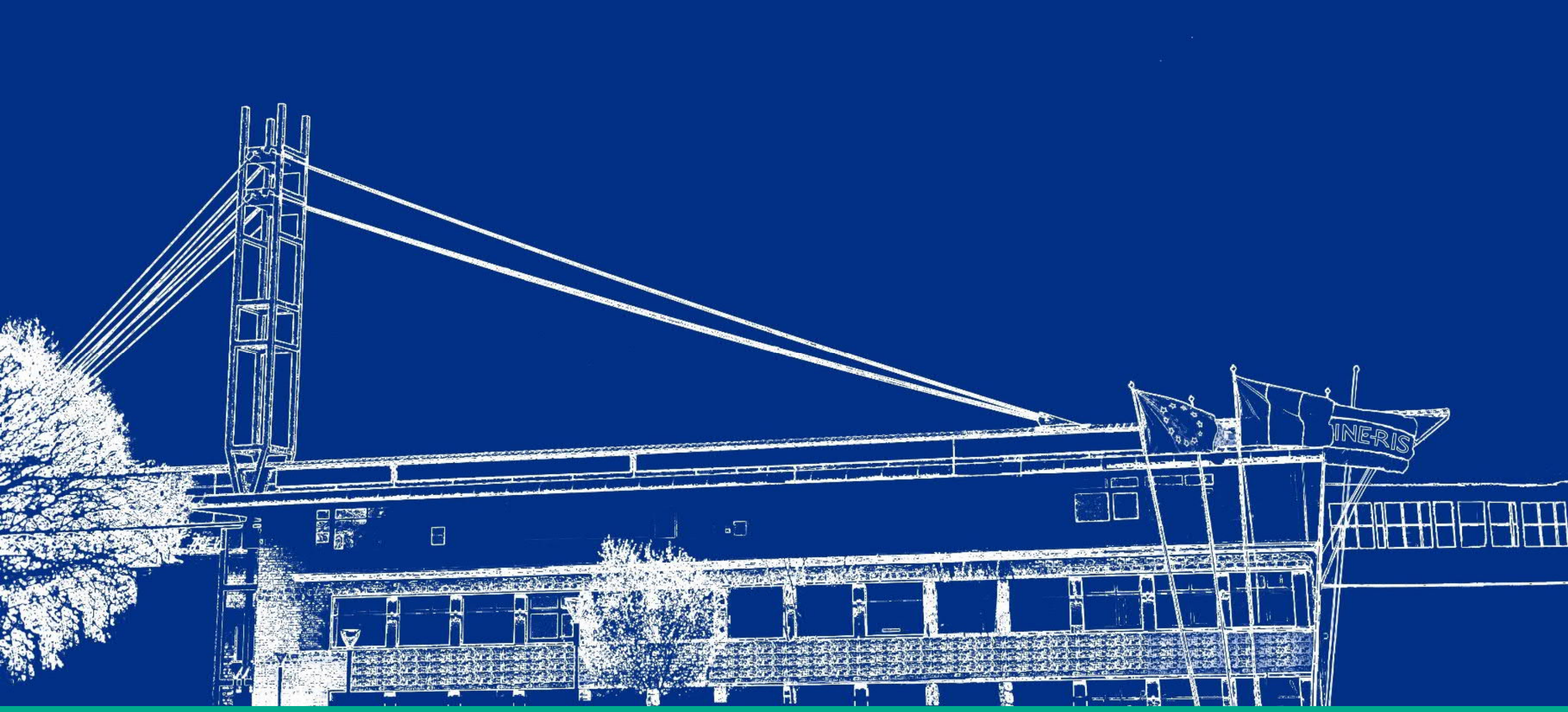

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National institute for industrial environment and risks

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RISKS ASSOCIATED WITH GAS STORAGE IN DEPLETED RESERVOIRS:

FEEDBACK EXPERIENCE FROM THE ALISO CANYON (US) INCIDENT

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1. Introduction

Underground storage of hydrocarbons originates at the beginning of the 20th century in the United States. In France, there are 28 storage sites, with a predominance of natural gas storage in porous formations (13 sites) [1]. These are located in the Paris and Aquitaine sedimentary basins and are regulated in the framework of the French mining and environmental codes. Their primary function is to adapt the natural gas supply to the seasonal variations of the energy demand.

