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# Potential Hazards of Compressed Air Energy Storage in Depleted Natural Gas Reservoirs

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# Potential Hazards of Compressed Air Energy Storage in Depleted Natural Gas Reservoirs

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**Abstract**

This report is a preliminary assessment of the ignition and explosion potential in a depleted hydrocarbon reservoir from air cycling associated with compressed air energy storage (CAES) in geologic media. The study identifies issues associated with this phenomenon as well as possible mitigating measures that should be considered.

# ACKNOWLEDGEMENTS

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# Introduction

Compressed air energy storage (CAES) in geologic media has been proposed to help supplement renewable energy sources (*e.g.*, wind and solar) by providing a means to store energy when excess energy is available, and to provide an energy source during non-productive or low productivity renewable energy time periods. Presently, salt caverns represent the only proven underground storage used for CAES. Depleted natural gas reservoirs represent another potential underground storage vessel for CAES because they have demonstrated their container function and may have the requisite porosity and permeability; however reservoirs have yet to be demonstrated as a functional/operational storage media for compressed air. Specifically, air introduced into a depleted natural gas reservoir presents a situation where an ignition and explosion potential may exist. This report presents the results of an initial study identifying issues associated with this phenomena as well as possible mitigating measures that should be considered.

# Compressed Air Energy Storage

A “conventional” CAES facility (Figure 1) consists of an electric generation system and an energy storage vessel or geologic reservoir. A CAES facility is an electro-mechanical system that functions like a large battery. Electrical motors drive compressors that compress air into an underground (*e.g.*, a cavern or reservoir) or above ground storage container. Then when electricity is requested, the air is released through modified combustion turbines to re-generate electricity. Natural gas or other fossil fuels are required to run the turbines however the process is more efficient than conventional fossil-fuel generation. This method uses less natural gas than standard electricity production because natural gas is not burned to pre-compress the air. CAES facilities utilizing underground geologic salt formations as the storage vessel (*e.g.*, the McIntosh facility located about 40 miles north of Mobile, Alabama and the Huntorf, Germany facility) have been demonstrated to provide utility-scale storage. Geologic structures that may be suitable for use as air storage vessels include the following: 1) solution-mined salt cavities; 2) excavated mine cavities; 3) aquifers; and 4) depleted natural gas reservoirs.

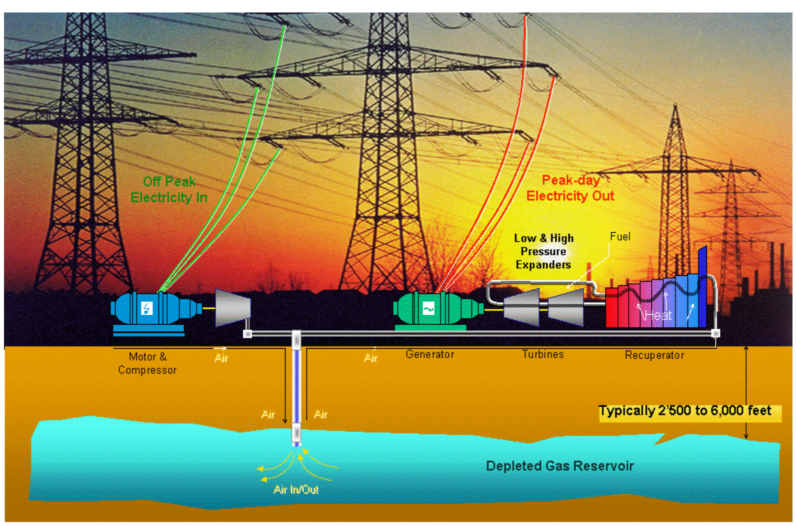


**Figure 1. CAES facility schematic with transmission, surface component mock-up, and depleted gas reservoir.**

## Issues and Concerns

Depleted natural gas reservoirs present a possible safety issue as a result of residual hydrocarbons remaining in the depleted formation. Some salt caverns are known to produce gas—a phenomenon is well documented in the Strategic Petroleum Reserve (Hinkebein, et al 1995; Ehgartner et al, 1998). The classic fire triangle shown in Figure 2 shows the basic three requirements that must be met for combustion to occur: heat (ignition source), fuel, and oxygen. An underground fire or explosion could occur if the three conditions for the fire triangle are met. Compressed air provides the oxygen, the fuel is available from residual hydrocarbons in the formation, and the heat or ignition source could be provided via a variety of mechanisms.  Possible ignition sources include the heat of compression energy generated as the air is compressed prior to injecting into the underground storage reservoir, by friction generated by relative motion of material within the formation during compressed air charging or discharge, by piezoelectric discharge from material within the formation, by a static electricity discharge, by a surface lightning strike, etc.


