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Dispersion of CNG Following a High-Pressure Release

U.S. Department
of Transportation
**Federal Transit
Administration**

U.S. Department of Transportation
Research and Special Programs Administration
John A. Volpe National Transportation Systems Center
Cambridge, MA 02142-1093

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13. ABSTRACT (Maximum 200 words)

This report discusses the results of tests to determine the dispersive behavior of compressed natural gas (CNG) when released in enclosed areas such as a transit bus facility, and presents the Volpe National Transportation Systems Center's conclusions concerning the results. The Federal Transit Administration (FTA) sponsored the tests as part of an effort to evaluate the adequacy of the current convention concerning safeguards against CNG-related fires in transit buildings where CNG-powered buses are fueled, stored, or maintained. This convention embraces the belief that precautions need to be taken only at or near the ceiling of the buildings. It is based on the premise that, since CNG is primarily methane and methane is approximately one-half the density of air at ambient temperature and pressure, any natural gas released would immediately rise to the ceiling as a buoyant plume.

The tests were conducted by Battelle Columbus Laboratories in February 1995 using infrared (IR) imaging to track the movement of the released gas. The conclusions presented in this report were made by the Volpe Center based largely on examination of calibrated IR images at 10-second intervals for the six tests for which data have been post processed. The images from two of the tests are included as part of the discussion of the results. An unpublished report prepared by Battelle is included as Appendix A.

The results of the tests show no evidence that CNG released horizontally from a high-pressure source that is close to the floor would rise as a buoyant plume toward the ceiling of a building. Instead, the results suggest that natural gas released under such conditions will remain in various locations, not only at or near the ceilings, of CNG-bus facilities long enough to pose a potential fire hazard.

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PREFACE

In response to recent releases of natural gas from buses powered by compressed natural gas (CNG), the Federal Transit Administration (FTA) and the John A. Volpe National Transportation Systems Center studied the dispersive behavior of natural gas in an enclosed area when released under high pressure through an orifice not greater than 6.25 mm in diameter. This study focuses on determining how natural gas might behave in an enclosed area when the gas is released under high pressure through the small orifice.

The research described in this report was designed to evaluate the adequacy of the current convention concerning safeguards against CNG-related fires in transit buildings where CNG-powered buses are fueled, stored, or maintained. This convention embraces the belief that precautions need to be taken only at or near the ceiling of the buildings. It is based on the premise that, since CNG is primarily methane and methane is approximately one-half the density of air at ambient temperature and pressure, any natural gas released would immediately rise to the ceiling as a buoyant plume. The experiments described here tested theoretical predictions that challenge this premise. During the tests, infrared imaging was used to track the movement of CNG following release from a high-pressure source close to the floor.

The authors wish to thank Ronald Kangas and Jeffrey Mora of the FTA Office of Research, Demonstration and Innovation, Office of Technology, for their guidance in preparing the report. Special appreciation is given to Dr. Ross Holstrom of the Volpe Center for his valuable analysis of the infrared images. The authors also thank William Hathaway of the Volpe Center for his guidance and direction in preparation of the report and David Knapton of the Volpe Center for his observations made during the testing.

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (ha) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x - 32)(5/9)]°F = y°C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2) = 1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5)(y + 32)]°C = x°F

QUICK INCH-CENTIMETER LENGTH CONVERSION

INCHES 0 1 2 3 4 5

CENTIMETERS 0 1 2 3 4 5 6 7 8 9 10 11 12 13

QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10286.

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1. INTRODUCTION

In February 1995, the Federal Transit Administration (FTA) sponsored a series of 32 experiments, which were conducted by Battelle Columbus Laboratories using infrared (IR) imaging, to determine the movement and dispersion of compressed natural gas (CNG) when released under high pressure from orifices of 6.25 mm in diameter and smaller. The tests were part of an effort by the FTA and the John A. Volpe National Transportation Systems Center to determine the location and extent of fire hazards posed by high-pressure releases of natural gas from CNG-powered buses in transit buildings. It was hoped that the results from the tests would provide insight on the areas of the buildings where maintenance personnel can expect to find hazardous concentrations of gas following releases under high pressure through an orifice of not greater than 6.25 mm in diameter. Such information could then be used by transit agencies in establishing safeguards and operating procedures for buildings where CNG buses are fueled, stored, or maintained.

Representatives from the Volpe Center and Technology and Management Systems (TMS), as well as other guests invited by Battelle, observed the tests. Battelle provided the following materials on the experiments:

- Calibrated IR images at 10-second intervals for six of the tests (These were included in an unpublished report, titled *Infrared Imaging of Compressed Natural Gas Releases*, prepared by Murphy and Klosterman of Battelle. The Battelle report, without the IR images from the tests, is included in this document as Appendix A);
- Five VHS video cassettes of the tests; and
- A series of photographs taken during the tests showing the various test set ups and the imaging camera.

Technical staff at the Volpe Center reviewed these materials. This report summarizes the staff's findings. The IR images from two of the tests are included in the discussion of test results in Section 4. Those images are consistent with the images from the other tests for which data are available.

The IR images and accompanying videotapes show no evidence that the CNG released during the tests rose immediately as a buoyant plume toward the ceiling of the test chamber. Instead, the gas appears to have accumulated at and the bottom of the camera view, mixed with air, gradually dispersed, and dissipated. Although flammable gas concentrations cannot be determined from the available test data for all locations in the test chamber,[1] the test results do suggest that natural gas released horizontally from a high-pressure source that is close to the floor will remain in various locations (not only at or near the ceiling) of CNG-bus facilities long enough to pose a potential fire hazard.

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[1]The IR measurements obtained by Battelle cannot show the vapor concentration of the gas at a particular point. IR images provide only a quantitative measure of the product of concentration and pathlength (CL) in parts per million meters. The average width of the vapor cloud in the direction of the view is needed to determine the average vapor concentration along that line sight. The large number of sensors required to provide the width of the cloud would have significantly increased the cost and could have disturbed the flow field.

2. BACKGROUND

Provisions for protecting CNG-bus facilities from fire have been based on the premise that any natural gas released would immediately rise to the ceiling as a buoyant plume, since CNG is primarily methane and methane is approximately one-half the density of air at ambient temperature and pressure. Thus, safeguards against CNG-related fires need be taken only at or near the ceiling of the buildings. However, personnel in transit buildings where high-pressure releases[2] have occurred reported contrary findings. They believed that gas vapors had remained at other areas of the building. Additionally, theoretical predictions[3] have shown that natural gas released from high-pressure storage could be heavier than air at exit. According to those analyses, CNG released close to the floor does not rise to the ceiling immediately, posing potentially hazardous conditions near the floor of buildings.

The analytical results show that the large pressure difference between a CNG fuel tank and the atmosphere expands the released gas adiabatically. In the process of expanding, the gas exiting from the tank becomes cold (i.e., -260° F or 112 K), increasing the density of the gas to approximately 1.5 times greater than that of the surrounding air. The analysis also showed that the high velocity of a release from a high-pressure source moves the gas in the direction of the gas jet and that the gas rapidly mixes with air. The diluted gas then continues to move along the jet axis, or in the direction that the gas is deflected by a solid object, until the magnitude of the inertial forces (due to momentum) diminishes and its effects become comparable to those from buoyancy force. That is, if the gas is released close to the floor and the jet direction is vertically down or nearly horizontal, the CNG vapors, even after mixing with air, will remain close to the floor for a significant amount of time.

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[2]These have included releases caused by failed pressure relief devices (PRDs); releases caused by leaks from sources such as a high-pressure regulator, a low-pressure solenoid, or a coupling on a fuel manifold; and releases from the fuel lines on buses with CNG tanks mounted under the bus.

[3]These predictions were documented in January 1994 in a technical memorandum, titled "CNG Release from a High-Pressure Cylinder," submitted to the FTA by Dr. Phani K. Raj.

3. EXPERIMENTAL PROCEDURES

The experiments were performed in Battelle's JS-10 high explosives test facility in West Jefferson, Ohio. The test chamber is a vertical cylinder with a domed ceiling. As shown Figure 1, the interior diameter is 12.2 m, and the interior height ranges from 4.6 m to 7.6 m. The total interior volume of the chamber is approximately 475 m^3. Although the size of the test chamber is comparable to some transit indoor fueling lanes, the building is smaller than transit bus garages or maintenance facilities. Also unlike most bus facilities, the test building was unheated. The temperature inside the test chamber, which was recorded before each test, ranged from about -5° C to +5° C.

The area depicted by the IR images (i.e, the camera view) and the position of the release orifices are shown in Figure 2. The bottom of the camera view was 0.75 m above the floor of the building. The top of the camera view was 3.8 m above the floor, 0.8 m below the top of the building wall, and 3.8 m below the apex of the ceiling. The camera view was approximately 4.9 m wide and was centered within the diameter of the building; that is, both the right side and the left side of the view were 3.65 m from the nearest point on the wall. The release orifice was located at the left side of the camera view 1.83 m above the floor, i.e., 1.08 m above the bottom of the camera view and 1.97 m below the top of the view. Additional information on the composition of CNG, the test building, the instrumentation, and IR imaging and radiometry can be found in the Battelle report (Appendix A).

Dry CNG was used in the tests. The flow of gas was controlled by a valve and an orifice located on the delivery tube extending from the CNG tank (see Figure 3). Rate of release was controlled by orifice size. Four orifices, with diameters of 0.64 mm, 0.99 mm, 3.18 mm, and 6.25 mm, were used. Direction of release was controlled by release geometry. Because high-pressure jets have substantial forward momentum and tend to travel in the direction of the release, the release configurations used were

