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Analysis of a gas explosion in Dimock PA (USA) during fracking operations in the Marcellus gas shale

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ABSTRACT

On January 1, 2009, a concrete slab covering a water-pump vault of a water well 400 m north of a Marcellus gas well in Dimock, Pennsylvania, USA was reported to have split into three pieces while being overturned. It was suggested that the cycling on of a water pump sparked the deflagration of a methane-air mixture causing the slab to overturn. Here, the conditions necessary to generate an explosion consistent with evidence, mainly a split and overturned concrete slab unmarked by soot or other evidence of a flame, are analyzed. Using more than one approach, calculations show that the maximum pressure to lift the concrete slab was roughly 0.3 bar. Considering among others the flammable range of methane, the explosion pressure as a function of equivalence ratio, the presence of methane gradients inside the vault, the absence of soot and possible ignition sources, the analysis did not yield a well-defined, credible gas explosion scenario to explain the observed damage, although the possibility cannot be ruled out with absolute certainty.

1. Introduction

Worldwide, the media called attention to the impacts on the environment and human health that hydraulic fracturing, fracking in short, had during the extraction of shale gas and tight oil deposits. Video of an opened tap with burning water in the kitchen of a house is well known (Schlanger, 2014), although such phenomena occur naturally including the so-called 'eternal flame' in the western part of New York State (Etiope et al., 2013).

Recent peer-reviewed literature focuses on the occurrence of methane in tap water in areas where natural gas is produced, especially in relation to fracking (Darrah et al., 2014; Molofsky et al., 2013; Osborn et al., 2011). The origin of methane in tap water may be thermogenic and/or biogenic (Osborn et al., 2011), it may be a consequence of hydrogeologic and topographic features of the area (Molofsky et al., 2013) or a consequence of incorrect casing and cementing during well completions leading up to fracking (Darrah et al., 2014). The potential hazard of fracking in relation to human safety came into sharp focus in 2009 when it was said to be responsible for a gas explosion. Sometime during daylight hours on January 1, 2009 the concrete slab covering a water-well pump vault about 400 m north of a Marcellus gas well in Dimock, PA, was disturbed (Legere, 2009). An event caused the concrete slab covering the well vault to split and overturn. The Pennsylvania Department of Environmental Protection (PA-DEP) concluded that a methane explosion was the most likely cause of the incident, based on the evidence available, which was an overturned concrete slab to the water well vault (Lustgarten, 2009).

Given the role of this explosion as an iconic image for water contamination associated with the gas industry, it is important to understand the facts of the 2009 New Year's Day event. The assumption is that a flammable methane-air mixture was ignited by a spark when a water pump sitting on the floor of the vault cycled on. No one was home and the water line was frozen so if the pump cycled on, it did so spontaneously and without any of the ordinary triggering mechanisms (McGraw, 2011).

To this day, the literature contains little in the way of quantitative data describing the outcome of in- ground water well pit or vault explosions. Newspapers dating back more than 120 years carry reports of water well explosions in a number of the states sitting over Devonian gas shale in North America. The number of American newspaper reports is extensive and in Table 1 only those explosions involving fatalities are listed. In nearly all cases, the explosions were triggered by human actions and in some cases resulted in extensive burns, if not death.

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Table 1
Historical overview of methane explosions in water wells. These water wells are located over Devonian gas shale in the northeastern United States.

Origin	Date	Location	Fatalities	Source
Water well	8/8/1890	Hamilton, Ohio	3	Anonymous (1890)
Dug well	6/30/1904	Hocking, Ohio	1	Anonymous (1904)
Water well	10/27/1910	Lorain, Ohio	1	Anonymous (1910)
Water well	9/20/1913	Lebanon, Pennsylvania	1	Anonymous (1913)
Water well	05-10-1920	Livingston, New York	2	Anonymous (1920)
Water well	06-02-1948	Wabash, Indiana	1	Anonymous (1948)
Water well	07-04-1969	Luzerne, Pennsylvania	4	Meyers (2003)
Basement	12/15/2007	Jefferson, Pennsylvania	3	Lusgarten (2009)

Fig. 1. Methane explosion in basement of house causing damage to the foundation in Chagrin Falls, Ohio, USA (Bair et al., 2012). The foundation has been cracked and paint peeled just above the vent points in the foundation.

