Manhole Explosions – Causes and Case Studies

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Overview - Questions

- What are manhole “events”?
- How often do manhole events occur?
- Are manhole “events” a problem?
- What are the causes of the events?
- What research has gone into solving the problem of manhole events?
- Can you avoid or prevent events?
- If events occur, how do you mitigate their effects ?
- What solutions are available to prevent events or mitigate the effects of the events?

Classification of Manhole Events

Manhole events can be separated into three main categories:

1. Smoking Events – events that do not involve flaming combustion, they only emit smoke and can often go un-noticed. Smoke may seep around manhole cover and through conduits to adjacent manholes and become visible to the public. They are often long term events that go un-noticed for extended period of time.

2. Fires – events that involve flaming combustion and emit substantial amount of smoke. Issue often involves how to extinguish the flames. Many fires will not generate sufficient pressure inside the manhole to dislodge the manhole cover. Fires result from combustion of materials in manhole, often cable insulation materials.

Classification of Manhole Events

3. Explosions - most severe manhole event involving sudden pressure rise inside manhole sufficient to propel cover to great heights. Explosions are very short term events – duration in msec. Explosions can be a significant danger to people in the vicinity of the manhole and cause severe damage to equipment inside manhole. Explosions can be a result of the release of chemical and electrical energy.

Frequency of Manhole Events

2013

- January 14 Boston MA
- January 26 Newark NJ
- January 27 Omaha NB
- February 10 Milwaukee WI
- February 18 Atlanta GA
- April 25 London UK
- May 6 Dubuque IA
- May 8 New York NY
- May 10 New York NY
- June 6 Guam
- June 6 Hartford CN

Frequency of Manhole Events

2012

March 6	Cincinnati OH
March 6	Laguna Nigel CA
March 15	Boston MA
April 22	Yorba Linda CA
May 13	Boston MA
June 22	New York NY
July 4	New York NY
July 4	Indianapolis IN
July 19	Jackson MS
Aug 13	Salt Lake City UT
Sept 18	Santa Monica CA
Sept 19	Albany NY
Nov 10	Manhattan NY
Dec 28	Scranton PA
Dec 29	New York NY

Frequency of Manhole Events

2011

- September 23 Ridgewood NJ
- September 10 Chicopee MA
- August 31 Morristown NJ
- August 18 Kenton England
- July 29 New York NY
- July 24 New York NY
- July 21 Boston MA
- July 7 Kansas City MO
- June 9 Morristown NJ
- May 31 Indianapolis IN
- May 4 San Jose CA
- April 27 Indianapolis IN
- April 22 San Francisco CA
- April 17 Hartford CT
- April 17 Pottstown PA
- April 2 Rio De Janeiro
- March 28 San Francisco CA
- March 5 Springfield MA
- February 8 Pottstown PA
- January 30 Indianapolis IN
- January 19 New York NY
- January 2 New York NY
- Winter –Spring 65 “events” in one city since Jan. 1

Are Manhole Events a Problem?

- Manhole events occur worldwide, however they are relatively rare
- When they do occur, they can be a serious safety problem to the public, firemen, maintenance crews
- Damage to equipment can be severe
- Manhole cover is the weakest link. Cover can be propelled over great distances and can become a potential projectile to public.
- Events occur more frequently in utilities with more extensive underground systems – large urban areas, high population density
- Events are more frequent in distribution systems. When events occur in transmission systems potential energy release is greater
- Litigation is a possibility

Long Term High Impedance Faults

Some Events Produce Only Smoke

Some Events Produce Only Smoke

Some Events Produce Only Smoke

Noah Berger / Special to The Chronicle

Some Events Produce Flames

Some Events Produce Flames

Damage to Electrical Equipment can be Significant

Some Damage can be Minor

Some Damage can be Minor

Effect on the Public Must be Considered

Rody Rosenbaum / Special to The Chronicle

Effect on the Public Must be Considered

Multiple Sources of Combustible Gases

- Aging/overheating electrical equipment (cables, splices, joints, transformers) can emit combustible gases – cable insulating materials are hydrocarbons – XLPE, EPR, PVC, PE; transformer and voltage regulator oils are combustible
- Weather related activities - salt applied to streets can generated combustible gases – frequency of some explosions correlate well with severity of winter weather and amount of salt applied to streets
- Decaying organic matter can create methane in a manhole
- Other utilities that share the manhole space can be source of combustible gases
- Public can dispose of combustible material in streets
- EPRI research has identified likely combustible gases resulting from overheated cables as – hydrogen, methane, acetylene, carbon monoxide and ethylene

Summary of Gas Properties

Gas	Heat of Combustion (kJ/kg)	Combustible Range (% by vol.)	Lighter than air?
CH_4 Methane	56,000	5 - 15	Yes
H_2 Hydrogen	140,000	4-75	Yes
C_2H_2 Acetylene	50,000	2.5 - 100	Yes
CO Carbon Monoxide	10,000	12.5 - 74	Yes
C_2H_4 Ethylene	50,000	2.7 - 36	Neutral

Three Basic Types of Manhole Explosions

1. Gas Explosion - energy comes from chemical energy release of gases when they burn

2. Electrical Explosion – energy comes from electrical energy dissipated by an arc resulting from a fault

3. Combination of Gas & Electrical Explosion - An electrical fault releases electrical energy – arc melts and then vaporizes surrounding combustible materials which are ignited by the arc and they release chemical energy

Explosion Characteristics

- **Gas explosions** are long events – 1-3 sec - flame speeds of many gases are about 1-5 m/s resulting in events that can last up to several seconds
- **Arcing faults** are usually short events limited by the protection system resulting in events that last about 5-30 cycles (80-500 msec)
- **Mitigation schemes differ** - As a result of these two different time frames, the mitigation schemes for gas explosions differ from those used to minimize the effects of electric faults

How Much Energy is Involved?