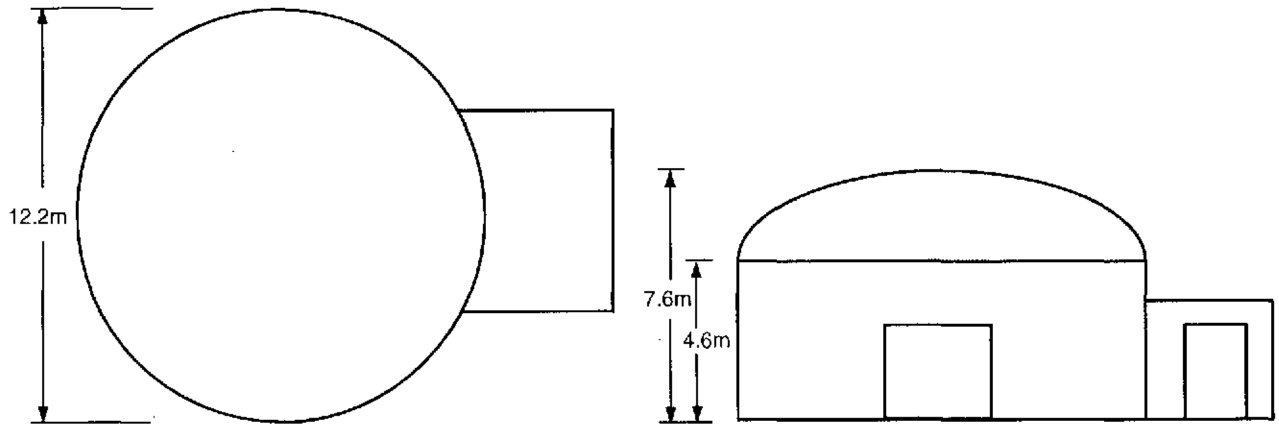

Figure 1. General Plan and Elevation for Test Building

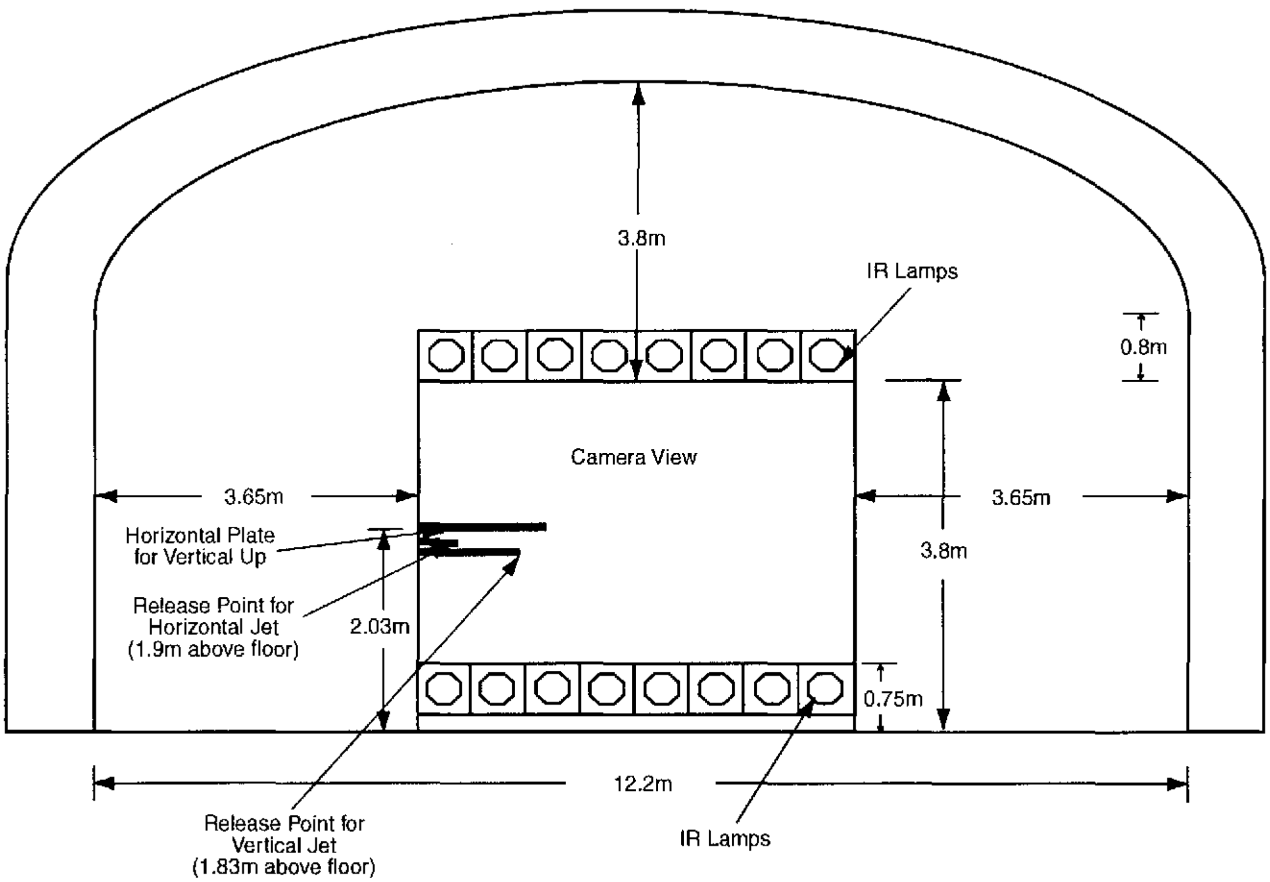

Figure 2. Infrared Camera View Relative to Test Building

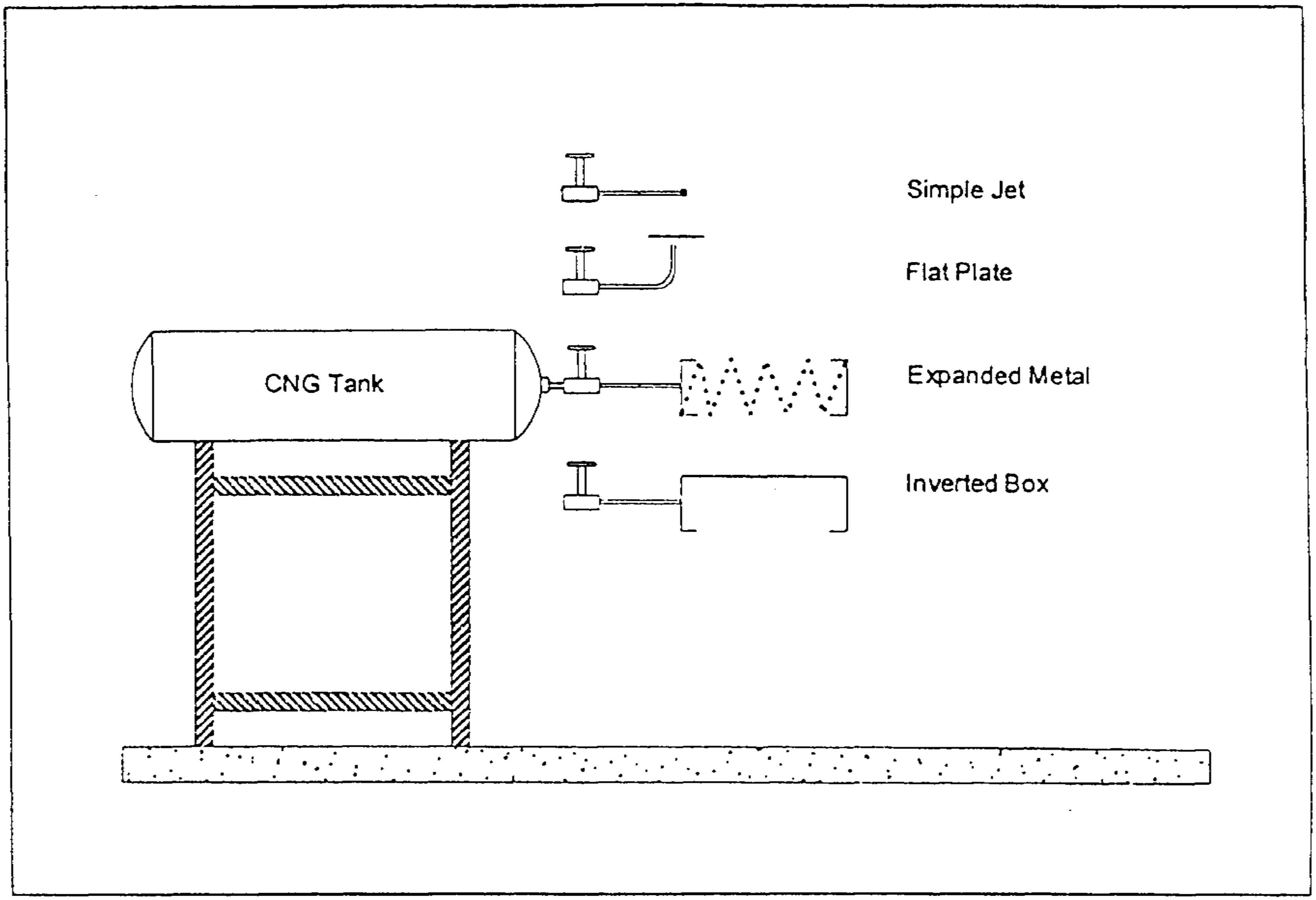

Figure 3. Gas Release Test Configurations

designed to show the location of the natural gas after the bulk of the jet momentum had been lost.

Four release configurations (which are shown in Figure 3) were used:

(1) **Simple horizontal jet** - This was selected for its simplicity.

(2) **Vertical jet directed upward or downward toward a horizontally placed 500-mm-diameter circular plate** - This was selected to represent a jet-like leak that strikes a horizontal surface, such as a bus or a large piece of equipment. The plate created a similar effect as a horizontal release.

(3) **Horizontal jet release with a tortuous path** - This was selected to represent a leak that may occur under the chassis of the vehicle where there are many irregularly shaped components in the path of the leak. Several expanded metal sizes were constructed in a 400-mm-deep box to provide the tortuous path. The box was open on the top and on the bottom. The flow area was 0.131 m^2 on the top and was 0.202 m^2 on the bottom.

(4) **Horizontal jet release directed into an inverted box open only on the bottom** - This model was intended to represent a leak that may occur in the undercarriage or engine compartment of a bus. The box was 400 mm deep with an opening of 0.245 m^2.

Calibrated IR images were obtained for 32 different combinations of release rate, release geometry, and initial pressure. These combinations are listed in Table 1. The duration of gas release for each test was limited by the amount of the CNG supply and by the upper limit of the dynamic range of the IR imagers in the test chamber. Release durations ranged from 20 to 60 seconds, and were often related to the size of the orifice. Small leaks, which may result from poor or loose fuel system fitting connections, were modeled using 0.64-mm and 0.99-mm orifices, which released gas at 10 to 80 g/s. Medium leaks, which are typical of broken or severed fuel lines,

Table 1. Summary of Gas Release Tests Performed

Test	Gas Release Geometry	Orifice Diameter, mm	Initial Pressure, MPa
1	Horizontal jet	0.99	22
2	Horizontal jet	0.99	19
3	Horizontal jet	6.25	16
4	Flat plate, jet up	0.64	22
5	Flat plate, jet up	0.99	21
6	Flat plate, jet up	3.18	18
7	Flat plate, jet up	3.18	12
8	Flat plate, jet up	6.25	23
9	Flat plate, jet up	0.64	24
10	Flat plate, jet up	0.99	19
11	Box with screen	0.99	24
12	Box with screen	3.18	19
13	Box with screen	0.64	24
14	Box with screen	0.99	22
15	Box with screen	6.25	18
16	Box with screen	6.25	7
17	Box with screen	6.25	23
18	Box, open bottom	0.64	24
19	Box, open bottom	3.18	19
20	Box, open bottom	0.99	11
21	Box, open bottom	0.99	24
22	Flat plate, jet up	0.99	24
23	Flat plate, jet up	0.99	22
24	Flat plate, jet up	3.18	19
25	Flat plate, jet up	6.25	11
26	Flat plate, jet up	6.25	22
27	Vertical jet	0.99	23
28	Vertical jet	6.25	21
29	Vertical jet	6.25	14
30	Flat plate, jet down	3.18	23
31	Flat plate, jet down	0.99	17
32	Flat Plate, jet down	3.18	15

were modeled using a 3.18-mm orifice, which released gas at 100 to 200 g/s. Large leaks (which are typical of releases caused by leaks from a high-pressure regulator, a low-pressure solenoid, or a coupling on a fuel manifold, or by a failed PRD) were modeled using a 6.25-mm orifice, which released gas at an initial rate of 300 to 500 g/s depending on the initial pressure.

4. TEST RESULTS

Complete data sets were obtained for each of the 32 tests. However, limited resources have prevented immediate analysis of all of the data. Data from only six of the tests have been post processed. The release conditions for each of those tests appear in Table 2. Analysis of all of the post-processed data revealed the presence of:

- A significant mass of methane vapors, in each test, at the bottom of the camera view for a significant amount of time (e.g., well over 1 minute in Test 8 and nearly 1 minute in Test 3), and
- A significant size region of lesser amounts of gas (i.e., a gap) between the vapor masses at the bottom of the camera view and those at the top of the view.

The only dispersion visible on the VHS videotapes (i.e., two instances of gas directed vertically up to a horizontal plate) showed no rising plume during or immediately after release. All of the released gas appears to have remained below the plate, which (as shown in Figure 2) was 2.03 m above the floor and 1.28 m above the bottom the camera view.

Because the results of the six tests are consistent, the results from one of the tests are presented here as an example for discussion. Since the likelihood of accumulation of flammable gas is greatest following release of large amounts under high pressure, the test involving the highest pressure and the longest duration of release (Test 8) has been chosen as the example. Sequential radiometrically processed color images from Test 8 appear in Figure 4. In Test 8, CNG was released from a 6.25-mm-diameter orifice that was directed vertically up toward a 500-mm-diameter circular plate that was horizontally placed approximately 200 mm above the orifice (see Figure 2 for location of plate and orifice). A horizontal plate redirects the gas, producing the effect of a horizontal release regardless of the direction of the jet when it leaves the

Table 2. Post-Processed Data

Test No.	Release Geometry	Orifice Diameter, mm	Initial Pressure, MPa	Gas Release Duration, Seconds	Release Category
3	Horizontal jet	6.25	16	Not measured	Large
25	Vertical jet up toward flat plate	6.25	11	22	Large
8	Vertical jet up toward flat plate	6.25	23	45	Large
30	Vertical jet down toward flat plate	3.18	23	11	Medium
14	Horizontal jet on screen	0.99	22	22	Small
17	Horizontal jet on screen	6.25	23	16	Large

Small release = 10 to 80 g/s
Medium release = 100 to 200 g/s
Large release = 300 to 500 g/s

orifice. This effect is evident when the dispersive behavior in Test 8 is compared with that from Test 3 (see Figure 5), which involved release from a horizontal jet directed from the same-size orifice used in Test 8. (Test 3 was not chosen as the discussion example because the duration of release was much shorter than that in Test 8 and the initial pressure was much less. The results are included only to show that a vertical jet striking a horizontal plate produces a dispersive pattern that is similar to that produced by a horizontal jet).

4.1 Infrared Images from the Example Test

CNG released during Test 8 is first visible in Figure 4d, which shows layering at the bottom of the camera view. The gas is beginning to layer above the horizontal plate in Figure 4e. The images taken during the release (Figures 4d through 4h) show the jet vertical momentum being converted to horizontal momentum by the plate and show horizontal progression, near the bottom of the camera view, of greater masses of gas with gradual accumulation[4] near the top of the view. Figures 4d through 4k show much higher amounts of CNG below the horizontal plate than above it until 20 to 30 seconds after the release ended. The remainder of the images in Figure 4 show nearly equal amounts above and below the plate. Each image (beginning with Figure 4e) shows lesser amounts of gas (i.e., a gap) between the layers at the top and at the bottom of the camera view.

The calibrated IR images in Figure 4 show, in aggregate, the released CNG moving in the direction of the jet source. The high-velocity upwardly directed vertical jet struck the plate and was deflected horizontally and radially. After passing the boundary of the horizontal plate, the gas appears to have descended gradually to the bottom of the camera view. After accumulating near the bottom of the camera view, the gas appears to have moved horizontally toward the far wall. In subsequent frames, gas appears near the top of the camera view.

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[4]In this context, "accumulation" refers to an increase in concentration.