**Figure 2. Fire triangle.**

Even if the three components of the fire triangle are present this does not necessarily imply that combustion will take place. The mixture of fuel and oxidizer must be within the lower explosion limit, also known as the lower flammability limit (LEL), and the upper explosions limit (UEL), also known as the upper flammability limit. In other words, if the fuel to oxidizer ratio is too rich or too lean combustion cannot take place. This concept is shown in Figure 3.

Two types of reaction are possible for fuel-air mixtures: combustion (deflagration), where the reaction rate proceeds well below the speed of sound in the reacting material and detonation, where the reaction proceeds well above the speed of sound. Typical maximum peak pressures for a deflagrating fuel-air system are nine times the starting pressure, while for a detonating system the pressure ratio could be as high as 18:1 (*Kuchta, J. M., 1985).*

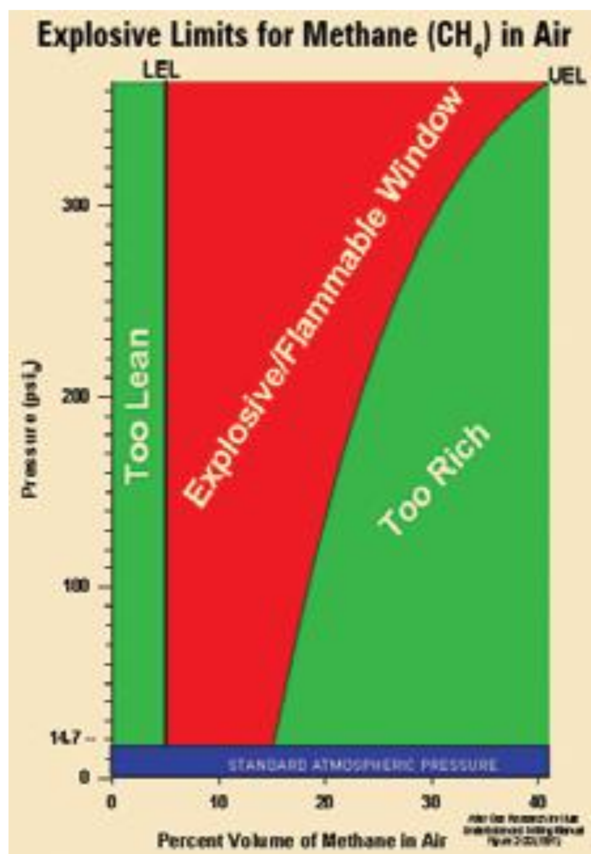


**Figure 3. Explosive limits for methane in air.**
**Source: March/April 2007 *Drilling Contractor***

Detonations can be directly initiated in fuel-air mixtures via a sufficient shock or they may be initiated through a deflagration to detonation transition (DDT) where the combusting fuel and mixture grows into a detonation.

In a pure methane and air mixture it is generally considered difficult to initiate detonations. Natural gas is primarily methane and various amounts of higher hydrocarbons but the concentration of higher hydrocarbons is important. For example, Union Gas provided the properties of a typical natural gas composition shown in Table 1. The composition given is considered representative and demonstrates that there can be a significant non-methane fraction of light end hydrocarbons.

**Table 1. Representative Natural Gas Composition**

| Component | Typical Analysis (mole %) | Range (mole %) |
|---|---|---|
| Methane | 95.2 | 87.0 - 96.0 |
| Ethane | 2.5 | 1.5 - 5.1 |
| Propane | 0.2 | 0.1 - 1.5 |
| Iso – Butane | 0.03 | 0.01 - 0.3 |
| Normal - Butane | 0.03 | 0.01 - 0.3 |
| Iso - Pentane | 0.01 | trace - 0.14 |
| Normal - Pentane | 0.01 | trace - 0.04 |
| Hexanes plus | 0.01 | trace - 0.06 |
| Nitrogen | 1.3 | 0.7 - 5.6 |
| Carbon Dioxide | 0.7 | 0.1 - 1.0 |
| Oxygen | 0.02 | 0.01 - 0.1 |
| Hydrogen | trace | trace - 0.02 |

Small quantities of higher hydrocarbons can increase the sensitivity to ignition and thereby the likelihood for transition to detonation considerably. Figure 3 shows the effect of decreasing ignition temperature with increasing amounts of hydrocarbons relative to air content.