In addition to the storage of hydrocarbons, the possibility of storing CO_2 in deep porous formations has been explored for about twenty years as a potential solution for reducing the impact of anthropogenic carbon emissions to the atmosphere. This concept of carbon capture and storage (CCS) involves injecting very large volumes of CO_2 into deep saline aquifers or hydrocarbon depleted reservoirs.

In spite of the fact that underground storage is a mature technology, this industry is not exempt from risks on human safety and impacts on the environment. The main risks that can be identified from the feedback on hydrocarbon storage are leaks from wells and underground reservoirs and containment losses from surface facilities, which may lead to explosions (as in Moss Bluff, Texas, 2004), fires (as in Hutchinson, Kansas, 2001) or air pollution (as in Aliso Canyon, California, 2015). Regarding CO_2 storage, which is still an emerging industry, the number of reported incidents is very limited [2]. However, the similarities between hydrocarbon and CO_2 storage are such that the experience gained from accidents in hydrocarbon storage is very useful for improving risk management in CCS.

The aim of this note is to explore the circumstances of the massive gas leak that occurred at Aliso Canyon (California) in 2015 in order to draw lessons on underground storage safety that may be transposed to CO_2 storage. This note is mostly based on a review of the literature and official US government reports concerning this incident.

2. Site context

The Tidewater Associated Oil Company discovered the Aliso Canyon oil field in 1938 [3]. The discovered zone was named “Porter” and two reservoirs were developed. The shallower was named “Aliso”, and the deeper one “Del Aliso”. These reservoirs produced oil with an API gravity below 20° and with approximately 8.5 m^3 (300 cft) of gas per barrel. Deeper reservoirs, “Sesnon” and “Frew”, located around 2,500 meters deep, were later discovered in 1940 and 1945 respectively, with approximately 2.8 billion m^3 (100 Bcf) of gas in the gas cap and 1.41 billion m^3 (50 Bcf) of gas dissolved in oil. The global oil reserve in the “Sesnon” and “Frew” reservoirs was estimated around 125 to 150 million barrels and, until 2000, only 27.7 million barrels, or 18 to 22% of the reserves had been produced [3].

Tidewater Associated and its successors operated the field until 1972 when SoCalGas (Southern California Gas Company) purchased the “Sesnon” and “Frew” reservoirs for natural gas storage. Between 1972 and 1993, SoCalGas used the two reservoirs for natural gas storage, while Texaco (Chevron, then Thermo Oil Company) operated other reservoirs for oil production. In 1993, SoCalGas acquired the majority of shares held by Texaco and became the principal operator of Aliso Canyon.

The Aliso Canyon gas storage site is located to the north of the San Fernando Valley (approximately 40 km north-west of Los Angeles), and covers an area of 3,600 hectares (see Figure 1). Gas is stored there at a depth of 2,500 meters and is mostly made up of methane and ethane. The site includes 115 wells with a storage capacity of approximately 4.8 billion m^3 (under standard temperature and pressure conditions[1]) [4], including 2.4 billion m^3 of working capacity (i.e. gas which is regularly accessed for commercial use), and the same quantity of cushion gas. In 2014, Aliso Canyon was the 4th largest underground gas storage facility in the United States, representing 2.1% of the country’s total natural gas storage capacity. This underground storage played an important role in balancing energy supply and demand in Southern California by supplying gas to nearly 11 million homes and 16 thermal power plants around Los Angeles.

[1] Temperature: 25°C; pressure: 1 bar.