4.2 Infrared Images from the Comparison Test

The release of CNG in Test 3 is first seen in Figure 5c. The gas jet (i.e., the thin blue stream) traveled nearly half way across the camera view before the gas began to disperse. The largest quantities are below the jet and extend to the bottom of the camera view. (The gas release point for Test 3 was at the far left side of the image area in Figure 5c where the thin blue stream begins.) As in Test 8, each image from Test 3 (beginning with Figure 5d) shows a gap between the layers at the top and bottom of the camera view.

4.3 Effects Produced by the Test Chamber

The conditions inside the test facility differed from those in typical bus garages or maintenance buildings. That is, the shape and size of the test chamber differ from those of a bus facility, the chamber was unheated, and it contained no buses or equipment to alter the movement of the gas. The effects of these differences must be considered before the test results can be properly evaluated.

The near freezing temperature, which ranged from -5° C to +5° C during testing, inside the unheated test building produced a colder environment than would be expected in a typical bus facility. However, the effects of ambient temperature on gas dispersion are expected to be small. Heat input, on the other hand, may be a significant variable. A radiant heat source, such as the twenty-four 300-watt quartz halogen lamps used to produce the IR radiance needed for each test, could heat the gas and enhance the positive buoyancy effects, causing the gas to rise more quickly. Thus, the IR lamp radiant energy absorbed by the gas under the test conditions could tend to understate the results, i.e., show less accumulation at the bottom of the camera view than would be expected near the floor in a bus garage or maintenance facility. The smaller size of the building could also tend to understate the results. A wider building would allow the gas to remain near the floor longer, since it would have to travel farther before being redirected by a wall. Obstacles (e.g., buses and equipment) could alter the flow of released gas. The shape, size, and locations of the obstacles would determine the redirected flow.

5. CONCLUSIONS

The gaps between the natural gas layers (shown in Figures 4 and 5) at the bottom of the camera view and those at the top of the camera view suggest that the gas initially present below the source of (or below an obstacle deflecting) a high-pressure horizontal (or downward) release will not rise immediately as a buoyant plume. Rather, the test results suggest a splashing dispersion, possibly resulting from recirculation caused by the wall and ceiling of the test chamber. The absence of evidence of a rising plume combined with the masses of methane vapors that appear to have persisted near the bottom of the camera view suggest that natural gas when initially released from a high-pressure source is at least as dense as air. The gradual downward deflection of the gas stream from the horizontal plate in Test 8 also indicates neutral, or possibly negative, buoyancy rather than specular deflection of the gas from the plate. This apparent neutral buoyancy combined with the layering of gas at the top of the IR camera view (which is well below the ceiling of the test chamber) suggest that gas released horizontally from a high-pressure source near the floor will remain in various locations of transit buildings long enough to pose a fire hazard.

It can be concluded that, following a downward or horizontal release of CNG near the floor, a fire hazard could exist in the parts of transit facilities that are not normally regarded as areas of concern. Thus, personnel working in facilities where CNG buses are fueled, stored, or maintained should be advised that the risk of spark ignition or asphyxiation could exist in any area of the building following a high-pressure release through an orifice not greater than 6.25 mm in diameter.

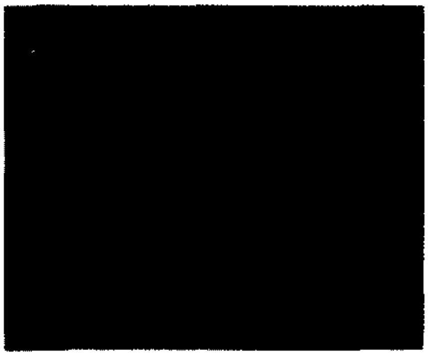

Figure 4a. t=0 seconds

Figure 4b. t=10 seconds

Figure 4c. t=20 seconds

Figure 4d. t=30 seconds

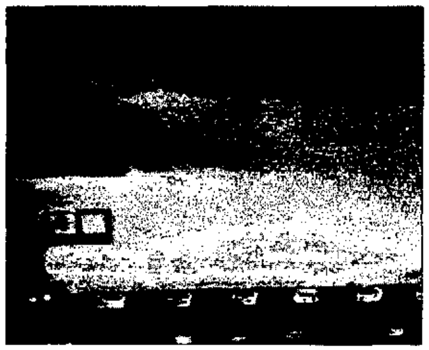

Figure 4e. t=40 seconds

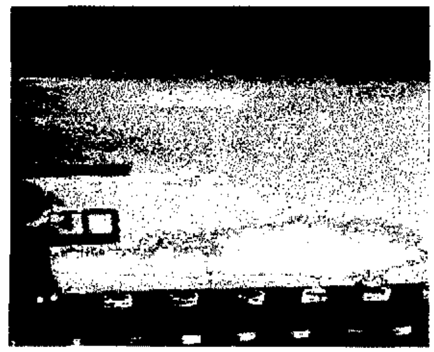

Figure 4f. t=50 seconds

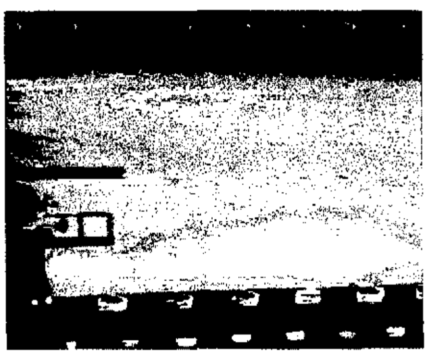

Figure 4g. t=60 seconds

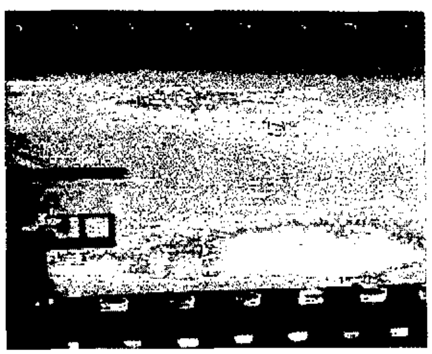

Figure 4h. t=70 seconds

Natural Gas Quantity Color Key

> than 200,000

150,000 - 200,000

100,000 - 150,000

50,000 - 100,000

< than 50,000

Measurements are parts per million meters (ppm m).

Figure 4. Sequential Infrared Images from Test 8

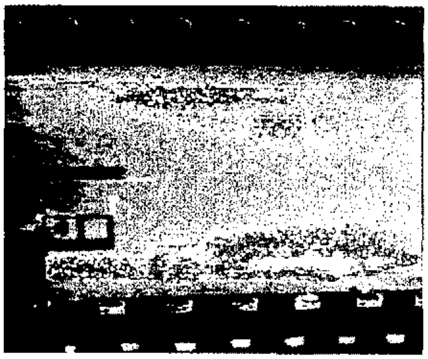

Figure 4i. t=80 seconds

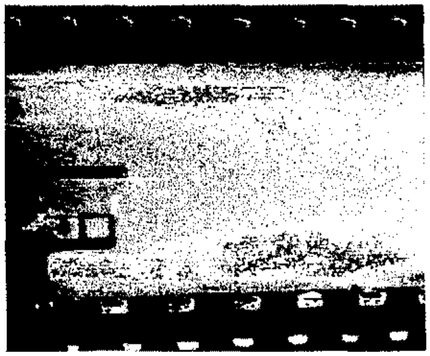

Figure 4j. t=90 seconds

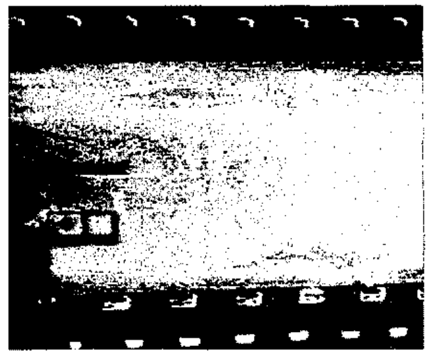

Figure 4k. t=100 seconds

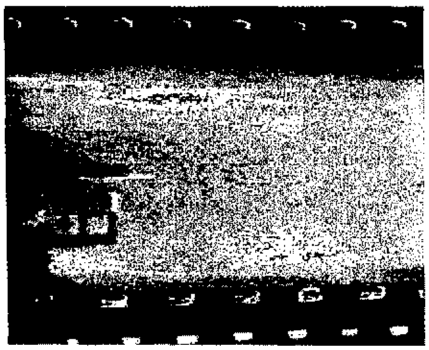

Figure 4l. t=110 seconds

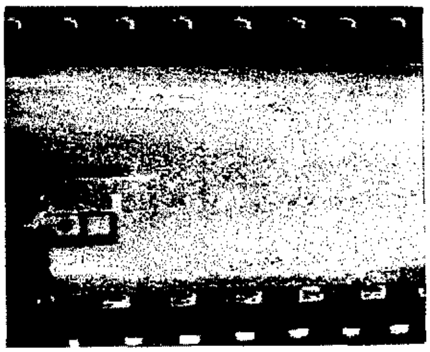

Figure 4m. t=120 seconds

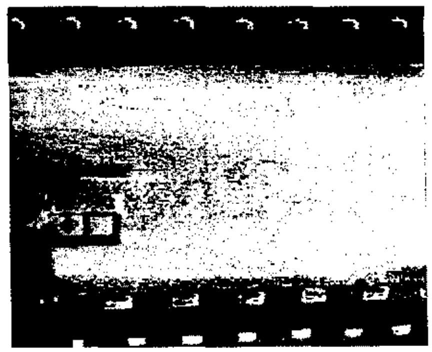

Figure 4n. t=130 seconds

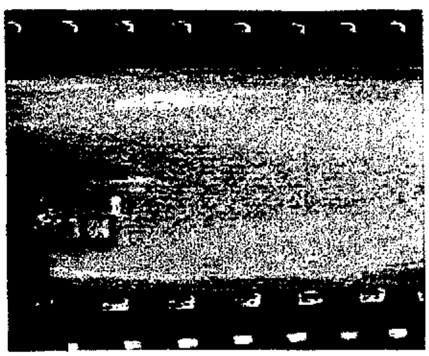

Figure 4o. t=140 seconds

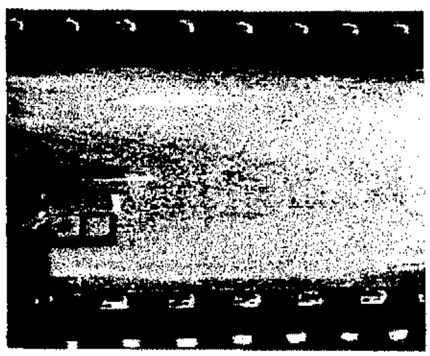

Figure 4p. t=150 seconds

Natural Gas Quantity Color Key

- > than 200,000
- 150,000 - 200,000
- 100,000 - 150,000
- 50,000 - 100,000
- < than 50,000

Measurements are parts per million meters (ppm m).

Figure 4. Sequential Infrared Images from Test 8 (continued)

