Manhole Event Mitigation Strategies

Explosion Testing of Manhole Covers with Pressure Relief Mechanisms

1012305

Manhole Event Mitigation Strategies

Explosion Testing of Manhole Covers with Pressure Relief Mechanisms

1012305

Technical Update, December 2006

EPRI Project Manager

R. Keefe

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

EPRI

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

CITATIONS

This document was prepared by

EPRI
3420 Hillview Avenue
Palo Alto, CA 94304

Principal Investigators
G. Gela
D. Rueger

This document describes research sponsored by the Electric Power Research Institute (EPRI).

This publication is a corporate document that should be cited in the literature in the following manner:

Manhole Event Mitigation Strategies: Explosion Testing of Manhole Covers with Pressure Relief Mechanisms. EPRI, Palo Alto, CA: 2006. 1012305.

ABSTRACT

Tests were performed in the M11 manhole using hydrogen gas of various concentrations and with the UL mixture of gases defined in previous studies. Comparison of results and observations from tests with hydrogen gas and the UL mixture indicates significant and important differences in explosion characteristics and in the behavior of the restraining mechanism.

It is therefore recommended that further selected tests be performed with the UL mixture of gases.

Test results confirm that the Stabiloc mechanism can restrain the cover while allowing it to rise about 2 inches to provide relief of internal pressure. However, for very significant explosions, pressure relief is not sufficient to prevent roadbed damage.

It was possible to determine pin sizes used in the Stabiloc locking mechanism that both (a) provide pressure relief and (b) prevent roadbed damage for minor and moderate explosion. For major explosions, pin sizes can be selected to restrain the cover, but pressure relief is not sufficient to prevent roadbed damage. In this case, the requirement for restraining the cover is perhaps moot, since collateral damage due to the lifting of the roof slab can be very significant, while the dislodgement of the cover may then be of secondary concern.

However, it is again emphasized that most of the tests were performed with hydrogen gas, and it is recommended to perform selected tests with the UL mixture.

Test results suggest that the hinged cover approach requires further development as pressure relief was insufficient to prevent dislodgement of the entire cover frame. Hence, the results of this test are to a large extent inconclusive as to the capabilities of hinged covers to provide pressure relief. **It is recommended to revisit this issue and re-design the attachment system of the frame to the roof slab, as this would further explore the possible advantages of hinged cover.**

CONTENTS

1
INTRODUCTION

EPRI has conducted a significant amount research on gas-related manhole explosion over the past decade. Prior tests included manhole solid covers, various designs of vented manhole covers, volume displacement methods to minimize the amount of accumulating gas, and rigid restraining systems such as an I-beam that allows the cover to rise a few inches, and steel tethers.

As part of 2006 base funded project within the EPRI Program 30 “Underground Distribution Systems” EPRI performed gas-related explosion tests on covers with a unique restraining and pressure relief system designed by Stabiloc, and on hinged covers designed by Saint Gobain.

Tests were preformed at the EPRI-Lenox Manhole Test Facility which includes an underground system consisting of:

- Two manholes (M11 and M14)
- One 13.8 kV transformer vault
- Three service boxes (S and TS boxes)
- Several parallel runs of PVC, galvanized steel, black iron and concrete conduit.

Figure 1-1 shows the general map of the facility. Tests were conducted in the M11 manhole. For safety reasons, the test site (the M11 manhole) is surrounded by protective netting consisting of Dacron mesh, see Figure 1-2.

For explosion tests, a controlled amount of gas is injected into the M11 manhole and the gas is ignited. A set of video cameras, including a high-speed camera, records the behavior of the cover during the explosion.

Tests were conducted with various concentrations by volume of hydrogen gas, and also with various concentrations by volume of the “UL mixture” of carbon monoxide (4 parts), methane (1 part), ethylene (3 parts) and acetylene (12 parts).

Objectives of the Research

The objectives of the research were:

- Determine by tests whether the Stabiloc locking mechanism is capable of preventing the cover from being dislodged from the frame
- Determine by tests whether the Stabiloc mechanism allows controlled release of explosion pressure
- Determine by tests the characteristics of the shear pin in the locking mechanism that allow controlled release of pressure without failure and without damaging the roadbed over the manhole roof slab, but fail (shear) for major explosions (and thus releases pressure more readily) for which the hazard of road bed damage exists

- Determine by tests whether the hinged cover is capable of performing controlled pressure release without being dislodged from its frame.

