A Systematic Framework for Root-Cause Analysis of the Aliso Canyon Gas Leak Using the AcciMap Methodology: Implication for Underground Gas Storage Facilities

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Received September 27, 2017; Accepted November 8, 2017

Abstract: According to the US Energy Information Administration [1], the natural gas industry supports 33% of electricity generation in the US. Despite this critical role, the importance of safety and safety culture in the natural gas industry has not been adequately highlighted. The absence of strict regulations and lack of attention towards precautionary measures have allowed the industry to persevere with insufficient urgency for implementing innovative technologies and safety-first protocols. On October 23, 2015, the Aliso Canyon natural gas accident highlighted how the lack of regulatory oversight in a low probability, high consequence industry could have such impactful and unpredictable repercussions.

This paper analyzes the concatenation of events that led to the Aliso Canyon gas leak. It adopts the AcciMap methodology, which was originally introduced by Rasmussen in 1997 as an accident investigation framework, to conduct a systematic root-cause analysis and capture different involved socio-technical factors that contributed to the leak. It is, however, noteworthy that the lessons learned from this study have implications for other underground gas storage facilities.

Keywords: Root-cause analysis, risk management, AcciMap, accident investigation, Aliso Canyon gas leak, natural gas

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DOI: 10.7569/JSEE.2017.629515

1 Introduction

1.1 Overview

Southern California Gas (SoCal Gas) Company, which owns 115 wells in the Santa Susana Mountains of Aliso Canyon in Porter Ranch, CA, has been at the center of a major environmental scandal that has shed light on the natural gas industry and safety culture in its entirety. SoCal Gas, a subsidiary of utility company Sempra Energy, is being held responsible for inadequate operations that ultimately led to a four month long natural gas leak, beginning in October 2015, that has affected the community, the company, the natural gas industry, national and state regulations and the environment in a detrimental way. This paper aims not only to discover what happened that led up to the accident at the Aliso Canyon, but why it happened and how it could have been prevented. Moreover, this paper does not aim to find culpability in SoCal Gas management or operators, but rather to suggest a safer process-oriented solution on how to perform with proper conduct.

The Columbia Accident Investigation Board (CAIB) [2, pg. 6], in their analysis of the Columbia Space Shuttle accident, declared that “complex systems almost always fail in complex ways, and we believe it would be wrong to reduce the complexities and weaknesses associated with the system to some simple explanation”. They strived to show how accidents occur not only from the final interaction of the failure, but more often when the entire process is culpable for compiling and weakening a situation. This paper will look at the progression of inadequate protocols that ultimately lead to the Aliso Canyon gas leak.

In this paper, we propose to investigate and analyze the events that led up to the Aliso Canyon gas leak, the steps taken to mitigate the leak and what policies and legal cases came from this event. We will utilize the AcciMap methodology, which was originally proposed by Jens Rasmussen in 1997, to analyze the accident and the interaction of decision-making in multiple levels of a socio-technical system. By using the AcciMap methodology, it is possible to take the findings from this specific case study and apply it to the entire industry in an effort to enforce preventative measures and promote a stricter safety culture with proactive risk management. We will systematically go through the managerial decisions and procedures that the SoCal Gas had taken in hopes of understanding how to prevent a macro ergonomics problem such as this in the future.

It is noteworthy that although this study analyzes the Aliso canyon gas leak and its root contributing causes, its lessons learned can be applied to other underground gas storage facilities existing across California and the US. Several of these facilities have a similar condition to the Aliso Canyon by being located at a depleted oil and gas well.

1.2 Background

Beginning October 23, 2015, a well in the Porter Ranch, CA, area allowed for a massive natural gas leak that continuously leaked from a gas storage facility reserve

DOI: 10.7569/JSEE.2017.629515

for four months. The well, Standard Sesnon 25 (SS-25), is 61 years old, 8,750 feet deep and was once used as an oil production well until it was converted into a gas storage well in 1973. The well previously had a safety valve until it was removed in 1979 and was never replaced [3]. Well SS-25 is part of one of the nation's largest containment locations, with the capacity to store 86 billion cubic feet of natural gas. The Aliso Canyon reservoir stores enough gas for distribution to nearly 22 million customers in the LA area and supports 17 power plants in the LA basin.

The Division of Oil, Gas and Geothermal Resources (DOGGR), whose program emphasizes prudent development that protects the environment, prevents pollution and ensures public safety of California, was notified of the accident when community members started complaining about the smell. South Coast Air Quality Management District started receiving reports of a gas smell from the community the next day. However, SoCal Gas did not acknowledge the leak publicly for several more days. The first aerial measurement was two weeks later due to some preventions from making this measurement earlier. The Air Resources Board stated to the LA Times that it was not notified of the leak until November 5 [4].

Natural gas mixture is typically pumped into reservoir wells when demand and prices are low and is expected to be extracted during extreme weather conditions or to fuel gas-run electricity plants during times of extreme energy needs. The CEO of SoCal Gas, Dennis Arriola, stated that "gas storage is an integral part of our state's energy environment, not just for natural gas but for electricity" [5]. Natural gas currently meets 33% of energy needs in America [1]. It is believed that SoCal Gas was pumping methane into the reservoir at beyond secure limits through not only the inner production tubing, but also the outer well casing in order to meet the demand of customers. This increased demand in pressure possibly caused extreme metal fatigue that weakened the system and resulted in the casing being undermined. Figure 1 illustrates the suspected leak and how the gas is escaping from the casing.