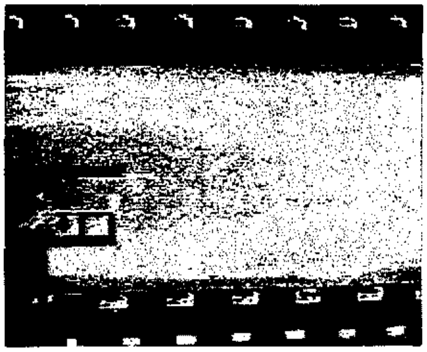

Figure 4q. t=160 seconds

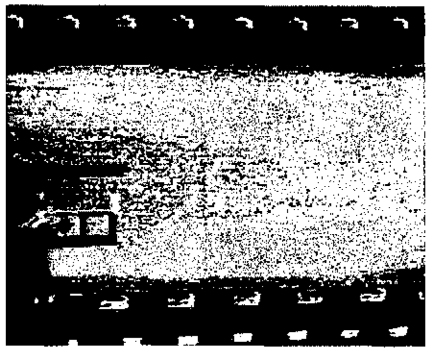

Figure 4r. t=170 seconds

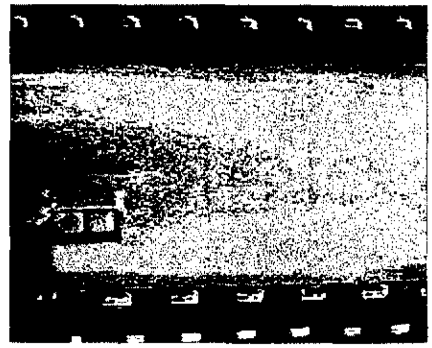

Figure 4s. t=180 seconds

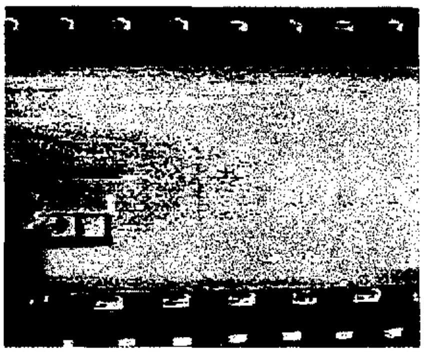

Figure 4t. t=190 seconds

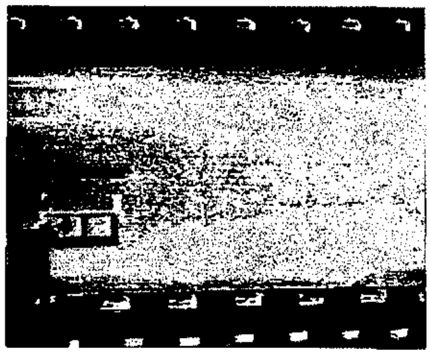

Figure 4u. t=200 seconds

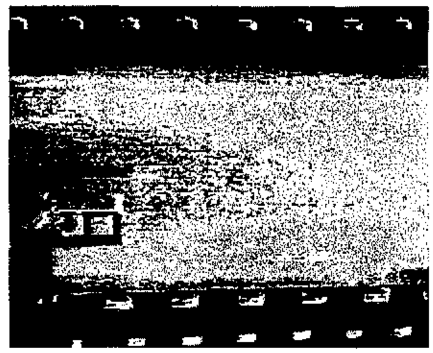

Figure 4v. t=210 seconds

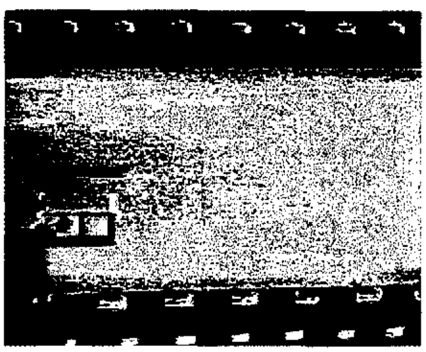

Figure 4w. t=220 seconds

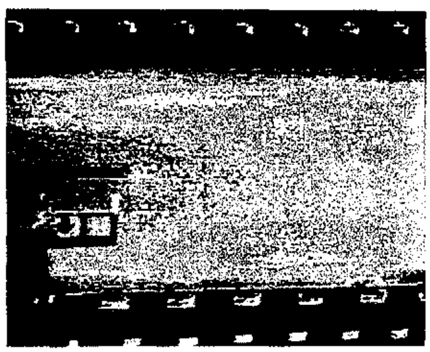

Figure 4x. t=230 seconds

Natural Gas Quantity Color Key

- > than 200,000
- 150,000 - 200,000
- 100,000 - 150,000
- 50,000 - 100,000
- < than 50,000

Measurements are parts per million meters (ppm m).

Figure 4. Sequential Infrared Images from Test 8 (continued)

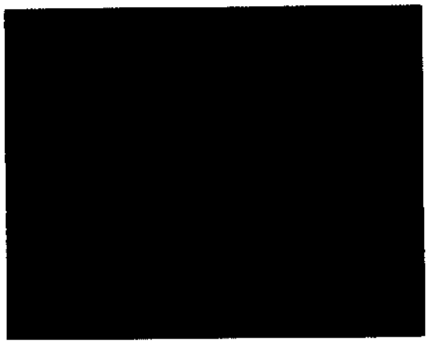

Figure 5a. t=0 seconds

Figure 5b. t=10 seconds

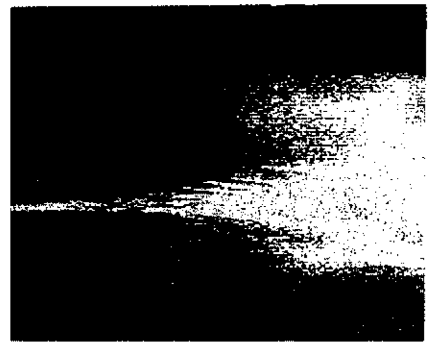

Figure 5c. t=20 seconds

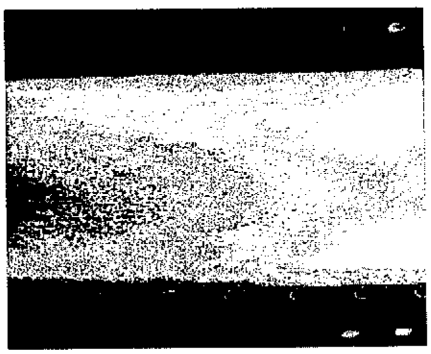

Figure 5d. t=30 seconds

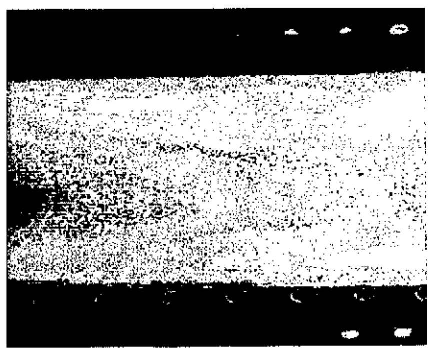

Figure 5e. t=40 seconds

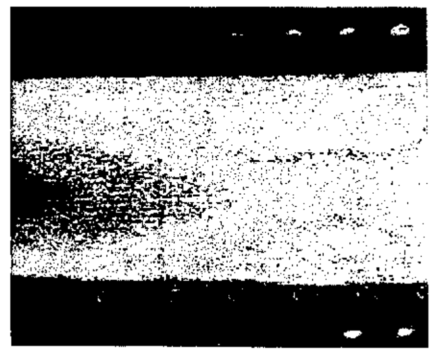

Figure 5f. t=50 seconds

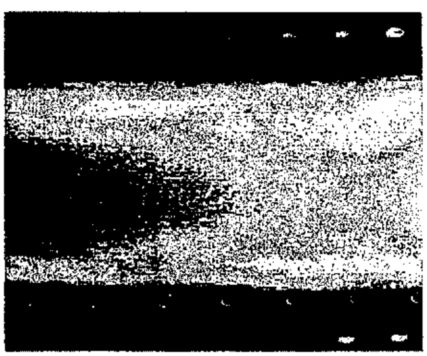

Figure 5g. t=60 seconds

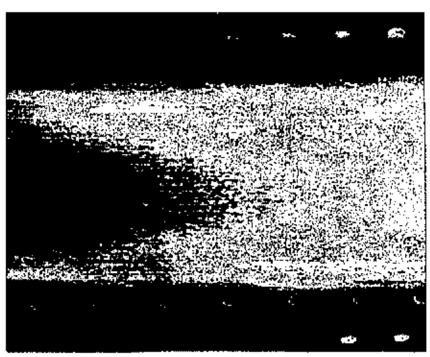

Figure 5h. t=70 seconds

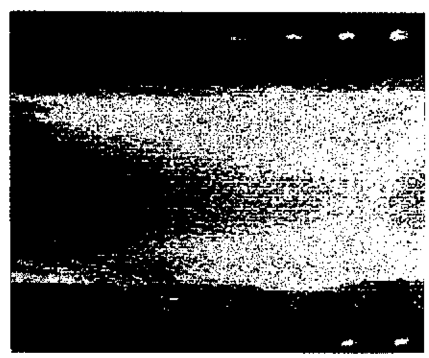

Figure 5i. t=80 seconds

See Figure 4 for Natural Gas Quantity Color Key.

Figure 5. Sequential Infrared Images from Test 3

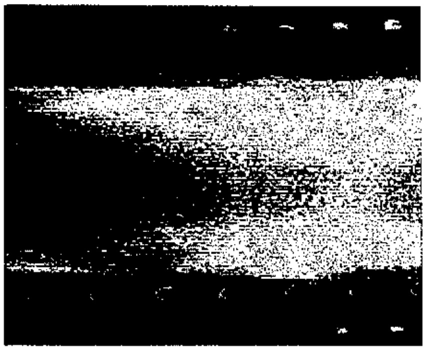

Figure 5j. t=90 seconds

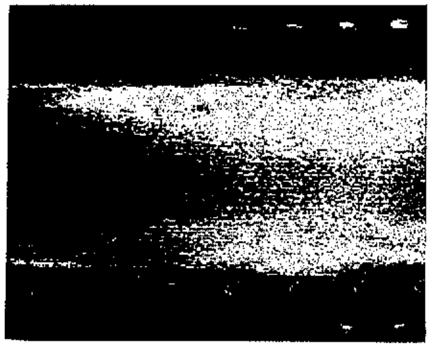

Figure 5k. t=100 seconds

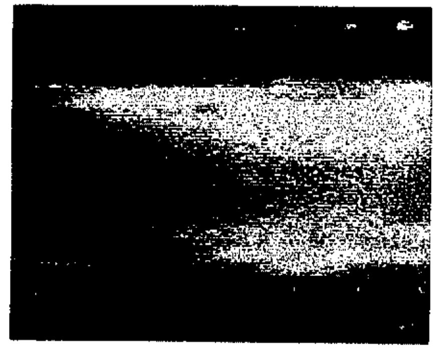

Figure 5l. t=110 seconds

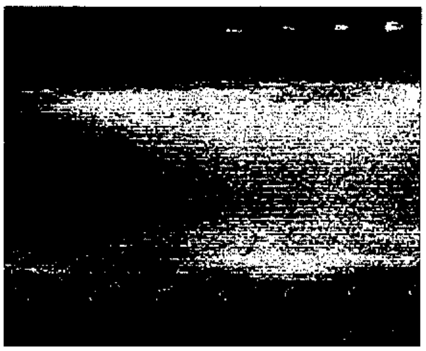

Figure 5m. t=120 seconds

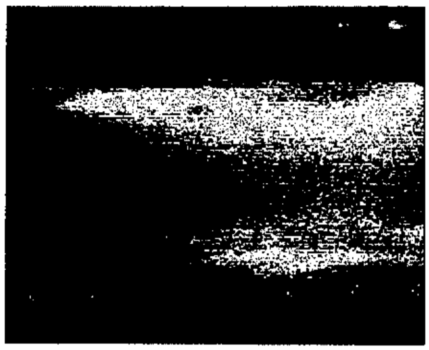

Figure 5n. t=130 seconds

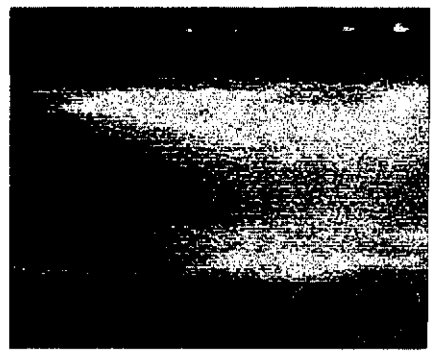

Figure 5o. t=140 seconds

Figure 5p. t=150 seconds

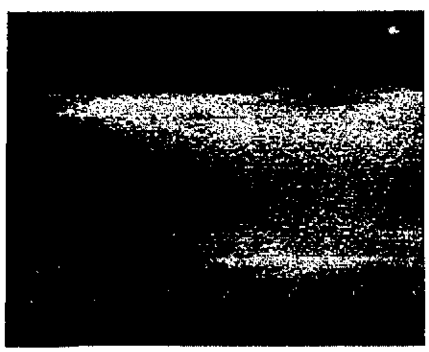

Figure 5q. t=160 seconds

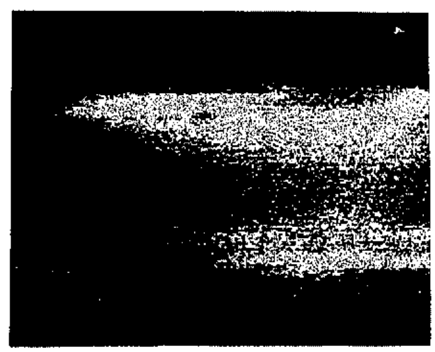

Figure 5r. t=170 seconds

See Figure 4 for Natural Gas Quantity Color Key.

Figure 5. Sequential Infrared Images from Test 3 (continued)

APPENDIX A

INFRARED IMAGING
OF
COMPRESSED NATURAL GAS RELEASES

Prepared for

Federal Transit Administration
Office of Engineering

21 November 1995

Prepared by

Michael J. Murphy and John K. Klosterman

Battelle
. . . Putting Technology To Work

INFRARED IMAGING
OF
COMPRESSED NATURAL GAS RELEASES

Michael J. Murphy and John K. Klosterman

1 Introduction

The use of compressed natural gas (CNG) as a fuel for transit buses is becoming more widespread. Transit buses carry up to 350 kg of fuel, and because compressed natural gas fuel is stored at a high pressure (typically about 25 MPa), fuel system failures can result in the rapid release of a substantial quantity of natural gas.

In fact, a number of accidental releases of CNG from transit buses have already occurred. Several such releases were due to pressure relief device (PRD) failures. It is expected that as the CNG bus fleet grows and ages, additional fuel system failures of various types will occur. If a transit bus fuel system failure occurs while the bus is inside a transit facility building, a fire or explosion may occur if the released gas reaches an ignition source.

Because of the possibility of unexpected natural gas releases from CNG-fueled bus fleets, transit facilities must be designed to minimize the presence of ignition sources in areas where a flammable natural gas plume could be present. Therefore, designers and operators of transit facilities for natural gas buses have raised questions about the extent and location of natural gas plumes that would result from fuel system failures.

