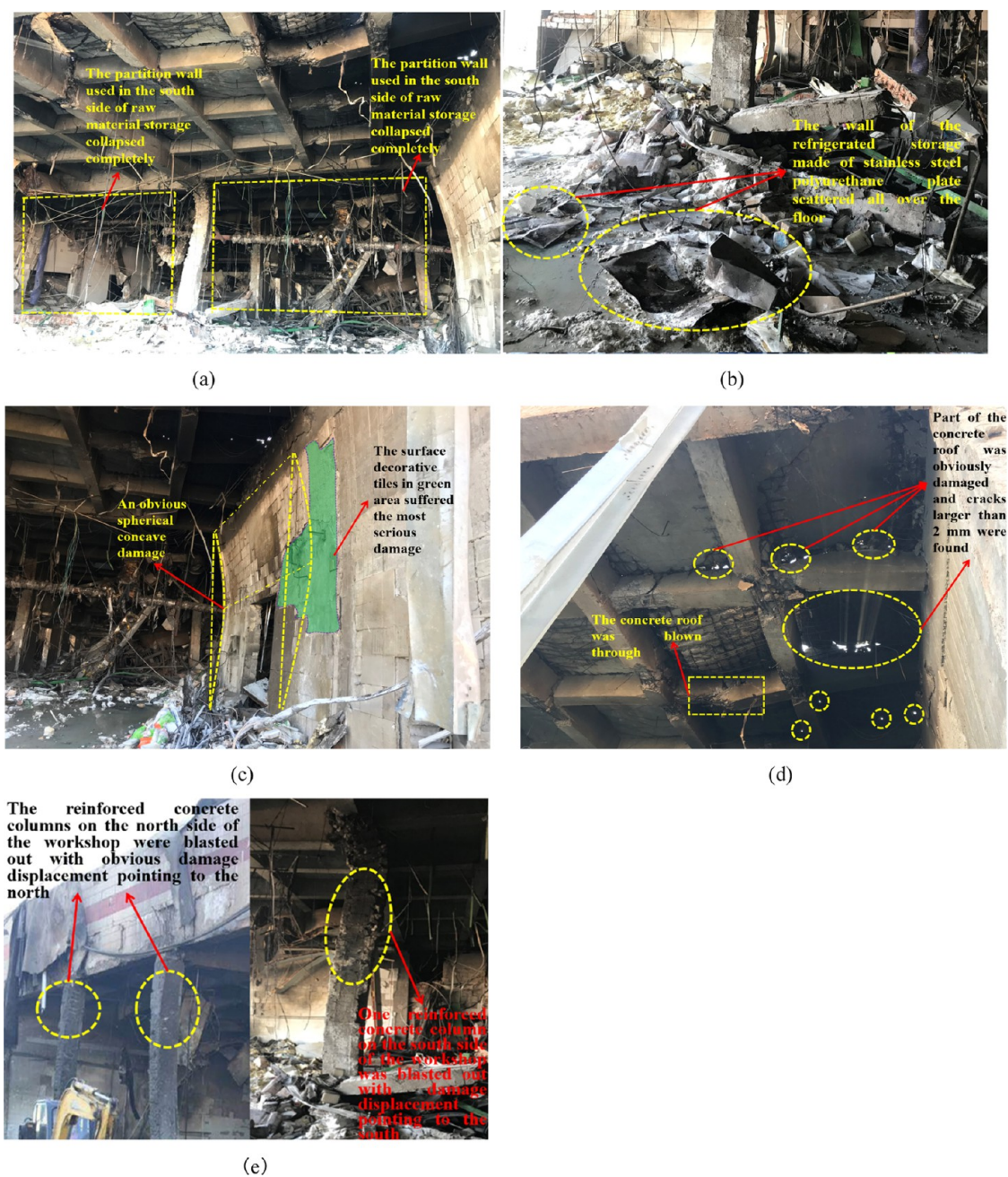
Figure 4. Damage condition of the main explosion area. (a) Perforated brick partition wall on the south side; (b) stainless steel polyurethane plate around the refrigerated storage; (c) reinforced concrete wall on the west side; (d) reinforced concrete roof; and (e) reinforced concrete columns.

characteristics, which are not consistent with the explosion characteristics of the condensed phase explosives. At the same time, according to transcripts of the survivors' confession, before the accident, workers at the scene had smelled a strong odor from the combustible gas, which was essentially the warning agent tetrahydrothiophene (C_4H_8S) added to LPG by the factory to help identify leaks of gaseous fuel.

In conclusion, it can be agreed that this accident was a gas explosion accident.

2.2. Analysis of Ignition Point and the Explosive Material. *2.2.1. Determination of Ignition Point Based on the Damage Trace of the Shock Wave Propagation Path.* The propagation of the shock wave is directional. The shock wave in the tunnel or pipeline space propagates along the direction of the tunnel or pipeline, while the shock wave in the

open space generally propagates evenly around. It will cause casualties and directional damage to the building on the shock wave propagation path.[30] Accordingly, the direction of the shock wave can be estimated, and the macroscopic location of the ignition source can be determined by estimating the direction of the shock wave in multiple directions.[22]

