Journal of Petroleum Science and Engineering, 6 (1991) 95–106
Elsevier Science Publishers B.V., Amsterdam

Environmental hazards of urban oilfield operations

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(Received February 1, 1991; accepted after revision May 10, 1991)

ABSTRACT

Endres, B., Chilingarian, G.V. and Yen, T.F., 1991. Environmental hazards of urban oilfield operations. *J. Pet Sci Eng.*, 6: 95–106.

One of the gravest dangers posed by urban oil-well drilling and production is the potential for explosive methane gas to migrate to the surface from several thousand feet underground. Unless the present-day practices are changed, underground migration of methane from oil and gas reservoirs will continue to pose a significant explosion threat. If the operators would systematically follow some basic preventive-management procedures, they could drill and produce safely, without prohibitive cost and in a manner that is environmentally sound. Today, unfortunately, many oil fields in urban settings are managed by catastrophe rather than preventive management.

This paper discusses appropriate standards for the monitoring of surface gas seepage, and the related problems created by land subsidence due to the fluid withdrawal, as well as procedures necessary to insure the mechanical integrity of well casing and cement, necessary to protect against unwanted gas seepage. Migration of gas along faults is also discussed in this paper.

Introduction

In only a very limited number of hydrocarbon-producing areas of the United States and elsewhere in the world has the production of oil and related fluids from subsurface reservoirs been correlated with surface subsidence and damages to property in the subsiding area, as well as damage to wells and producing facilities as a result of compaction and aggravation of subsurface faulting.

Even less attention has been given to the interrelated problem of oil and gas surface seeps that create a serious risk of explosion if the gas enters a confined area of a surface structure where a myriad of ignition sources could give rise to devastating explosion.

These hazards become especially acute as urbanization encroaches on oil-producing regions that once were devoted exclusively to the production of oil and gas. Additionally, as oil supplies dwindle, pressures will mount to exploit to the fullest, old oil fields, including those located in highly urbanized areas. For example, developments in horizontal well drilling and enhanced oil recovery techniques will permit recovery of additional oil and gas even in highly-depleted oil fields.

No prior study has addressed a systematic evaluation of the combined hazards of surface subsidence and surface seepage of oil and gas. The importance of such a study is dramatized by the following examples:

(1) On March 24, 1985, the Ross Dress For Less Department Store in the Fairfax area of Los Angeles exploded, causing injury to over 21 people and the destruction of the store. An entire shopping center was closed down as the seeping gas burned for days through cracks in the sidewalks and around foundation struc-

0920-4105/91/$03.50

tures. The site was located directly over a producing oil field.

(2) On December 14, 1963, water burst through the foundation of the earthen dam of the Baldwin Hills Reservoir, a hilltop water storage facility located in the metropolitan Los Angeles. A square mile of residences was inundated with mud and debris, and damaged or destroyed 277 homes. Injection of water into the geologic formations for secondary oil recovery and waste water disposal triggered the surface faulting that was responsible for the demise of the dam (Hamilton and Meehan, 1971).

Unfortunately, many oilfields located in urban settings are managed by catastrophe rather than through preventative management.

The primary objective of this paper is to identify procedures and standards for the safe operation of oilfields in an urban environment, based upon a systems analysis approach, as augmented by a monitoring program for gas seepage and surface subsidence.

The basic approach

The basic approach will be to establish and define procedures and standards for the safe drilling in, and production of, oilfields, especially for those located in an urban setting. A necessary adjunct to these procedures is the establishment of a measurement program that will permit detection of the problem before occurrence of serious property damage or personal injury. This requires:

(A) Monitoring for surface seepage of gas.
(B) Monitoring for surface subsidence through periodic surveys.
(C) Establishment of the oilfield geologic characteristics, including fault planes and potential areas and zones for gas migration to the surface, and the potential for surface subsidence.
(D) Establishing procedures for the systematic evaluation of the integrity of both producing and abandoned oil wells.

To support this will require developing fundamental models of the underlying geology, well details, production history and all other relevant data necessary for the complete characterization of a particular oilfield. This can then be used to develop a system model that will allow prediction of hazardous conditions before they create serious harm.