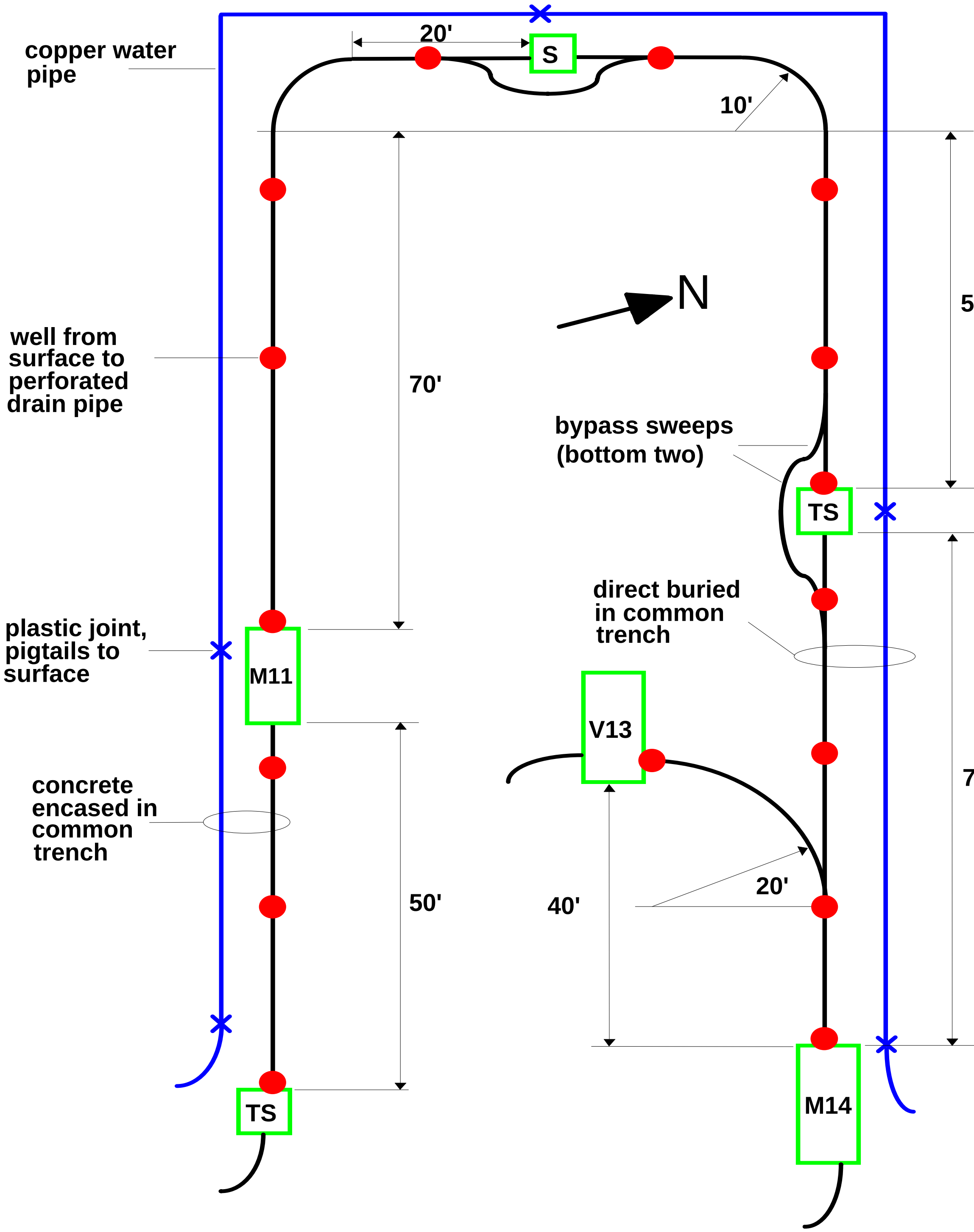

Figure 1-1
General map of the EPRI-Lenox Manhole Test Facility

Figure 1-2
Protective tent around the M11 test site

2

COVERS TESTED

Three types of covers were tested as part of this project:

- Cover with the Stabiloc locking mechanism installed, see Figure 2-1, designated in this report as Cover #1,
- Cover identical to Cover #1 but with the Stabiloc mechanism removed, see Figure 2-2, designated as Cover #2,
- Hinged cover provided by Saint Gobain with Stabiloc locking mechanism, see Figure 2-3, designated as Cover #3.

Figure 2-1
Cover #1 – solid, white with Stabiloc locking mechanism

Figure 2-2
Cover #2 – solid, brown, without Stabiloc locking mechanism

Figure 2-3
Cover #3 – Hinged Saint Gobain solid, white with Stabiloc locking mechanism

Cover 1 has a locking mechanism that consists of two parts:

- A passive fixed lip at the rim of the cover that engages against the cover frame
- An active swivel lip at the edge of the cover diametrically opposite from the fixed lip; this active lip swivels on a brass pin that shears at a design force (pressure) level.