Since the explosion accident was extremely powerful, the equipment and materials with weak compression resistance were seriously damaged, and the displacement trajectories and damage traces were difficult to verify. At this time, investigating the damage traces of components with strong compression resistance such as the reinforced concrete walls and reinforced concrete columns can help to understand the propagation direction of the shock wave and then determine the location of the ignition point. Figure 5 shows the characteristics and
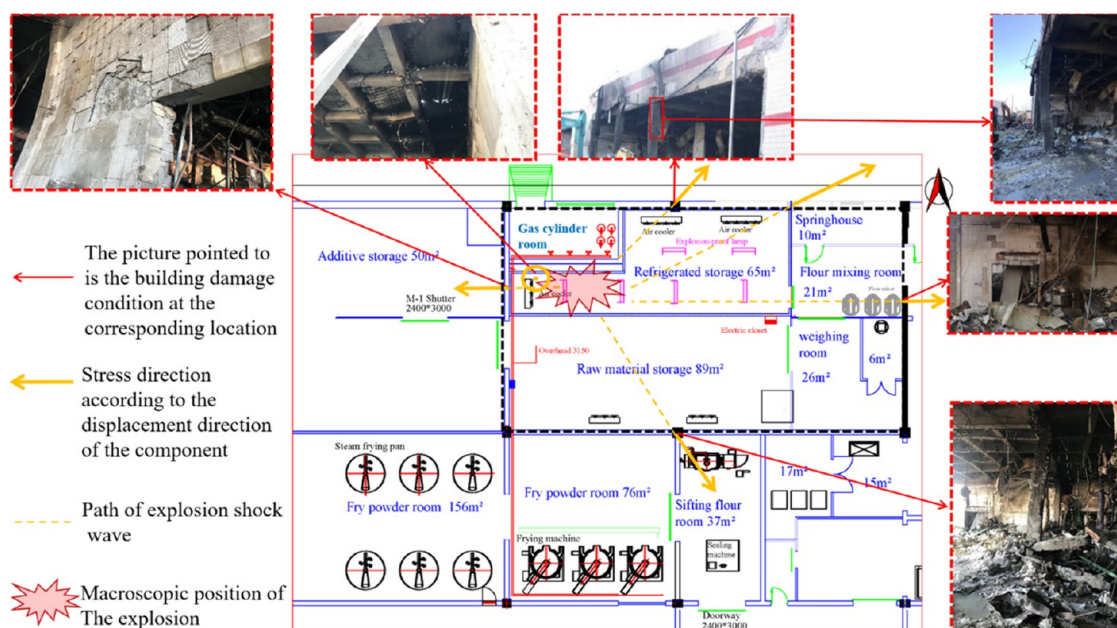
Figure 5. Characteristics and distribution of damage traces of components with strong compression resistance at the explosion site.

distribution of damage traces of components with strong compression resistance at the explosion site.

The stress directions of the components can be determined according to the damage traces and displacement directions of the reinforced walls on the east and west sides of the refrigerated storage, the two reinforced columns on the north side of the refrigerated storage, and one reinforced column in the center of the south side of the raw material storage. In Figure 5, the stress directions of the abovementioned components were marked using yellow arrows. By drawing the reverse extension lines (yellow dotted lines) for the stress directions, the intersection range of multiple reverse extension lines was obtained. Therefore, it was determined that the macroscopic location of the ignition point was on the west side of the refrigerated storage. Furthermore, the point with maximum damage displacement on the reinforced wall on the west side of the refrigerated storage was about 3 m. It can be seen from Figure 4d that the decorative tiles around this height fell most seriously. In addition, this location was consistent with the height of the ceiling of the refrigerated storage. Therefore, the vertical location of the ignition point can be determined. In summary, it was determined that the ignition point of the gas explosion was near the ceiling on the west side of the refrigerated storage.

2.2.2. Determination of the Explosive Substance Based on Analysis and Identification of Material Evidence. There was a gas cylinder room at the explosion accident site. At the time of the incident, four 50 kg LPG cylinders were stored in the gas cylinder room at the same time. Figure 6 shows the LPG cylinders that were damaged after the explosion. At the same time, there were three LPG stir-frying machines in the stir-frying powder room connected to the gas cylinders through the gas pipeline, as shown in Figure 7. According to the surveillance video and the survivors' testimony, around 23 min before the accident, many workers on site smelled "gas"— the smell of tetrahydrothiophene in fact, which confirmed the leakage and the presence of LPG.

Besides, although there were still a large amount of combustible organic dusts such as powdered sugar and flour

Figure 6. LPG cylinders after the explosion (damaged).

Figure 7. LPG stir-frying machines before the explosion.

in the workshop near the explosion area, no obvious sticky black soot was found at the explosion site. In addition, only one explosion process was captured in the surveillance video. If it was a dust explosion caused by the gas explosion, it would

Table 2. Gas Chromatographic Analysis Results of 1# and 2# Gas Samples

| no.	component name	component proportion (vol %)		no.	component name	component proportion (vol %)	
		1#	2#			1#	2#
1	ethane	0.07	0.17	9	cis butene	0.04	0.02
2	propane	54.54	64.47	10	1,3-butadiene	0.14	0.09
3	propylene	0.05	0.08	11	pentane	0.64	0.40
4	isobutane	8.19	6.89	12	1-pentene	0	0
5	n-butane	7.71	5.69	13	DME	28.59	22.15
6	isobutylene	0	0	14	methyl tert-butyl ether	0	0
7	n-butene	0.03	0.04	15	methanol	0	0
8	trans butene	0	0	16	acetone	0	0
total	100%						
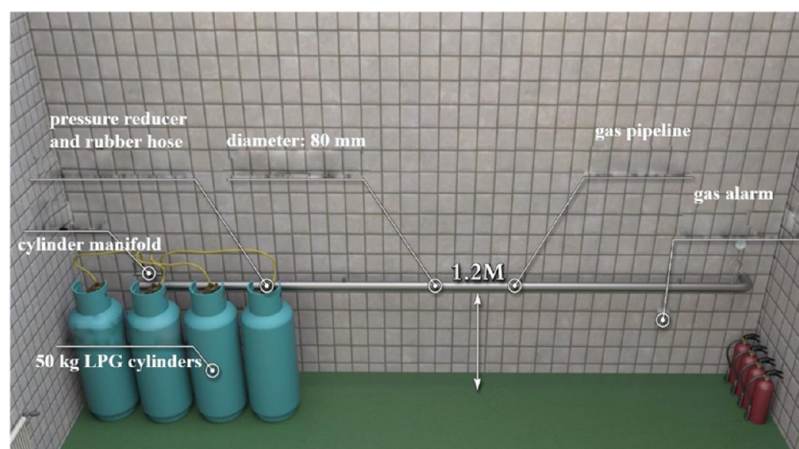
Figure 8. Connection condition of gas cylinders and the gas pipeline in the gas cylinder room.

lead to the formation of a dust cloud after the first explosion and trigger a second explosion. Considering that the above two phenomena did not exist, the possibility of dust explosion can be ruled out. In summary, it was preliminarily determined that the explosive substance was LPG.