Background regarding oil and gas seeps

The existence of oil and gas seeps in oil-producing regions of the world has been recognized for a long time. For example, Link (1952), then the Chief Geologist of Standard Oil Company (N.J.), wrote a comprehensive article on the significance of oil and gas seeps in World oil exploration. In this important publication, he documented oil and gas seeps located throughout the world. Although the primary purpose of Link's paper was to identify the importance of surface oil and gas seeps in the exploration and location of oil and gas, it is of no less importance in identifying the hazards associated with the surface seepage of oil and gas. According to one of the authors (G.V.C.), 90% of all oil and gas seeps in the World are associated with faults.

Various state agencies have published maps identifying surface seepage of oil and gas. For example, the Division of Oil and Gas of the State of California has published a detailed listing of surface seepages located throughout the State of California (Hodgson, 1987).

Most of these seeps are located either near or in the immediate vicinity of producing or abandoned oilfields. Furthermore, as time passes, the pressure in the old abandoned oilfields may build up, *increasing* the possibility that oil and gas will be forced to the surface.

Oilfield operational modeling: An evaluation approach

The evaluation approach will require the development of a functional model of the oilfield operations. It will identify the basic drive mechanisms that are responsible for the movement of gas and oil in the reservoir, i.e., solution-gas drive, water drive, gravity drainage, compaction drive, etc. Emphasis is to be placed on well performance evaluation, such as gas/oil ratio analysis and pressure history assessments of individual wells. Performance curves must be available for *individual* wells. This will be used to identify the increased hazard of gas migration as fluids are produced from a reservoir with an associated drop in pressure allowing a "freeing-up" of gas (e.g., as gas cap) that was originally stored in solution. For example, in gravity drainage pools, oil moves downdip and gas moves updip. As the gas/oil ratio of updip wells increases, these wells are shut-in. Most of the production occurs at practically zero pressure in gravity drainage pools. Gas which accumulates at the top of the structure, becomes available for migration if there is an avenue for its migration or such avenue is created. The freeing-up of gas substantially increases the risk of surface seepage, especially in the vicinity of faults. As production matures, pressure typically drops, and gas which separates out becomes available for migration. This is contrary to the general belief that the risk of seepage is reduced as reservoir pressure declines through production.

Well performance modeling is also important in the evaluation of well casing and cement integrity. Namely, in a well, located in an area that has greater potential for gas migration (e.g., due to the presence of faults), good cement on the outside of the casing and lack of corrosion (i.e., lack of holes in the casing) must prevent the gas from migrating into the surrounding geologic strata. The gas migrating around the casing may eventually find its way to the surface.

Evaluation of well casing and cement (placed around casing) integrity should include at least the following:

(1) **Well-casing-corrosion evaluation:** Well-casing-corrosion evaluation, with an emphasis on using downhole inspection techniques for periodic assessment of the condition of the well casing, e.g., borehole televiewer tool, multifrequency electromagnetic thickness tool (Schlumberger), and multifinger caliper tool. Although corrosion is recognized in the oil industry as the number one problem in causing deterioration of well casings, companies frequently operate using a catastrophe management approach, not taking action until a serious leak has already occurred. The best approach, however, is protecting casings against corrosion, e.g., using cathodic protection (see Chilingarian et al., 1989): "An ounce of prevention is better than a pound of cure."

(2) **Cement bonding integrity evaluation**: Periodic evaluation – using established downhole inspection procedures – of the condition of the cement on the outside of the well casing. Although the cement is intended to prevent migration of the fluids and gas between various geologic horizons, cement channels or voids can develop allowing gas to migrate up the back-side of well casing (see classical book by Nelson, 1990). Various downhole measurement devices have been developed – including acoustic sensors – that are very effective in detecting gas movement, including that on the back-side of the well casing. Movement of gases can be detected with these "sound" logs. Unfortunately, oil companies are not routinely using this technology to detect impending problems with gas seepage hazards.

It is important to note that the cement condition can deteriorate from seismic activity, especially in areas where the well casing intersects fault planes that can "shift" as the result of an earthquake. Special attention is required to inspect the well casing at these locations.