In order to address these issues, a series of experimental tests was conducted in which actual releases of compressed natural gas were made inside a building using several different initial pressures, leak rates and leak geometries. The initial pressures, the leak rates, and the leak geometries were intended to match or model transit leak scenarios.

1.1 Scope of Current Work

Infrared imaging was used to visualize the shape and extent of the natural gas cloud resulting from CNG releases inside a building. Unlike classical instrumental gas analysis techniques, the infrared absorption method yields information on the presence of natural gas throughout the field of view. The infrared technique was based upon the well-known Beer's Law for absorption of light by chemical species.

The use of classical gas analysis instrumentation for this purpose would require a three-dimensional array of sensors to locate the gas cloud. To adequately track the released gas, such sensors would need a response time of one second or less. And, even with a grid as large as one-half meter, an array of over 100 sensors would have been required to adequately map the space. Not only would such a sensor array be costly, but the presence of so many sensors could disturb the flow field.

1.2 Objectives

Specifically, the objectives of this proposed work were as follows:

- To gain an insight into the shape and extent of the natural gas plumes that may be formed from various CNG leak rates and leak geometries.
- To explore the effects of initial pressure, gas release rate, and leak geometry on the shape and extent of these plumes.
- To observe the gross motion of natural gas plumes from CNG fuel system leaks.

1.3 Results

Calibrated infrared images were obtained for 32 different combinations of compressed natural gas release rate, release geometry, and initial pressure,* These radiometric images were taken at 10-second intervals by a digital camera looking across the gas release axis. Simultaneous analog data were also taken at 20 or 30 frames per second by infrared and visible video cameras looking both across the gas release axis and down on the gas release.

Due to the significant amount of effort required for post-processing of the digital radiometric infrared images and the limitations of project resources, partial data reduction could be accomplished for only six of the 32 tests, chosen to obtain a range of gas release geometries and flow rates. For these six cases, successive infrared image frames are presented as false color images.

The data from the analog cameras have not been analyzed or processed. These cameras could provide additional information on the motion of the gas and the spatial extent of the gas cloud. Frames from these cameras could be digitized to provide additional information simultaneous with the radiometric infrared frames presented in this report.

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* See Appendix A for complete listing of gas release test configurations.

The results of the investigation showed that for the six cases investigated, gas momentum was an important factor in determining the initial location of the natural gas plumes. For the geometries studied, this initial jet action was followed by a general dispersion of natural gas. Areas of high concentration pathlength product* were seen at various locations within the field of view and some such areas persisted in the same location over time. After the gas releases ceased, we did not see coherent bodies of gas moving either upwards or downwards during the 260 seconds that infrared data was being acquired. These results are consistent with the model assumptions of Rasouli and Williams[1] that CNG releases are neutrally buoyant and with the experimental results of McRae and Altpeter[2] that natural gas leaks displayed no major bouyancy traits.

1.4 Limitations

This work was performed in a building of modest size. Although the building size was comparable to some transit indoor fueling lanes, it was small in comparison to the size of transit bus storage facilities. Additional work is needed to characterize the gas release behavior in larger facilities. Also, the duration of the gas releases was limited by the ability of the building to absorb long releases without saturating the IR camera's response.

The gas release geometries tested represent only a small subset of the configurations of interest. For example, several failures of PRDs on buses with roof-mounted fuel tanks have occurred; this geometry was not included in the current work.

The two-dimensional concentration pathlength data are not sufficient to fully describe the three-dimensional shape of the gas cloud. Analysis and comparison of the data from infrared cameras at different locations could provide some additional information on the three-dimensional shape of the gas release cloud.

Also, not all data collected during the test releases could be fully analyzed within the resources available. We feel that further data analysis will reveal additional insights.

2 Equipment and Apparatus

2.1 Test Building

2.1.1 Building Shape and Dimensions

The tests were performed in Battelle's West Jefferson Ohio JS-10 high explosives test facility. The test building was a circular domed building approximately 12 meters in diameter

* See concentration pathlength product definition and discussion in Section 2.5.1, below.

with a maximum interior height of approximately 7.6 meters. The total interior volume was about 475 m^3. Because the building was constructed for testing explosive devices, the construction was robust. The walls and ceiling were constructed of reinforced concrete about 0.6 m thick. Figure 1 shows plan and elevation views of the test building.

During the gas release tests, the CNG gas release rig, the lamps for infrared illumination, the reflective back panels, and the infrared cameras were located within the test building. Personnel and data acquisition equipment were located in a control room attached to the outside wall of the test building.

2.1.2 Building Conditions

The test building was not heated and was in equilibrium with the average outdoor temperature. The thermal mass of the thick walls made the building resistant to temperature changes. The inside air temperature was recorded prior to each test run. These temperatures ranged from about -5 to 5 C during the week the tests were conducted.

During the tests, all openings to the building were blocked, so there was no source of air flow. Tests for air currents were made two ways. The first was the use of a vane anemometer sensitive to 0.1 m/s. This instrument showed no measurable air flow prior to the test runs. The second test for air currents was the release of small puffs of propane gas. These puffs could be seen and tracked with the infrared cameras. The movement of these puffs, as well as that of subsequent natural gas releases, showed that, with the exception of small upward convection currents in the immediate vicinity of the quartz lamps, the speed of air flow inside the building was less than 0.01 m/s, and there were no significant air currents in any direction.

2.2 Compressed Natural Gas

2.2.1 Natural Gas Supply

The supply of compressed natural gas was obtained from a commercial CNG refueling station in Columbus, Ohio operated by Columbia Gas of Ohio. This CNG station had a gas drier on the outlet of the compressor. The CNG was transported to the test site in trailer-mounted gas bottles and loaded into the test cylinder as necessary.

A range of initial tank pressures was used, depending on the status of the gas supply available. Initial pressures were generally 20 to 24 MPa, except for tests in which a lower initial pressure was desired.

2.2.2 Natural Gas Composition

The results of a gas chromatographic analysis of the natural gas composition are shown in Table 1. Table 2 shows some calculated properties of this gas.

Table 1. Natural Gas Analysis

Constituent	Volume Percent
methane	95.44
ethane	2.293
propane	0.405
isobutane	0.088
n-butane	0.094
isopentane	0.034
n-pentane	0.026
hexanes	0.096
nitrogen	0.703
carbon dioxide	0.823

Table 2. Calculated Properties of Natural Gas

Property	Value
Density	0.716 kg/m^3*
Specific gravity	0.586*
Molecular weight	16.97

* At standard conditions of 15.6 C and 101.3 kPa.

2.3 CNG Release Apparatus

Figure 2 shows an overall view of the CNG release test apparatus. Each portion of the apparatus is discussed separately below.

2.3.1 Gas Cylinder

The CNG was contained in a CNG Cylinder Corporation Model 1350 composite reinforced aluminum cylinder. This cylinder is 330 mm in diameter and 1270 mm long. The cylinder had a water capacity of 74.4 liters. This cylinder is the same type and diameter as the fuel tanks used on some transit buses, but somewhat shorter.

2.3.2 Control of Gas Flow

The duration of flow of gas was manually controlled by a full-flow pneumatic ball valve. The data acquisition record of cylinder tank pressure was used to ascertain the exact duration of the gas releases.

The rate of flow was determined by an orifice located at the end of the tube from the gas supply cylinder. Four orifice diameters were used. Table 3 lists the orifice drill sizes and diameters.

Table 3. Orifices Used to Control CNG Release Rates.

Orifice Size	
Drill Size	**Diameter, mm**
No. 72	0.64
No. 61	0.99
1/8 inch	3.18
Letter D	6.25

2.3.3 Gas Release Geometry

High pressure jets have substantial forward momentum, so a jet of compressed natural gas will tend to travel in the direction of the release until the forward momentum has been lost. The goal of these experiments was to show the location of the natural gas after the bulk of the jet momentum has been lost.

In CNG bus fuel system gas releases, there may be other components, equipment, or building surfaces nearby which can deflect or intercept the flow of gas. While the number of possible configurations and orientations is essentially infinite, four specific configurations were chosen to model the rest. All these configurations are shown in schematic form in Figure 2. All vertical and horizontal portions of the jets and jet targets were leveled to be within one-half degree of angle from true vertical or horizontal. The design of the test configurations was necessarily robust as the jet reaction force could be as much as 1000 N.

- The first model configuration was a simple horizontal jet. This case was chosen for simplicity.

- The second model configuration was a vertical jet directed upwards or downwards towards a circular horizontal flat plate. This configuration is intended to represent a jet-like leak that strikes a horizontal surface. The plate was 500 mm in diameter.

- The third model configuration was a horizontal jet release with a tortuous path. This configuration is intended to represent a leak that might occur inside the vehicle where there are many irregularly shaped components in the path of the leak. For the experimental tests, three sizes of expanded metal were used to provide a tortuous path inside a square box with an open top and bottom. The box was 400 mm deep; the flow areas through the top and bottom of the box were 0.131 and 0.202 m^2, respectively.

- The fourth model configuration was a horizontal jet directed into an inverted box closed at the top. This configuration was intended to represent a leak that might occur in the undercarriage or engine compartment of a bus. The box was 400 mm deep; the flow area through the bottom of the box was 0.245 m^2.

2.4 Instrumentation

2.4.1 Pressure

The cylinder pressure was measured by an Omega Model PX931 strain gage pressure transducer. The transducer had a rated accuracy of 0.1 percent. Immediately after the test runs the transducer was calibrated by the Battelle instrument lab to pressure standards traceable to NIST. The results of that calibration were used for all data analysis.

2.4.2 Temperature

Temperature inside the tank, in the jet, and in the room was measured with type K thermocouples. The thermocouple choice represented a compromise between the desire for rapid temperature response and the need to withstand high pressures and high flow velocities.

- The thermocouple inside the tank was an Omega model GKMQSS type K thermocouple with a grounded, 1.6 mm inch diameter stainless steel sheath. The tip of the thermocouple was located about 120 mm from the closed end of the tank.

- An Omega SA1-K fine-gage adhesive-backed thermocouple was located on the tank wall, near the outlet of the tank.

- Another 1.6 mm diameter sheathed thermocouple (same model as used inside the tank) projected about 8 mm through the flat circular plate target. To avoid drilling through the web of the steel angle support, this thermocouple was located about 20 mm off from the center of the plate.

- A 1.0 mm diameter sheathed thermocouple was tied to the expanded metal screen in the tortuous path target and was located along the centerline of the jet.

2.4.3 Combustible Gas Monitor

To ensure that the experimental staff did not enter the building when a flammable mixture of natural gas and air was present, a Bacharach Model Sniffer 301 combustible gas detector was used to monitor the natural gas concentration in the building space. This analyzer was operated remotely. The on-board sample pump was used to draw air samples through a 10 mm ID polyethylene tube which ran from the instrument room to a location within the test building about 3 meters from the test stand and about 1.5 meters from the floor. This location is indicated with a solid triangle in Figure 4.

2.4.4 Data Acquisition

The output of the pressure transducer and the two or three thermocouple channels were recorded with a multi-channel datalogger. This datalogger recorded values every 650 milliseconds throughout the release. These data were used to verify the duration of the release and the beginning and ending pressures.

2.5 Infrared Imaging and Radiometry

2.5.1 Principles

Natural Gas Absorption Bands. Mid-wave infrared (MWIR) and long-wave infrared (LWIR) imagers and imaging radiometers were used to detect the gaseous flow field of the natural gas jets and to observe the subsequent nature of the flow and mixing of the gas after the flow. The MWIR instruments responded to 3-5 micrometer (μm) infrared radiation; the LWIR instruments to 8-13 μm radiation. Both of these versions of the infrared imaging technique exploit the infrared spectral absorptivity of natural gas. All the paraffin hydrocarbons in natural gas, including methane, have a C--H stretching vibration that absorbs infrared energy in the 3 to 4 micrometer range.

The atmosphere has a very transmissive spectral "window" in both the MWIR and LWIR bands. Since natural gas absorbs radiance at wavelengths from about 3.3 to 3.5 μm, as well as 7.7 to 8.0 μm in the LWIR, natural gas may be detected by measuring the extinction of a high IR radiance backplane as the radiance is transmitted through the gas to the aperture of the imaging instrument. Figure 3 shows the spectral transmission of methane, the principal constituent of natural gas, as reported by the MODTRAN gaseous extinction database code.

Concentration Pathlength (CL) Measurements. The infrared cameras looked through a path from the camera to the back panels. This path was about 10 meters long. Any natural gas located along this 10-meter path absorbed infrared radiation. The resulting two-dimensional images show only the concentration pathlength product. No information can be obtained from the images about the location or distribution of the gas along the pathlength. For this reason, the description of the results must be stated in concentration pathlength product terms.

Alternatively, the concentration pathlength product may be thought of the total mass of gas contained in an imaginary tube as wide and as high as one pixel and as long as the pathlength. Thus, if the CL product is high in a portion of the image, one may infer that the total mass of gas was greater in that portion.

In some cases the CL product information can be combined with a physical intuition about the fluid flow to draw a conclusion about the location of the gas. For example, a high CL product directly in front of the jet is undoubtedly because the gas is issuing from the jet. However, other cases are more ambiguous and in general no conclusion can be drawn from the CL pathlength data on the images present in Appendix B concerning the location of the gas along the horizontal path.