1.3 Environmental Effects and Community Impact

The stated Aliso Canyon incident was one of the largest methane leaks from a natural gas storage facility in United States history. It is estimated that the leak emitted 97,100 metric tons of methane, the equivalent of 2.1 million metric tons of carbon dioxide into the atmosphere [6]. This is more air pollution than 440,000 cars emit in a single year. Well SS-25 released two times more than the emissions of every power plant, oil and gas facility, airport, smoke stack and tailpipe in LA combined [6]. In three months, well SS-25 alone emitted more greenhouse equivalent gases than any other facility in California [7]. The California Air Resources Board (CARB) established that when the leak was at its worst in late November, about 60,000 kilograms were being released per hour. In January, that number went down to 18,400, and the reservoir went from being 90% full to only 37% full by January 10 [4]. A timeline of the estimated monthly emissions can be seen in

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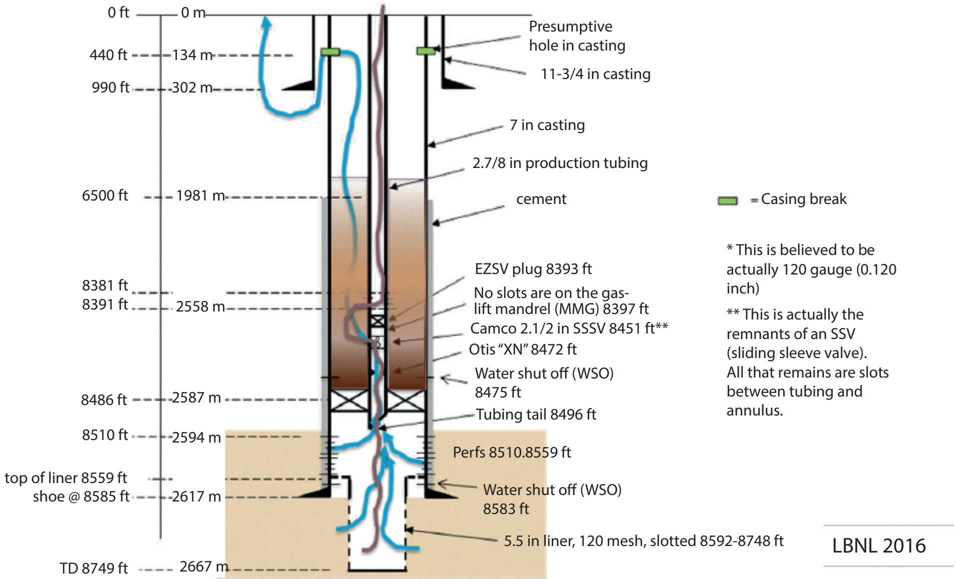

Figure 1 Well schematics and the illustration of well SS-25 suspected leak in the casing [11, p.21] (Blue line represents the methane gas and the brown line indicates the kill fluid).

Figure 2. In total these accumulative emissions have doubled the total emissions associated with natural gas production in all of California and represent 25% of the state's total methane emissions. Methane has a greenhouse effect 25 times stronger than carbon dioxide when in the atmosphere, with a stronger heat trapping magnitude that lives longer in the stratosphere, where it does the most harm. Methane gas is not covered under the Clean Air Act in the United States, but still has a large ability to cause damage to the environment and needs to be stringently regulated.

After the leak was successfully stopped, The California Office of Environmental Health Hazard Assessment (OEHHA) assessed six weeks of air samples to successfully assure the Porter Ranch neighborhood does not have signs of acute toxicity health hazard issues [8]. South Coast Air Quality Management District (SCAQMD) is providing additional air samples [8]. Following the accident, SoCal Gas stated the company developed a mitigation plan to address the emissions. The company is investigating methane mitigation from multiple sources, such as dairies and landfills in California [9]. The company has been providing regular progress reports on their mitigation plan to assure the community and regulators that they will compensate for their environmental effects as well, and that the cost will fall on them and not the customers.

The accident relocated more than 11,000 residents from the Porter Ranch community to Los Angeles County. Many residences complained of headaches, bad

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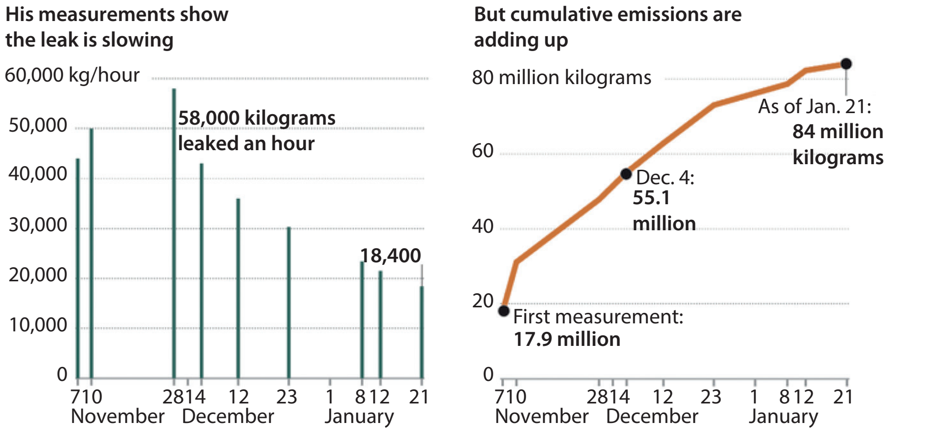

Figure 2 Measurement of the emissions leaked over time [55].

smell, nose bleeds and nausea. Experts believe these symptoms are not a side effect of the methane gas, but rather of mercaptan, the smelly chemical added to natural gas mixtures to signal a leak. This olfactory reassurance is a necessary safety precaution, considering that methane is an odorless gas. The company asserted that there are no known long-term effects of the methane and mercaptan mixture. However, angry residents and concerned policy makers demanded that SoCal Gas be held accountable to conduct and fund research on possible long-term health effects of the various chemicals involved. An additional chemical found in many natural gas mixtures is benzene, which is known to increase the risk of cancer when there is long-term exposure.