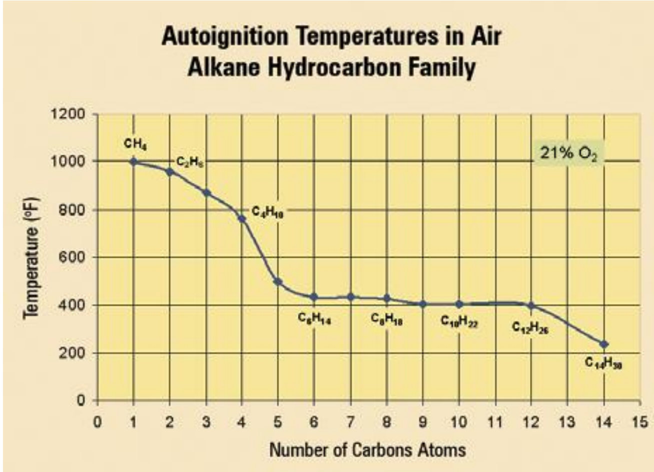


**Figure 4. Autoignition temperatures in air for the alkane hydrocarbon family.**
**Source: March/April 2007 *Drilling Contractor***

If the flammability limits of the component mixture are known (Table 2), then the ignition limits can be calculated by Le Chatelier's principle. The specific form of the equation is

$$\mathbf{L}=100/(C1/L1+C2/L2+\ldots..C_n/L_n)$$

where C# is the proportion of each combustible gas in the mixture and L# is the lower or upper combustion limit for each component gas where and **L** is lower or upper combustion limit of the mixture of gases.

**Table 2. Flammability Limits***

| Combustible | Flammability limits, vol pct | | | |
|---|---|---|---|---|
| | Air | | Oxygen | |
| | $L_{25}$ | $U_{25}$ | $L_{25}$ | $U_{25}$ |
| **HYDROCARBONS** | | | | |
| Methane | 5.0 | 15.0 | 5.0 | 61 |
| Ethane | 3.0 | 12.4 | 3.0 | 66 |
| Propane | 2.1 | 9.5 | 2.3 | 55 |
| n-Butane | 1.8 | 8.4 | 1.8 | 49 |
| n-Hexane | 1.2 | 7.4 | 1.2 | [2]52 |
| n-Heptane | 1.1 | 6.7 | .9 | [2]47 |
| Acetylene | 2.5 | 100 | ≤2.5 | 100 |
| Ethylene | 2.7 | 36 | 2.9 | 80 |
| Propylene | 2.4 | 11 | 2.1 | 53 |
| α-Butylene | 1.6 | 10 | 1.8 | 58 |
| Cyclopropane | 2.4 | 10.4 | 2.5 | 60 |
| Benzene | [2]1.3 | [2]7.9 | ≤1.3 | NA |

* Source: Bulletin 680 "Investigation of Fire and Explosion Accidents in the Chemical, Mining and Fuel-Related Industries-A Manual" by Joseph M Kuchta, Bureau of Mines 1985.

In practice, mitigating the occurrence of detonations is to avoid situations where a deflagration can accelerate to a condition where transition from deflagration is possible (*i.e.*, a high-pressure deflagration). In other words, the fuel and air mixture should be below the lower combustion limit or above the upper combustion limit. It may be that a CAES installation is in direct conflict with this mitigation strategy! It should be noted that most data given for the flammability limits is given at standard temperature and pressure condition. Figure 5 illustrates the increase in the flammability limits with pressure—as the pressure increases the oxygen requirement for the lower limit of combustion decreases.