Figure 1: location of the Aliso Canyon storage site

3. The incident timeline, effects and consequences

3.1. Incident timeline

On 23 October 2015, a major natural gas leak was detected at one of the 115 wells of the Aliso Canyon storage site: well SS-25. The incident progressed as follows [13]:

- 3:15 p.m.: the smell of gas is reported to SoCalGas by the staff of a subcontracting company;
- 3:20 p.m.: SoCalGas staff are deployed to the zone, find and repair a leak on a metal pipeline located on the surface near wellhead SS-25. Then they scan the zone with a portable gas detector, but no trace of natural gas is detected;
- at around 7 pm, a gas leak is observed on the main road leading to well SS-25 (see Figure 2). Staff are evacuated from the zone and the road is closed. SoCalGas mobilises to prepare for well control operations and starts recording wellhead pressures every 30 to 60 minutes.

This leak lasted for 16 weeks from its detection on 23 October 2015 until the well was permanently plugged on 18 February 2016.

Figure 2: Location of the first gas leak zone on 23 October 2015 [14]

3.2. Human and social consequences

Over the 16 weeks that the gas leak was ongoing, the Los Angeles County Department of Public Health (LADPH) received more than 700 reports of symptoms that could potentially be attributed to the gas leak, including headaches, nausea/vomiting, diarrhoea, nosebleeds, breathing problems, chest tightness, coughing and dizziness [7].

Nausea, nosebleeds and headaches observed in some residents close to the gas leak zone were suspected to be connected to exposure to mercaptan [6]. This chemical additive is added to gas so as to detect a leak based on its odour (methane is odourless and invisible). Analysis of the records and the medical follow-ups of the Department of Veterans Affairs patients (approximately 17,000 records) corroborated the impact of this leak on the increase in breathing problems during the incident [12]. This analysis was possible thanks to 60,000 US military veterans living in the San Fernando Valley region, including 9,000 in the Porter Ranch neighbourhood close to the leak zone.

It should also be noted that the Aliso Canyon leak resulted in SoCalGas temporarily relocating about 2,824 households (approximately 11,296 people) living in Porter Ranch and the surrounding areas [7][8].

Certain volatile organic compounds known as BTEX (benzene, toluene, ethylbenzene and xylenes), which are carcinogenic to humans, were measured at various air quality monitoring sites between December 2015 and July 2017. Monitoring results showed concentrations of BTEX in the air below the chronic exposure thresholds for serious health problems set by California's Office of Environmental Health Hazard Assessment (OEHHA) and the California Air Resources Board (CARB) [9]. However, it should be noted that no monitoring of BTEX concentrations was conducted around Porter Ranch in the first few weeks following the leak.

After the plug-in of well SS-25, the air quality monitoring campaign showed that the concentration of pollutants related to the natural gas leak decreased in the neighbourhoods near Aliso Canyon, then gradually returned to normal thresholds for the Los Angeles Basin [9].

3.3. Environmental consequences

Conley et al. [4] monitored the leak zone between 7 November 2015 and 13 February 2016 using an aircraft fitted with measuring instruments. The analysis of air samples showed that the natural gas was composed of methane, ethane and sulphurous odour (mercaptan) with leakage rates into the atmosphere of up to 60 tonnes of methane and 4.5 tonnes of ethane per hour. In total, approximately 97,100 tonnes of methane (approximately 141 million m^3 under standard conditions) and 7,300 tonnes of ethane were released into the atmosphere [4].

The methane leak is the second largest of its kind recorded in the United States, surpassed only by the 169 million m^3 (60 billion scf) released into the atmosphere when the Moss Bluff underground storage cavern in Texas collapsed [3]. By contrast, the impact on the climate and therefore the environmental impact of the Aliso Canyon leak is by far the most significant on record because the explosion and fire that occurred during the Moss Bluff leak resulted in the combustion of the released gas to produce CO_2. As a comparison, methane remains in the atmosphere for less time but has a global warming potential 34 times greater than CO_2 over a period of 100 years [10].