As residents started to repopulate their homes, SoCal Gas paid $500 million in relocation costs for 59,000 reimbursements [10]. They also assisted the Community Resource Center (CRC) in providing 38,000 air filtration systems in homes, schools and businesses [10].

1.4 Kill Procedure Attempts

SoCal Gas mobilized internal crew and equipment to address the well failure. There were multiple attempts to stop the leak using well kill procedures that involved pumping mud and brine down the well. Eight attempts were conducted, which were all unsuccessful to slow the leaking. These abatement attempts further weakened the well and increased the possibility of a massive blowout. Boots and Coots, an expert well control service that offers services such as blowout response procedures and well kill operations, were called in to facilitate a proper kill procedure [11, p.19]. Following, a relief well began construction on December 4, 2015. This well is approximately 1500 feet away from Well SS-25 at an angle, with the goal of hitting the main well below the cap rock. The relief well was designed to

DOI: 10.7569/JSEE.2017.629515

introduce kill fluids and drilling muds and pour them down the main well to seal it off.

On January 6, 2016, Governor Jerry Brown declared a state of emergency. This order called for action from the Governor's Office of Emergency Services to establish an incident command structure that held responsible the DOGGR to investigate the leak, the Office of Environmental Health Hazard assessment to review air quality measurements, the California Public Utilities Commission (CPUC) to investigate the leak and determine the cause, the California Air Resources Board (CARB) to measure the leak and estimate the total emissions, the Division of Occupational Safety and Health to ensure on-site worker safety and the California Energy Commission to maintain energy reliability during the crisis. The key implications included stopping the leak, protecting public health and safety, ensuring accessibility and strengthening oversight.

On February 11, 2016, after 4 months of leaking, the relief well pierced Well SS-25 8,500 feet below the ground's surface through the casing, and workers started injecting a mud-like compound. You can see the illustration of the successful relief well in Figure 3. Once the concrete was pumped into Well SS-25, state regulatory officials were allowed to inspect the well and assured the community of a safe kill procedure. Although this was a huge and long awaited victory, residents were skeptical on celebrating too early. There were still concerns about safe air quality and whether it was safe for families to move back home. The Department of Energy enforced strict mitigation guidelines during its investigations to ensure residents were compensated and criteria were put in place to assure safe air quality. Jason Marshall, the chief deputy director of the California Department of Conservation, confirmed that air quality regulators approved the gas emissions as being under control and five separate tests were completed to assure the integrity of the cement sealing was complete and satisfactory. Even though the leak may be plugged, the consequences following up in the community and in state laws are still pending. Los Angeles Mayor Garcetti was quoted saying, "stopping the leak is only the first stage of recovery… and the city of Los Angeles is here to help people return to their homes, start doing business again, and get back to normal as quickly as possible" [12].

2 Rasmussen's Risk Management Framework and AcciMap Methodology

2.1 Accident Investigation Models

There have been several developed methodologies to better understand and analyze accidents. Some examples of these methodologies include the Systems-Theoretic Accident Model and Processes (STAMP) by Leveson [13,14], Reason's model of organizational accidents [15] and Rasmussen's AcciMap approach [16]. Rasmussen's AcciMap approach is particularly useful for this purpose as it models