Simultaneous analysis of the IR data from the downlooking camera could provide additional insight into the location of the gas along the horizontal pathlenghs. However, such analysis could not be accomplished within the resources of the project.

2.5.2 Apparatus

Infrared Source. To perform these experiments, a large diffuse IR reflective back board was constructed. To create the high IR radiance, specifically MWIR radiance, the back panels were illuminated with arrays of 300 watt quartz halogen lamps. Because the quartz envelopes on the lamps transmit the 3200 kelvin tungsten filament radiance out to parts of the MWIR spectral bands, up to and including the methane MWIR absorption band, these quartz halogen lights produced large amounts of appropriate MWIR radiance.

The two IR-reflective rectangular back panels were each 6.1 meters wide by 3 meters high. One panel was mounted vertically behind the gas release apparatus; the other panel was located on the floor underneath the axis of the jet. The surface of the back panels was chosen to be both very reflective, in order to make the panels very bright in the mid-wave infrared, as well as very diffuse, in order to make then as uniformly illuminated as possible. Each back panel had twenty-four lamps illuminating its surface. The position and pointing vector of each lamp were adjusted to efficiently achieve a high level of IR "brightness" as well as uniformity of surface radiosity across the width of the back panels.

Infrared Imaging Equipment. Several IR imagers were operated during the gas release experiments. Some of the imagers were 20 and 30 Hz frame rate devices, non-radiometrically calibrated and only recorded using S-VHS analog magnetic tape. These imagers worked very well for recording the relative infrared intensity during the very active period of very vigorous jet action.

Calibrated MWIR and LWIR imaging radiometers were used to digitally record the calibrated broad band MWIR and LWIR measurements of the experiment. The slower frame rates of these calibrated imagers allowed them to provide a more sensitive, accurate and physically meaningful field value for each pixel in each of the images.

These calibrated imagers scanned at the rate of one frame per second and were able to resolve the quantity of infrared radiation received into one of 256 levels. They were used to record a one second frame of the infrared image every 10 seconds. These images, as well as all imager settings were recorded to digital media. Data from both a crosslooking imager station and a down looking imager station were recorded. The down looking station was elevated at 5.2 meters above the level floor, looking down at an illuminated IR-reflective backboard.

Specifically, the following instruments were operated to gather image data in these experiments:

- Two Inframetrics InfraCam PtSi FPA MWIR imagers
- Amber Radiance InSb FPA MWIR imager
- Mikron TH1101 HgCdTe LWIR calibrated imaging radiometer
- Mikron TH1102 InSb MWIR calibrated imaging radiometer
- Cohu 0.8 - 1.1 um near IR imager
- Cohu visible imager
- Black and white television camera

In addition to the imaging sensors, a variety of recording equipment and data communications equipment was used to capture the data. A sketch of the test setup and the locations of the imager stations is given in Figure 4.

3 Test Procedures

3.1 Duration of Release

The duration of the release was limited by the finite nature of the CNG supply (trailer-mounted cylinders) and by the fact that once the gas concentration in the building reached the upper limit of the dynamic range of the infrared imagers, releasing additional gas did not yield additional data.

3.2 Rate of Release

Due to the variety of possible CNG fuel system leak scenarios, as well as the range of possible initial pressures, a wide range of fuel system leak rates is possible. Four orifice sizes were chosen to represent three postulated gas release scenarios.

Small leaks. Small leaks are those which might result from poor or loose fuel system fitting connections. Previous work conducted on behalf of FTA[3] has provided some guidance as to the size of such leaks. Experimental measurements with leaking fittings have shown leak rates that range from very tiny to up to about 80 g/s. The 0.64 and 0.99 mm diameter orifices produced flow rates in this range.

Medium leaks. Medium leaks are those which might result from a broken or severed fuel line. CNG-fueled vehicle fuel lines usually range from 6.2 to 12.5 mm ID. If such a line were severed, typical resulting natural gas flow rates would be about 100-200 g/s. The 3.18 mm orifice produced a flow rate in this range.

Large leaks. Large leaks are those which might result from a PRD failure. For such a failure, flow rates have been estimated to be around 500 g/s. The 6.25 mm orifice produced a flow rate in this range.

Severe leaks with still larger flow rates might result from breaking a cylinder valve off at the neck. This might happen after a collision that impacted the fuel tanks. For this scenario, leak rates could range up to 5 kg/s. This scenario was considered much more improbable and was not included in the scope of this study.

3.3 Data Reduction

Post-processing of the digital radiometric IR image data allowed the radiometric data to be transformed into a Concentration Length (CL) product along the line of sight of each image pixel. This CL product, measured in parts per million times meters (ppm·m), expresses the average amount of gas concentration along the distance from the imager aperture to the illuminated back panel. The relative pixel to pixel error associated with the computation of CL product is on the order of 10 percent.

3.4 Image Rendering

The results are presented as false color images in which different concentration pathlength products correspond to different colors on the image. Each image has a color scale on the left side that is related to the concentration range shown. The imagers were capable of sensing 256 different levels of infrared radiance. These data are mapped into 207 false colors, from black to white, on the images. However, because of the relative error level associated with with the computation of the CL product, adjacent colors may not represent significant CL product differences.

The scale range was chosen such that the range of colors showed the greatest amount of visual information. The concentration pathlength product associates with the "highest" color on the scale is listed in the image caption. The maximum observed concentration pathlength product was generally much greater than the scale maximum. If the scale maximum color had been set to the observed maximum, much less detail would have been visible in the areas of the image where the concentration pathlength was less. The color scale is linear. For example, if the scale maximum is 2×10^5 ppm·m (200,000 ppm·m), then the color half way down the scale is equal to half the scale maximum, or 100,000 ppm·m and the color 1/10 of the distance up the scale is equal to one tenth of the scale maximum, or 20,000 ppm·m.However, the relative error associated with the computation of CL product is on

4 Results

4.1 Organization of Results

A complete list of tests performed and associated experimental parameters is presented in Appendix A. Due to resource limitations not all test data could be analyzed. Data from six of these tests was selected for post processing.

Table 4 lists the test numbers, the type of gas release geometry, orifice diameter, initial pressure, test duration, and the flow rate scenario for these six tests. Figure 5 shows a typical radiometrically processed image.

Complete time sequence sets of images of the six gas releases are contained in Appendix B. Each series of image frames in Appendix B is identified by an image caption listing the test number and the CL scale maximum. The frames show the infrared scans made at 10-second intervals. Often the first frame or frames is blank, indicating that the gas release had not yet begun. The uniform black color of these blank frames is an indication that the radiometric data reduction procedures produced a stable result.

Table 4. Images Included and Associated CNG Release Conditions.

Test No.	Release Geometry	Orifice Diameter, mm	Initial Pressure, MPa	Gas Release Duration, sec	Leak Scenario (Approx. Flow Rate)
3	Horizontal jet	6.25	16	Not meas.	Large (300-500 g/s)
25	Vertical jet up towards flat plate	6.25	11	22	Large (300-500 g/s)
8	Vertical jet up towards flat plate	6.25	23	45	Large (300-500 g/s)
30	Vertical jet down towards flat plate	3.18	23	11	Medium (100-200 g/s)
14	Horizontal jet on screen	0.99	22	22	Small (20-80 g/s)
17	Horizontal jet on screen	6.25	23	16	Large (300-500 g/s)

4.2 Description of Gas Release Results

4.2.1 General

All the gas releases proceeded smoothly. No interruption or irregularity in flow due to frost or gas condensate in the high pressure piping or the rate-controlling orifice was observed. However, during a few runs the pressure and temperature data channels did not produce data.

It is believed that static electricity buildup from the rapidly flowing gas adversely affected these low level circuits.

In general, the released gas could not be seen in either the visible or the near IR. Figures 6, 7, and 8 show simultaneous visible, near IR and MWIR images of a gas release. In Figures 6 and 7 there was no visible indication of gas, except some condensation between the jet orifice and the flat plate. The MWIR image shown in Figure 8 is completely opaque, because light in that range was absorbed by the natural gas.

However, during some tests the ambient conditions were such that the relative humidity in the test building was at or near 100 percent. Under these conditions visual observation showed the formation of ice or water fog during the time gas was flowing; this fog dissipated within a few seconds after the gas flow stopped. The images in Figures 9 and 10 show a test under 100 percent relative humidity conditions. Both images are in the visible spectrum. Figure 9 shows conditions while the gas had been flowing for about seven seconds; fog may be seen flowing both upwards from the top of the box and downwards to the floor. The image in Figure 10, taken about 10 seconds after the gas flow ceased shows the fog has largely dissipated, although there is still some slight fog observed below the cold steel box.

4.2.2 Infrared Images

A short description what was observed on the false-color images of each of the CNG releases follows. Note that the time scale listed for each frame starts when data recording was initiated and does not correspond to the length of time since the release started. Also, note that on each image there is a black strip at the top and bottom which is beyond the vertical extent of the back panels and does not contain valid data. On some frames the rows of quartz lamps may be seen in this area.

The extensive blue region seen on some images is not a background, but represents a region of relatively low CL product. In some images various shades of blue are present, though they may be difficult to discern with the eye.

All of the tests analyzed contained a maximum CL product value at some location on some frame on the order of about one million. The false color scale was chosen to maximize the range of data displayed and so the maximum on the false color scale is generally much less than the maximum CL product value observed.

Horizontal jet (Test 3). The initial frames show the pre-release conditions. After the release starts the gas travels mostly horizontally and slightly downwards. The portion of the building within the field of view begins to fill with gas and an area of increased concentration pathlength product (CL), representing an increased mass of gas, may be seen both above and below the centerline of the jet. There appears to be more gas located above the jet than below the jet, however the field of view is not large enough to show the full extent of the gas cloud. In the remaining fames, the basic pattern appears similar.

Flat Plate (Test 25). The first frame shows the jet just beginning to strike the flat plate. After striking the horizontal plate, the jet momentum is directed horizontally outward. The gas plume from the jet goes downward after leaving the plate, and gas starts to accumulate in the lower portion of the field of view (see frames t=10 and t=20). As time progresses, the green area of higher CL product (average concentration) in the lower part of the image decreases and the entire image is filled with blue, indicating gas is present, but at a lower average concentration.

Flat Plate (Test 8). The first three frames are prior to the gas release. Then the gas release begins and gas accumulates in the part of the building shown in the lower part of the field of view. The release continues and the amount of gas shown in the lower part of the field of view continues to increase. The amount of gas above the level of the flat plate also increases with time. In the later image frames, from time t=120 seconds to t=240 seconds, there is little change in the observed pattern. No gross movement of the pattern of CL values was observed after the release stopped.

Note: Tests 14 and 17 were both performed during a time when the ambient relative humidity in the building was at or near 100 percent. This caused a water and/or ice fog to form during the gas release. Visual observations indicated that this fog cleared within a few seconds of the time the gas release ceased. During the time that natural gas was being released, the IR image frames show the effects of attenuation by both the natural gas and the ice fog. A comparison of the IR and visible images could show the exact extent of the fog in time and space. However, such project resources did not allow such an analysis to be performed as part of the current Task 9 effort.

Box with Screen (Test 14). The gas exits from both the top and bottom of the box. At t=10 seconds gas is visible in the entire lower portion of the image. At t=20 seconds, gas is visible in both the upper and lower portions of the image. The release terminated at about t=70 seconds with a final bit of gas leaving the bottom of the box. For the balance of the time the images are filled with a uniform CL signal. Note that some initial frames contain black pixels within the concentrated portion of the gas. These are believed to be pixels where scattered light from water drops or ice crystals has prevented valid data from being obtained.

Box with Screen (Test 17). The release began with gas flowing from both the top and bottom of the box, but with a stronger flow from the bottom. From t=10 to t=40 seconds, a large amount of fog was observed visually and much of the image contains pixels that are not valid data. The gas release continues. At t=50 seconds the release is over and gas is found throughout the field of view. From t=50 to t=230 seconds the image of the gas CL product appears fairly uniform throughout the field of view.

Inverted Flat Plate (Test 30). In this test the jet and flat plate configuration was inverted so that the gas flowed vertically downwards towards a horizontal flat plate. In this configuration the plate was located very near to the bottom of the image. Therefore, the amount of data available for the area below the level of the plate is minimal.

The gas flow starts and proceeds horizontally. At about t=10 seconds the release is completed. Some gas remains at the release elevation. There is also gas observed above and below the release elevation, however the field of view of the camera is such that only a small viewing area below the release elevation is available. From t=60 to t=230 seconds nearly the same pattern of higher CL product is observed in both the upper and the lower portions of the image; no gross movement of the gas was observed.

4.3 Combustible Gas Meter Data

The readings from the Bacharach combustible gas meter were noted at various times during and after the gas releases. Spot readings from this meter showed natural gas concentrations in excess of the lower flammability limit for all the gas release tests in which the 6.25 mm orifice was used, although the time delay through the sampling line makes it difficult to associate the readings with a particular IR image frame.