Fig. 2. Dimock water well vault and the two sections of the split and overturned concrete slab with the top course of concrete blocks still attached. View looking to the southeast. A reporter from the Scranton Times-Tribune appeared with a photographer the morning after the event in question (Legere, 2009). The reporter believes that the broken concrete slab had not been moved between the time of the January 1st 'explosion' and the time of this photograph was taken less than 24 h later (L. Legere, 2013, personal communication).

One example with which to compare the Dimock water-pump vault is a buried water tank in Decatur, IL, which partially filled with gas. When an electric pump switch provided an ignition spark, a hole was blown in the ground comparable to the size of the water tank (Browers, 2014). Volumetrically, the Decatur water tank and Dimock water-pump vault are similar but the outcome was different. The explosion in Decatur was powerful whereas the Dimock event was not. Another datum against which the Dimock incident can be measured is a violent explosion inside a well pit near Spring Mills, Pennsylvania, USA (Gold et al., 1970). This explosion created a cone-shaped crater in bedrock, the Ordovician Hatter Limestone, with a rim crest diameter of 7.6 m and a depth of 3.6 m. The energy of this explosion, attributed to the ignition of gasoline vapors from a leak in a nearby gasoline tank, threw the water pump 56 m into an adjacent field.

A third event that has considerable similarities with Dimock comes from Chagrin Falls, OH, USA, where gas migrated up a water well and mixed with air at explosive levels in a basement (Bair et al., 2012). The natural gas – air mixture was ignited with the resulting pressure wave lifting one end of the home from its foundation just enough to jostle some concrete foundation blocks (Fig. 1). Heat from the venting flame peeled paint from the outer wall of the home but did not cause a fire. This natural gas – air deflagration could be traced back to methane migrating into the local water table from the outside of an incorrectly cemented casing of a nearby gas well less than 300 m to the south. The difference between the Dimock and Chagrin Falls gas wells is that in the former case the top of the open hole was 468 m below the surface in a 2271 m deep Marcellus gas shale well, whereas in the latter case the top of the open hole was 80 m below the surface in a 1197 m deep Clinton sandstone well, a conventional well.

What these examples also show is that the conditions leading to the respective incidents have a significant influence on their outcome and can range from severe damage down to a weaker flash fire.

2. Description of the event

As there are no witnesses to the Dimock event and no direct measurements available, the best piece of the evidence for what happened is the concrete cover. Assuming the concrete slab to be thrown upward by the deflagration of a methane-air mixture, the spot where and how it landed gives an indication of the impulse and force needed. There are at least four photographs in the public domain that record the vault, the concrete slab covering the vault, and the slab's trajectory (Fig. 2).

The concrete slab with one course of concrete blocks still attached was split during an upward acceleration with the two pieces subsequently overturning before coming to rest. Two-thirds of the slab was thrown eastward and the remaining one-third was thrown westward (Fig. 3).

The western third may have been overturned with the western wall of the vault acting as a fulcrum. More than 50% of the eastern two-thirds of the slab landed back on top of the vault which means that the outside edge of the eastern slab did not turn on a fulcrum but rather was lifted clear of the vault and spun in space before dropping back down. The lifting forces were uneven as indicated