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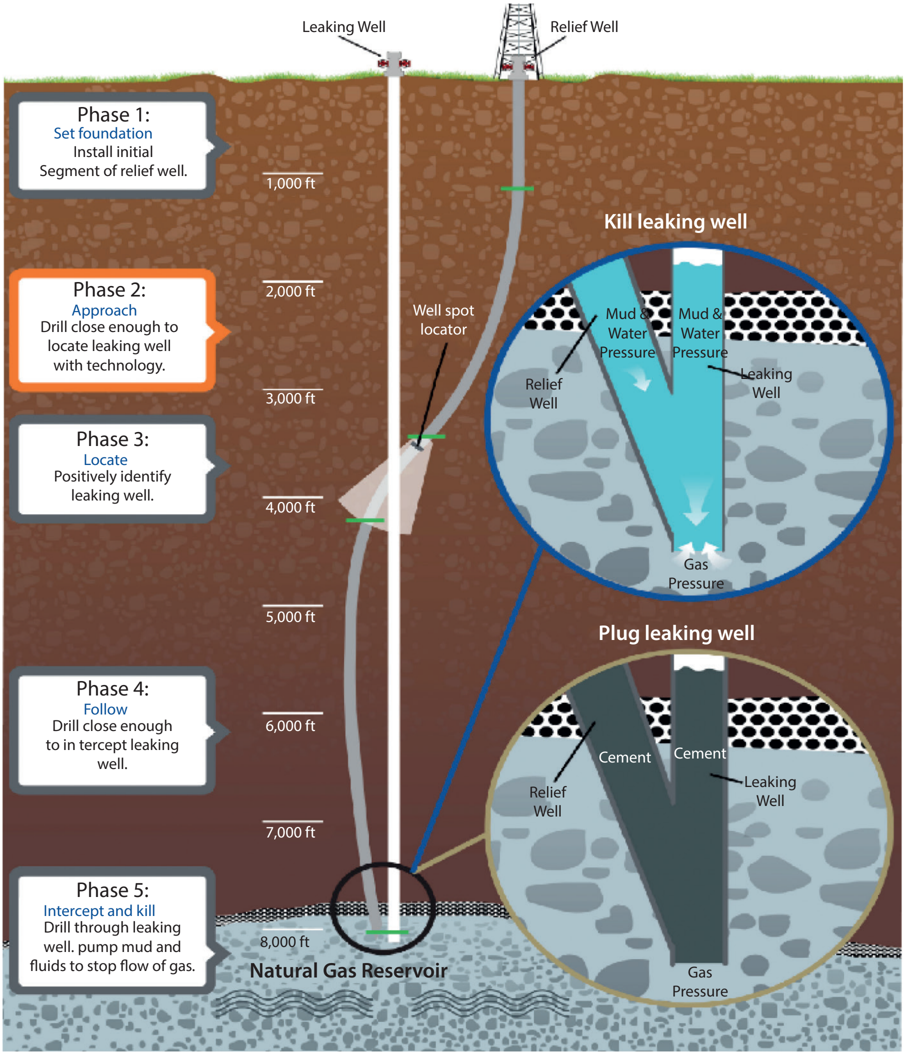

Figure 3 Phases of stopping the leaking well [56].

different contributing factors of an accident, and their interactions, in a causal diagram.

In general, focusing on how a certain accident was allowed to happen is beneficial for the entire industry that can adapt newly suggested protocols and avoid the same mistakes that have already been made. It is important to look at the system as a whole and understand how and why there was a failure on one level and how

DOI: 10.7569/JSEE.2017.629515

that contributed to inadequate controls on the next level, interweaving the levels of an accident.

2.2 *AcciMap Methodology*

Rasmussen has introduced a 6-layer, hierarchical framework (Figure 4), known as risk management framework, with each level representing a main group of involved decision-makers, players or stakeholders in a studied system [16]. These six levels, from top to bottom, are: government, regulators and associations,

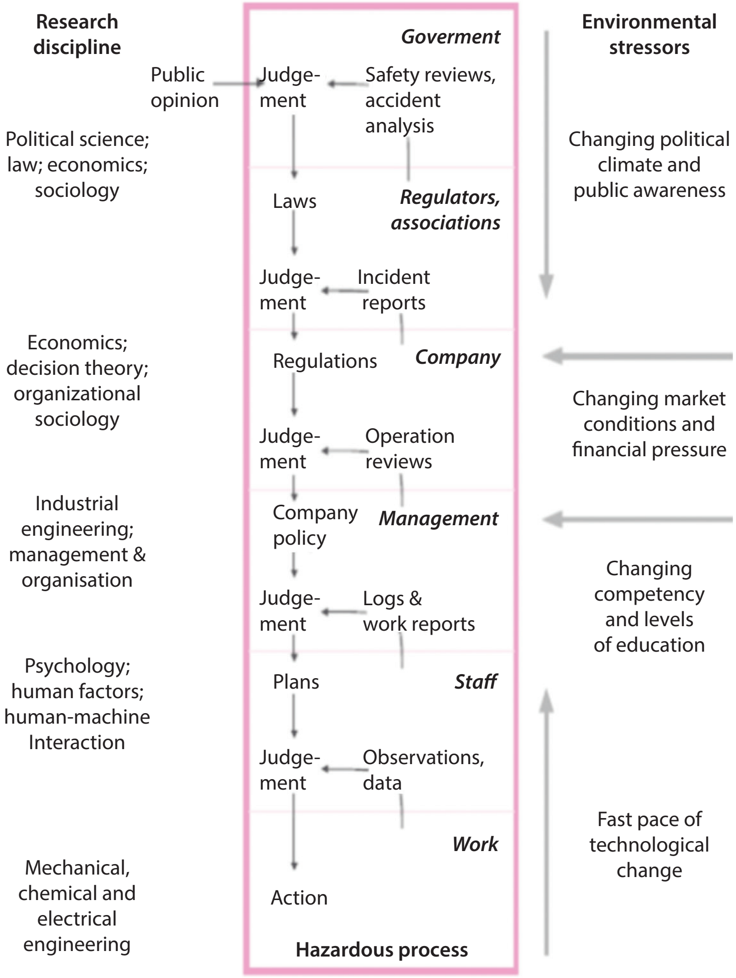

Figure 4 Rasmussen's risk management framework [18].

DOI: 10.7569/JSEE.2017.629515

company, management, staff, and work. Analysis using this framework not only considers the activities of players in each level but more importantly, the interactions between them, which take the form of decisions propagating downward and information propagating upward [17, 18, 19].