(3) **Water disposal evaluation:** Monitoring programs related to water disposal (where salt water produced from oil production is routinely re-injected into the geological strata) need to be established. Water disposal creates special problems of disturbing the natural equilibrium existing in the area of water injec-

tion, usually causing gas to migrate from the area into the upper geologic strata, increasing the hazard of surface seepage of gas. Also, great care is required during acidizing of these disposal wells. Acidizing is frequently used to "clear out" the pore space in the geologic strata where the water is being disposed of. This reduces water-disposal pressure requirements. Problems arise when the acid is injected under high pressure causing fracturing of the rocks, thus creating avenues of migration for gas displaced by the fluids.

(4) **Water flooding/secondary oil recovery:** A common practice in older oilfields – including those located in urban settings – is to utilize waterflooding for the purposes of enhancing oil recovery. This technique, although effective, frequently ignores the problems associated with gas migration. Crossflow often occurs between subzones, and cracks formed during the waterflooding can form additional avenues for gas migration. Additional fractures can be formed by the rebound of the ground due to the large pressures used during waterflooding in the subsided area.

Additionally, special precautions must be taken in areas where abandoned wells are located. The mechanical integrity of the abandoned wells must be assured in areas where waterflooding is undertaken; otherwise, gas seepage is bound to occur along these paths of least resistance to the surface. Conversely, if mechanical integrity of the abandoned wells cannot be assured, waterflooding should not be undertaken in these areas.

Hydrocarbon migration – fault plane interaction

It is now generally accepted within the scientific community that fault planes serve as conduits of hydrocarbon seepage from the reservoir area of an oil or gas field to the surface (see Chapman, 1983; Doligez, 1987). Consensus of opinion *up to the mid-1960's* was that faults generally act as barriers to petroleum or water migration. The authors believe that, at best, they are "leaky" barriers. Differential pressure of 100–300 psi across the fault plane could result in a breakthrough and lateral movement. Accordingly, evaluation of fluid flow along (and across) these fault planes is an important consideration, especially when monitoring for surface seepage.

In particular, the identification of fault planes within the geologic setting of any oil or gas field is essential in establishing the potential migration paths that the hydrocarbons can take to the surface. This, in turn, can be used to prioritize the surface locations where effective surface seepage monitoring programs can be undertaken. Namely, the location where the subsurface fault planes intersect the surface of the earth (or their projected intersections) will establish the most likely locations where oil and gas seepage will occur. There is no doubt that many faults provide permeable avenues for hydrocarbon migration (Jones and Drozd, 1983).

Another important aspect of this evaluation is to identify the flow characteristics of the oil and gas seepage. This is especially important, for example, in establishing sampling intervals for a gas seepage monitoring program. Inasmuch as the flow may be non-uniform, a continuous monitoring is needed to obtain scientifically valid results. If only isolated samples are collected, which do not form part of a systematic measuring program, the failure to detect a hazardous condition may result.

An additional important consideration is the need to correlate seismic (earthquake) activity with the migration and surface seepage of hydrocarbons. Movement along faults increases their permeability. Following the San Fernando, California, earthquake of February 9, 1971, it was clearly recognized, that seismic activity could "trigger" the migration of oil and gas to the surface (Clifton et al., 1971). Direc association between the oilfield operations an surface faulting has been established, whic makes the mapping of *surface* faults an esse tial operation. Subsurface faulting and the resulting surface cracking are also related to the exploitation of the oilfields.

Hydrocarbons can also migrate through (via) secondary collector zones on their way to the surface. Migration from these zones can be precipitated by the seismic activity as a result of movement along faults, which makes them more permeable, and formation of new faults. Hydrocarbons may not move to the surface at a uniform rate, being interrupted by a series of geologic impediments. Accordingly, these must be modeled as time variables (Tek, 1987).

This understanding of hydrocarbon movement is also important in establishing and interpreting surface-monitoring-measurement data relating to gas seepage. For example, seismic activity can cause a large surge in the seepage of hydrocarbons to the surface over a relatively short interval of time. This is superimposed on a lower level of seepage that is more uniform. This is not unlike, for example, "sun spot" activity in which large surges of solar radiation occur over short periods of time, superimposed on a relatively uniform background rate of radiation.