The cover is designed to lift to a certain height (about 2 inches) for minor explosions, and is restrained by the passive and the active lips from dislodging from the frame. For major explosions, the shear pin in the locking mechanism breaks and allows the cover to be dislodges from the frame.

Because of the unsymmetrical design of the cover and retraining mechanisms, the cover, when dislodged, does not rise vertically but tends to sway and fall to one side. For the same reason, the internal pressure waves are also not symmetric, as shown later.

3
TEST SETUP AND PROCEDURE

The tests were performed at the EPRI-Lenox manhole test facility, using the M11 manhole.

Tests were performed mainly with the hydrogen gas for practical reasons (duration of the gas injection period is much longer and the post-event venting procedure is more complicated with the UL gas mixture). A few tests were performed with the UL mixture to explore differences in characteristics.

Pressure and temperature sensors were placed in explosion-proof boxes mounted on each internal wall of the M11 manhole. Gas injection tubing and all instrumentation cables are brought into the M11 manhole through underground ducts at the East wall of the manhole. The ignition source is located on the floor approximately in the center of the M11 manhole, and a mixing fan is located at the South-East corner. Figure 3-1 shows the East wall with the sensor box, gas injections tubing, and instrumentation cables.

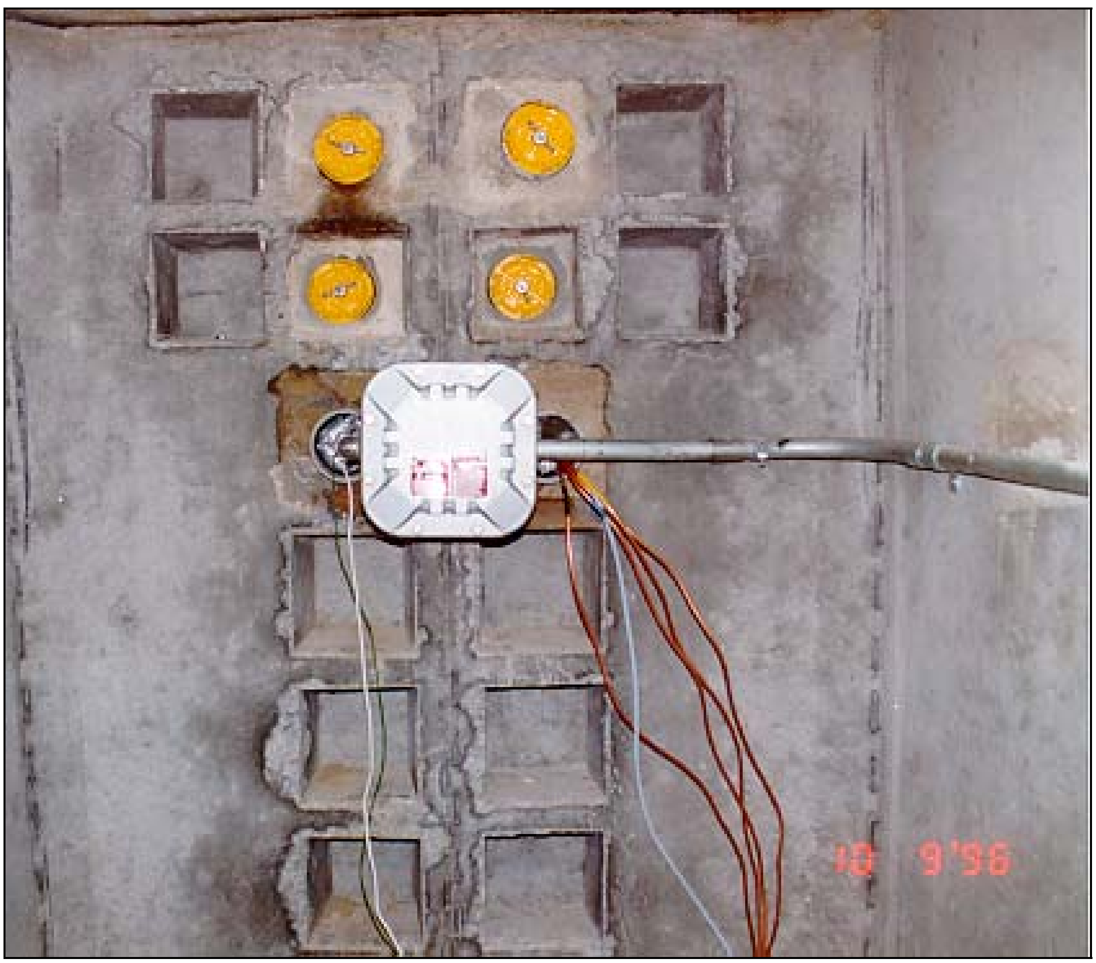

Figure 3-1
Photograph of the East Wall of the M11 Manhole Showing the Feed Tubes Entering the Manhole