The AcciMap methodology was developed by Professor Jens Rasmussen [16] in conjunction with his 6-layer risk management framework, which was illustrated in Figure 4. This methodology captures the associated socio-technical factors of an accident within an integrated framework and analyzes the contribution of those factors in causing the accident. This graphical representation is useful in structuring the analyses of hazardous work systems and in identifying the interactions between different levels of decision-makers, which shape the landscape in which accidents may "unfold" themselves [18].

It is noteworthy that AcciMap is part of a broader proactive risk management process to develop risk assessment strategies from generalizing the analysis of previous accidents [17]. In general, analysis of past accidents within the stated framework can define patterns of hazards within an industrial sector. Such analysis can lead to the definition of preconditions for safe operations, which is a main focus of proactive risk management systems.

The AcciMap methodology has been used as an independent tool for accident analysis in different domains as well. These applications include chemical processing [20, 21], transportation [18, 22, 23, 24, 25], aviation [17, 26], public health [27, 28, 29], anti-terrorism [30], gas production [31], and oil and gas drilling [32, 33]. This methodology has been used for the analysis of other accidents in different countries as well [34].

In the context of the natural gas industry, to our knowledge, the AcciMap methodology has been only applied by Hopkins [31] to analyze the explosion at the Esso Gas Plant in Longford, Australia. The scope of that study was different than the Aliso Canyon Accident; that was a gas plant while our study is related to a gas storage facility. Therefore, our study can be safely considered as the first systemic investigation that also uses the powerful AcciMap framework to analyze a major recent natural gas leak, the Aliso Canyon accident.

In this paper, the AcciMap methodology has been used to investigate and explain how certain managerial decisions, organizational processes and other contributing factors lead to an accident the scale of the one seen at Aliso Canyon. Studying this case using the AcciMap methodology will contribute to improving the industry's understanding on how human factors contributed to this accident. By utilizing this information, facilities can apply newly suggested protocols to future circumstances with the goal of creating better operational systems with exceptional work environments using the most compatible technology in the field.

Creating an AcciMap can help regulators, law makers and natural gas companies understand the interaction and interdependency of various socio-technical systems; it illustrates that not one independent factor or failure leads to the accident in its entirety, rather it was likely a compilation of various mistakes added

DOI: 10.7569/JSEE.2017.629515

under the burden of financial and high demand pressures within a competitive market. From a managerial standpoint, there is often a tradeoff between meeting demands and making a profit, and improving safety culture with updated safety protocol and innovative technology. Sometimes the safety of workers is compromised because their wellbeing does not directly affect the company's bottom-line. Safety culture is determined by management, and employees can only react to what tools they are given. For the operators, there is a balance between cost and effort. This balance is delicate and can push production towards the boundary of functionally acceptable performance. The motivation of pushing for better, faster, cheaper products starts to push an organization past this boundary and once crossing it, it becomes irreversible. This is when accidents are more likely to occur.

The mixture of ergonomic factors along with social, environmental and political inputs can be applied to many industries to create enhanced methodologies with better procedural executions that apply to all levels of the system. This application of safety culture is not only for the better of the companies' bottom-line; worker satisfaction and community approval will increase and our environment will not have to pay for the externalities that it cannot protect itself against. This, in turn, is for the benefit of everyone. The culture of leadership, having a questioning attitude, personal accountability, good communication, and innovative technology are necessary to highlight and ensure that systems act to their full potential. By incorporating safety culture procedures as a preventative measure, accidents like the one seen at the Aliso Canyon can be avoided, saving the company time and money, the community peace of mind and the environment years of repairing a mistake that took relatively no time to happen.

3 The AcciMap Framework of the Aliso Canyon Gas Leak

In this section, the AcciMap framework has been utilized for the analysis of the Aliso Canyon gas leak, which occurred on October 23, 2015, in the SoCal Gas storage facility in Porter Ranch, CA. There have been some adjustments to the illustrated risk management framework in Figure 4 to make the AcciMap specific to the context of our analyzed problem.

Our developed AcciMap in this paper, which has been shown in Figure 5, consists of 6 main layers. In this AcciMap, the first five layers of the framework are: government and regulators; parent company (Sempra Energy); SoCal Gas Company; technical and operational management and crew; and physical events, processes and conditions. Finally, the sixth layer is the outcome, which is the Aliso Canyon gas leak. In Figure 5, each level has been depicted by a separate color code in order to highlight the impact of the different layer components on each factor/box in the AcciMap. In addition, the main source of reference for each captured contributing factor has been cited in its box.

The developed AcciMap framework illustrates the contributing factors to the Aliso Canyon accident from each of the stated layers. It also depicts the interactions