- **Gas Explosion** - for a typical size manhole filled with stoichiometric CH_4, explosion lasting for 500 msec
  - Energy released by the explosion is approx 40 MJ or average power is 80 MW
- **Arcing Fault** – assuming a fault of 7,200V with an available fault current of 5,000 amps for 10 cycles or 160 msec
  - Energy released by arcing fault is approx 6 MJ or average power is 36 MW

(one stick of dynamite has energy of 2 MJ)

Energy release from a manhole explosion is significant

Complicating Issues for Manhole Explosions

- **Manhole is rigid** and unable to absorb energy. All generated energy must go into the air in the vault.
- **Event is very rapid** and any mitigation design must react rapidly. Timing is very critical.
  - Relay system reacts within 100-200 msec
  - Flame speeds limit explosion times to 500-1000 msec
- **Vault is basically closed** and venting is limited.
- Attempting to bolt down cover is poor decision. Explosive pressure can break most bolts and welds.

Problem is Very Complex

There are basically two approaches to the design of safety equipment:

Testing : Simply design a test apparatus and test all the possible mitigation designs - expensive

Software: Use a computer simulation of the event and design a system based on the results of most promising mitigation scheme – can evaluate numerous options until most promising solution emerges –relatively cheap

EPRI Test Facility Lenox Massachusetts

- Full-scale buried manholes
- Ability to inject and ignite a combination of combustible gases
- Manhole instrumented with pressure and temperature transducers
- Several safety covers have been tested

EPRI Test Facility Lenox Massachusetts

Description of Explosion Software

- Software has been developed over the past 20 years.
- Software has been recently used to simulate the events during an explosion in a full-scale underground explosion and to design devices to mitigate the effects of an explosion.
- Pressure rise calculations with the software compare well with measured values during explosions.

Explosion Computer Design Code

- Computer code can simulate a gas explosion and an arcing fault in a manhole. It can model faults in transformers and voltage regulators
- Computer results can be used to predict pressure and temperature rise during the explosion
- Results can be used to design an explosion mitigation scheme
- Results suggested by code is an inexpensive alternative to full-scale explosion tests