The gas injection system consisted of:

- Gas bottles contained in a protective shed,
- Break-away connection (linear actuator) that isolates the gas bottles from the manhole and ignition source immediately before ignition is applied (this is a safety feature),
- Feed tubes (one for each gas) between the gas bottles and the linear actuator,
- Feed tubes (one for each gas) between the actuator and the manhole.

The ignition spark was provided by a small wire-to-wire spark gap placed in the manhole. The spark was generated by an oil furnace transformer.

The entire gas injection and ignition sequence is controlled by the controller-data acquisition computer. In the case of the UL gas mixture tests, the gas injection system is designed to end the injection process at the same instant of time for all gases. Because of the different desired amounts of various gases and dissimilar gas flow rates, the injection intervals are different for different gases. In practice, this means that the injection process of individual gases is initiated at different times (staggered start) and arranged so as to end injecting all gases simultaneously.

The typical injection sequence is described below:

- Start Gas Injection Sequence
- User-Controlled Pause
- Open Gas Solenoid Valves (Stagger Start for the UL Gas Mixtures)
- Dispense Gases into Manhole
- Close All Valves Simultaneously
- Energize Linear Actuator to Disconnect Feed Tubes From Gas Sources
- User-Controlled Pause
- Apply the Ignition Spark and Begin Data Acquisition

The gases are stored in pressurized bottles. When the gases are released, their volume expands and temperature drops. Therefore, the temperature of the gases just prior to ignition is most likely significantly lower than it would be in a real pre-explosion situation in a manhole. In order to compensate for the temperature decrease the gases were heated before they enter the manhole. The heating system consisted of a copper pipe inserted through the concrete duct between the entry point of the feed tubes (the TS service box in the south-east corner of the facility) and the M11 manhole. The copper heating pipe is about 50 ft long. The feeding tubes are inserted into the heating pipe and the pipe is heated by passing about 300-500 Amps of current (provided by a current transformer). The pipe temperature is limited to about 120^{o}F, which is the temperature limit for hydrogen specified in Hazmat sheets. As a result of this heating arrangement, the temperature of the gases exiting the feeding tubes and entering the manhole was about 70^{o}F, i.e., 10-20^{o}F above the typical ambient temperature of the manhole atmosphere. It is important to note that this moderate elevation in temperature does not represent the much higher gas temperatures typically generated by cable faults and the resultant fires.

After a test (whether or not an explosion has occurred), the manhole volume is purged with nitrogen gas which is injected through a separate feed tube (this tube obviously bypasses the linear actuator disconnect switch). After purging with nitrogen, normal atmosphere inside in the manhole is re-established by pumping air from an air compressor.

The data acquisition system consists of blast transducers (pressure sensors) and thermocouples (temperature sensors), a computer, data acquisition boards, interconnecting cables, and signal conditioning circuitry.

Four blast transducers and four K-type thermocouples are located inside the M11 manhole. The thermocouples are K-type and have a range of 0-3000 degrees Fahrenheit.

Inside the M11 manhole, the blast transducers and the thermocouples are placed in explosion-proof steel boxes, which are mounted approximately in the center of each of the four walls

In addition to internal pressure sensors, external sensors were also used to measure the pressure wave (blast) around the manhole cover and frame as the cover rises. This information is important for assessing the possible extent of collateral damage and possible hazards to the public near a cover.

4
SUMMARY OF RESULTS

Test data were recorded using a high-speed data acquisition system and a set of video cameras. The following data were recorded:

- Pressure values, in psi, on each interior wall of the M11 manhole
- Temperature values, in ^{o}C, on each interior wall of the M11 manhole
- In some tests, external pressure values, in psi, at three locations around the manhole frame
- Cover trajectory using a high-speed digital camera
- Cover trajectory using a normal-speed digital camera
- Other general observations

Detailed processing of test results is now underway. Estimated maximum pressures and cover heights based on the height reached by the top edge of the cover are summarized in Tables 4-1 and 4-2. Explanatory comments are also included as appropriate.

While Tables 4-1 and 4-2 summarize important measured data, the videos of the explosions provide some especially valuable and interesting information.