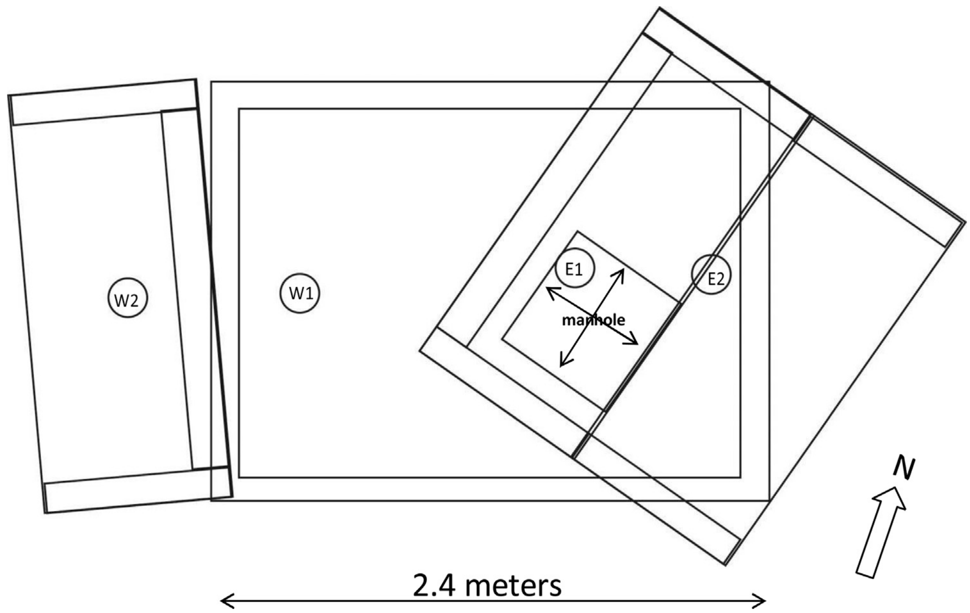

Fig. 3. Map of rectangular water well vault (central rectangle) and the position of the overturned split concrete slab after the incident. The position of the top course of concrete blocks is shown on the concrete slab (narrow edge rectangles). The position (circles) of the center of mass of the two sections of the concrete slab are indicated before (1) and after (2) the incident. This diagram is drawn from a series of photographs taken by a reporter from the Scranton Times- Tribune (Legere, 2009).

by a torque that spun the eastern slab at least 35° about a vertical axes and in excess of 90° about a horizontal axes. This is related to the restraining forces, i.e., the forces needed to fracture the mortar. Depending on the location of the horizontal spin axis, the upward throw must have approached z = 2 m to allow the slab to flip and land upside down without hitting the edge of the vault as it spun. The lift could have been higher but that would have increased the likelihood of shattering the concrete slab upon crashing back down on the well vault. The force of the landing was uneven causing the eastern slab to split again as indicated by the juxtaposition of the two eastern pieces. The slab was not shattered by an explosive force while being lifted.

The center of mass of both the larger and smaller pieces of slab moved directly apart, each displaced approximately 0.7 m (i.e., E1 to E2 and W1 to W2 in Fig. 3). The center of mass of the eastern two-thirds of the concrete slab never reached the eastern edge of the vault whereas the center of mass of the western third passed over its hypothetical fulcrum point on the western edge of the vault. The symmetry of the post-explosion centers of mass suggest that the lifting force on the concrete slab was initially directed upward. Two horizontal axes of opposite spin developed during and immediately following the initial one-third, two-third split.

In the publicly available photos a ladder was present with rungs spaced every 12 in. (0.305 m) which allows a reasonably accurate estimate of the vault volume (i.e., the amount of fuel available for the explosion) and mass of the concrete slab (i.e, size of the projectile). The dimensions of the vault are approximately 6 ft (1.83 m) in the north-south direction by 8 ft (2.44 m) in the east-west direction by 7 ft deep (2.13 m) yielding a volume of approximately 336 ft3 (9.51 m^3). The mass of the concrete slab (≈10 cm thick) and approximately 24 concrete blocks (≈21 kg per block) still attached equals 1306 kg, assuming a concrete density of 2408 kg/m^3. The vault cover had a manhole occupying about 10% of its area. The manhole was covered with a plastic trashcan lid (McGraw, 2011). Although the manhole is a partial vent after the manhole cover was blown off, the concrete slab will still lift under explosive pressure as long as a seal prevents sideways venting along the edges of the slab (Anonymous, 2012; Bailey, 1935).