5 Discussion

5.1 Properties of CNG Releases

The vapors from liquid fuels have relatively high average molecular weights and are consequently much heavier than air. Thus, designers of facilities where these fuels are used have traditionally concentrated on removing ignition sources within a given distance from the floor level.

As a low molecular weight gas, natural gas is normally lighter than air at the same temperature and pressure. For example, at atmospheric pressure and normal ambient temperature, a cubic meter of natural gas has a mass of 0.70 kg, whereas the same volume of air has a mass of 1.2 kg. (By comparison, the same volume of gasoline vapor has a mass of 2 to 5 kg.) Because the molecular weight of natural gas is less than that of air, some designers have suggested that the design experience with liquid fuels simply be inverted with ignition sources removed only from the ceiling area.

However, experience with conventional fuels does not provide adequate guidance for predicting the location of plumes from compressed natural gas releases because the physical properties of compressed natural gas are quite different from the vapors from liquid fuels such as gasoline and diesel fuel. Two factors especially act to make the situation different and more complex.

- First, compressed natural gas is released from a high pressure and the released gas generally has significant jet momentum that will tend to drive the gas in a direction dictated by the leak geometry. Jet momentum will also lead to entrainment of ambient air, thus causing dilution of the natural gas by ambient air.

- Second, when natural gas under high pressure is released, it expands and cools. The resulting reduction in temperature will increase the density of the released gas over that expected from a consideration of molecular weight alone. At a temperature of about -100 C, natural gas would have the same density as ambient air, and at lower temperatures it would be more dense.

  A theoretical analysis by Phani Raj[4] has suggested that temperatures this low or lower may be attained in natural gas releases from CNG fuel tanks.

5.2 Interpretation of Imaging Results

Examination of the infrared images obtained from these experiments shows that natural gas from the CNG releases initially moved in a direction determined by the momentum of the jet. The gas was not observed to immediately flow towards the ceiling or the floor. After the release had ceased and the gas had come to rest, the images of average natural gas concentration (CL product) did not show gross upward or downward movement over remainder of the 240 second duration of the data. The IR images showed that areas of significant CL product could be found nearly anywhere in the field of view, depending on the release geometry and the elapsed time.

Although the IR data showed CL product rather than concentration, the maximum pathlength that could contain gas was bounded by the 10-meter distance from the cameras to the back panels. Given that the lower flammability limit of natural gas is 5 percent by volume, or 50,000 ppm, any CL product greater than 500,000 ppm·meters was certain to have a flammable mixture present over part or all of the pathlength. The limited data from the combustible gas meter provided a confirmation that flammable mixtures of natural gas and air were sometimes present.

6 Conclusions

1. The infrared imaging technique was successful in showing the presence of natural gas and the location of the gas within the field of view.

2. Radiometric analysis of the IR absorption, combined with the 10-meter upper bound on the pathlength, showed that flammable concentrations were indicated

on some images. Limited spot readings on a traditional combustible gas meter provided a confirmation of this analysis.

3. For the geometries studied, we observed a general dispersion of natural gas. Areas of high CL concentrations seen within the field of view persisted over time. After the release had ceased, we did not see coherent bodies of gas moving either upwards or downwards.

4. Areas of significant average natural gas concentration (CL product) were found at all levels within the field of view.

7 Acknowledgments

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REFERENCES

1. "Application of Dispersiõn Modeling to Indoor Gas Release Scenarios," Firooz Rasouli and Ted A. Williams. J. Air & Waste Manage. Assoc. 45, 191 (1995).

2. "Although natural gas is generally lighter-than-air, the leakage plumes displayed no major buoyancy traits at any of the leak sites." Quoted from "Natural Gas Leak Dispersion Studies using an Infrared Gas Imaging System," by T.G. McRae and L.L.("Tom") Altpeter, Jr., 1992 International Gas Research Conference, Orlando, Florida, 16-19 November 1992. p. 1316.

3. "Extent of Indoor Flammable Plumes Resulting from CNG Bus Fuel System Leaks," Michael J. Murphy, Susan T. Brown, and David B. Philips, Federal Transit Administration technical report, November, 1991.

4. "An Analysis of Compressed Natural Gas Release from a High Pressure Cylinder," Phani K. Raj, Technology and Management Systems, 6 January 1994.

APPENDIX A

Summary of Gas Release Tests Performed

Test	Gas Release Geometry	Orifice Diameter, mm	Initial Pressure, MPa
1	Horizontal jet	0.99	22
2	Horizontal jet	0.99	19
3	Horizontal jet	6.25	16
4	Flat plate, jet up	0.64	22
5	Flat plate, jet up	0.99	21
6	Flat plate, jet up	3.18	18
7	Flat plate, jet up	3.18	12
8	Flat plate, jet up	6.25	23
9	Flat plate, jet up	0.64	24
10	Flat plate, jet up	0.99	19
11	Box with screen	0.99	24
12	Box with screen	3.18	19
13	Box with screen	0.64	24
14	Box with screen	0.99	22
15	Box with screen	6.25	18
16	Box with screen	6.25	7
17	Box with screen	6.25	23
18	Box, open bottom	0.64	24
19	Box, open bottom	3.18	19
20	Box, open bottom	0.99	11
21	Box, open bottom	0.99	24
22	Flat plate, jet up	0.99	24
23	Flat plate, jet up	0.99	22
24	Flat plate, jet up	3.18	19
25	Flat plate, jet up	6.25	11
26	Flat plate, jet up	6.25	22
27	Vertical jet	0.99	23
28	Vertical jet	6.25	21
29	Vertical jet	6.25	14
30	Flat plate, jet down	3.18	23
31	Flat plate, jet down	0.99	17
32	Flat plate, jet down	3.18	15

APPENDIX B

Radiometrically processed images

of Tests 3, 8, 14, 17, 25 and 30.

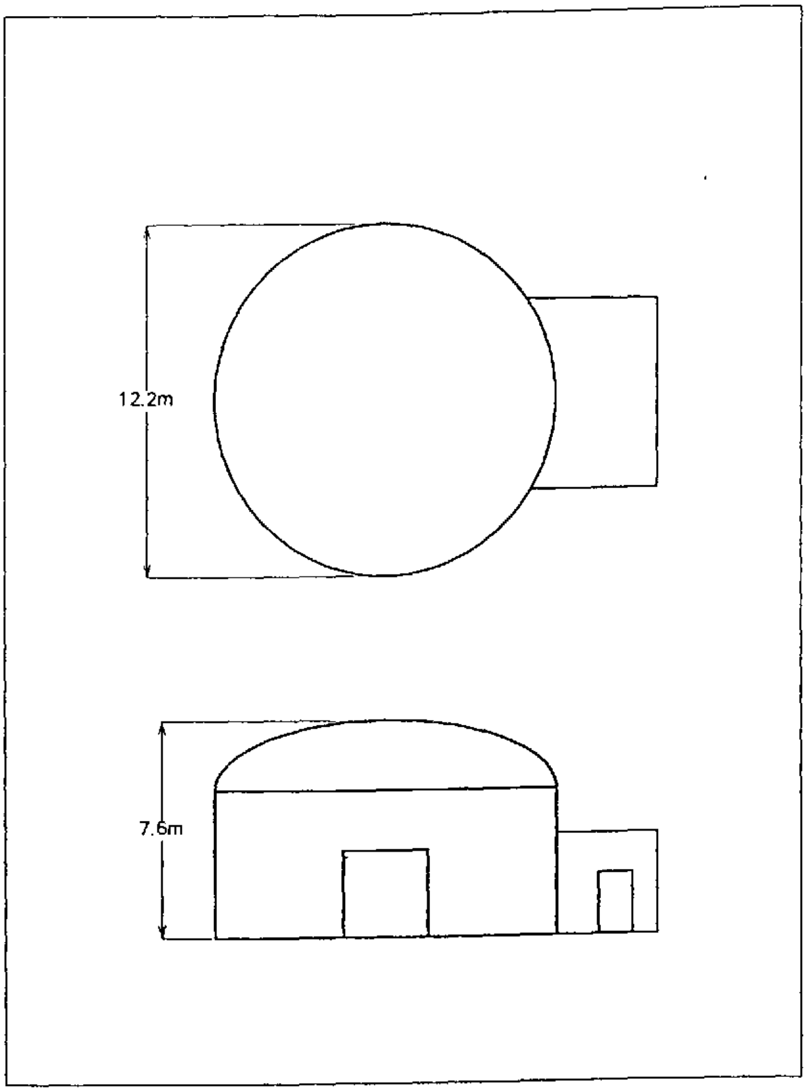

Figure 1. General Plan and Elevation of Test Building

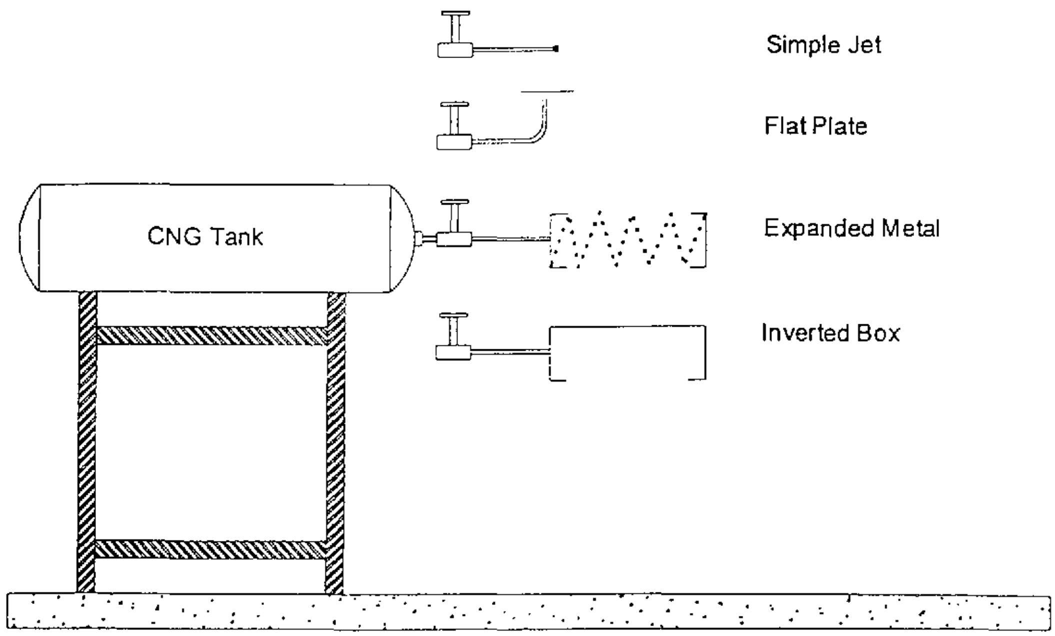

Figure 2. Gas Release Test Configurations

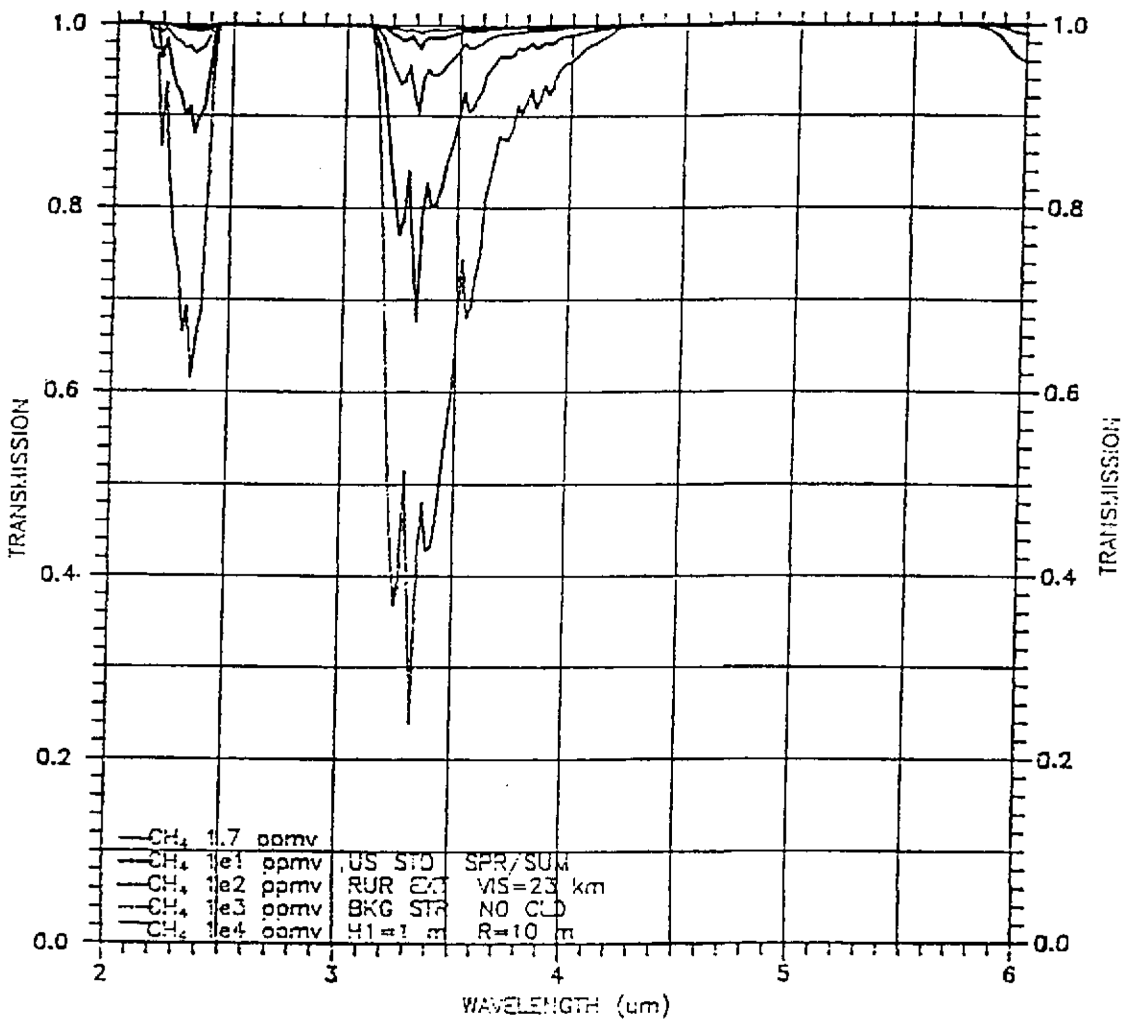

Figure 3. MWIR spectral extinction coefficient of methane.