The volume of natural gas released by well SS-25 during the incident doubled the total natural gas emission for the whole of California over the period of the leak and represented 25% of total annual methane emission in the state [5].

3.4. Economic consequences

SoCalGas estimated the total cost of the Aliso Canyon leak to be around 1.07 billion dollars. This cost includes the cost of plug-in operations for well SS-25, analyses carried out to assess the impact of the leak on the health of local residents and the environment, the relocation of residents, and the funding of 38,000 air filtration systems for homes, schools and enterprises [11].

4. Causes of the incident

4.1. Origin

Well SS-25 was drilled in 1954, initially for the purposes of oil production. It is covered by two concentric casings, a first 11"3/4 diameter casing anchored at a depth of 300 m (990 ft) and a second 7" diameter casing anchored at about 2,600 m (8,585 ft). The 7" casing is cemented from the casing shoe to a depth of 2130 meters (7,000 ft), the remainder of the annulus being filled with drilling fluid left in place during well construction (see Figure 3). The 11"3/4 casing has no good quality cementing above a depth of 120 meters (400 ft).

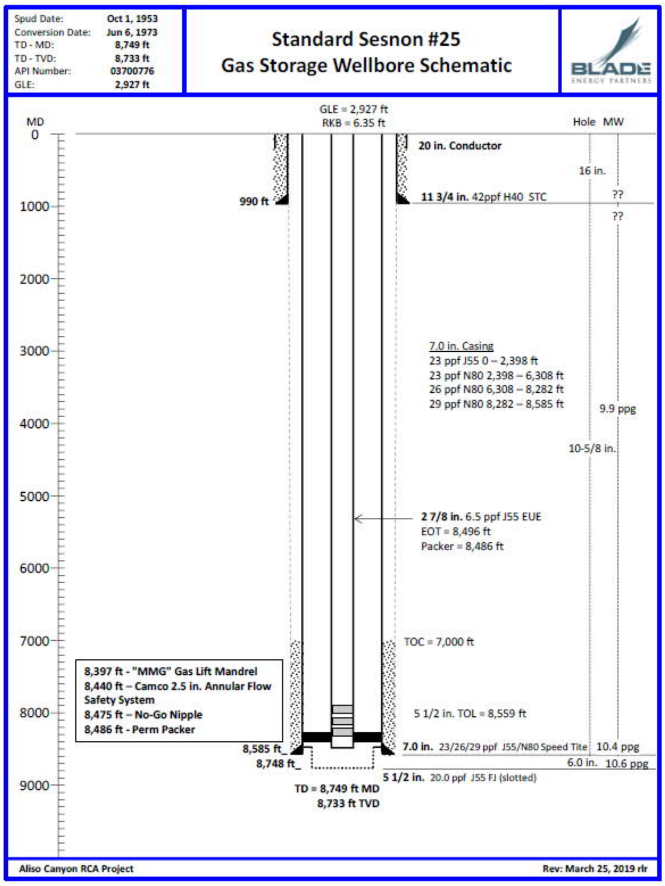

Figure 3: Schematic diagram of well SS-25 in February 1979[13]

As an oil producer, the well was completed with a 2"7/8 production tubing, through which the oil circulated and which acted as the primary barrier, while the secondary barrier was the 7" casing.

In 1973, well SS-25 was converted into a natural gas storage well. For flow optimisation purposes, the gas was then injected and withdrawn through both the production tubing and the 2"7/8-7" annulus. The 7" casing then became the primary barrier, the 11"3/4 casing acting as the secondary barrier. Nevertheless, no risk analysis was carried out during this change of configuration. No reports mention an analysis of the quality of the cementing around the 7" casing, i.e. there was no log control of the cement around this casing, or any corrosion control of the casing itself [13]. Only pressure tests were performed to check the proper holding of the casing.