3. Analysis of Dimock event

In the literature, methodologies are available to determine the force that was needed to lift, break and turn the two pieces of concrete slab. Here the method of Baum (Baum, 1988, 1993; Baum et al., 1978) and the method presented in the so-called Yellow Book (Committee, for the Prevention of Disasters, 2005) are used. An important starting point is whether or not the slab was cemented to the second layer concrete blocks or that it was loosely laying on top of it. Based on the damage observed, it is plausible that the slab was cemented, as this may explain its break up as is, as a cemented slab will require a higher pressure to create projectiles. This situation is the worst-case scenario and will be used in our analysis. Using the methodology of Baum, the distance a projectile travels, S, after an explosion is directly related to the maximum velocity of that projectile as follows:

$$S = \frac{3V_{\max}}{g} \quad (1)$$

The maximum velocity of the projectile is derived from:

$$V_{max} = 2\sqrt{F}a_0 \quad (2)$$

with

$$F = \frac{P_0 A R}{M a_0^2} \quad (3)$$

where P_0 is the overpressure needed to launch the projectile, A is the surface area of the projectile, R is the radius of the vault, M the mass of the projectile and a_0 the speed of sound in the medium through which the pressure wave travels to exert force on the concrete slab. It should be noted that the method of Baum assumes an initially cylindrical vessel from which the projectile is being launched. As such, for the vault radius R the equivalent spherical radius is determined. Aside from the required overpressure, a minimum pressure is needed to overcome the gravitational force working on the concrete slab:

$$P_{min} = \frac{Mg}{A} \quad (4)$$

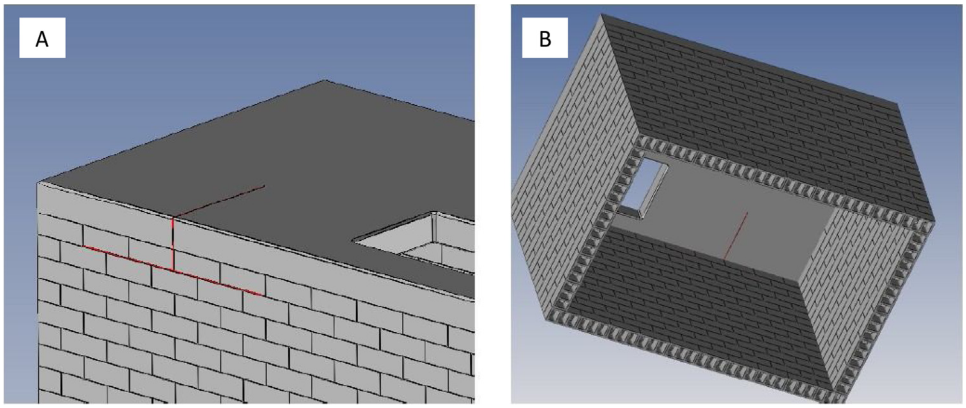

Fig. 4. (A) Crack propagation (red line) starting in the mortar keeping the concrete blocks together due to the overpressure generated and (B) subsequently propagating fracture across the slab (view from bottom of vault). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Using Eqs. (1)–(4) the total pressure needed to launch the concrete cover of the vault is 3.2 kPa (0.032 bar). This is an exceptionally low overpressure that can only be achieved near the flammability limits of methane-air mixtures, if measurable at all. The concrete slab had a manhole but it was loosely covered making it possible that the entire vault filled with a flammable mixture (McGraw, 2011). If the entire vault was filled with a flammable mixture near the lower (≈5% vol.% CH4) or upper (≈15% vol.% CH_4) flammability limit (Zabetakis, 1965), this would mean that the ignition source must have been strong, comparable to that of an open flame. This possibility can be ruled out under the given circumstances. This makes it more plausible that a local, small volume of a near-stoichiometric methane-air mixture ignited inside the vault coincident with the pump when the pump switched on. This mixture would have been well inside the flammable range, hereby enabling ignition from a spark that a non-explosion-proof pump is capable of generating. As the pressure wave travelled from the point ignition to the underside of the concrete slab, the peak pressure is damped as a function of distance.