By analogy, the sun radiation creates a serious hazard to astronaut travel during periods of major sun spot activity, in the same sense that seismic activity creates an increased risk of explosion from gas seepage during transient intervals of time.

Seismic activity is not limited to major earthquake events. California oilfields, for example, are subjected to literally hundreds of minor seismic events during any given year. Furthermore, the geologic stresses, that can build up as a result of compaction caused by fluid withdrawal and resulting subsidence during petroleum production, can cause self-induced microseismic activity within the oilfield. This occurs when the geological stratum shifts (moves) along a fault plane to relieve the buildup in stresses within the subsurface formations.

In summary, the removal of fluids during petroleum production precipitates microseismic activity. This, in turn, can cause release of hydrocarbons "trapped" in secondary entrapment zones, allowing the hydrocarbons to migrate along fault planes and eventually reach the surface. This is in addition to major earthquake events that can trigger the release of significant gas.

Gas fingerprinting procedures and methodology

If the presence of surface gas seepage is determined – usually through the initial detection using portable gas detectors – frequently, uncertainty exists as to the source of the seeping gas. Namely, the typical portable gas detectors in use today measure the content of explosive gas in air, but do not provide information on the chemical composition of the gas, necessary for its correct identification.

Fortunately, significant advances have been made in recent years using gas fingerprinting procedures that allow unequivocal identification of the source of the gas (Coleman, 1987). The methodology employed in performing the gas fingerprinting studies, however, is crucial in the correct identification of the gas.

Background regarding gas fingerprinting

Geochemical fingerprinting involves the use of a variety of chemical and isotopic analyses for distinguishing gases from different sources (Coleman et al., 1977, 1990). Table 1 lists the chemical compounds typically found in gas associated with oil and gas production. This can sometimes be differentiated from gases of other sources using only standard chemical analyses. For example, the presence of significant quantities of ethane, propane, butane, etc., indicates that the gas is from a thermogenic oilfield source.

Thermogenic gases (also referred to as petrogenic gases) were formed by thermal de-

TABLE I

Composition of natural gases

Component	Type of gas field			Natural gas separated from crude oil		
	Dry gas. Los Medanos* (mol%)	Sour gas, Jumping Pound** (mol%)	Gas condensate, Paloma* (mol%)	Ventura*		
				400 psi (mol%)	50 psi (mol%)	Vapor (mol%)
Hydrogen sulfide	0	3.3	0	0	0	0
Carbon dioxide	0	6.7	0.68	0.30	0.68	0.81
Nitrogen and air	0.8	0	0	0		2.16
Methane	95.8	84.0	74.55	89.57	81.81	69.08
Ethane	2.9	3.6	8.28	4.65	5.84	5.07
Propane	0.4	1.0	4.74	3.60	6.46	8.76
Isobutane	0.1	0.3	0.89	0.52	0.92	2.14
n-Butane	Trace	0.4	1.93	0.90	2.26	5.02
Isopentane	0		0.75	0.19	0.50	1.42
n-Pentane	0		0.63	0.12	0.48	1.41
Hexane	0	0.7	1.25			
Heptane	0			0.15	1.05	4.13
Octane	0		6.30			
Nonane	0					
	100.0	100.0	100.0	100.00	100.00	100.00

*California.
**Canada.

composition of buried organic material made up of the remains of plants and animals that lived millions of years ago, and buried to depths of many thousands of feet.

In contrast, microbial gases (also referred to as biogenic gases) are formed by the bacterial decomposition of organic material in the near-surface subsoil. These gases are usually composed of almost pure methane.

In actual practice, the gas samples that are collected at or near the surface undergo compositional transformation due to migration through several thousand feet of geologic strata. Upon migration, the gas composition can become primarily methane, giving the appearance of microbial or biogenic gas.

Accordingly, a more definitive method for distinguishing gases from different sources is necessary. The isotopic analysis is a state-of-the-art scientific method based on the fact that migration of gases in most situations does not change appreciably the isotopic composition of the hydrocarbons. For example, diagrams for genetic characterization of gases have been developed in which the carbon isotopic composition of methane is correlated with other parameters. In these diagrams, compositional fields have been defined for primary gases such as biogenic and thermogenic gases (Schoell, 1983).