Also, very useful information on pressure waves was obtained by observing empty plastic bottles placed near the frame. In many tests, the bottles appeared to be initially “sucked” toward the frame opening, and then blown away. This indicated very dynamic and rapid pressure changes near the frame which include pressure reversals. In particular, it indicates the presence of a strong lateral pressure wave near the frame than could present significant hazards to the public near the frame. This behavior of pressure changes was confirmed by data collected by the external pressure sensors.

Cover #1

Cover # 1 is designed to lift and release pressure for minor or medium explosions without searing the pin or damaging the roadbed.

In those cases, the cover rose about 2 inches as allowed by the locking/restraining mechanism, fell back into the frame thus allowing internal pressure to increase again. Then toe cover rose and fell back, repeating this behavior several times until the internal pressure decreased below that value needed to lift the cover (overcome gravity). This is shown in Figure 4-1 in a sequence of frames copied from the video.

In major explosions, the entire roof slab of the M11 manhole, weighing 13,200 lbs (which approximately represents a roadbed) lifted because the pressure relieving action of the restrained cover was not adequate if the shear pin did not break. This is shown in Figure 4-2.

If the shear pin broke, the cover was dislodged and thrown off the frame, see Figure 4-3.

Table 4-1
Results from tests with H_2

Event #	Cover type	% H_2	Max. press. (psi)	Cover height (ft-in)	Comments
1	#1, lock engaged	4	About 0.32		Cover lifted about 2" and dropped back about three times. Pin held.
2	#1, lock engaged	5	n/r	0	Cover lifted about 2" and dropped back about four times. Pin held.
2a	#1, lock engaged	-	-	-	System checkout, no ignition applied
3	#1, lock engaged	6	-	-	No explosion
4	#1, lock engaged	6	About 0.8	2" (as allowed by the lock)	Cover lifted about 2", dropped back, lifted again and fell back about six times. Pin held.
5	#1, lock engaged	8	About 4.8	2" (as allowed by the lock)	Cover lifted about 2" stayed up until pressure was released, and dropped back. Pin held.
6	#1, lock dis-engaged	8	About 3.2	8" on one side	Cover lifted about 8" (on the restraining lip side), stayed up tilted until pressure was released, and dropped back into frame. Pin held.
7	#2, locking mechanism removed	8	No data	About 1'	Cover lifted about 1', remained flat (did not tilt), fell back into frame
12	#2, locking mechanism removed	4	Nil	0	No explosion. Cover did not lift
13	#2, locking mechanism removed	6	Nil	0	No explosion. Cover did not lift
14	#2, locking mechanism removed	8	About 1.1	About 5"	Cover lifted about 5", tilted, fell back
15	#2, locking mechanism removed	12.8	About 4.3	About 2.5'	Cover lifted about 2.5', tilted, fell down, bounced and fell beside frame
16	#1, lock engaged, 0.250" dia shear pin	13	About 5.7	About 4'	Cover lifted about 4', tilted, fell down, bounced and fell inside frame tilted. Pin failed
17	#1, lock engaged, 0.275" dia shear pin	13	About 5.8	About 5'	Cover lifted about 5', tilted, fell down, bounced and fell inside frame tilted. Pin failed
18	#1, lock engaged, 0.300" dia shear pin	13	About 6	About 8'	Cover lifted about 8', tilted to nearly vertical orientation, fell down, turned upside-down, bounced and fell inside frame upside-down. Pin failed. Roof slab lifted about 2".

19	#1, lock engaged, 0.325” dia shear pin	13	About 5.8	About 7’	Cover lifted about 7’, tilted, fell down, bounced and fell inside frame. Pin failed. Roof slab lifted about 3”.
20	#1, lock engaged, 0.350” dia shear pin	13	About 10	2” (as allowed by the lock)	Cover lifted about 2”, stayed up until pressure released, and dropped back. Pin held. Roof slab lifted about 3”.
21	#1, lock engaged, 0.350” dia shear pin (same pin #1)	13	-	-	No ignition signal
22	#1, lock engaged, 0.350” dia shear pin (new pin #2)	10	No data	2” (as allowed by the lock)	Cover lifted about 2”, dropped back, lifted again and fell back several times. Pin held.
23	#1, lock engaged, 0.350” dia shear pin (new pin #2)	10	About 6.6	2” (as allowed by the lock)	Repeat of Event 22. Cover lifted about 2”, dropped back, lifted again and fell back several times. Pin held.
24	#1, lock engaged, 0.325” dia shear pin (new pin #2)	10	About 7.2	2” (as allowed by the lock)	Cover lifted about 2”, dropped back, lifted again and fell back several times. Pin held. Pin held.
25	#1, lock engaged, 0.300” dia shear pin	10	About 6.4	2” (as allowed by the lock)	Cover lifted about 2”, dropped back, lifted again and fell back several times. Pin held.
26	#1, lock engaged, 0.275” dia shear pin	10	About 6.1	2” (as allowed by the lock)	Cover lifted about 2”, dropped back, lifted again and fell back several times. Pin held.
27	#1, lock engaged, 0.250” dia shear pin	10	No data	2” (as allowed by the lock)	No ignition signal. Ignited manually. Pin held.
28	#1, lock engaged, 0.250” dia shear pin	10	About 1.8	2” (as allowed by the lock)	Repeat of Event 27. Cover lifted about 2”, dropped back, lifted again and fell back several times. Pin held.