It is pointed out that the Aliso Canyon storage site has known a total of 124 incidents related to gas leaks through casings [13]. Two of these incidents resulted in huge underground gas leaks, specifically from well Frew-3 in 1984 and well FF-34A in 1990. These wells were plugged by injecting mud into the tubing. No analyses were carried out following these incidents to identify the cause of the leaks, and no preventive measures were put in place to prevent these types of leaks, before the incident of 23 October 2015.

It should also be noted that in 1988, SoCalGas planned a two-year campaign to assess the mechanical integrity of the casings of 20 wells, including well SS-25. These wells were selected on the basis of their history and the time elapsed since their last workover. In practice, well SS-25 was considered of low priority, and out of the 20 wells selected, SoCalGas only performed inspection logs on 7 wells. The results of these inspections showed material losses on the external surfaces of the casings of around 20 to 60% of the thickness on 5 of the 7 wells analysed. No subsequent investigations were conducted to examine the origin of the external corrosion of these wells.

4.2. Technical causes

On the morning of 23 October 2015, gas injection into well SS-25 started between 3 and 4 a.m. with a wellhead injection pressure of around 18.61 MPa (2,700 psi). Some time after the onset of injection, the 7" casing deformed radially and an axial rupture appeared at a depth of 270 m (892 ft). The gas that escaped along this rupture expanded, causing the temperature of the steel casing to drop, thus reducing its resistance. Between 7 and 8 a.m., this resulted in a radial rupture at the stop point of the axial rupture (see Figure 4).

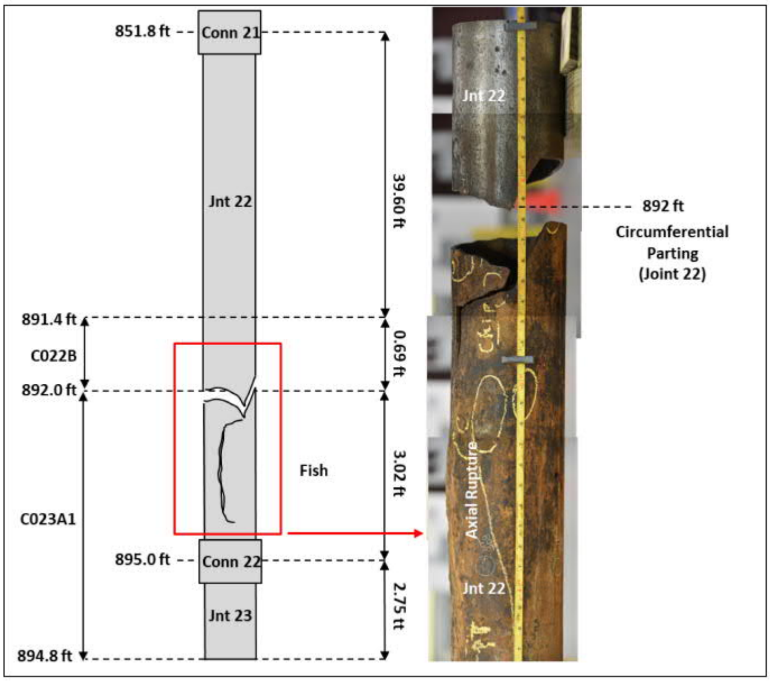

Figure 4: Diagram and photo of the casing rupture[13]

During this time, gas continued to be injected. The consulting company Blade Energy Partners, commissioned by the California Public Utilities Commission (CPUC) to carry out the third-party expert assessment on the origin and cause of this incident, estimated the leakage rate through the axial rupture at the time of the incident to be around 4.53 million m^3/day (160 MMscf/d), of which around 2.55 million m^3/day (90 MMscf/d) came from stored gas and 1.98 million m^3/day (90 MMscf/d) from injection. The change in pressure in the injection system brought about by the leak compensation was too small to be detected in real time by the monitoring system in place at the site. The gas leak resulted in an increase in internal pressure in the 11"3/4 casing, creating holes in the corroded parts of the casing walls. These integrity losses led to natural gas rising to the surface, where the leak was detected at 3:15 p.m.