Another calculation method considers the height the vault was lifted. Based on the damage to the vault, the concrete slab may have been lifted upwards roughly h = 2 m (Fig. 4). Knowing that the surface area of the intact slab was A = 4.465 m^2, having a mass of M = 1306 kg, the force balance states:

$$AP_{min}\mathrm{x} = Mgh \tag{5}$$

where x is the height the slab travelled before the pressure inside the vault was equalized with the ambient pressure. This height is conservatively taken as twice the thickness of the concrete slab (Committee, for the Prevention of Disasters, 2005). Based on the energy balance, the pressure needed to lift slab equals 2.87 × 104 Pa or 0.29 bar. Albeit a higher pressure than calculated according to the method of Baum (Baum, 1988, 1993; Baum et al., 1978), this is still a pressure only found near the flammability limits. This result also points to the fact that a localized volume inside the vault may have occurred instead of a flammable mixture present in the entire vault near one of the flammability limits. It should be noted that both calculations above assume that the pressure is generated in a closed system, while the concrete slab had a manhole that occupied about 10% of the surface area. The plastic cover on the manhole had no physical strength so any pressure buildup would immediately blow the plastic cover off the manhole. An open manhole will vent part of the overpressure generated in the vault.

4. Discussion

A few months before the incident, a Marcellus gas well 1.6 km to the south was spudded and its drill bit jammed after hitting a pocket of gas at a depth of about 271 m. Operations to retrieve the jammed drill bit were not successful and the bit had to be considered lost. The well was plugged with cement inside the conductor casing and down into the open hole but not before gas had time to diffuse into groundwater. In January 2009, after the incident with the concrete slab, the concentration of methane was measured in the headspace of several wells for a period of roughly a month.[1] Only one sample showed a volume of methane at potentially explosive levels, which is when methane concentration is 5% by volume, whereas most samples came in far lower than that (<1%). It should be noted that in a (partly) closed system without ventilation, like the vault, the concentration can increase to higher levels.

Any naturally occurring methane in groundwater, either free or dissolved, is called stray gas. When industry causes a concentration of methane in groundwater above the level of naturally occurring gas, the additional methane is considered a contaminant. When methane gets into the air, it is called a fugitive emission. Stray gas is not harmful whereas fugitive emissions can explode. There are two mechanisms by which industry can mobilize stray gas, thus causing a local increase in methane concentration. The first is the migration of groundwater driven by pressurized air used for pneumatic drilling of a well through an aquifer. The groundwater surging away from the pressurized air actually transports the methane, as was the case for the wells drilled in the area (Zhang and Soeder, 2016). A pressure pulse from air drilling can reach water wells 300 m away in a matter of hours, thus transforming stray gas to fugitive emissions (Geng et al., 2013). The second mechanism is when the cement between well casing and gas-bearing formations are inadequate. As was the case for several early wells drilled in the vicinity of Dimock, there was no cement along 1674 m of an open borehole 370 m to the south of the pump vault and this led to the accumulation of methane in the gas-well annulus (Maykuth, 2009; Watson and Bachu, 2009). Fugitive emissions inside the water-pump vault could have come from any of four sources: a natural background of preexisting groundwater methane (Osborn et al., 2011), a large methane charge from the jammed bit in the well 1.6 km to the south (Wilber, 2012), a surge of methane from air-drilling 370 m to the south (Geng et al., 2013), or the slow leakage

[1] http://www.damascuscitizensforsustainability.org/dep-data-for-dimock-pa/.

of methane from the open portion of the same air-drilled well and back into Upper Devonian sandstones and then up through a significant thickness of overburden (Harrison, 1985). This leaves the possibility that methane slowly but continuously leaked into groundwater from a nearby gas well (Jackson et al., 2013), or that the methane came from the natural background and had nothing to do with the drilling activities (Siegel et al., 2015). As there are no previous methane measurements available, the exact source of the methane in the Dimock well vault cannot be unambiguously identified.

Assuming a near-stoichiometric mixture of methane in air (9.5% v/v) and that the pressure would have equalized in the entire volume (9.51 m^3) before the concrete slab on the vault would lift, which is not realistic, the Baum method allows the volume of stoichiometric methane-air mixture equal to approximately 0.4 m^3 inside the (closed) vault. Such a small volume of stoichiometric gas, 4% of the entire vault volume, would, coincidently, have to be located around the pump, as this was the only potential ignition source present. A stoichiometric methane-air mixture burns quite cleanly, leaving behind predominantly water and potentially a little bit of soot. As soon as the mixture is off the stoichiometric point, especially on the fuel rich side, the occurrence of soot increases. Although hypothetically possible that a stoichiometric mixture was present in a small volume of the vault and shrouding the pump, the likelihood of a methane concentration gradient inside the vault is more realistic.