Table 4-2
Results from tests with UL gas mixture

Event #	Cover type	% UL	Max. press. (psi)	Cover height (ft-in)	Comments
8	#2, locking mechanism removed	6	About 7.5	About 30’	Significant explosion. Cover lifted about 30’ vertically and fell back onto the frame. Roof slab lifted about 4”.
9	#1, lock engaged	6	-	-	Ignition signal failure.
10	#1, lock engaged	6	About 4.9	2” (as allowed by the lock)	Significant explosion. Cover lifted about 2”. Pin held. Roof slab lifted about 16”.
11	#3, with Stabiloc locking mechanism	6	About 7.8	2” (as allowed by the lock)	Very significant explosion. Cover lifted about 2” out of the frame. Pin held. However, the frame and cover were ripped off the roof slab and hurled together about 14’, and landed on the grass about 8’ from the M11 manhole. Roof slab lifted about 8”.

(a) Initiation of explosion. Cover still in its frame.

(b) Cover rose about 2 inches for the first time.

(c) Cover fell back into its frame.

(d) Cover rose again.

Figure 4-1
Cover relieves internal pressure by “bobbing” up-and-down about 6 times. Test with 6% hydrogen by volume (Event 4).

(a) Initiation of explosion. Cover still in its frame.

(b) Cover rose about 2 inches for the first time.

(c) Cover remains aloft. Note that the bottles are being "sucked" towards the frame.

(d) Cover remains aloft. Bottles are blown away from the cover.

Figure 4-2
Cover relieves internal pressure by rising and remaining aloft for a significant length of time. Bottles are initially "sucked" towards the frame, then blown away. Test with 8% hydrogen by volume (Event 5).

The sequence of frames in Figure 4-2 indicates the presence of a lateral pressure wave in the vicinity of the annulus between the rising cover and its frame.

(a) Explosion. Cover rises and partially relieves pressure. Lateral pressure wave is visible.

(b) The roof slab begins to rise.

(c) Roof slab rises to about 1.5 ft. Cover remains restrained by the locking mechanism.

(d) Roof slab falls back down. Cover remains restrained by the locking mechanism.

Figure 4-3
Cover does not relieve the internal pressure. The entire roof slab is lifted to relieve the pressure. Test with 6% UL mixture by volume (Event 10).

The maximum internal pressure recorded in this test is about 5 psi by one internal sensor before the roof slab started to lift. Assuming that the internal pressure wave is spherical (internal sensors indicate that it is not spherical, so this assumption is a gross simplification), the external pressure around the frame when the cover is lifted but the roof slab has not started moving yet can be estimated roughly as the ratio of the area of the annulus to the area of the frame opening. Assuming the frame opening is 32 inches in diameter, the frame opening area is approximately 812 sq. inches. The area of the annulus is its height of about 2 inches times the circumference of the 32 inch cover, i.e., about 200 sq. inches. Then, the lateral pressure through the annulus is about 5 x 812/200 = 20 psi. The maximum pressure measured by one external sensor about 1 ft away from the annulus was about 6.2 psi. However, this maximum occurred much later in time.

The reasons for the discrepancies are many, and measured data indicate that such simple calculations are not accurate or appropriate. However, measured data also indicate that the lateral external pressure near the cover can be significant.

Tests were also performed on Cover #1 with the locking mechanism disengaged under test conditions similar to those in Event 5 in Figure 4-2. In this case, the cover rose to a height of about 8 inches, remained aloft for a period of time and fell back into its frame, see Figure 4-4.

(a) Cover begins to rise.

(b) Cover rises unevenly since the restraining mechanism is disengaged on one side.

(c) Maximum height reached. Cover remains partially restrained on one side by the passive lip.

(d) Cover falls back into its frame.