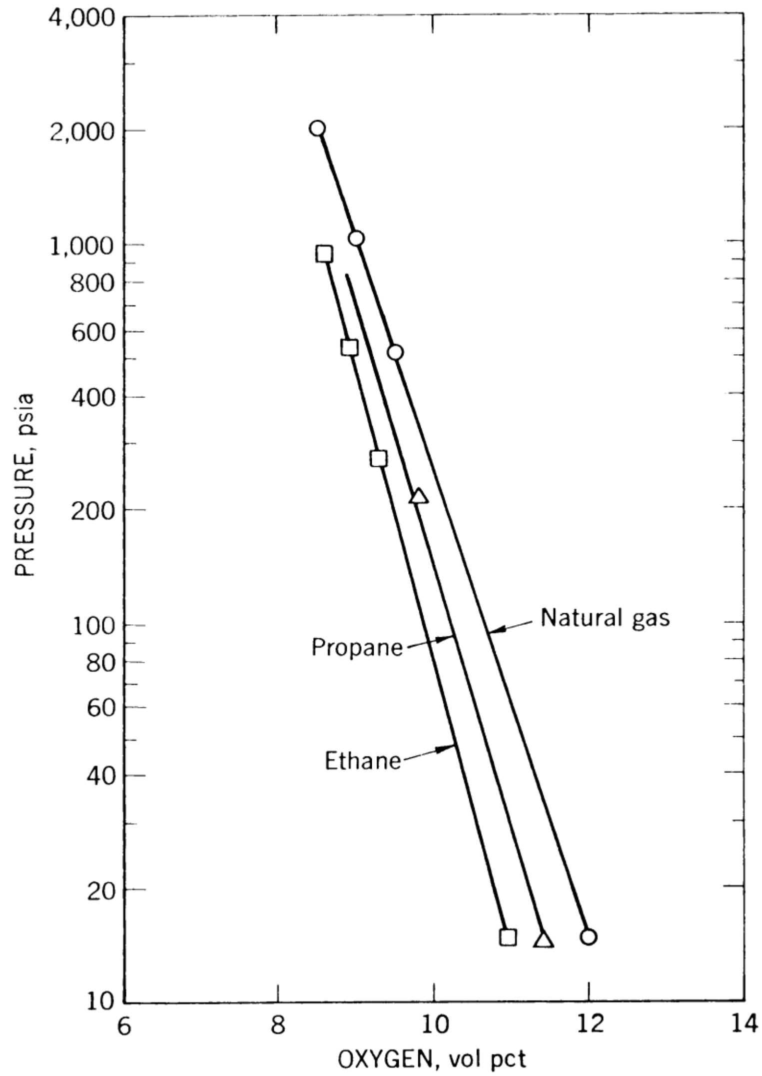


**Figure 5. Oxygen volume percent versus pressure for natural gas, propane, and ethane.** **Source: Bulletin 680 "Investigation of Fire and Explosion Accidents in the Chemical, Mining and Fuel-Related Industries- A Manual" by Joseph M Kuchta, Bureau of Mines 1985.**

# Possible Ignition Mechanisms

Ignition sources underground as applied to mining applications have been studied extensively by the Mine Safety and Health Administration (MSHA). The ignition energy can be small (0.3 mJ=0.0002 ft-lb) and still be effective/detrimental. The ignition sources identified are discussed below.

### *Heat of Compression*

Heating due to adiabatic compression of air upon pressurization can result in ignition according to the relationship shown in Figure 6. While this temperature rise will be dissipated due to the large heat sink provided by the reservoir, its potential effect locally should be evaluated. Local failure of the storage facility could produce rapid local pressurization.

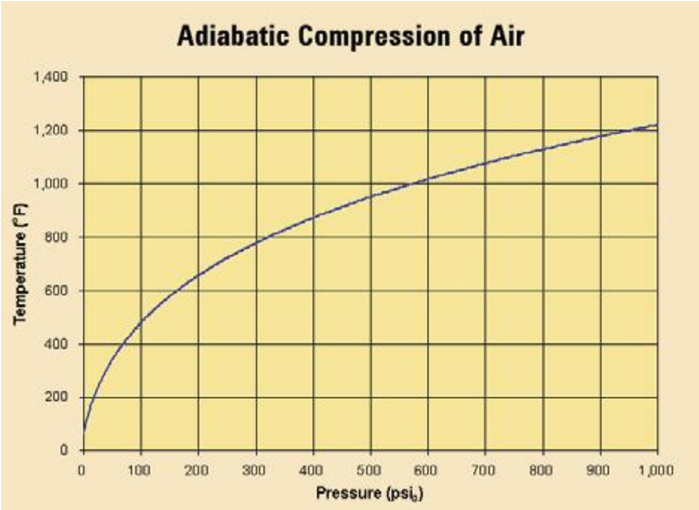


**Figure 6. Adiabatic compressionof air P-T relationship.**
**Source: March/April 2007 *Drilling Contractor***

### *Piezoelectricity*

Piezoelectricity is a well understood phenomenon in certain earthen materials wherein a piezoelectric material will generate an electric potential when specific stress/strain conditions are applied (Figure 7). Cycled stress conditions, especially near boreholes, may facilitate this phenomenon.