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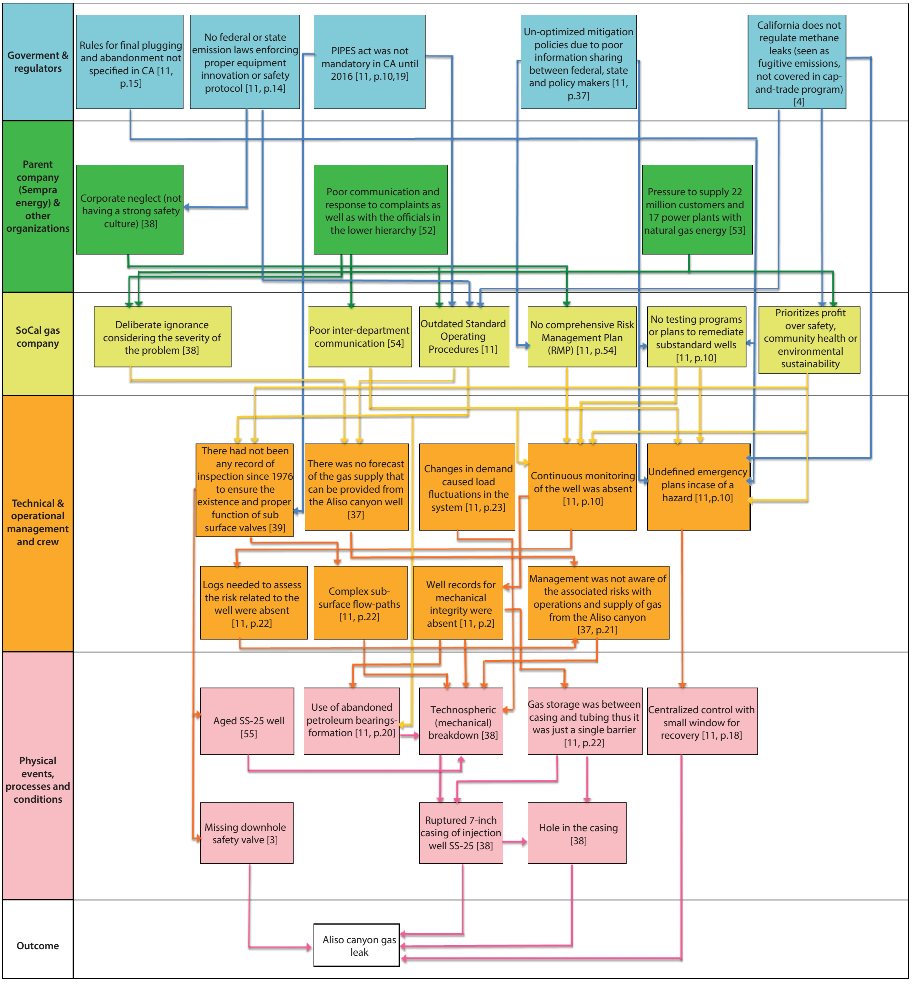

Figure 5 The developed AcciMap framework for the analysis of the Aliso Canyon accident.

of different factors and involved decision-makers and key players in all these layers, which contributed to the accident. The following sub-sections provide more detail regarding the involved contributing factors in each of the stated layers of the AcciMap framework.

3.1 Government and Regulators

The first influential level of the AcciMap is government and regulators. A multitude of key governmental factors that contributed to this accident were found.

DOI: 10.7569/JSEE.2017.629515

First, nationally, there were not stringent enough laws enforced by the Pipeline and Hazardous Materials Safety Administration (PHMSA) prior to the accident. Additionally, the state of California does not regulate methane emissions because they are seen as fugitive emissions that are not regulated under the clean air act.

California has worked hard as a state to have some of the most stringent climate change regulations in the country and Governor Brown had recently set targets in 2015 to reduce methane emissions in the state by 40% or higher by the year 2030. This target was ambitious considering that there were no federal laws regulating methane emissions at the time. Since this accident, Governor Brown has asked state officials to draft a plan for SoCal Gas to fund projects in California that counteract climate air pollutants in order to offset their mistake. The Investigatory Task Force developed a mitigation plan for SoCal Gas to address the greenhouse gas emissions from the leak. The company is exploring methane emissions mitigation options from multiple sources, such as dairies and landfills in California. We have discussed some of the details of the taken actions by the government, regulatory agencies and the utility companies in section 4.2 of the paper.

California's Senators Barbara Boxer and Dianne Feinstein anticipate passing an amendment to the energy legislative through the senate in hopes of preventing and having better responses to accidents like the one at Aliso Canyon. California's climate change regulations exempt methane leaks, no matter how large scale, because they are categorized under fugitive emissions and are not subject to California's cap-and-trade program. Methane is scarcely regulated in America because it is not covered in the Clean Air Act, unlike carbon monoxide. The Obama Administration has hoped to tighten natural gas facility regulations across the country. The then President proposed a new methane regulation in August of 2015 to reduce methane emissions anywhere from 40-50% over the next 10 years. In June 2016, Congress passed the Protecting our Infrastructure of Pipelines and Enhancing Safety (PIPES) Act of 2016, signed into law by President Obama. This act created the task force led by the Secretary of Energy that led the investigation on the Aliso Canyon accident. The interagency Task Force consists of representatives from the Department of Transportation, the Environmental Protection Agency, the Federal Energy Regulatory Commission, the Department of Health and Human Services, Department of Commerce, the Department of the Interior, and from state and local governments. The details of this Act have been discussed in section 4.2.

The United States operates the largest number of underground gas storage facilities, with over 350 operational in 2005 [35, p.7]. These reservoirs total to over 14,000 wells, which had no national streamline risk analysis methodology to prevent failures prior to the Aliso Canyon incident [35, p.12; 33, p.2]. PIPES was not mandatory in CA until 2016 [11, p.10, 19].

Natural gas storage operations on average lose 5% of deliverability from certain determinants over time [35, p.12]. These damages may result from sanding, which is when the pressure drop associated with withdrawal causes poorly cemented

DOI: 10.7569/JSEE.2017.629515

foundation to weaken, and is a common occurrence with well operations [35, p.12]. However, for larger scale failures, risk evaluations must be put in place to identify possible hazards, predict frequency of such hazards, and quantify the consequence of these hazards [35, p.3]. Risk analysis is vital for safe well operations and relies on analyzing prior data records, yet no national standards for well records were in place prior to the accident [35, p.3]. In this domain, the critical role of human errors and poor safety and operational controls should be considered in the process of risk analysis.