To further determine the specific components of an explosive substance, two gas cylinders were selected from the four damaged LPG cylinders as the analysis objects, and sampling and gas chromatographic analysis were carried out. The gas chromatographic analysis results of 1# and 2# gas samples are listed in Table 2.

It can be seen from Table 2 that the C3 + C4 hydrocarbon components in 1# and 2# gas samples were 70.71 and 77.28%, respectively. However, in GB11174-2011 "liquefied petroleum gases", it is required that the volume fraction of C3 + C4 hydrocarbon components ≥is 95%. As a result, the 1# and 2# gas samples did not meet the requirement and both the gas samples belonged to nonstandard LPG. In addition, 1# and 2# gas samples were blended with a large amount of DME, with proportions as high as 28.59 and 22.15%, respectively. From this, it was further determined that the explosive substance was the LPG/DME-blended gas.

2.3. Analysis of the Causes of Gas Leakage. In 2015, the European Gas Pipeline Incident Data Group (EGIG) collected 1309 pipeline accidents in Europe from 1970 to 2013 and found that the accident frequency of gas pipelines was 0.33 accident/1000 km/year. The main reasons for the failure of buried gas pipelines from 2003 to 2013 included external interference, corrosion, construction defects, and ground movement, which accounted for 35, 24, 16, and 13% of the total number of cases, respectively. The above reasons are basically the external factors of the pipeline. For overhead gas pipelines, the probability of being affected by external factors is extremely low, especially for indoor gas pipelines. Therefore, it is feasible to consider the internal factors of the gas pipeline: whether there is "a low-pressure pipeline operating under high pressure," and whether there are components or substances blended in the gas that can corrode gas pipelines, flange gaskets, valve gaskets, and gas hoses.

2.3.1. Conditions of the Gas Pipeline Connection. On the northwest side of the workshop, a gas cylinder room with a width of 5.76 m and a depth of 2.7 m was partitioned by 240 mm thick perforated lightweight bricks. The partition wall extended up to the ceiling and was about 5.5 m high. The ceiling of the gas cylinder room was 3 m high, and the door was directly opened to the outside. Before the accident, there were four 50 kg LPG cylinders in the southeast corner of the gas cylinder room, which were connected to a gas pipeline with a diameter of 80 mm through the cylinder manifold. Forced ventilation facilities were located in the northeast corner to vent outside the roof. The main layout is shown in Figure 8.

The stir-frying powder room was located to the south of the gas cylinder room, with the refrigerated storage and the raw material storage in the middle. In the stir-frying powder room, there were three LPG stir-frying machines with a rated pressure of 1.96−3.23 kPa, which were low-pressure operation equipment. The gas pipeline started from the LPG cylinders in the gas cylinder room and was connected to the cylinder angle valves, adjustable pressure reducer, rubber hose, and cylinder manifold in sequence, and then was connected to the DN80 main gas pipeline. The pipeline passed through the south wall on the west side of the cylinder room and bent upwards (the
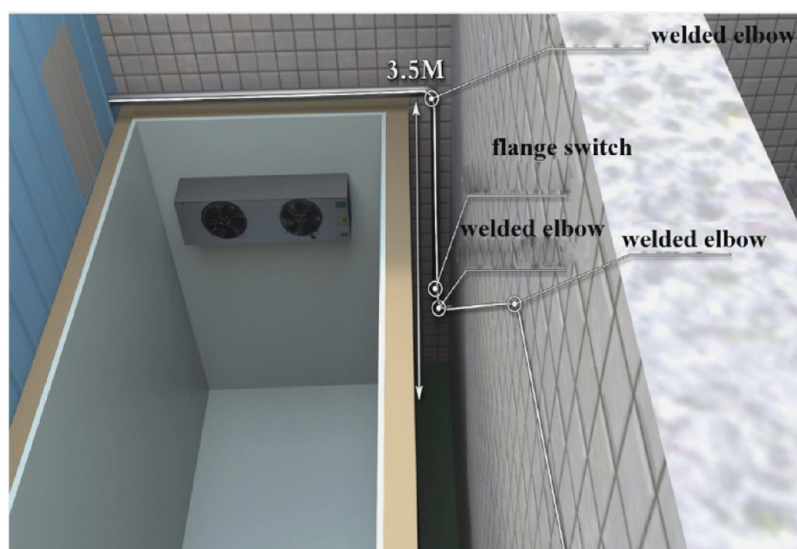
Figure 9. Connection condition and locations of the ball valve and the flanges.
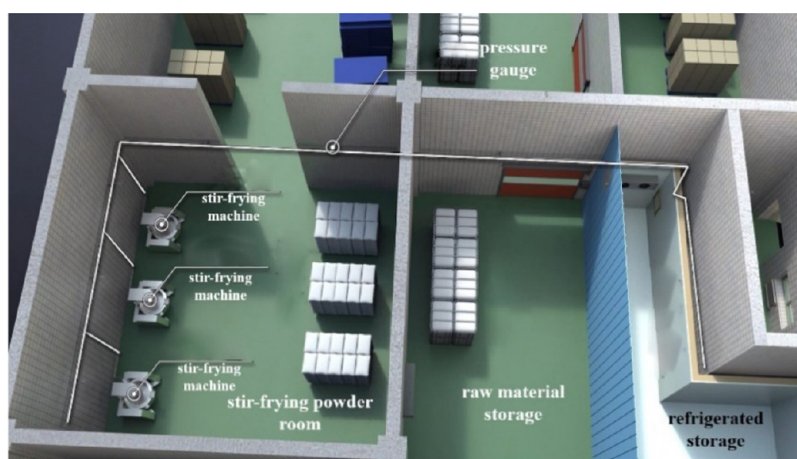

Figure 10. Connection conditions of the entire gas pipeline.

ball valve was about 10 cm upward from the bend). The inlet and outlet of the ball valve were connected to the pipeline using flanges. An access hole was set on the partition wall of the refrigerated storage corresponding to the location of the ball valve, as shown in Figure 9. Then, the pipeline bent to the south at a height of about 3.5 m above the ground, crossed the roof of the refrigerated storage along the west wall of the building, passed through the partition wall on the south of the refrigerated storage and the south wall of the raw material storage, extended to the south wall of the stir-frying powder room, extended to about 30 cm from the ground through three vertical pipes, and finally, connected to three LPG stir-frying machines using hoses. The connection condition of the entire gas pipeline is shown in Figure 10.