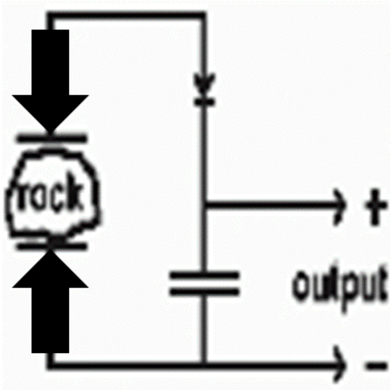


**Figure 7. Schematic of piezoelectric phenomena.**

### *Static Electricity*

A static electricity discharge is caused by the proximal positioning of two materials with an imbalance of positive and negative charges (Figure 8). A buildup of charge on dust particles caused by the filling or emptying of the underground storage facility could provide an ignition source for the fuel-air mixture. The grounding of all piping reduces the potential for this ignition source.

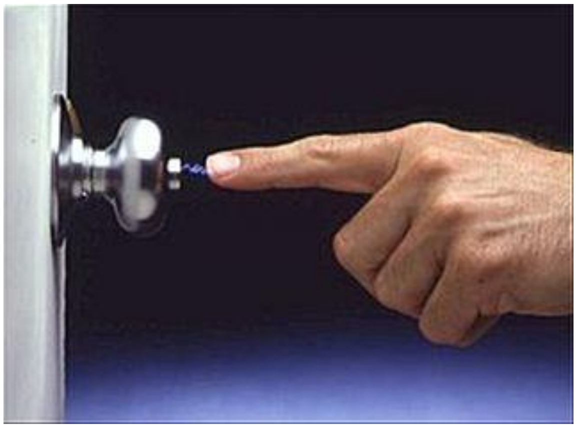

**Figure 8. Static electricity.**

### *Lightning*

Lightning (Figure 9) is an atmospheric discharge of electricity. In the atmospheric electrical discharge, a leader of a bolt of lightning can travel at speeds of 36,000 km/h (22,000 mph), and can reach high temperatures. Lightning strikes have been attributed to causing underground fires.

**Figure 9. Lightning.**

### *Friction*

Ignition caused by friction is defined as the ignition of a flammable mixture of fuel plus oxygen that is initiated by frictional heating (Figure 10). A natural phenomenon that may generate such heat includes dissipation of energy during an earthquake in the form of frictional heating or the fracturing of rock caused by stress changes during filling or emptying of an underground storage facility.

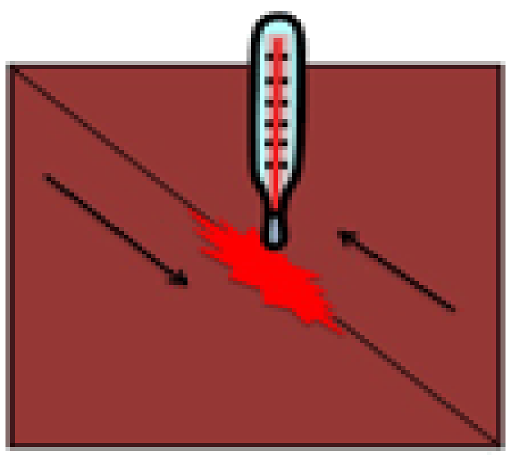

**Figure 10. Frictional heating schematic.**

## Suggested Mitigation and Safety Strategies

Based on the above discussions, the following measures are recommended to be during site preparation and operation of a CAES facility installed in a depleted natural gas reservoir:

1. Purge the reservoir before use. The reservoir should be emptied of natural gas to the extent that safety analyses coupled with economics permit. This may require site-specific analyses to determine a safe condition. Part of the emptying process may include the flushing or cycling of air to dilute the gas composition. Based on the assumptions and conditions of the analysis presented above, low pressure air cycling could be conducted below the flammability limit to remove natural gas with more comprehensive safety analysis.

2. An in-situ gas monitor should be installed down hole to provide a near source measure of natural gas presence.

3. Similarly, the natural gas content entering the surface equipment should be monitored. This is important so the air-fuel ratio in gas turbine can be adjusted to include the natural gas content of the compressed air from the underground storage facility.