The density of methane is substantially lower than that of air. Assuming methane leaked into the vault, its concentration would have increased by buoyancy-driven flow from the floor upward in the vault. By buoyancy, methane would have accumulated in its most concentrated form under the concrete slab and plastic cover on the manhole. At the same time the methane-air mixture at the bottom of the vault must achieve a near-stoichiometric concentration if ignition from a water-pump spark is to occur. Hence, there should have been a considerable amount of gas in the vault within the flammable range, and the explosion severity should have been much larger than our calculations show for the observed damage. Also, this density gradient implies that the flammable gas mixture in the upper part of the vault would have been fuel rich, sufficiently so to leave soot as evidence of an explosive event. Instead, no trace of soot was found neither inside the vault nor on the underside of the concrete slab (Fig. 2).

Because of the density of methane and its concomitant buoyancy, the hypothesis that slab damage was the consequence of the ignition of a small volume of a near-stoichiometric mixture in the direct vicinity of the pump is not very likely, unless the required amount of methane was instantly released and mixed with air in the direct vicinity of the pump at the moment the pump was switched on and created the spark. This latter hypothesis is not considered likely either.

It should be noted that for our analysis it was assumed that the force of the pressure was equally distributed over the surface area under the slab. However, due to the presence of the manhole located to the side of the slab, a deflagration will not have caused an even force distribution under the slab. This combined with the likelihood of a localized explosion in the vault, supports the observed landing locations of the two concrete slabs. This can be explained as follows. The first crack due to the lifting forces on the cemented slab will have started in the mortar keeping the concrete blocks together (Fig. 4A). Subsequently, stresses accumulate in the slab and the fracture runs across (Fig. 4B). The slab pieces are then both launched upwards with the given spins. For the eastern slab the remaining fracture forces and with part of the slab still attached while the lift force is building, causes this part to spin around its vertical axis.

One unresolved issue is the fact that at the time of the event, no one was present to turn on the tap and with that, trigger the cycling mechanism on the pump motor. This unresolved issue is further compounded by the fact that the water line to the house was frozen at the time of the incident (McGraw, 2011). Without the pump motor cycling there is no other credible source that could have triggered an explosion.

No soot marks were present in the vault and neither were there any thermal burn marks on the plastic insulation on the electrical wires in the vault. This could have occurred with a lean methane-air mixture which hardly produces soot. Depending on the location and size of the flammable envelope, in combination with the stoichiometry of the flammable atmosphere upon ignition, it is technically possible not to find observable thermal marks on the pump (Technical, Committee on Fire Investigations, 2013; Tomlin, 2015). However, a situation in which there was a spark-ignitable, flammable mixture present at the bottom of the vault would have required the presence of a methane concentration gradient as a consequence of an upward buoyancy-driven flow. This would mean that the vault should have been filled with a gradually richer flammable mixture, which would have left observable traces of soot. As such, it cannot be unambiguously stated that a methane explosion occurred and the weight of the evidence implies it is unlikely an explosion indeed occurred.