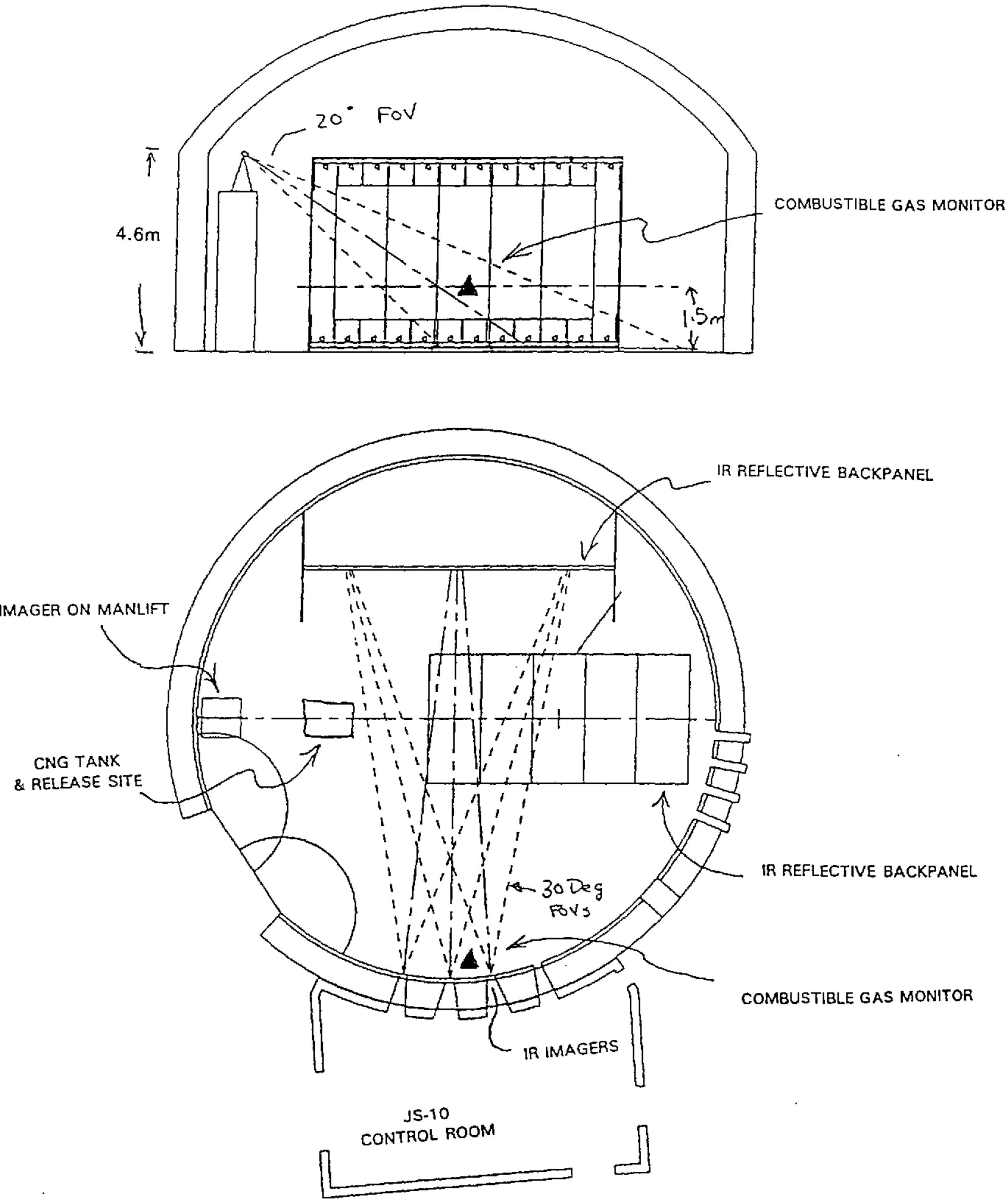

Figure 4. Sketch of Back panel Layout and IR Imager Stations.

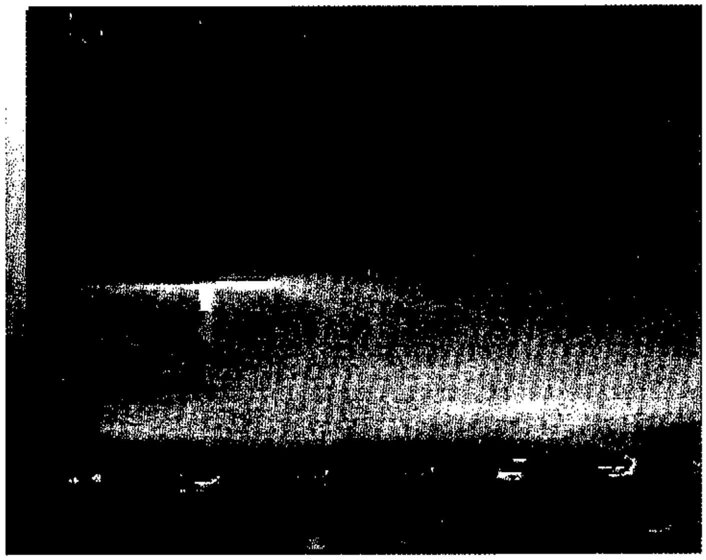

Figure 5. Typical Radiometrically Processed Image.

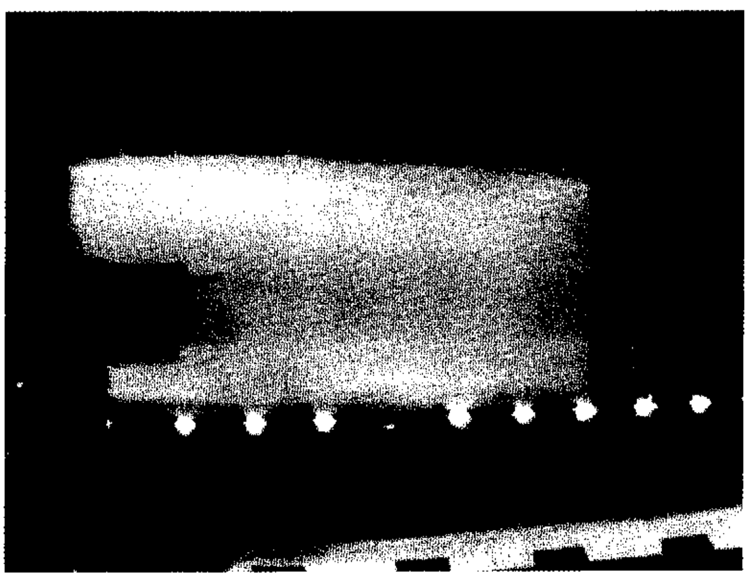

Figure 6. Visible Image of Gas Release Directed at Flat Plate. Note condensation is seen only between the jet orifice and the plate.

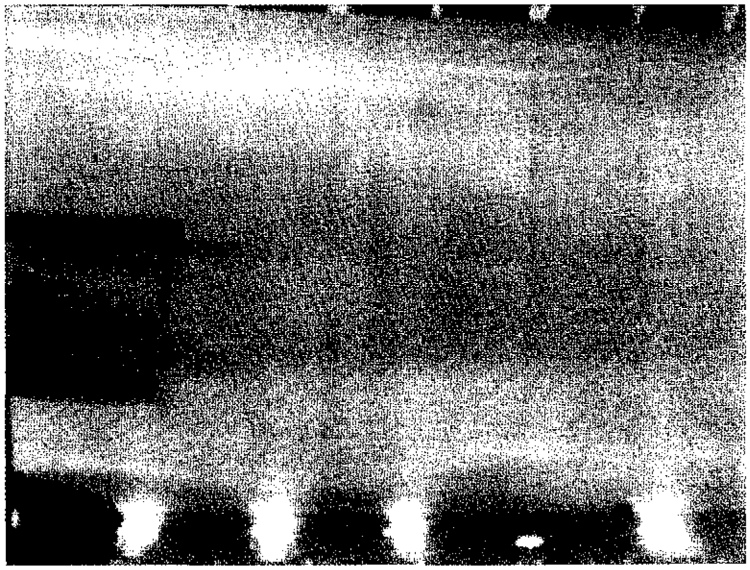

Figure 7. Near IR Image of Gas Release Directed at Flat Plate. Note condensation is seen only between the jet orifice and the plate.

Figure 8. MWIR Image of Gas Release Directed at Flat Plate. Image is totally opaque due to absorption of MWIR by the natural gas. This image was taken by an Inframetrics PtSi InfraCam and the analog output was recorded on video tape.

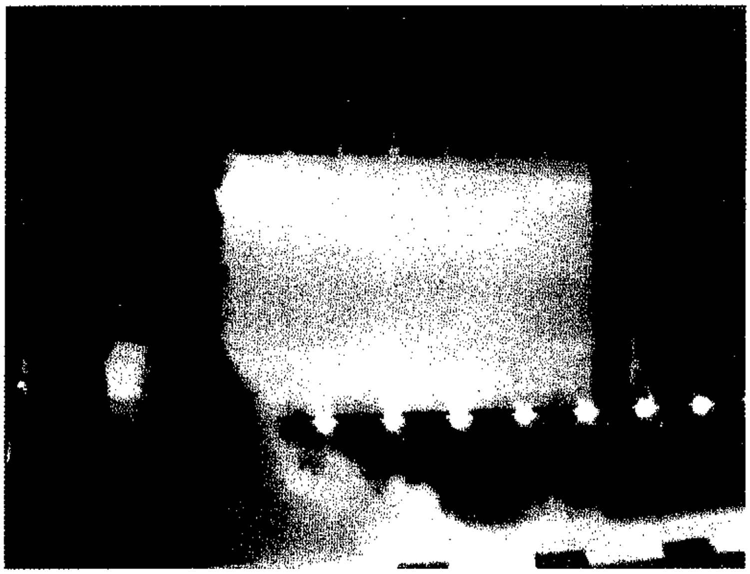

Figure 9. Visible Image of Gas Release Test 17 During Gas Flow Under 100 Percent Relative Humidity Conditions. Fog may be seen flowing upwards and also downwards to the floor.

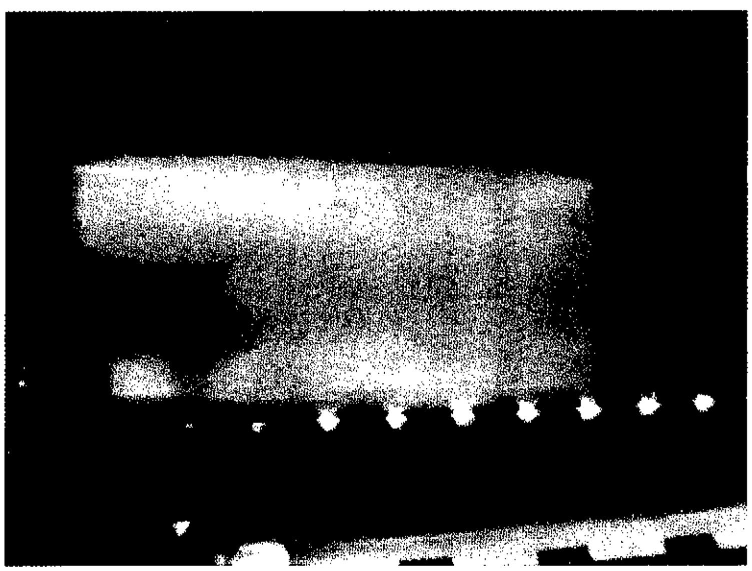

Figure 10. Visible Image of Gas Release Test 17 Under 100 Percent Relative Humidity Conditions Shortly After Gas Flow Has Ceased.