2.3.2. Flange Connections and the Medium Resistance Test on Flange Gaskets. As for the connection and installation of flanges, the two flanges used in the pipeline were both 8-hole flanges (temporarily named flange A and flange B), and both flanges A and flange B were equipped with only four sets of M16 bolts. In addition, no spring washer was used when tightening the bolts, and for both flange A and flange B, two sets of bolts were loose. The connection condition between the ball valve and the flange is shown in Figure 11.

Figure 11. Connection condition between the ball valve and the flange.

Two flange gaskets (flange gasket A and flange gasket B) were removed from the explosion site. The original condition of the gaskets is shown in Figure 12. Overall, the condition of flange gasket A was slightly better than that of flange gasket B. In addition, flange gasket B was severely corroded and there were two obvious fractures. As for the concentricity of the
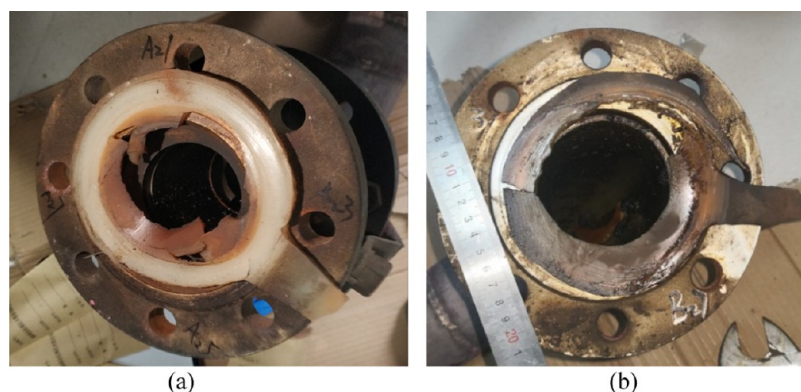
Figure 12. Flange gaskets: (a) flange gasket A and (b) flange gasket B.

gaskets, there was no locating slot between the gaskets and the flanges. The compressed area of flange gasket A had a good concentricity, while the compressed area of flange gasket B had a large eccentricity. As for the thickness of the gaskets, flange gasket A was 1.62 mm thicker than flange gasket B on average. When tightening, the compression of flange gasket A was higher and the sealing effect of flange gasket A was better than that of flange gasket B.

As shown in Figure 12, the crack on the right side of flange gasket B conformed to the characteristics of a long-term corrosion crack, and the location of the leakage hole was directly facing the access hole of the refrigerated storage. The crack on the left side of flange gasket B was relatively new and there was no obvious evidence of corrosion along the crack. The crack on the left side did not conform to the characteristics of a long-term corrosion crack. This was because after the crack on the right side fractured and leaked, the corresponding location on the left side of the gasket was subjected to a large torque generated by the gas ejection and it was twisted and fractured.

Some materials were selected from flange gaskets A and B and sent to China National Tyre Quality Supervision and Inspection Center for testing. The test results showed that the materials of both flange gaskets A and B were methyl vinyl silicone rubber. At the same time, it was detected that both the outer parts and the inner parts of the gaskets contained DME, which indicated the long-term leakage of the blended gas.

To further clarify the swelling or corrosion effect of the DME/LPG blended gas, a medium resistance test on the flange gaskets was carried out according to the relevant requirements of GB/T 7512-2017 "valves for liquefied petroleum gas cylinders". The test results are shown in Table 3. In Section 6.1.2.1.4 "media compatibility clause" of GB/T 7512-2017 valves for liquefied petroleum gas cylinders, it is required that "After the rubber sealing ring is soaked in a n-pentane solution at a temperature of 23 ± 2 °C for 70 h, the volume expansion

rate should ≤25% or shrinkage rate should ≤1%, and the mass loss rate should ≤10%". However, it can be seen from Table 3 that after the test flange gasket was soaked in n-pentane for 70 h, the volume change rate and the mass change rate were as high as 147.51 and 244.8%, respectively. As a result, both flange gaskets A and B are far from meeting the requirements of the national standard, i.e., they are nonstandard products. In addition, after the test flange gaskets were soaked in LPG/ DME (20%) and pure DME environments for 70 h, the volume change rates reached 96.6 and 80.45%, respectively, and the corresponding mass change rates reached 201.4 and 128.45%, respectively. Obviously, the swelling or corrosion effect of the LPG/DME (20%)-blended gas was more serious than that of pure DME.

In summary, the laminar fractures or radial cracks were formed on the nonstandard flange gaskets under the long-term swelling and corrosion effects of nonstandard LPG, resulting in a decrease in the mechanical strength (such as the tensile strength) of the gaskets. In addition, under the action of the gas pressure inside the pipeline, the gasket was torn and a leakage hole was formed, causing a gas leakage. The spatial location of the failed flange gasket is shown in Figure 13. The flange gasket was located exactly in the space between the refrigerated storage and the gas cylinder room, and its height was consistent with the height of the access hole.

2.4. Analysis of Gas Leakage and Ignition Processes. *2.4.1. Calculation of Leakage Mass and Distribution Characteristics of Gas.* From the surveillance video, it was found that it took about 39 min from turning on to turning off the LPG cylinders. According to the inspection and calculation by Beijing Quality Supervising and Test Station for Gas and Gas Appliances, the leakage mass of LPG in each gas cylinder in the gas cylinder room at the explosion accident site is shown in Table 4.