5. Conclusions

The possibility of an explosive pressure event associated with the disturbance of a concrete slab covering a well-pump vault near natural gas development in Dimock, Pennsylvania, was investigated. As there were no witnesses, the only evidence for a deflagration was the overturned concrete slab once covering the in-ground vault of a domestic water pump. Using more than one approach, the pressure needed to lift the concrete slab without shattering would have been at most 0.3 bar. A spark from a cycling water pump could have ignited the flammable mixture but this requires a near stoichiometric methane-air mixture coincidently in the vicinity of the water pump on the floor of the vault and presumably near the point where methane leaks into the vault. A near stoichiometric mixture generates a 0.3 bar pressure only if the explosion consumed a volume of flammable gas occupying a small fraction of the total vault volume. This scenario is not considered likely. Due to the buoyancy of methane, if a near stoichiometric flammable mixture would have been present near the pump at the vault floor, this would also have meant that methane would have accumulated near the top of the pump vault. Such a rich mixture, if burned, would have left a clear residue of soot on the inside of the vault, aside from making the explosion more powerful and with that resulting in an overpressure far beyond the required 0.3 bar. While the presence of a stoichiometric methane-air mixture in just a fraction of well-pump vault is consistent with overturning the concrete slab without shattering it, the lack of soot is inconsistent with the physical distribution of methane necessary to maintain that stoichiometry near the vault floor. As such, a combination of the apparent lack of both a plausible ignition source (the water lines were frozen at the time) and soot or other evidence of a flame plus a relatively small volume of a stoichiometric methane-air mixture coincidentally surrounding the ignition source does not make a strong case for a methane explosion in the well-vault, although the possibility cannot be ruled out with absolute certainty.