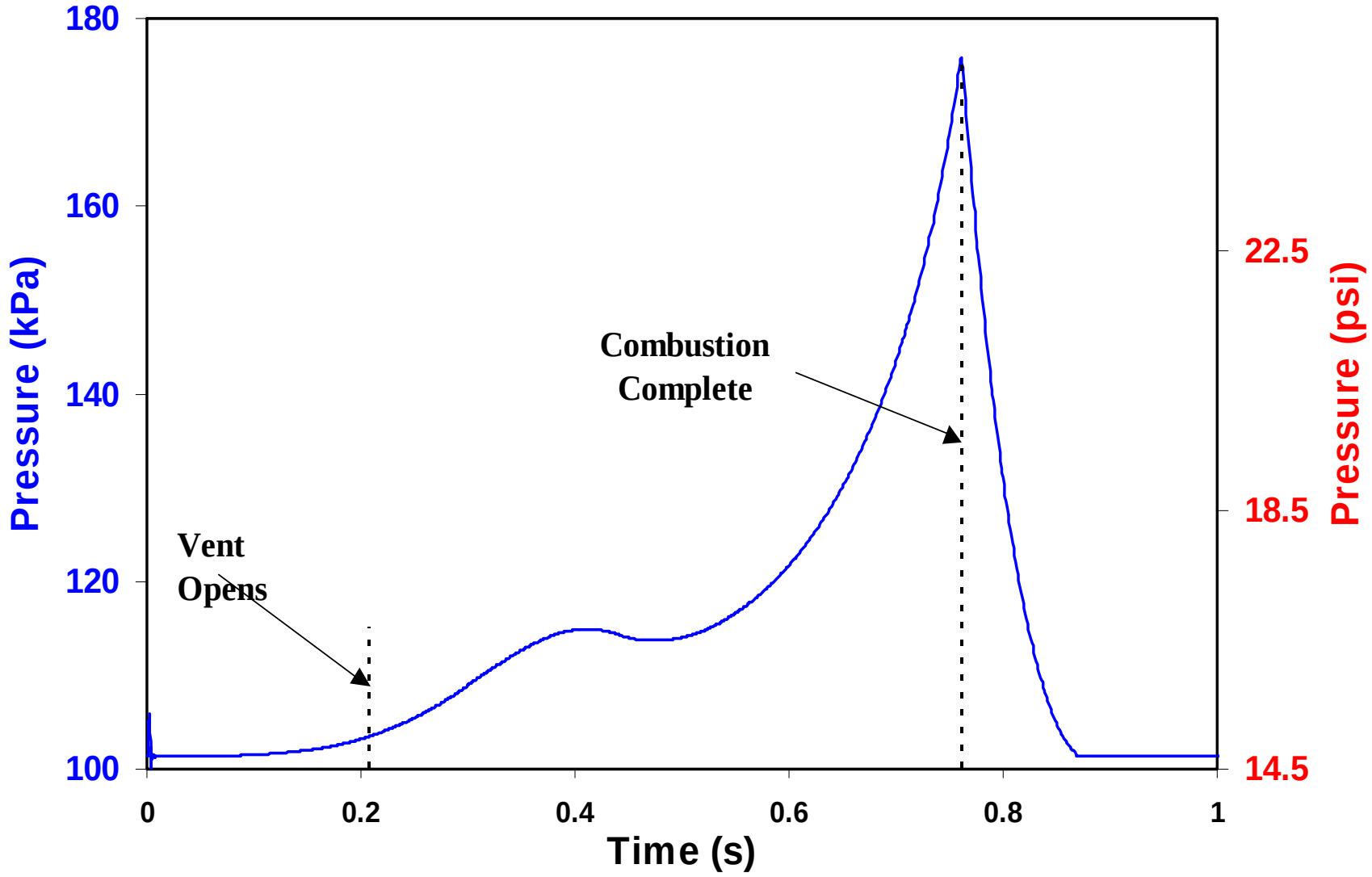
Goal of Software

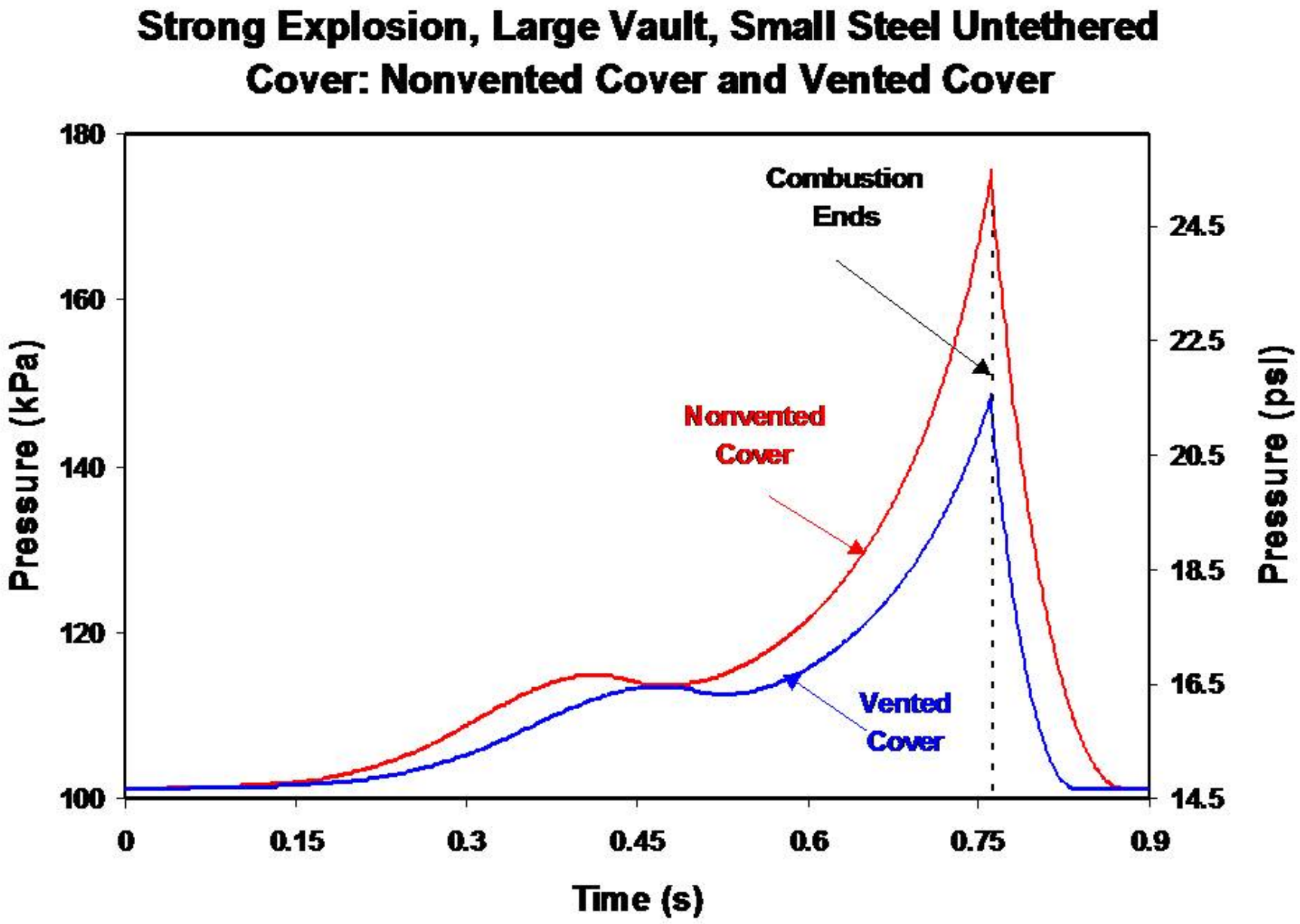
- The “design tool” program can be used to determine the merit of safety mechanisms that can help mitigate the problem of manhole events
- The program would be a guide for an experimental program
- Software will direct work toward schemes that are the most promising such as tethers, venting devices, gas displacement designs etc.
- Computer code could be used in other enclosures events - transformers, switches etc.