Figure 4-4
With the restraining mechanism disengaged, the cover lifts on one side, pressure is relieved and the cover falls back into its frame. Test with 8% hydrogen by volume (Event 6).

Cover #2

Cover #2 did not have a locking mechanism during tests. Figure 4-5 shows that in this case the cover is dislodged and hurled away. Significant collateral damage is possible.

(a) Cover begins to rise.

(b) Cover at maximum height.

(c) Cover falls.

(d) Cover lands on the ground near the M11 manhole.

Figure 4-5
Without the restraining mechanism, the cover is dislodged, rises to about 2.5 ft and lands near the M11 manhole. Test with 12.8% hydrogen by volume (Event 15).

Cover #3

Cover #3 is a hinged cover. It was equipped with the Stabiloc restraining mechanism for these tests. The cover did not provide sufficient pressure relief. It and its frame were ripped off the M11 manhole and hurled to a height of about 14 ft in a test with 6% UL mixture, see Figure 4-6.

(a) Cover begins to open to relieve pressure.

(b) Cover and its frame are ripped off the M11 manhole roof slab and hurled upwards.

(c) Cover and frame at maximum height.

(d) Cover and frame land on the ground away from the M11 manhole.

Figure 4-6
The hinged cover did not provide sufficient pressure relief. Test with 6% UL mixture by volume (Event 11).

Cover #1 with Various Shear Pins

The objective of this set of tests was to determine the characteristics of the shear pin in the locking mechanism that allow controlled release of pressure without failure and without damaging the roadbed over the manhole roof slab for minor explosions, but fail (shear) for major explosions (and thus releases pressure more readily) for which the hazard of road bed damage exists. That is, the shear pin should be designed to withstand pressures that do not result in roadbed damage and to relieve the internal pressure by rising to the designed height as in Figure 4-2. For major explosions, the pin should fail (i.e., shear or break) when the pressure inside the manhole reaches levels that would result in lifting of the roof slab as shown in Figure 4-3. In this case, the failure of the pin would allow pressure release in a more controlled manner, but the cover would be dislodged from its frame.

The shear strength of the pin was adjusted by beveling two notches as shown in Figure 4-7. This introduces controlled weak points in the pin. The amount of remaining material in the notch area determines the shear strength of the pin.

Figure 4-7
Shear pin with notches.

Tests discussed previously used a pin 0.5 inch in diameter without notches. Additional brass pins were manufactures with remaining material diameters ranging from 0.350 to 0.250 inches, in decrements of 0.025 inch.

The test sequence was as follows:

1. Using 13% hydrogen, which would result in the cover being dislodged if the locking mechanism is not installed or not engaged, as demonstrated in Event 14. Use the weakest pin, i.e., 0.250 inch remaining metal diameter. **Result:** The 0.250" pin broke, the cover lifted about 4', **and the roof slab did not lift** (Event 16).
2. Using 13% hydrogen concentration, use the 0.275" pin. **Result:** The 0.275" pin broke, the cover lifted about 5' (this is because the pin held a bit longer and finally failed at a higher internal pressure), **and the roof slab did not lift** (Event 17).
3. Using 13% hydrogen concentration, use the 0.300" pin. **Result:** The 0.300" pin broke, the cover lifted about 8' (this is because the pin held a bit longer and finally failed at a

higher internal pressure), **and the roof slab lifted** about 2" (Event 18). This case would result in **roadbed damage**.

4. Using 13% hydrogen concentration, use the 0.325" pin. **Result:** The 0.325" pin broke, the cover lifted about 7', **and the roof slab lifted** about 3" (Event 19). This case would result in **roadbed damage**. The cover height is less than in Event 18 probably because the roof slab lifted which provided another path for pressure relief.
5. Using 13% hydrogen concentration, use the 0.350" pin. **Result:** The 0.350" pin did not brake, the cover lifted about 2" (as allowed by the locking mechanism), **and the roof slab lifted** about 3" (Event 20). This case would result in **roadbed damage**.

At this point, it was concluded that the further testing with stringer pins would not be instructive since we reached the situation where:

- Either the pin breaks and the cover is not restrained (it is hurled and can cause significant collateral damage),
- OR the pin does not break (i.e., the cover is restrained), but the roof slab is dislodged resulting in roadbed damage.