After the incident, cylinder 2 had been leaking slightly, and cylinder 4 had been emptied. As a result, only the total leakage mass of LPG in cylinders 1 and 3 was the leakage mass before the accident. Therefore, the average leakage mass of LPG in each cylinder was calculated according to the average leakage mass of LPG in cylinders 1 and 3. Then, the total leakage mass of LPG before the accident M_{leak} was

$$M_{leak} = 4 \times (17.1 + 18.2)/2 = 70.6 \text{ kg}$$

At 5 °C and 1 atm, the density of LPG $\rho_{blend} \approx 2.04$ kg/m^3. According to the relationship between mass, density, and volume, the volume of the leaked LPG was

Table 3. Medium Resistance Test Results of Flange Gaskets

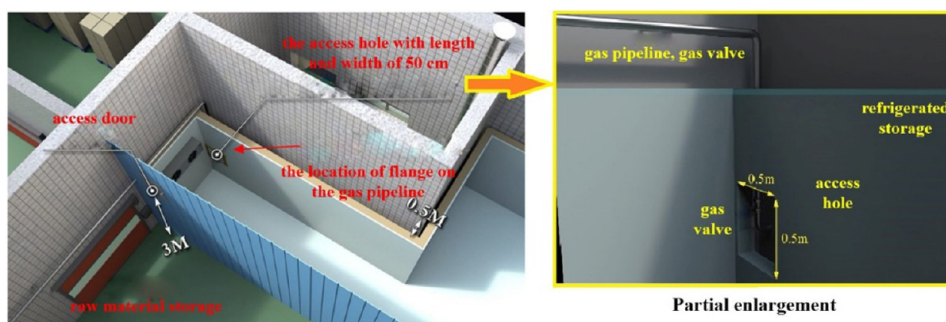|	index (%)	n-pentane (%)	LPG/DME (%) (20%)	DME (%)
after being soaked in the test liquid for 70 h	volume change rate	147.51	96.6	80.45
	mass change rate	244.8	201.4	128.45

Figure 13. Spatial location of the leakage hole.

Table 4. Calculation of the Leakage Mass of LPG in Each Gas Cylinder (kg)

no.	total mass when supplied	cylinder mass	original LPG mass	total mass after the accident	remaining LPG mass	total leakage mass
cylinder 1	95.5	45	50.5	78.4	33.4	17.1
cylinder 2	95.5	46	49.5	74.5	28.5	21
cylinder 3	95.5	45	50.5	77.3	32.3	18.2
cylinder 4	95.5	45	50.5	45.6	0.6	49.9

Table 5. Component Proportions of Gas-Phase Substances in cylinders 1 and 3

component	ethane	propane	propylene	isobutane	n-butane	n-butene	cis butene	1,3-butadiene	pentane	DME
cylinder 1	0.07	54.54	0.05	8.19	7.71	0.03	0.04	0.14	0.64	28.59
cylinder 3	0.17	64.47	0.08	6.89	5.69	0.04	0.02	0.09	0.4	22.15

$$V_{leak} = M_{leak}/\rho_{blend} = 70.6/2.04 = 35 \ m^3$$

Therefore, the volume flow rate of the gas leakage was calculated to be about 0.9 m^3/min, which was about 15 L/s.

2.4.2. Gas Distribution Condition. According to the inspection by Beijing Quality Supervising and Test Station for Gas and Gas Appliances, the specific component proportions of the gas phase substances in cylinders 1 and 3 were obtained, as shown in Table 5.

The upper and lower explosion limits and the proportion of each component were substituted into eq 1 (i.e., Le Chatelier's formula) to obtain the explosion limits of the blended

Table 7. Explosion Limit of the Blended Combustible Gas in Cylinder 3

component (%)	content	upper explosion limit (%)	lower explosion limit (%)	upper explosion limit of the blended gas (%)	lower explosion limit of the blended gas (%)
ethane	0.17	16.00	3.00	10.96	2.22
propane	64.47	9.50	2.10		
propylene	0.08	11.00	2.00		
butane	12.58	8.50	1.64		
butene	0.06	9.61	1.77		
1,3-butadiene	0.09	12.00	2.00		
DME	22.15	27.00	3.42		

Table 6. Explosion Limit of the Blended Combustible Gas in Cylinder 1

component (%)	content	upper explosion limit (%)	lower explosion limit (%)	upper explosion limit of the blended gas (%)	lower explosion limit of the blended gas (%)
ethane	0.07	16.00	3.00	11.48	2.26
propane	54.54	9.50	2.10		
propylene	0.05	11.00	2.00		
butane	15.9	8.50	1.64		
butene	0.07	9.61	1.77		
1,3-butadiene	0.14	12.00	2.00		
dimethyl ether	28.59	27.00	3.42		

combustible gas in cylinders 1 and 3, as shown in Tables 6 and 7.

$$FL_{blend} = \frac{1}{\sum_{i=1}^{n} \frac{x_i}{FL_i}} \qquad (1)$$

where FL_{blend} is the explosion limit of the blended gas, vol %; x_i is the mole fraction of each component gas in the blended gas,

vol %, and the sum is 1; and FL_i is the explosion limit of each component gas in oxygen or air, vol %.

According to Tables 6 and 7, the most dangerous situation was selected as the explosion limit of LPG at the accident site, where the lower and upper explosion limits were 2.22 and 11.48%, respectively. Therefore, in theory, 35 m^3 of leaked combustible gas can form 305−1577 m^3 of the explosive gas mixture.

According to the measurements, the bottom area and the height of the refrigerated storage were 65 m^3 and 3 m, respectively. Therefore, the volume of the refrigerated storage was calculated to be 195 m^3. The volume of the space between the color steel plate of the refrigerated storage and the surrounding walls was 16 m^3, and the volume of the top space of the refrigerated storage was 162 m^3. Therefore, the volume of the internal and top spaces of the refrigerated storage was calculated to be approximately 373 m^3. Obviously, the volume of the explosive gas mixture was likely to be larger than 373 m^3, indicating that the combustible gas filled the internal and top spaces of the refrigerated storage.

To sum up, the explosive gas mixture of LPG/DME−air was mainly present in the internal and top spaces of the refrigerated storage, and a small part of it diffused into the adjacent spaces.

2.4.3. Ignition Source Analysis. There were electrical devices such as lighting lamps, electric closets, and air coolers in the refrigerated storage, and electric sparks could be generated during the operation and startup processes. According to the onsite surveillance video, it was found that about 0.33 s before the explosion, a worker surnamed Lyu had a suspected action to turn on the lamp switch of the refrigerated storage. The lighting lamps in the refrigerated storage were non-explosion-proof fluorescent lamps. After the switch was turned on, the ballast would work with a delay, and electric sparks were generated, which ignited the explosive gas mixture.