Operations to determine the exact causes of the leak from well SS-25 began in February 2016, after the well was secured and permanently plugged beneath the ruptures. Blade Energy teams carried out a series of actions, including logging and imaging the monitored wells, followed by extraction of the affected casing section in July 2017.

Based on these investigations, it became apparent that the steel casing had corroded extensively and had lost 85% of its material in the leak initiation zone. It was confirmed that the external corrosion of the 7" casing was significant below the depth of 213 meters (700 ft), with a corrosion thickness greater than

15 to 20% of the thickness of the casing. The fissured 7" casing section displayed several corrosion marks greater than 50% of the thickness of the casing (see Figure 5).

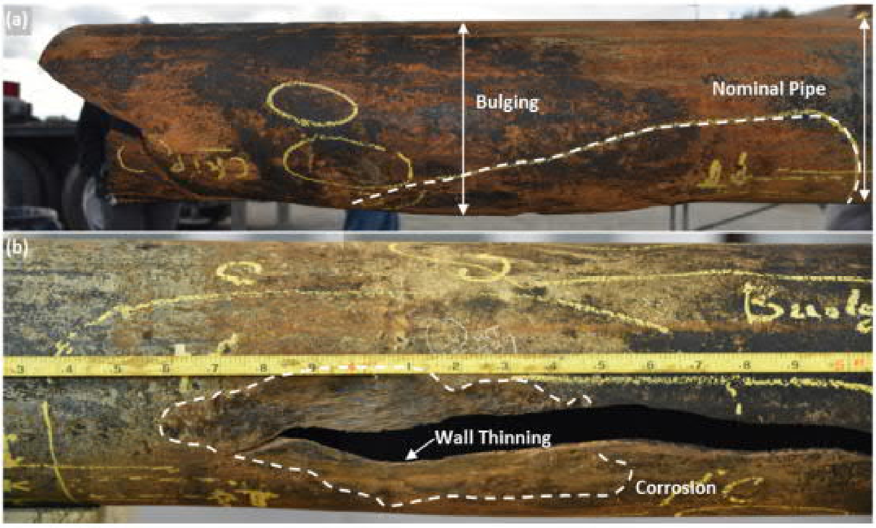

Figure 5: Photos of the radial elongation of the corrosion (a) and the rupture zone (b) of the 7" casing [13]

This external corrosion around the casings is linked to the environment of the well. Indeed, in the absence of good quality cementing of the casings, groundwater containing micro-organisms likely to corrode the casings mixed with the drilling fluid that was supposed to protect the 7" and 11"3/4 casings, and then gradually drain it. With the storage and withdrawal of natural gas in the 7" casing and tubing, small amount of CO_2 from the reservoir ended up in the annular space between the 7" and 11"3/4 casings. CO_2 migration took place through some of the connections of the 7" casing. The presence of this CO_2 in the environment promoted the proliferation of micro-organisms and resulted in physicochemical reactions leading to the corrosion of the casings. Therefore, the pressure of 19 MPa (2,761 Psi) applied to the 7" wellhead produced a radial elongation of the casing due to the loss of resistance at the level of the most corroded zone. This flaw constituted a mechanical weakness and the corrosion grooves generated on the external surface of the casing contributed to stress concentration around this zone. This radial deformation was accompanied by axial initiation of a 53.9 mm (2.12 in) ductile crack. This crack propagated vertically up and down the initiation zone and then stopped once the stored energy dissipated. According to the simulations carried out, the gas leak along the axial rupture resulted in a drop in the local temperature from 26°C before the leak to -34°C after the leak. Due to the drop in temperature, another rupture was initiated and propagated radially (see Figure 4) to cut the 7" casing at a depth of 271 meters (892 ft).

4.3. Profound causes

The Aliso Canyon gas leak highlighted both deficiencies in SoCalGas' risk prevention procedures and regulatory shortcomings at the time of the event.