4. Ensure that no surface breach is possible and prevent venting of hot combustion gas to the surface equipment in the event of an ignition. This could be accomplished through a combination of choosing a facility with sufficient overburden (determined through analysis) coupled with a down-hole shutoff valve (common in the natural gas storage industry in Europe).

5. Ensure that the composition of natural gas and air remains outside the ignition envelope. This concept is critical in maintaining safety. If the mixture of natural gas and air is either too rich or too lean combustion cannot occur. For example, if we assume the underground storage facility is filled with 100% natural gas and we admit air, combustion cannot take place until we admit enough air to be below the upper flammability limit. As we continue to add air we pass through the ignitable range of air and natural gas mixture. Finally, with enough air the mixture becomes too lean to burn. Once the underground storage facility is filled to significantly above this lower flammability limit the mixture cannot burn. Residual intruding natural gas could act to bring the mixture back to an ignitable concentration. Clearly this condition should be avoided.

6. Further effort must be undertaken to study and determine the effect of more complex phenomena regarding safety. An example presented in the Appendix assumes that the air is admitted to an underground storage facility and is well mixed. In reality, the geometry of the underground storage facility and the geologic conditions will be much more complex and mixing may not take place. Density differences between the air and natural gas, as well as underground storage facility permeability, could act to stratify the air and natural gas mixture. This stratification could produce areas that are too rich and too lean to ignite as well as areas that can be ignited. Furthermore natural gas may migrate to or from the underground storage facility depending on time and the degree of pressurization. Ideally a model would need to be developed that takes into account both the spatial and temporal characteristics of the air and natural gas mixture within the formation as well as the structural and thermal effects on the formation should and ignition event take place.

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# Appendix

This appendix describes the thought process used to determine the potential adverse implications of pressurizing spent natural gas reservoirs with compressed air.

Let's start out with the assumption that the reservoir is initially at atmospheric pressure. Also let's assume that the reservoir is filled, at that pressure, with natural gas. Natural gas is mostly methane, but has other hydrocarbon gasses mixed in it. A typical in-situ 'wet' gas composition is shown in the table below.*

| Component | Typical Analysis (mole %) | Range (mole %) |
|---|---|---|
| Methane | 95.2 | 87.0 - 96.0 |
| Ethane | 2.5 | 1.5 - 5.1 |
| Propane | 0.2 | 0.1 - 1.5 |
| iso - Butane | 0.03 | 0.01 - 0.3 |
| normal - Butane | 0.03 | 0.01 - 0.3 |
| iso - Pentane | 0.01 | trace - 0.14 |
| normal - Pentane | 0.01 | trace - 0.04 |
| Hexanes plus | 0.01 | trace - 0.06 |
| Nitrogen | 1.3 | 0.7 - 5.6 |
| Carbon Dioxide | 0.7 | 0.1 - 1.0 |
| Oxygen | 0.02 | 0.01 - 0.1 |
| Hydrogen | trace | trace - 0.02 |

* Source: Union Gas, Ltd.

The flammability limits of this mixture are LEL-4 (volume % in air) to UEL-16. The concern of accidentally igniting the gas in the reservoir comes when the air being pumped in brings the composition down to that of the upper (rich) explosion limit (UEL). That limit, 16%, would be reached when the pressure had increased (due to the addition of more air) to only 6.25 atmospheres. That in itself doesn't mean the gasses will ignite, only that they *may* ignite. There also has to be an ignition source present. This source could be an electric spark. A spark with an energy content as little as a third of a millijoule can ignite natural gas/air mixtures. How can that be? Because if the increase in pressure causes formation fractures to expand and start to grow, or forms new fractures, hot spots or sparks can be generated in the crack tips. Such crack growth at these low pressures seems highly unlikely.

The possibility of ignition remains while air is continued to be added until the lower (lean) explosion limit (LEL) is reached. That limit, 4%, would be reached when the pressure had increased to 25 atmospheres. As more air is added, the mixture gets leaner and leaner. So the danger of accidental ignition only exists during the brief period when the pressure in the reservoir is between 6- and 25-atmospheres.

If the temperature in the reservoir rises, the ignition limits will expand and the minimum spark energy will decrease. If the temperature rose to above 590 °C, and the gas mixture was within the ignition limits, then the mixture would auto-ignite.

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