3. RESULTS AND DISCUSSION

3.1. Explosion Process. The silicone flange gaskets were subject to the long-term corrosion of the LPG/DME-blended gas, forming laminar fractures and radial cracks on the gaskets, resulting in a decrease in the tensile strength of the gaskets. Under the action of the gas pressure inside the pipeline, the gasket was torn and a leakage hole was formed. The pressure in the gas pipeline reached 0.2 MPa. Under this pressure, the gas was rapidly ejected through the leakage hole to form a large amount of leakage, which led to the formation of a large amount of explosive gas mixture in the internal and external spaces of the entire refrigerated storage. The three air coolers in the refrigerated storage accelerated the mixing of the leaked gas and air in the refrigerated storage, forming an explosive gas mixture in the entire space. The explosive gas mixture in the refrigerated storage encountered the electric sparks generated by the non-explosion-proof lamps on the top or other electric sparks, and then the explosion accident occurred. After the explosive gas mixture inside the refrigerated storage was ignited, a high-pressure shock wave was formed and developed rapidly. First, the lightweight polyurethane color steel plate of the refrigerated storage was severely damaged. Then, the shock wave continued to develop around. At the same time, the gas that leaked to the adjacent spaces (such as the upper part of the refrigerated storage and the raw material storage in the south) also participated in the explosion. The explosion caused varying degrees of damage and injury to the workshop buildings, equipment, and workers.

3.2. TNT Equivalent. The explosive gas mixture was mainly present in the internal and top spaces of the refrigerated storage. The total volume of the spaces was about 373 m³. It can be judged from the explosion damage and combustion traces on site that the gas concentration in this explosion accident was close to a lean-burn concentration of the stoichiometric concentration. According to the calculation, the explosion limit of the blended combustible gas was 2.22−11.48%. Here, 5%, which was close to the equivalent concentration, was used as the representative lean-burn concentration. The mass of combustible gas involved in the explosion process was calculated to be about 38 kg. According to the calculation formula of TNT equivalent of the vapor cloud[31]

$$W_{TNT} = \alpha \frac{W_f \cdot Q_f}{Q_{TNT}} \qquad (2)$$

where W_{TNT} is the TNT equivalent of the combustible gas, kg; α is the efficiency factor of the vapor cloud explosion, with a statistical average of 0.04; W_f is the total mass of the combustible gas, kg; Q_f is the calorific value of the combustible gas, MJ/kg; and Q_{TNT} is the TNT explosion heat, which is generally set to 4.52 MJ/kg.

It is averagely assumed that the typical components and proportions of the leaked blended gas are 59.51% propane, 14.24% butane, and 25.37% DME. Then, based on the combustion heat of each substance, the calorific value of the leaked blended gas was calculated to be 44.82 MJ/kg using the weighted average method. Substituting this calorific value into eq 2, W_{TNT} = 15.07 kg. Therefore, in this explosion accident, the TNT equivalent of the combustible gas involved in the explosion was about 15.07 kg.

3.3. Systematic Analysis of the Causes of the Explosion Accident. *3.3.1. Technical Design Defects.* The technical design defects are the inherent and essential defects of the system. The details are as follows.

(1) The design of the material, shape, concentricity, and thickness uniformity of the flange gaskets had serious defects.

(2) The number of bolts for fixing the flanges was insufficient, and the bolt installation was loose.

(3) The air pressure in the gas pipeline did not match that of the stove, and the pipeline had been under high pressure for a long time, which accelerated the corrosion and leakage.

From the perspective of technical design defects, the combustible gas pipeline does not meet the requirements of intrinsic safety design.

3.3.2. Safety Culture Defects. Safety culture defects are defects that can be eliminated during the operation of the system. The so-called safety culture is the product of individual and group values, attitudes, concepts, abilities, and behavior patterns, which determine an organization's commitment and proficiency in safety and health issues.[32−34] The term "safety culture" was first recognized and used in the International Atomic Energy Agency (IAEA) to describe the thoughts and behavior patterns of the safety managers in the accident at the Chernobyl nuclear power plant in 1986.[35] Since then, safety culture has been widely used to investigate the causes of other major accidents and has played an important role. Nowadays, safety culture has become an important part of process industry safety. Obviously, the safety culture defects of Kyo-Nichi Todai Foods Co., Ltd. are obvious, and the details are as follows.

(1) The ability to identify and evaluate hazards was insufficient. The safety managers did not fully understand the use of gas, had no knowledge of the DME blending situation, and seriously lacked knowledge of the corrosion characteristics and explosion hazards of the blended gas. At the same time, they did not assess the potential risks of a low-pressure pipeline operating under high pressure.

(2) The daily safety inspection system was inadequate. The safety managers had a form of "going through the motions" in the daily inspection of gas pipelines, turning a blind eye to the problem of bolt loosening. In addition, there was a fluke mentality, and the number of bolts for fixing the flanges was not increased as required.

(3) Safety monitoring measures were not in place. The safety managers did not monitor the main parameters of the pressure pipeline and did not build a safe operating pressure threshold and alarm model. As a result, the workers were not able to realize the safe operating status of the pressure pipeline, which made the pressure pipeline completely in the blind zone of safety management. The consequence was that the safety managers would never find out that the pipeline had violations of high-pressure operation, and, at the same time, they would not be able to realize the occurrence of leakage in the first time. In addition, the inadequate safety monitoring measures were also reflected due to the fact that separate gas detection and alarm devices were not installed along the pressure pipeline, especially at the flange connections.

3.3.3. Emergency Disposal Procedure Defects. The emergency disposal procedure defects are defects that can be avoided when and after a system accident occurs. Good emergency disposal procedures can prevent the expansion of the disaster or strive for the safety of more workers. Everyone is a participant in the emergency disposal. Whoever discovers a gas leakage should follow the following four steps.

(1) Report to the full-time safety managers immediately and take measures to turn off the gas valves in the shortest time.
(2) Open the nearby doors and windows to dilute the gas below the lower explosion limit.
(3) Release news and evacuate the workers.
(4) During the emergency disposal procedures, no ignition behaviors, such as making phone calls and switching electrical appliances, are allowed.