For the next sequence of tests, a lower concentration (10%) of hydrogen was used and the pin strength was reduced in steps with the following results:

- Using 10% hydrogen concentration, use the 0.350" pin. **Result:** The 0.350" pin did not brake, the cover lifted about 2" (as allowed by the locking mechanism), **and the roof slab did not lift** (Event 22). This case would **not** result in roadbed damage**.**
- Using 10% hydrogen concentration, use the 0.325" pin. **Result:** The 0.325" pin did not brake, the cover lifted about 2" (as allowed by the locking mechanism), **and the roof slab did not lift** (Event 24). This case would **not** result in roadbed damage**.**
- Using 10% hydrogen concentration, use the 0.300" pin. **Result:** The 0.300" pin did not brake, the cover lifted about 2" (as allowed by the locking mechanism), **and the roof slab did not lift** (Event 25). This case would **not** result in roadbed damage**.**
- Using 10% hydrogen concentration, use the 0.275" pin. **Result:** The 0.275" pin did not brake, the cover lifted about 2" (as allowed by the locking mechanism), **and the roof slab did not lift** (Event 26). This case would **not** result in roadbed damage**.**
- Using 10% hydrogen concentration, use the 0.250" pin. **Result:** The 0.250" pin did not brake, the cover lifted about 2" (as allowed by the locking mechanism), **and the roof slab did not lift** (Event 22). This case would **not** result in roadbed damage**.**

At this point, it was decided that the objective of the test sequence was reached since conditions (pin size, explosion severity) were found for which the restraining mechanism provides adequate pressure relief without failure, and no roadbed damage occurs. Furthermore, conditions were also found for which the restraining mechanism does not provide pressure relief without failure, or does not prevent roadbed damage.

It should be noted, however, that all these tests were performed with hydrogen explosions only. The few tests performed with the UL mixture clearly indicate that explosion characteristics are significantly different from hydrogen explosions, and that the behavior of the restraining mechanism may also function differently. Further tests were not conducted since funds have been exhausted.

5
OBSERVATIONS, CONCLUSIONS AND RECOMMENDATIONS

Tests were performed in the M11 manhole mainly with the hydrogen gas (various concentrations by volume), with only a few tests with the UL mixture of gases. Comparison of results and observations from tests with hydrogen gas and the UL mixture indicates significant and important differences in explosion characteristics and in the behavior of the restraining mechanism.

It is therefore recommended that further selected tests be performed with the UL mixture of gases.

The first objective – can the Stabiloc locking mechanism prevent the cover from being dislodged – was met. Test results confirm that the mechanism can restrain the cover while allowing it to rise about 2 inches to provide relief of internal pressure. However, for very significant explosions, pressure relief is not sufficient to prevent roadbed damage.

The second objective – controlled release of pressure – was also met as discussed above.

The third objective – study of appropriate shear pin strength – was met with great success and provided very significant and useful information. Pin sizes were determined by test that both (a) provide pressure relief and (b) prevent roadbed damage for minor and moderate explosion. For major explosions, pin sizes can be selected to restrain the cover, but pressure relief is not sufficient to prevent roadbed damage. In this case, the requirement for restraining the cover is perhaps moot, since collateral damage due to the lifting of the roof slab can be very significant, while the dislodgement of the cover may then be of secondary concern.

However, it is again emphasized that most of the tests were performed with hydrogen gas, and it is recommended to perform selected tests with the UL mixture.

The fourth objective – study of the hinged cover – was met and the results suggest that this approach requires further development as pressure relief was insufficient to prevent dislodgement of the entire cover frame. Hence, the results of this test are to a large extent inconclusive as to the capabilities of hinged covers to provide pressure relief. **It is recommended to revisit this issue and re-design the attachment system of the frame to the roof slab, as this would further explore the possible advantages of hinged cover.**

A
SELECTED FRAMES CAPTURED FROM VIDEOS

Selected Frames

This Appendix contains several selected frames captured from the recorded videos. Copies of complete videos will be provided with the Final Report, now under preparation.

Figure A-1
Event 17. Pin size 0.275". Hydrogen concentration 13%.

Figure A-2
Event 20. Pin size 0.350". Hydrogen concentration 13%.

Figure A-3
Event 28. Pin size 0.250”. Hydrogen concentration 10%.

Export Control Restrictions

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case-by-case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

The Electric Power Research Institute (EPRI)

The Electric Power Research Institute (EPRI), with major locations in Palo Alto, California, and Charlotte, North Carolina, was established in 1973 as an independent, nonprofit center for public interest energy and environmental research. EPRI brings together members, participants, the Institute's scientists and engineers, and other leading experts to work collaboratively on solutions to the challenges of electric power. These solutions span nearly every area of electricity generation, delivery, and use, including health, safety, and environment. EPRI's members represent over 90% of the electricity generated in the United States. International participation represents nearly 15% of EPRI's total research, development, and demonstration program.

Together…Shaping the Future of Electricity

Printed on recycled paper in the United States of America

1012305

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com