Well SS-25's transition from being an old oil reserve to a storage unit meant there were less stringent regulations in comparison to the ones enforced for newer facility. However, even up-to-date regulation standards at the time of the accident were more lenient than they are today. About 80 percent of the country's 400 active underground natural gas storage wells were constructed before 1980 [11, p.8]. The Department of Energy's investigation suggests that technology in the natural gas industry must be up to date for constant and consistent data gathering to monitor gas reservoirs. Considering methane is a fast acting greenhouse gas that is several times more powerful than carbon dioxide that directly influences global warming, regulation in the natural gas industry is imperative. The investigation recommends that risk management plans should be comprehensive and reviewed periodically to assure the most robust safety initiatives [36, p.3]. Having accessible records of data in a management system will allow for facilities to apply their data to higher-risk systems and to verify their actions with regulators and the public [11, p.59]. In a time when America is concerned with climate change, looking towards innovating our natural gas production could be the most economically and environmentally friendly solution.

Additionally, South Coast Air Quality Management District Hearing Board is pushing an independent comprehensive appeasement program to cut and counteract air pollution. It involves specifications such as funding an independent study on health effects on the community, funding continuous air monitoring of the area, developing and implementing leak detection and reporting programs at all the wells, monitoring the well with an infrared camera 30 days after the leak ended, providing data to regulators to help calculate the total amount of methane that was leaked, and requires submitting a plan that will notify residents and government of future emissions in a more timely manner and obtaining approval from regulators before using any odor suppressants if needed. SoCal Gas must also conduct a root cause analysis of the accident while working with state regulatory agencies to assure compliance and establish a comprehensive leak detection program for the remaining 114 wells to prevent future leaks. Complications occurred with regulatory bodies after the leak began as well. There was no clear overarching agency that was in control of the accident's intervention and aftermath. "Besides the Air Quality Management District, agencies responsible for responding to the leak included the State Energy Commission; the Los Angeles County Department of Public Health; the Air Resources Board; the Public Utilities Commission; the

DOI: 10.7569/JSEE.2017.629515

Division of Occupational Safety and Health; the Department of Conservation's Division of Oil, Gas and Geothermal Resources; the Environmental Protection Agency; the Office of Environmental Health Hazard Assessment; the County Fire Department; and the Governor's Office of Emergency Services. In January, the Los Angeles County Board of Supervisors called for the creation of yet another regulatory "structure," to oversee gas-storage facilities." [6]. Without an authoritative or governing body, there was no clear path SoCal Gas could have taken to address the issue as quickly as possible.

3.2 *Parent Company (Sempra Energy) and other organizations*

SoCal Gas's parent company Sempra Energy did not have sufficient organizational sociology within the company and therefore, this level experienced tradeoffs between safety and profit. The company has always tried to put forth an image of environmental sustainability and community outreach yet repetitive history and dangerous work procedures show otherwise. The culture of the company is blaming individuals and doing the bare minimum for safety measures. The utility company tries to do its best while still providing reliable energy to its customers. The pressure to supply 22 million customers and 17 power plants with natural gas energy pushed upper management to prioritize unsafe supply to meet increasing demands [37]. The company's neglect for safety culture was a starting point for what ultimately led to the Aliso Canyon accident [38].

3.3 *The SoCal Gas Company*

The SoCal Gas outweighed possible disasters on multiple levels and accentuated profit and supplying the demanded gas over quality assurance. This attempt to increase production is the first example we see of SoCal Gas picking profit over safety. By trying to increase output in a smaller amount of time, they jeopardized the integrity of the system that ultimately led the company to a greater financial burden and loss of market share and lowered reputation than they could have predicted. Their cost-benefit analysis did not account for the possibility of such extreme repercussions, emphasizing the managerial team's lack of concern for preventative and precautionary measures.

Moreover, SoCal Gas's management decisions allude to lack of leadership, which in turn affects the dependent following levels, such as the staff that looks up to them for guidance. Management sets the safety culture and enforces proper protocols to be followed by the employees. Their responsibility is to be held accountable for their actions even if their employees are the ones in direct contact with the technology. The employees will act within the components of the safety control structure. SoCal Gas management made the decision to ignore possible technological gaps in their system when previous, smaller-scale accidents could have been indicating a larger issue [11, p.62]. Within the organization, there were

DOI: 10.7569/JSEE.2017.629515

interdepartmental communication issues that did not allow for the proper flow of information.

Additionally, no comprehensive risk management plan was established prior to the accident, making mitigation difficult and prolonging the kill procedure timeline [11, p.54]. There were also no testing programs or plans in place to remediate substandard wells [11, p.2]. In 2008, the British Geological Survey [35, p.127] iterated how important having mitigation and remediating risk plans in place prior to accidents are to bring a system back under control as quickly and safely as possible. The United States did not have parallel legislations to allow SoCal Gas to have a timely mitigation plan at the time of the accident.