However, in this accident, people followed only the first step and failed to follow the remaining three steps. Contrary to the emergency disposal procedures, onsite workers did not evacuate but repeatedly entered and exited the refrigerated storage for inspection. On the premise that there was a gas leakage, a worker repeatedly turned on and off the non-explosion-proof lamps in the refrigerated storage. This unsafe behavior undoubtedly triggered the gas explosion. The defects in the emergency disposal procedures reflected not only the failure of safety training and safety education, but also the serious lack of safety knowledge and safety capabilities among workers.

4. CONCLUSIONS

After being soaked in LPG/DME (20%) and pure DME environments for 70 h, the volume change rates of the methyl vinyl silicone rubber reached 96.6 and 80.45%, respectively, and the corresponding mass change rates reached 201.4 and 128.45%, respectively. Obviously, the swelling or corrosion effect of the LPG/DME (20%)-blended gas was more serious than that of pure DME. The LPG/DME-blended gas can effectively corrode the silicone flange gaskets, forming laminar fractures and radial cracks on the gaskets. As a result, the tensile strength of the gasket decreased. Under the action of the gas pressure inside the pipeline, the gasket was torn and a leakage hole was formed.

The pressure in the gas pipeline reached 0.2 MPa. Under this pressure, the gas was ejected through the leakage hole at a speed of 15 L/s. The total mass of the leaked gas reached 70.9 kg, which can be converted into a volume of 35 m^3. Based on

the gas chromatographic analysis and Le Chatelier's formula, the lower and upper explosion limits of the combustible gas were calculated to be 2.22 and 11.48%, respectively. As a result, it was derived that 305−1577 m^3 of explosive gas mixture was formed on site. According to the location of the leakage hole and the connection condition of the spaces, it was determined that the leaked combustible gas was mainly distributed in the internal and top spaces of the refrigerated storage with a total volume of 373 m^3.

According to the power of the explosion, it was assumed that the concentration of the combustible gas in the explosion was 5%, which was the lean-burn concentration (close to the equivalent concentration). Then, it was derived that the mass of the combustible gas participating in the explosion accident was 38 kg. According to the evaluation formula of TNT equivalent based on the concept of energy equivalent conversion, it was calculated that the TNT equivalent of the combustible gas explosion was 15.07 kg.

Based on the accident cheese principle, a systematic analysis method of explosion accident causes was established based on the design defects before the system operation, the safety culture defects during the system operation, and the emergency disposal defects during the incubation and development of the system accident. In addition, these three major defects that led to the accident were systematically analyzed. This explosion accident reflected the practical problems, such as the imperfect safety management system of the production enterprise, inadequate emergency management measures, and insufficient safety education.

5. CAUSE ANALYSIS METHOD

The Swiss cheese model was proposed by James Reason of the University of Manchester in 1990. The cheese principle is that
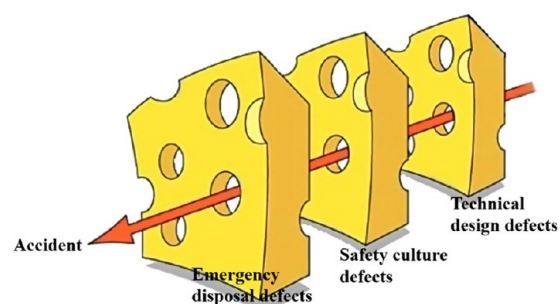

Figure 14. Three defects in the process of accident preparation based on the cheese principle.

it is difficult for light to penetrate several pieces of cheese stacked together, but there are several holes in each piece of cheese, representing the possible mistakes or technical defects in each operation link. When mistakes or technical defects are exposed, the light can pass through the piece of cheese. If the light coincides with the hole position of the second piece of cheese, the light will pass through the second piece of cheese. When the holes in many slices of cheese just form a series relationship, the light will pass through completely, and then there will be a safety accident or quality accident. Here, the cheese principle is used to analyze the three links of the explosion accident, which are the design defects before the system operation, the safety culture defects during the system operation, and the emergency disposal defects during the system accident breeding and development. In this accident,

there are defects in the three links and, under specific conditions, the defects match, the light passes, leading to the explosion. The process of the explosion is shown in Figure 14.

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Notes

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■ REFERENCES

(1) Zhang, X. P.; Cheng, X. M. Energy Consumption, Carbon Emissions, and Economic Growth in China. *Ecol. Econ.* **2009**, *68*, 2706−2712.

(2) Gould, C. F.; Urpelainen, J. LPG as a Clean Cooking Fuel: Adoption, Use, and Impact in Rural India. *Energy Policy* **2018**, *122*, 395−408.

(3) Arya, P. K.; Tupkari, S.; K, S.; Thakre, G. D.; Shukla, B. M. DME Blended LPG as a Cooking Fuel Option for Indian Household: A Review. *Renewable Sustainable Energy Rev.* **2016**, *53*, 1591−1601.

(4) Richesson, B. *The Developing DME Market: What it Means for LPG*; LPGas, 2015.

(5) Lu, X.; Han, D.; Huang, Z. Fuel Design and Management for the Control of Advanced Compression-Ignition Combustion Modes. *Prog. Energy Combust. Sci.* **2011**, *37*, 741−783.

(6) Park, S. H.; Lee, C. S. Combustion Performance and Emission Reduction Characteristics of Automotive DME Engine System. *Prog. Energy Combust. Sci.* **2013**, *39*, 147−168.

(7) Park, S. H.; Lee, C. S. Applicability of Dimethyl Ether (DME) in a Compression Ignition Engine as an Alternative Fuel. *Energy Convers. Manage.* **2014**, *86*, 848−863.

(8) Fleisch, T. H.; Basu, A.; Sills, R. A. Introduction and Advancement of a New Clean Global Fuel: The Status of DME Developments in China and Beyond. *J. Nat. Gas Sci. Eng.* **2012**, *9*, 94−107.

(9) Rockall, J.; de Calan, B. In *DME Opportunities in LPG Gas Markets*, Second International DME Conference, London, 2006; pp 15−17.

(10) Chen, Y.; Qian, X.; Zhang, Q.; Fu, L.; Yuan, M. Study on the Effects of Initial Pressure and Temperature on the Explosion Characteristics of DME-Blended LPG Mixtures in an Obstructed Confined Pipeline. *Fuel* **2019**, *257*, No. 116047.