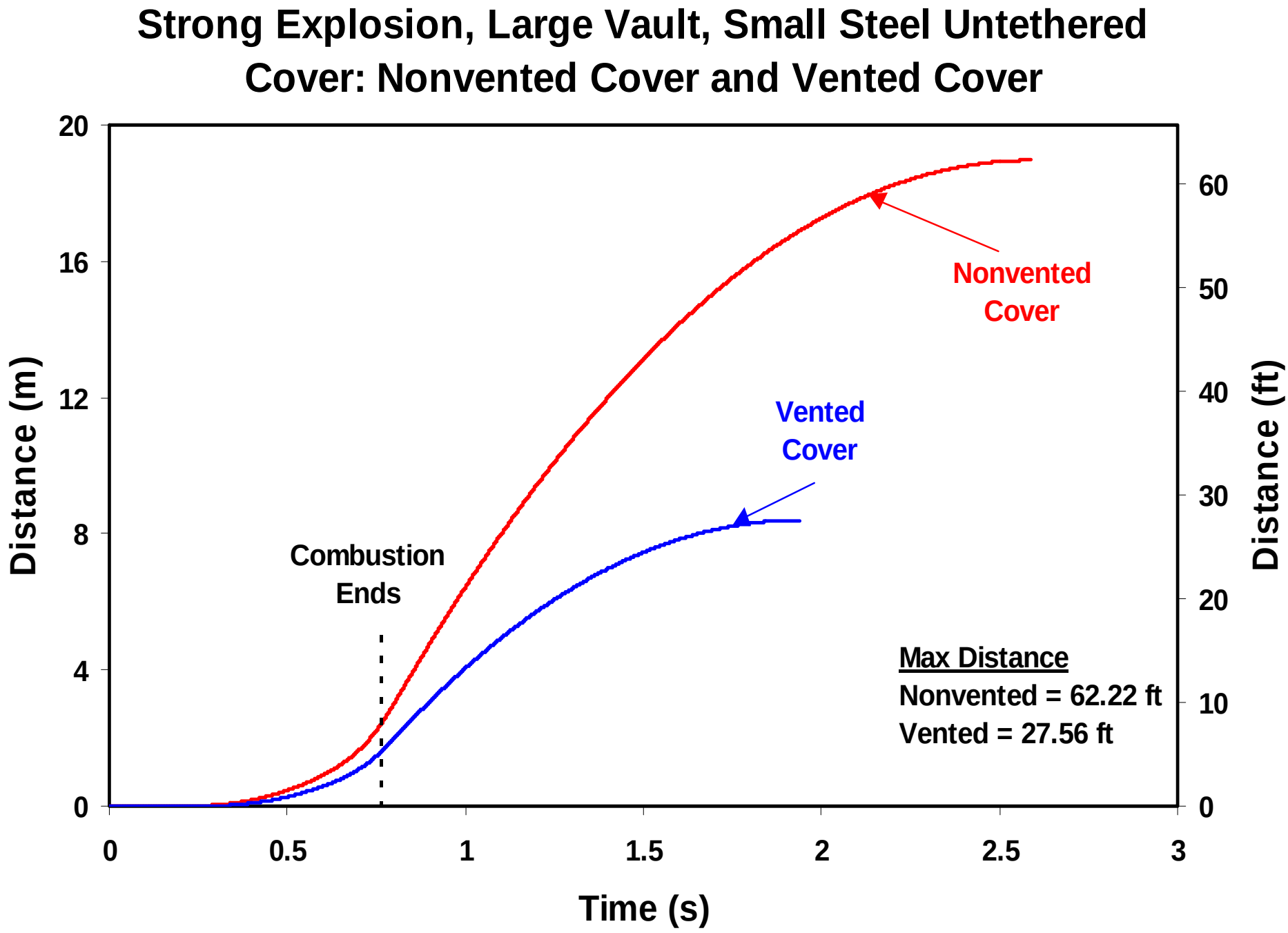
Software Capabilities

- Input:
  - Geometry of vault and cover
  - Amount and composition of gas in vault
  - Arc voltage and current waveforms, arc duration
- Output:
  - temperature and pressure rise inside manhole
  - forces on vault and cover
  - motion of cover
  - required strength of tether & effect of vents.
- Present focus is on design of mitigation schemes

Strong Explosion, Large Vault, Small Cover




Strong Explosion, Large Vault, Small Steel Untethered
Cover: Nonvented Cover and Vented Cover
Combustion
Ends
Nonvented
Cover
Vented
Cover
Pressure (kPa)
Pressure (psi)
Time (s)
180
160
140
120
100
24.5
22.5
20.5
18.5
16.5
14.5
0
0.15
0.3
0.45
0.6
0.75
0.9


Strong Explosion, Large Vault, Small Steel Untethered Cover: Nonvented Cover and Vented Cover
Distance (m)
Distance (ft)
Time (s)
0
4
8
12
16
20
0
10
20
30
40
50
60
0
0.5
1
1.5
2
2.5
3
Nonvented Cover
Vented Cover
Combustion Ends
Max Distance
Nonvented = 62.22 ft
Vented = 27.56 ft

Results of Computer Simulations

- Pressure rise for gas explosion is greatest for large manhole
- Pressure rise for an arcing fault is greatest for small manhole
- Vented covers will not be successful for all explosions – vented covers will still not be able to sufficiently vent high velocity gases regardless of size of vents
- Tethered covers have greater potential for success if restrained with a flexible device – polyester or nylon webbing is good, metallic cable or chain is bad
- Venting of high pressure gases generated during explosion is the safest way to mitigate the effects of the explosion
- Gas displacement schemes will solve the problem of a potential gas explosion, but will be ineffective if an arcing fault should occur

Explosions in Transformers & Voltage Regulators

- Electrical faults in transformers can generate levels of energy similar to those experienced from gas explosions in manholes.
- Insulating oils in transformers and voltage regulators are flammable and incompressible. Tank is rigid. Pressure rise is rapid and can reach levels sufficient to rupture tank. If that occurs combustion outside the tank is likely.
- Energy of fault creates a gas bubble of flammable oil that tries to expand, creating excessive internal pressures.
- Tank's strength is insufficient to withstand generated pressures when event is strong – high $I^2\Delta t$.