The isotopic analysis is based upon the following fundamental concepts: Isotopes are different forms of the same element, varying only in the number of neutrons within their nuclei and thus their mass. Carbon, for example, has three naturally-occurring isotopes: carbon-12, carbon-13 and carbon-14. The two stable (nonradioactive) isotopes of carbon, carbon-12 and carbon-13, are present in all organic materials and have average abundances of 98.9 and 1.1%, respectively. These two isotopes of carbon undergo the same chemical reactions. Once methane is formed, its carbon isotopic composition is relatively unaffected by most natural processes.

The third naturally occurring isotope of carbon, carbon-14, is a radioactive isotope formed in the upper atmosphere by cosmic rays and has a natural abundance in atmospheric carbon dioxide of about 1×10^{-10}%. Carbon-14, the basis for the radiocarbon dating method, is present in all living things.

Hydrocarbon gases which are formed from the decomposition of organic materials have a carbon-14 concentration equivalent to that of the organic material from which they were formed. Microbial gases formed from organic material that is less than 50,000 years old contain measurable quantities of carbon-14.

Thermogenic (petroleum related) gases, on the other hand, are generally formed from materials that are millions of years old and thus contain no carbon-14. Accordingly, this method of analysis can be used to distinguish between thermogenic (petrogenic) and microbial (biogenic) gas. This is one of the most important aspects of gas fingerprinting in the practical world.

Hydrogen also has two naturally occurring stable isotopes: protium, more commonly just referred to as hydrogen (H) and deuterium (D). The hydrogen isotopic composition (D/H ratio) is used as a fundamental gas distinguishing parameter. It has been demonstrated that the hydrogen isotopic composition of methane gas can be used to identify its source. Other work, more specially related to the study of methane formed by microbial processes, has shown that hydrogen isotope analysis of methane can be used to elucidate the microbial pathway by which the gas was formed.

In summary, the isotopic analysis permits distinguishing between the sources of various gases that can be expected to be encountered in the evaluation of near-surface seepage problems. The potential sources that may be necessary to distinguish among are:

(1) **Natural gas pipelines**: If the seepage problem is located in an area where buried gas lines exist, leakage from these pipelines can result in subsurface accumulations of gas.

(2) **Producing or abandoned oil or gas wells**: If the seepage evaluation is made in the vicinity of a producing or an abandoned well, leakage from the producing wells, or from abandoned wells that have been improperly plugged, can result in near-surface accumulations of gas. Also, near-surface gas accumulations are frequently observed as a result of upward seepage of gas along faults or fissures in the rocks.

(3) **Underground gas storage reservoirs**: In many parts of the country, natural gas is stored underground in porous rock formations, commonly in abandoned oilfields. If gas leaks from one of these reservoirs (through fractured caprocks, for example), it can migrate (sometimes several miles along faults, for example) and appear at the surface.

(4) **Landfill gas**: Landfills generate a substantial quantity of methane gas, including areas where organic materials have been previously dumped by human activity and are now undergoing decomposition. Also, significant lateral migration of methane (for up to several miles) from landfills has been documented.

(5) **Coal beds**: Coal beds are also a potential source of gas because many coals contain gas. Coal gas, which is typically high in methane, could be the source of subsurface accumulations of gas.

(6) **Sewer gas**: Gas can also originate within a sewer system. Sewage decomposes through microbial action and can result in the production of significant quantities of methane. The gas can migrate over large distances within the sewer and then move along subsurface cracks and fissures.

The isotopic analysis procedure outlined above is a fundamental and necessary element of any successful gas identification study effort. Figure 1 is an example of the use of isotopic analysis for the genetic characterization of natural gas. The example presented was