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References

Anonymous, 1890. A Fatal Gas Explosion, vol. 123 (39). The Philadelphia Inquirer, p. 5.
Anonymous, 1904. News of Our Ohio, vol. 64 (1). Hocking Sentinel, p. 2.
Anonymous, 1910. Trapped in Fiery Pit, Plain Dealer Cleveland March 5, p. 2.
Anonymous, 1913. 1 Killed, 2 Hurt in Gas Explosion. vol. 169 (82). The Philadelphia Inquirer, p. 3.
Anonymous, 1920. Blown Up by Explosion of Gas in Well. vol. 26 (191). Schenectady Gazette, p. 1.
Anonymous, 1948. Soldier Dies After Blasts Hurls Him 80 Feet Through Air. Morning Avalanche, Lubbock (Texas), June 3, p. 10.
Anonymous, 2012. Standard on Explosion Protection by Deflagration Venting. National Fire Protection Association, Quincy, Massachusetts, USA, v. NFPA 68.
Bailey, E.B., 1935. Tectonic Essays: Mainly Alpine. Clarendon Press.
Bair, S., Tomastik, T., Benko, T., Hill, T., 2012. Geologic and Hydrogeologic Factors Controlling How Stray Gas from the English #1 Well Invaded Residences in Geauga County, Ohio, Causing an In- House Explosion. Groundwater Protection Council Stray Gas Incidence & Response Forum, Cleveland, OH http://www.gwpc.org/sites/default/files/event-sessions/Bair_Scott- reduced%20file%20size.pdf.
Baum, M.R., Kulesz, J.J., Ricker, R.E., Westine, P.S., Parr, V.B., Vargas, L.M., Mosley, P.K., 1978. Workbook for Estimating Effects of Accidental Explosions in Propellant Ground Handling and Transport Systems, NASA Contractor report 3023.
Baum, M., 1988. Disruptive failure of pressure vessels: preliminary design guidelines for fragment velocity and the extent of the hazard zone. J. Pressure Vessel Technol. 110 (2), 168–176.
Baum, M., 1993. Velocity of a single small missile ejected from a vessel containing high pressure gas. J. Loss Prev. Process Ind. 6 (4), 251–264.
Browers, R., 2014. Personal Communication.
Committee, for the Prevention of Disasters, 2005. In: Van den Bosch, C.J.H., Weterings, R.A.P.M. (Eds.), Methods for the Calculation of Physical Effects, 'Yellow Book', Publication CPR14E, Third Edition, Second Revised Print. SDU Publishers, The Hague, The Netherlands.
Darrah, T.H., Vengosh, A., Jackson, R.B., Warner, N.R., Poreda, R.J., 2014. Noble gases identify the mechanisms of fugitive gas contamination in drinking-water wells overlying the Marcellus and Barnett Shales. Proc. Natl. Acad. Sci. 111 (39), 14076–14081.
Etiope, G., Drobniak, A., Schimmelmann, A., 2013. Natural seepage of shale gas and the origin of "eternal flames" in the Northern Appalachian Basin, USA. Mar. Petrol. Geol. 43, 178–186.
Geng, X., Davatzes, N.C., Soeder, D.J., Torlapati, J., Rodriguez, R.S., Boufadel, M.C., 2013. Migration of high-pressure air during gas well drilling in the Appalachian Basin. J. Environ. Eng. 140 (5), B4014002.
Gold, D., Parizek, R., Giddings, T., 1970. Water well explosions: an environmental hazard. Earth Miner. Sci. 40, 17–21.
Harrison, S.S., 1985. Contamination of aquifers by overpressuring the annulus of oil and gas wells. Ground Water 23 (3), 317–324.
Jackson, R.B., Vengosh, A., Darrah, T.H., Warner, N.R., Down, A., Poreda, R.J., Osborn, S.G., Zhao, K., Karr, J.D., 2013. Increased stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction. Proc. Natl. Acad. Sci. 110 (28), 11250–11255.
Legere, L., 2009. DEP Probes Blast in Gas-Drilling Region. Times Tribune, Scranton, PA http://www.uppermon.org/news/Other/ST-DEP_Probes_Blast-3Jan09.htm.
Lusgarten, A., 2009. Water Problems From Drilling Are More Frequent Than PA Officials Said. ProPublica, July 31, 2009 https://www.propublica.org/article/water-problems-from-drilling-are-more- frequent-than-officials-said-731.
Lustgarten, A., 2009. Officials in Three States Pin Water Woes on Gas Drilling. ProPublica, April 26th 2009 http://www.propublica.org/article/officials-in-three-states-pin-water-woes-on-gas-drilling-426.
Maykuth, A., 2009. Susquehanna Residents Wary of Gas-Drilling Operation. Philadelphia Inquirer, Philadelphia, PA http://www.philly.com/philly/news/special_packages/inquirer/marcellus- shale/20091213_Susquehanna_residents_wary_of_gas-drilling_operation.html.
McGraw, S., 2011. The End of Country. Random House, New York City, 245 p.
Meyers, T., 2003. Looking Back: Winters Boarding House Tragedy: Explosion of Dispute Thirty Years Later, Debate Surrounds What Ignited Fatal Blast. Walks-Barre Times Leader, September 14, 2003.
Molofsky, L.J., Connor, J.A., Wylie, A.S., Wagner, T., Farhat, S.K., 2013. Evaluation of methane sources in groundwater in Northeastern Pennsylvania. Groundwater 51 (3), 333–349.
Osborn, S.G., Vengosh, A., Warner, N.R., Jackson, R.B., 2011. Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. Proc. Natl. Acad. Sci. 108 (20), 8172–8176.
Schlanger, Z., 2014. Fracking Wells Tainting Drinking Water in Texas and Pennsylvania Study Finds. NewsWeek, September 15th 2014 http://www.newsweek.com/fracking-wells-tainting-drinking- water-texas-and-pennsylvania-study-finds-270735.
Siegel, D.I., Azzolina, N.A., Smith, B.J., Perry, A.E., Bothun, R.L., 2015. Methane concentrations in water wells unrelated to proximity to existing oil and gas wells in Northeastern Pennsylvania. Environ. Sci. Technol. 49 (7), 4106–4112.
Technical, Committee on Fire Investigations, 2013. Guide for Fire & Explosion Investigations. National Fire Protection Association, Quincy, Massachusetts, USA, v. NFPA 921.
Tomlin, G.B., 2015. Gas Explosions in Dwellings: The Effects of Interconnected Rooms and Obstacles, and the Interpretation of Thermal Damage: PhD Thesis. University of Leeds, Leeds, UK.
Watson, T., Bachu, S., 2009. Evaluation of the potential for gas and CO2 leakage along wellbores. SPE Drill. Complet. 24 (1), 115–126.
Wilber, T., 2012. Under the Surface. Cornell University Press, 272 p.
Zabetakis, M.G., 1965. Flammability Characteristics of Combustible Gases and Vapors: USBM Bulletin 627. Bureau of Mines, Washington DC.
Zhang, L., Soeder, D.J., 2016. Modeling of methane migration in shallow aquifers from shale gas well drilling. Groundwater 54 (3), 345–353.