Explosion Test Videos

- The software was used to design a tether system for two transmission circuits in the U.S.
- A series of tests were conducted to verify computer results and verify that a tether system could safely restrain manhole covers during simulated faults in a manhole.
- **Above ground test**: Bolted fault on 138 kV extruded dielectric 2250 kcmil copper conductor cable
- **Underground manhole test**: Bolted fault on 138 kV cable and splice. Manhole had two covers equipped with polyester tethers

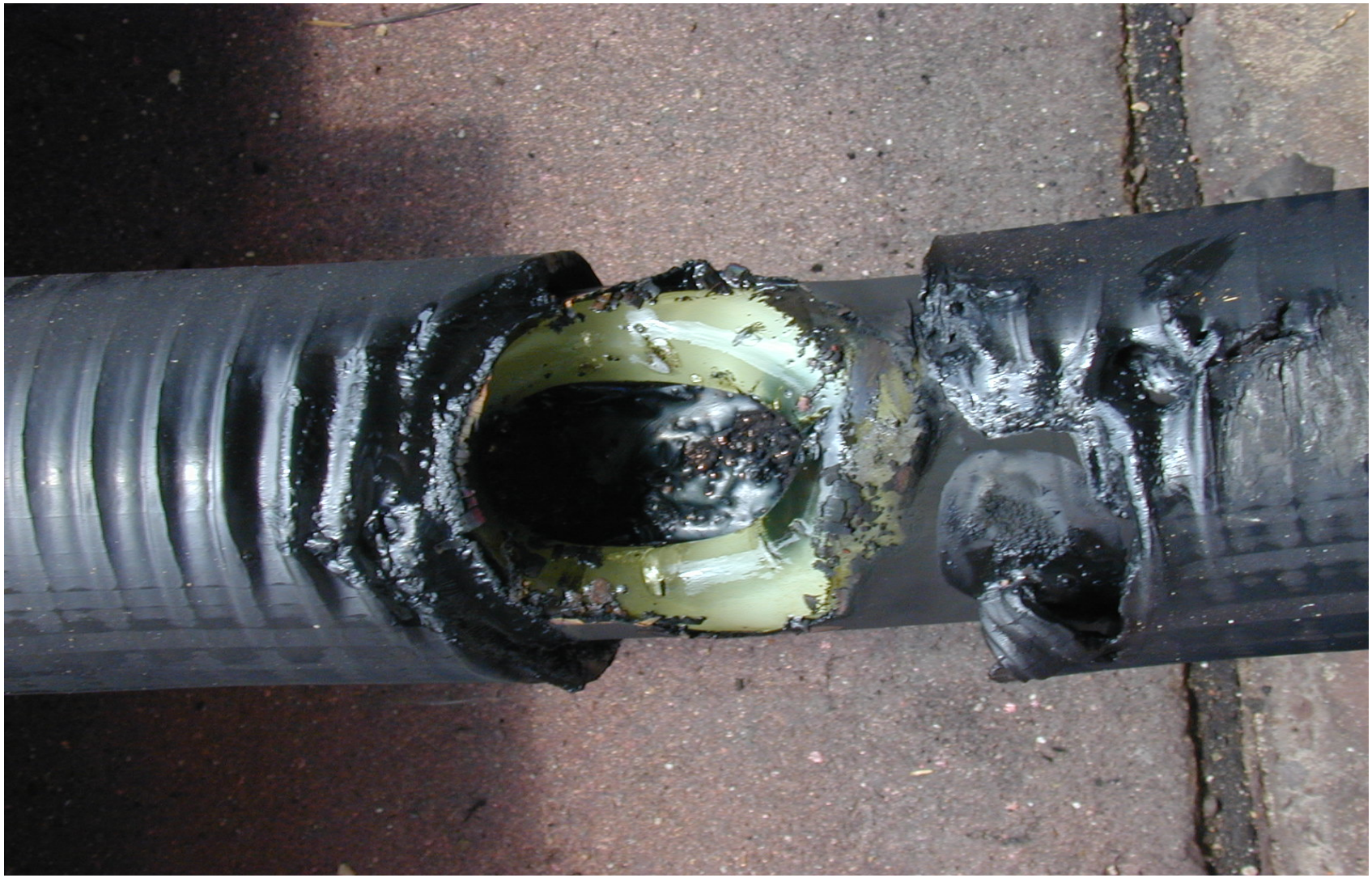
Short Circuit Test

05087-B Trial #3.mpg

- **Above ground test**: Bolted fault on 138 kV extruded dielectric 2250 kcmil copper conductor, 850 mil XLPE insulation, PE jacket

  Resulting arc generated sufficient energy to melt and vaporize approximately 125cc of cable insulation which then burned – combination of fault plus gas combustion contributed to explosive energy

Cable After Fault



Full-Scale Test with Tethered Cover

Full-Scale Test with Tethered Cover

Short Circuit Test

splice overview 30fps.avi

- **Underground manhole test**: Bolted fault on 138 kV cable splice

  Manhole covers were equipped with two flexible tethers that moved about 1m vertically during the explosion. Maximum pressure rise generated inside manhole was about 9 psi (60 Pa)