(11) Zhang, Q.; Qian, X.; Fu, L.; Yuan, M.; Chen, Y. Shock Wave Evolution and Overpressure Hazards in Partly Premixed Gas Deflagration of DME/LPG Blended Multi-Clean Fuel. *Fuel* **2020**, *268*, No. 117368.

(12) Chen, Y.; Zhang, Q.; Li, M.; Yuan, M.; Wu, D.; Qian, X. Experimental Study on Explosion Characteristics of DME-Blended LPG Mixtures in a Closed Vessel. *Fuel* **2019**, *248*, 232−240.

(13) Zhang, Q.; Chen, Y.; Fan, T.; Yuan, M.; Liu, Z.; Huang, P.; Qian, X. Flame Dynamics and Flammability Limit of DME(30%)/ LPG Blended Clean Fuel in Elongated Closed Pipeline under Multi-Factors. *Fuel* **2019**, *254*, No. 115731.

(14) Weidou, N.; Lijian, T.; Dewei, F. In *Rational Cognition of DME Market in China*, Proceedings of 3rd Asian DME Conference, 2006; pp 21−38.

(15) Fujimoto, K. *DME Handbook*; Japan DME Forum: Ohmsha, Japan, 2007; Vol. 3.

(16) Sung, T.; Yong, J.; Jae, D. Experimental Investigations on the Deflagration Explosion Characteristics of Different DME−LPG Mixtures. *Fire Saf. J.* **2012**, *49*, 62−66.

(17) Cao, W.; Li, W.; Zhang, Y.; Zhou, Z.; Zhao, Y.; Yang, Z.; Liu, X.; Yu, S.; Tan, Y. Experimental Study on the Explosion Behaviors of Premixed Syngas-Air Mixtures in Ducts. *Int. J. Hydrogen Energy* **2021**, *46*, 23053−23066.

(18) Cao, W.; Li, W.; Zhang, L.; Chen, J.; Yu, S.; Zhou, Z.; Zhang, Y.; Shen, X.; Tan, Y. Flame Characteristics of Premixed H2-Air Mixtures Explosion Venting in a Spherical Container through a Duct. *Int. J. Hydrogen Energy* **2021**, *46*, 26693−26707.

(19) Lin, S.; Liu, Z.; Qian, J.; Gu, Z.; Ali, M.; Zhao, H. Laboratory Investigation of Powder Deflagration Flame Propagation and Quenching Behaviors Suppressed by ZrO2 Ceramic Foam. *Powder Technol.* **2021**, *388*, 17−25.

(20) Lin, S.; Liu, Z.; Wang, Z.; Qian, J.; Gu, Z. Flame Characteristics in a Coal Dust Explosion Induced by a Methane Explosion in a Horizontal Pipeline. *Combust. Sci. Technol.* **2020**, 1−14.

(21) Kundu, S. K.; Zanganeh, J.; Eschebach, D.; Moghtaderi, B. Explosion Severity of Methane−Coal Dust Hybrid Mixtures in a Ducted Spherical Vessel. *Powder Technol.* **2018**, *323*, 95−102.

(22) Li, H. *Simulation Study on Gas Leakage Explosion in Open Kitchen*; Gas Industry, 2019.

(23) Pearson, C.; Delatte, N. Ronan Point Apartment Tower Collapse and Its Effect on Building Codes. *J. Perform. Constr. Facil.* **2005**, *19*, 172−177.

(24) At least three dead as nine-storey building collapses in Russia.

(25) Rizvi, F. *Collapsed Apartment Building In Russian Magnitogorsk To Be Split Into 2 Houses*; UrduPoint, 2019.

(26) Zhang, L.; Chen, G. Review on Accident Investigation and Analysis Methods. *China Saf. Sci. J.* **2009**, *19*, 169−176.

(27) Liu, X.; Nie, W.; Hua, Y.; Liu, C.; Guo, L.; Ma, W. Behavior of Diesel Particulate Matter Transport from Subsidiary Transportation Vehicle in Mine. *Environ. Pollut.* **2021**, *270*, No. 116264.

(28) Xiu, Z.; Nie, W.; Yan, J.; Chen, D.; Cai, P.; Liu, Q.; Du, T.; Yang, B. Numerical Simulation Study on Dust Pollution Character-istics and Optimal Dust Control Air Flow Rates during Coal Mine Production. *J. Cleaner Prod.* **2020**, *248*, No. 119197.

(29) Zhang, Q.; Zhou, G.; Hu, Y.; Wang, S.; Sun, B.; Yin, W.; Guo, F. Risk Evaluation and Analysis of a Gas Tank Explosion Based on a Vapor Cloud Explosion Model: A Case Study. *Eng. Fail. Anal.* **2019**, *101*, 22−35.

(30) Zhang, Q.; Qian, X.; Chen, Y.; Yuan, M. Deflagration Shock Wave Dynamics of DME/LPG Blended Clean Fuel under the Coupling Effect of Initial Pressure and Equivalence Ratio in Elongated Closed Space. *J. Cleaner Prod.* **2020**, *250*, No. 119572.

(31) Guo, Y.; Liu, C.; Wang, D.; He, R. Numerical Study and Safety Spacing of Buried Parallel Gas Pipelines: A Study Based on TNT Equivalent Method. *Int. J. Pressure Vessels Piping* **2018**, *168*, 246−257.

(32) Mohamed, S. The Nature of Safety Culture: A Survey of the State-of-the-Art. *Saf. Sci.* **2007**, *45*, 993−1012.

(33) Sorensen, J. N. Safety Culture: A Survey of the State-of-the-Art. *Reliab. Eng. Syst. Saf.* **2002**, *76*, 189−204.

(34) Health and Safety Commission. Human Factors Study Group Third Report: Organizing for Safety. In *Advisory Committee on the Safety of Nuclear Installations*; ACSNI: Sheffield, 1993.

(35) Hamilton, E. I. Summary Report on the Post-Accident Review Meeting on the Chernobyl Accident: Rep. Int. Nuclear Safety Advisory Comm. Safety Series No. 75-INSAG-1-STI/PUB/940. *Sci. Total Environ.* **1986**, *66*, 279−280.