- From a technical and organisational point of view, one may note:
  - an insufficient feedback on the causes of the numerous gas leaks at Aliso Canyon in the past. Moreover, despite the external corrosion detected on some wells following investigations, no additional studies were conducted to determine the origin of the loss of material;
  - the failure to update risk assessment when converting the well;
  - an insufficient protection of the casings that became primary and secondary barriers after reconversion, in particular the absence of cementing of sufficient height and quality;
  - the absence of a subsurface safety valve at the head of well SS-25. The presence of such a valve was not required by the law of the State of California (as the well was located approximately 1.5 km from the first dwelling, i.e. beyond the regulatory distance of 100 m);

    - a lack of preparation of emergency response to well blow-outs (procedure to be followed, composition and density of mud to be applied, etc.), which resulted in the failure of the first six attempts to control the leak (see § 5).
- From a regulatory point of view, one may note:
    - insufficient provisions for the prevention of corrosion risks and for the periodic inspection of the thickness of the casings;
    - the absence of any obligation to equip the well with a subsurface safety valve;
    - inadequate provisions for emergency measures to be adopted in the event of a leak.

5. Immediate action and securing the site

Between 24 October and 22 December 2015, seven successive attempts to secure the well were made by the operator.

The first attempt to control the leak began on 24 October 2015, the day after it was detected. This attempt was unsuccessful because the fluid injected to counter the influx of gas was not dense enough and had a very high crystallisation temperature. Therefore, injection of mud resulted in the creation of ice plugs (hydrates) clogging the tubing and the casing. The presence of these plugs created an increase in pressure below the plugs and a rupture in the rock below the 11"3/4 casing shoe, which exacerbated the leak. The following five attempts between 13 and 25 November 2015 also failed, again due to the use of mud that was not dense enough. Each of these attempts caused additional damage, both deep down and at the level of the wellhead. On 22 December 2015, based on further analysis, a seventh attempt to control the leak was initiated. The pressure at the wellhead fell to zero for a moment, but mud pumping had to be stopped due to wellhead movement resulting from cumulative damage from previous attempts.

At the same time, on 4 December 2015, a relief well (P-39A) was drilled to intercept the leaking well at a depth of approximately 2,500 meters with the aim of circulating mud to stop gas influx and then cementing the well. To increase the chance of success of this operation, SoCalGas reduced the reservoir pressure as much as possible (by withdrawing gas from other wells). The injection of mud and then cement in well P-39A enabled to stop the leak on 11 February 2016.

6. Lessons learned

The analysis of the causes of the incident at Aliso Canyon enabled to draw lessons and identify measures to be planned during the construction or conversion of a well, particularly in the context of an underground CO_2 storage project:

- Ensure a good <u>quality cementing over the entire length of the casings</u>, in order to protect them as far as possible from external corrosion;
- Conduct a <u>periodic log inspection</u> of the casings with regard to corrosion (internal and external);
- Provide a <u>control annulus</u>[2] to detect possible leaks outside the well. At Aliso Canyon, the drop-in pressure was masked by gas injection.
- The operator must <u>integrate its internal feedback</u> in the analysis of leakage risks and implement adapted corrective measures;
- Any substantial modification in the configuration of a well (in particular when converting a well for other uses) must go hand in hand with an <u>update to the risk analysis</u>;
- The operator must <u>prepare for emergency situations</u>, specifically with regard to the control of well blowouts;
- In the event of a leak, air quality should be monitored <u>from the very start of the leak</u>.

[2] I.e. an annular space between the tubing and the casing, filled with inhibited brine or nitrogen and whose head pressure is monitored for leak detection purposes.

Glossary

Bcf: Billion cubic feet

API gravity: Unit used to measure the density of oil

ft: feet (1 ft = 0.3048 meters)

MMscf/d: Million standard cubic feet of gas per day

scf: Standard cubic feet

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