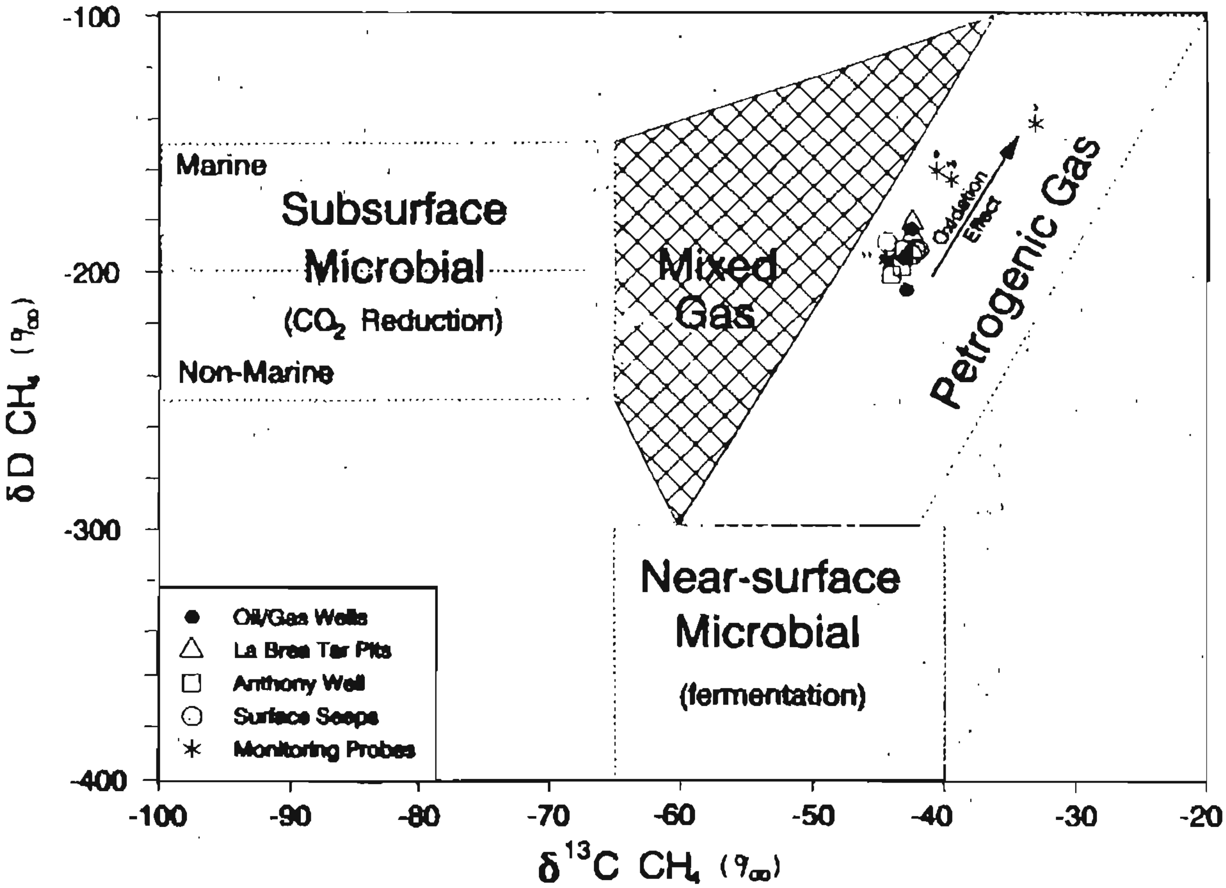

Fig. 1. Diagram showing the use of isotopic analysis for the genetic characterization of natural gas. (Courtesy of D.D. Coleman.)

based on gas samples collected in the Fairfax area of the City of Los Angeles, California, following a devastating department store explosion on March 24, 1985. The analysis includes samples that were isotopically analyzed by Jenden and Kaplan (1989).

Figure 1 has been prepared by Dr. Dennis D. Coleman of the Illinois State Geological Survey, Champaign, Illinois, who is a leading authority on the subject of natural gas fingerprinting. This figure dramatically demonstrates the ability to identify the origin of the gas sample as being from a petrogenic source (oilfield related), as opposed to a biogenic source (for example, from near-surface decomposing organic material). In this figure, the $\delta^{13}C$ of methane is plotted against the δD of methane. For a more detailed discussion of the basic methodology used, see Coleman et al. (1977, 1990) and Coleman (1987).

Monitoring procedures for hydrocarbon seepage identification

Measurement instrumentation and gas sampling procedures need to be considered for the reliable determination of gas seepage hazards. Three separate areas will be addressed, each distinguished by the functional objectives to be achieved: (1) gas identification and source determination, (2) seepage pattern characterization, and (3) long-term gas sensing for detection and warning.