Splice After Fault

Manhole After Fault

Conclusions

- Manhole events can be classified as smoking combustion, flaming combustion or explosions
- Manhole events are relatively rare but when they occur consequences can be serious
- Magnitude of explosions is great – lots of energy involved
- Events are due to electrical faults, ignition of combustible gases or a combination of the two
- Gases involved in explosions can results from overheated, aging cables and accessories
- Tests have led to a number of cover designs to mitigate the effects of manhole explosions
- Software has been developed and used to design a tethered cover and it has been proven successful in a full-scale test

Manhole Explosions – Mitigation Methods

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Design Considerations for Safety Devices

Safety - number one priority is safety of work crews and the public

Cost – device must be installed in numerous manholes/service boxes.

- One utility has 57,000 manholes with 50 events/year.
- Another utility has over 225,000 manholes with about 1000 events per year, 20-30 of which are serious

Maintenance - design should not inhibit service inside vault.

Reliability – device must work for any type of explosion – every time, without fail.

Longevity – little or no service or maintenance – install it and forget it.

Managing Manhole Explosions

There are two basic ways to manage the effect of manhole explosions:

1.Pro-active approach: attempt to **prevent** event from occurring in the first place

2.Re-active approach: if an event occurs, design a scheme that will **mitigate** the effects of the event and improve safety to public and work crews

Preventing Manhole Explosions

Pro-active approach – attempt to **prevent** explosions before they occur

- Replacement of aging cable, splices, joints terminations
- Ventilation of manhole
- Increase routine inspection frequency
- Installation of gas analyzers and arc detection equipment in conjunction with communication equipment
- Installation of inflatable bladders filled with inert gas
- Reduction of salt applied to streets
- Cooperation with other utilities
- Education of public about disposal of flammable liquids

Mitigating Effects of Manhole Explosions

Re-active approach - what are possible ways to **mitigate** effect of an explosion if one occurs

- Tethered covers to capture cover and allow high pressure gases to escape
- Vented covers to allow lighter-than-air gases to escape
- Restrained and hinged covers to allow high pressure gases to escape
- Bolt covers down and let street deform to vent high pressure gases to escape through asphalt
- Burst diaphragms to release the internal pressure

Mitigating Effects of Manhole Explosions

- **Pressure history** is the key to designing an explosion mitigation scheme
- **Venting** is the basic principle to quickly minimize the enclosure pressure
- **Good Mitigation Designs**

  Light-Weight, Vented Covers – they can permit greatest vertical motion of the cover while maintaining safe pressure levels

  Cover Restraint – a flexible tether allows the manhole cover to lift, but limits motion to a safe level
- **Poor Mitigation Designs**

  Covers Bolted Down – pressures developed during explosion can easily break bolts or rigid restraints

One Solution Doesn't Solve Both Types of Events

- The effects of a gas explosion are minimized in small manholes
- The effects of an arcing fault are minimized in large manholes
- A gas detection system may prevent gas explosions, but will not prevent explosions due to a fault
- An arc detection system may prevent explosions due to faults, but will not necessarily prevent explosions due to ignition of gases

Pro-Active Solutions

- Arc Detection Systems
- Gas Detection Systems

Continuous Gas Monitoring Cover

Battery operated cellular-based telemetry system
Capable of multiple sensors – temperature, water level, voltage change etc.

Continuous Monitoring Covers

- **Pros**
  - Real-time monitoring
  - Proactive prevention measure
  - Immediate notification of danger
  - Battery operated
  - Unlimited sensing available
    - Temperature, Water Level, Voltage, Unauthorized Access, etc.
- **Cons**
  - Requires routine maintenance, battery replacement
  - Requires a network (cell, radio, or hardwired)

Electronic Wireless Monitoring

Electronic Hybrid Composite Cover

Electronics

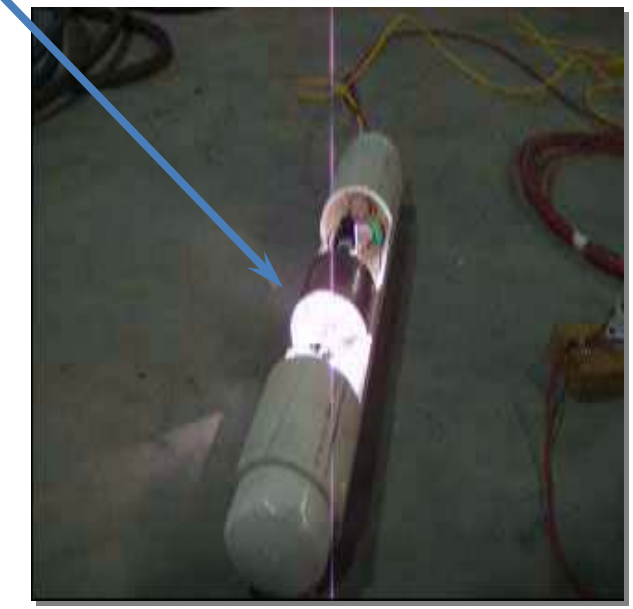
Arc Detection Systems

Secondary Cable Arcing Fault

- High impedance faults create low current levels that cannot be detected via conventional devices such as fuses or circuit breakers. Arcs may persist for extended periods and generate combustible gases.