This distinction is important because the instrumentation and measurement techniques are different for each of these functional areas.

Gas identification and source determination

Gas chromatographic analysis involves the separation of the gas into its constituents for the purpose of determining their contents. For example, natural gas that is found in an oilfield environment contains ethane, propane, isobutane and other higher-molecular-weight hydrocarbons. The mere presence of these higher-MW hydrocarbons establishes that the gas is of a petrogenic (petroleum) origin. Additionally, the relative percentages of the respective higher-MW hydrocarbons are sometimes used to identify the origin of the gas. If the gas has migrated through thousands of feet of geologic strata in reaching the surface (where the sample has been gathered), however, substantial changes usually occur in the relative percentages of the gas constituents.

Isotopic analysis, as previously described, is the preferred method for gas identification. This technique, however, requires considerable care in the procedures used for data sample gathering – in order to obtain reliable results. Use of subsurface depth probes and the selection of the depth from which the samples are collected are important in obtaining credible results. In general, the gas sample must have a sufficiently high concentration of natural gas, and must have been collected from a sufficient depth, i.e., below the near-surface clay caprocks, in order to prevent misinterpretation of the results.

Seepage pattern characterization

The isotopic analysis method of gas characterization – although required for accurate gas identification – is also relatively expensive. Sophisticated laboratory-type instrumentation is required, and data samples must be collected from depth probes that are not inexpensive to install.

On the other hand, relatively inexpensive portable or semi-portable gas detectors are available that allow determination of the percent composition in air of explosive gases, such as methane. These gas detectors can be used to efficiently characterize gas seepage patterns, and identify localized concentrations of explosive gases.

It is also appropriate to use portable gas detectors in identifying the field locations and the selection of depths for performing gas sampling for isotopic analysis. This will usually assure that sufficient gas concentrations exist in the samples collected, thus allowing meaningful scientific results to be obtained with a minimum of repeat sampling required.

Long-term gas sensing for detection and warning

Continuous gas sensing and detection systems have been developed. This technology is especially suitable for buildings that are located above seeping oilfields.

The basic concept relies on a system of gas sensors located throughout the basement and/or first floor areas of a building to detect the accumulation of methane gas (or natural gas). A low-level alarm condition can be established safely below any possible explosion level. Exhaust fans can be activated by the system to purge accumulated gas from the building until the gas levels return to normal. A central control panel can be used to activate the exhaust fans as well as to transmit a signal to an outside, central, 24-h sentry station. This can be tied into the burglar alarm, fire protection, or other sentry systems to alert central control, especially if higher levels of explosive gas develop (high-level alarm).

Although this type of system is practical for installation in new commercial construction or in retrofitting existing commercial structures, it is generally cost prohibitive for use in residential homes and small apartment houses.

Surface subsidence hazards and monitoring procedures

Although numerous studies have addressed the subject of surface subsidence (e.g., Poland, 1972; Chilingarian and Wolf, 1975, 1976) – the classic cases being Wilmington, California; Goose Creek, Texas; and Lake Maracaibo, Venezuela – these studies focused primarily on developing procedures to arrest or ameliorate subsidence. This was largely accomplished by maintaining or replenishing underground pressure, usually through water injection (waterflooding) (e.g., California Public Resources Code, Article 5.5, *Subsidence*, Section 3315(c) and Section 3316.4, *Repressuring Operations Defined*).

Unfortunately, these studies failed to address the increased hazards of gas migration resulting from the water injection. Typically, the water injection significantly increases pressures in the reservoir causing gas to migrate to the surface along paths of least resistance. The latter can include faults, fractures, abandoned wells, and producing or idle wells lacking mechanical integrity. Thus, water injection is hazardous in a producing oilfield that also contains improperly abandoned oil wells.

The basic problem of subsidence is caused by the fact that oil production causes stresses to build up in the subsurface geologic strata, increasing the prospect of formation of new fissures and faults and movement along preexisting fault planes. This will allow migration of gas to the surface, substantially increasing the risk of explosion in surface structures located in the vicinity of an oilfield.