Arc Produces:

- Electrical field
- Magnetic field
- Variations in electric current
- Acoustic waves
- Arcing Current



Portable Manhole Arc Recognition System

- Probe is lowered into manhole to detect possibility of arcing
- Device is portable
- Every maintenance crew is supplied with the device to check for arcing prior to and during work
- Unit has been field tested
- Arcs with as little as 1 amp can be detected

Sensor Pod deploys into manhole

Proactive Solution – Arc Monitoring

Pros

- Real-time monitoring
- Proactive prevention measure
- Immediate notification of danger
- Battery operated
- Sensors can detect arcing current, E-Field, H-Field

Cons

- Requires routine maintenance
- Requires a network (cell, radio, or hardwired)
- Signal processing techniques are needed to eliminate false alarms

Re-Active Solutions

Vented covers

Spring mounted covers

Hinged covers

Tethered covers

Solid restrained covers

Basic Design Criteria for Re-Active Schemes

In the event of an arcing fault or a gas explosion basic design rules are:

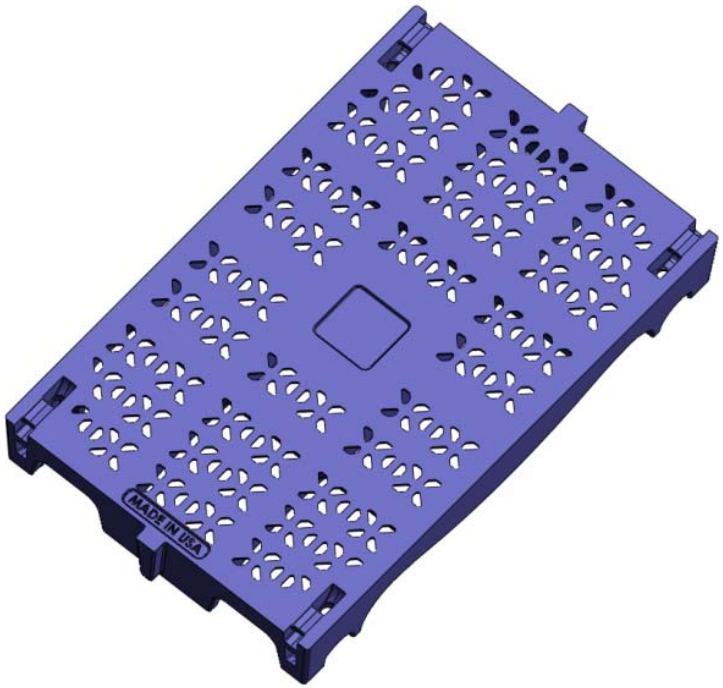
Vent the manhole as efficiently and quickly as possible

- Utilize vented covers
- Allow cover to rise creating openings to the atmosphere
- Capture cover so that it doesn't become a projectile

Use flexible components to minimize impact forces – tethers should be similar to seat belt material to reduce acceleration forces

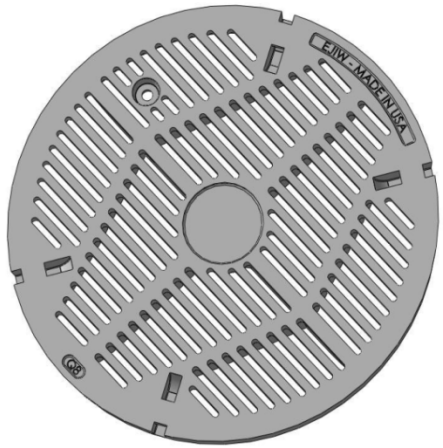
Permanent Venting – Composite Covers

Pros: Can allow light gases to vent
Cover is light to allow quick movement
Cons: Allow water intrusion
Cover can lift in strong explosion



Permanent Venting Covers

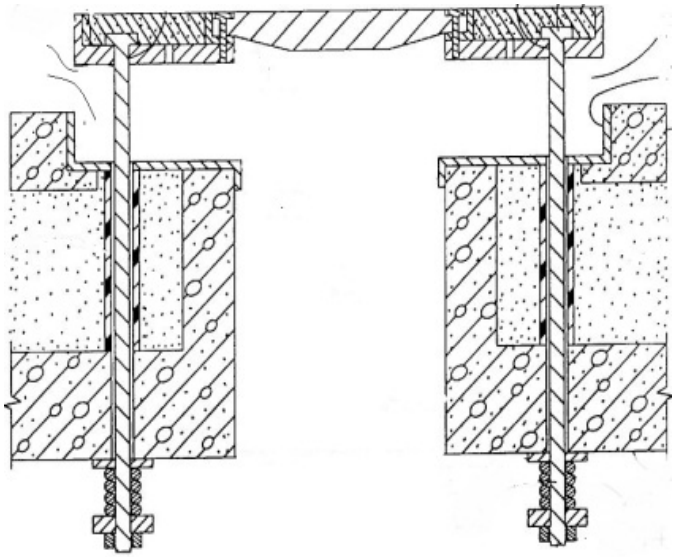
- **Pros**
  - Allows buoyant gases to escape
  - Vehicle travel creates air circulation
  - Provides some pressure relief
  - Inexpensive retrofit, simply replace solid cover
- **Cons**
  - Open to intrusion (water, fuel, debris,..etc.)
  - Allows heavy gases to accumulate
  - Explosion forces can still cause dislodgment



Permanent Venting – Iron and Composite Hybrid

- Cover is lighter than traditional solid metal cover
- Electrically non-conducting, reduces danger of contacting charged cover

Restrained Cover – Spring Mounted

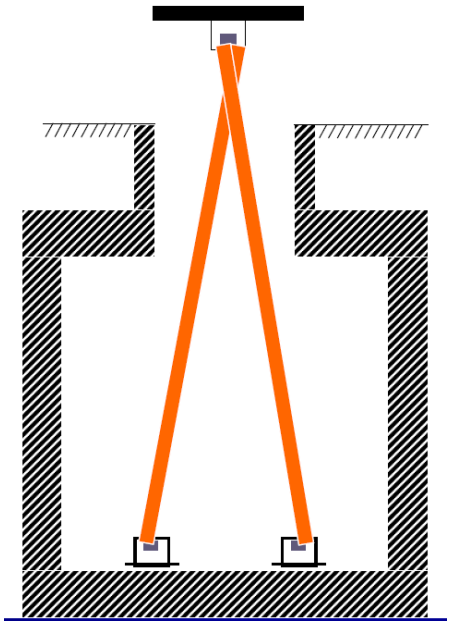


Restrained Hinged Cover

- Increase in pressure opens cover to vent high-pressure gases
- Cover hinges and rotates open
- Cover returns to closed position after explosion
- Rigid attachments create large explosive forces

Tether Restrained Cover

- **Pros**
  - Positive cover restraint during explosion
  - Tethers absorb cover momentum during explosion
  - Can be used in retrofit applications
  - Covers and tether have been blast tested
- **Cons**
  - Cover and manhole have to be modified
  - Tethers may impede manhole access



Tether Restrained Cover

- Tethered covers allow venting and reduce pressures while improving safety to public
- Tether-based designs use inexpensive, common materials – polyesters, nylons – seat belt materials
- Flexible tether does not inhibit maintenance inside vault – cover can be removed and set aside
- Rigid tethers (metallic chains and cables) are not viable options due to their inability to absorb energy

Cover Solid Restraint System

Venting from Fixed Restraint Covers

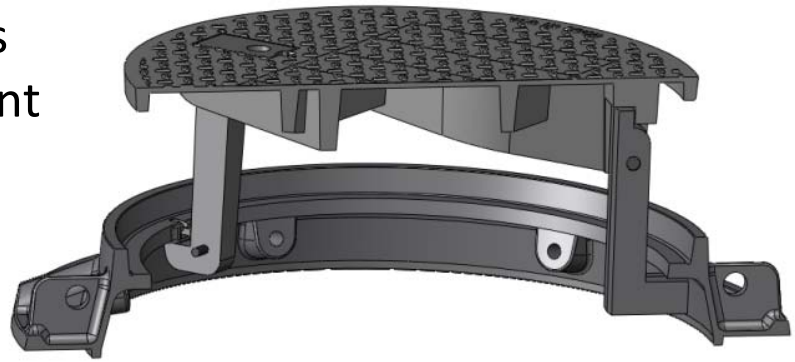
- **Pros**
  - Cover rises 2” for venting during minor–moderate explosion
  - Stronger explosion shears metallic pin and allows greater venting
  - May be used in retrofit applications
  - Blast tested for minor-moderate explosions
  - Cover returns to seated position
- **Cons**
  - No visual verification that cover is secure
  - Retrofit may require additional frame anchors
  - Requires special tool to access
  - Intricate device with moving parts
  - May require maintenance
  - Allows some pressure build up before relief

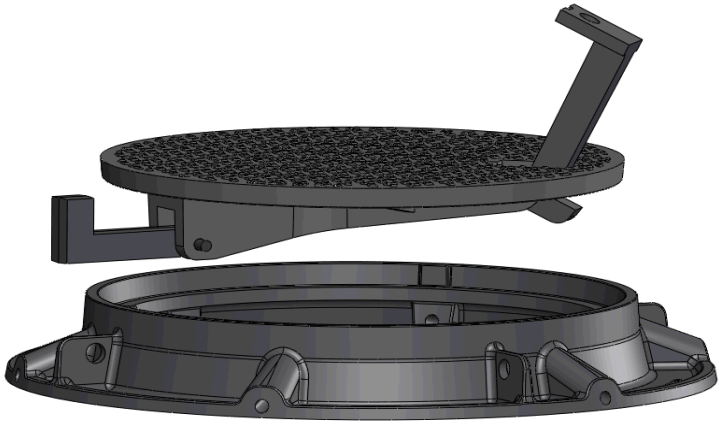
Restrained Cover with Extended Spikes

- Cover is rigidly attached to frame
- Extended spikes create larger surface area for attachment to roadway
- Explosion lifts cover, frame and roadway attached to spikes creating expanded surface area for venting of high pressure gases
- Cover is not commercially available
- Venting is limited
- Explosion will damage street

Fixed Restrained Cover

- Cover is supported by three pivoting legs
- Cover opens to vent high pressure gases
- Vent area is increased to provide efficient venting
- Legs pivot to facilitate removal of cover
- Solid cover prevents intrusion of debris and water





Conclusions

- Both gas- and fault-generated explosions release a very large amount of energy
- Manholes are not designed to absorb that energy Mitigation designs must be selected to dissipate or absorb the explosion energy.
- Resulting damage can be great and safety is a major issue
- Mitigation schemes are available:

  Reactive solutions: Vented, tethered, composite and fixed-restraint covers

  Proactive solutions: Gas and arc monitoring equipment
- Mitigation designs are different for gas explosions and fault-generated explosions
- Several reactive and proactive designs have built, tested and installed in the field