This problem is compounded in areas that are subject to seismic activity, such as California. Initially, the geologic stresses are set up as a result of depletion of reservoir pressure (reduction in reservoir pressure due to fluid withdrawal). An earthquake can precipitate the movement along fault planes, allowing gas to migrate along these planes to the surface. As previously discussed, this phenomenon was recognized in several areas following the San Fernando, California, earthquake of February 9, 1971.

Likewise, injection of fluids into the ground for oil recovery or waste water disposal can trigger faulting. For example, on December 14, 1963, water burst through the foundation of the earth dam of the Baldwin Hills Reservoir, a hilltop water-storage facility located in metropolitan Los Angeles. The contents of the reservoir, some 250 million gallons of water, emptied within hours onto the communities below the dam, damaging or destroying 277 homes (Hamilton and Meehan, 1971). A detailed study following this disaster established that significant geologic stresses had built up in the subsurface resulting from oil withdrawal from the underlying Inglewood oilfield. This was aggravated by the injection of fluids under high pressure into the previously-faulted and subsidence-stressed subsurface, which triggered the earth movement and undermined the dam. Hamilton and Meehan (1971) concluded that "fault activation was a near-surface manifestation of stress-relief faulting triggered by fluid injection." This mechanism was also identified as being responsible for the 1962–1965 Denver earthquakes at the Rocky Mountain Arsenal and for generation of small earthquakes at the Rangely oilfield in western Colorado.

It is important to mention here that subsidence (due to the fluid withdrawal) area is twice (or more) as large as the area of the producing field.

In summary, the identification of the hazards associated with subsidence resulting from fluid withdrawal must be carefully evaluated as part of any prudent oilfield operation. This is best accomplished by establishing a systematic monitoring program for measuring surface subsidence and gas seepage, used in conjunction with a system model of the entire oilfield operation.

Regulatory aspects of oil and gas protection

Although most states have a regulatory agency established to oversee the oil and gas production activities within the state, including certain safety aspects, none of these agencies have developed a systematic or comprehensive program for dealing with the hazards associated with oil and gas seepage, and land subsidence. Accidents which did occur in the past shows this to be true.

Clearly, there is a great need for a uniform set of procedures and guidelines to be established for the monitoring of dangerous levels of gas seepage and land subsidence, especially in urban areas where the surface dwellers usually have no idea of the hazard that underlies them. They are generally helpless to take action, even if they become aware of the hazard.

Seepage from underground gas-storage facilities

The subject matter of seepage from underground gas storage facilities could easily be the topic of an entire article in its own right. For the purposes of this discussion, however, suffice it to say that the vast experience gained in this area provides an important body of knowledge for predicting seepage problems associated with oilfield operations.

The underground storage of natural gas is a well-developed technology that is widely used in many parts of the world. Its importance to this discussion is the fact that many underground storage facilities were once oilfields. The causes of seepage problems from these facilities are usually related to the same causes that produce seepage in producing oilfields.

These storage facilities usually have characteristics, including fault planes and active and abandoned wells associated with them, that cause seepage in the same way that occurs in a producing oilfield. Because of the much more careful evaluation and monitoring that is usually associated with a gas storage field, however, the root causes of the seepage are more amenable to quantitative assessment.

For example, in October of 1980, a serious gas leak developed in a storage field located in Mont Belvieu, Texas, a suburb of the greater Houston area. The gas seepage was detected when an explosion ripped through the kitchen of a house upon starting a dishwasher. More than 50 families were evacuated from their homes as a result of the gas leak.

The evaluation of the migration characteristics of the seeping gas is also of considerable importance to the concerns herein, in that a primary objective is to establish appropriate monitoring procedures for locating seeping gas. For example, in the above instance, high concentrations of the gas were found around the foundations of the homes involved. Gas was also detected throughout the sewer lines, which acted as conduits for the gas.

In the Mont Belvieu case, gas identification was important. For example, inasmuch as the gases were primarily a mixture of ethane and propane, it was possible to identify the location within the storage field primarily responsible for the leak. This can be related to the importance of establishing reliable fingerprinting procedures and the methodology as previously described herein.

Acknowledgement

The help extended by Matthew B.F. Biren is greatly appreciated by the writers.

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