A "Noise and Temperature Survey" record from 1992 shows that SoCal Gas was aware of a possible leak in well SS-25 [38]. The Flow-Log survey record states "check for potential leakage past shoe as high as 8150 [feet]" under the 'reason for survey' section [38], exemplifying SoCal Gas' lack of urgency to improve their systems and disregard for safety prevention. Actions like these show how companies are quick to blame individual incidents for errors rather than taking the time to make a cultural change within the company. Although it may be a longer solution, taking the time to set a tone of equality, openness and creativity, in the end save the company money and lowers the possibility of risks because safety is not forgone. This accident could have been prevented if only there was a stronger emphasis on safety culture and a well-established preventative risk assessment system. The key traits of a positive safety culture include leadership, problem identification, personal accountability, continuous improvements, respectful work environment with limited intimidation and a questioning attitude that does allow for complacency. When these traits are compromised, lives, environmental sustainability, health and safety are being jeopardized for the sake of making a profit.

3.4 Technical and Operational Management and Crew

The staff may not have been aware of or in control of the fact that the technology they were using was not state of the art because of the existing lack of questioning attitude in the company culture. With no federal or state regulation baseline to compare standards to and little leadership from within the company, there was little motivation among operators to work within the boundary of functionally acceptable performance. Management never fully comprehended or relayed the associated risks with operation and supply of gas from the Aliso reservoir to their employees.

Considering the age of the well SS-25, precautions should have been taken to bridge the gap between venerable infrastructure and safety measures. At Aliso Canyon, many Downhole Safety Valves (DHSVs), which are designed to shutoff flow to the surface when off-normal conditions are observed, were then removed and not replaced during later well workover operations [11, p.19]. In some cases, the DHSVs were replaced with subsurface sliding sleeve valves, which provide

DOI: 10.7569/JSEE.2017.629515

connections between the tubing and casing and are used during normal well operations to facilitate maintenance operations, permitting fluid circulation between the tubing and the tubing-casing annulus [11, p.19]. The Task Force's investigation shows that 60 of the 115 did not have any indication of DHSV being installed [11, p.19]. Well SS-25 subsurface valve last recorded inspection was in 1976 [39]. The British Geological Survey [35, p.128] suggested regular sonar logging runs in underground gas storage wells to assist in monitoring and detecting leaks, but Aliso Canyon only installed infrared thermal imaging cameras after the accident was contained [40].

During the accident, no continuous monitoring of the wells was put in place on the complex sub-surface flow paths used in this system [11, p.22]. Further, changes in the load put on the wells fluctuated constantly due to changes in demand, and upper legal limits were often ignored to assure natural gas was meeting demand [11, p.59]. The company also had lenient requirements for record keeping. Logs needed to assess possible risks associated to the wells and records for mechanical integrity were both absent [11, p.21, 22].

3.5 Physical Events, Processes and Conditions

This level in the AcciMap works as a final layer of defense against accidents. The flow of events depends on all the preceding interdisciplinary sectors. The work of pumping the gas can be maintained when there is not a burden to pump the gas at a rate faster than the infrastructure allows, however greed and time pressures work against this safety precaution. The energy industry is highly interdependent with tightly linked operations, which magnify each failure through every segment of the company. The concatenation of having an aged well using an abandoned petroleum bearing formation allowed for the mechanical breakdown of the system to go unnoticed until it was too late to stop [11, p.20]. In addition, the gas storage was between casing and tubing, thus it was just a single barrier [11, p.22]. "The well was built with two outer steel casings that surround and protect an inner steel pipe, or tubing, just under three inches in diameter, designed to carry gas in and out of the storage reservoir. However, SoCal Gas was pushing gas through the 7-inch casing surrounding that pipe, enabling it to move large volumes", as CBS News [41] states. This intentional move of gas through both the outer well casing, and the inner production tubing was a contributing cause of the loss of containment [42].

The suspected break and the leak from the casing of the well was illustrated in Figure 1. The missing downhole safety valve could have shutoff flow to the surface in the off-normal condition of the crack in the 7-inch tubing. In addition, the small window for recovery did nothing to help stop this accident from playing out [35]. These accumulated factors have a compounding effect that in the end cost the utility companies more than any safe precautionary investments would have been in the first place, and have additional external cost of community detriment and environmental degradation.

DOI: 10.7569/JSEE.2017.629515

4 Conclusion

4.1 Model Analysis

There are different sets of learning points from the analysis of the developed AcciMap model described in the previous section for the investigation of the Aliso Canyon gas leak. A very important characteristic of the AcciMap approach is placing the events and conditions that finally released the accident into the necessary context to enable the understanding that how and why the accident occurred. This characteristic avoids the unfair blame of the frontline operators, since it provides a big-picture perspective and background on where those events and conditions come from and what the sources of operators' decisions are.

This concept in the context of analyzing the Aliso Canyon accident is equivalent to not only considering the immediate physical events and conditions or the decisions and actions made by the crew and technical management on the day of the accident as the contributing causes of that tragedy, but also to investigating the role and the contribution of factors in higher levels of the company or the external elements. In another word, AcciMap enables analysts to identify high-level contributing factors relating to organizational, governmental and regulatory practices as well as direct contributing causes of the outcome, by investigating all these stated factors within the scope of the illustrated levels in Figure 5. For instance, referring to Figure 5, one of the direct contributing factors to the Aliso Canyon gas leak was a hole in the casing (Refer to the Physical Events, Processes and Conditions level). Using the AcciMap, we can trace all the other causes which led up to the creation of a hole in the casing.

Following the AcciMap, the existence of no Federal or State emission laws enforcing proper equipment innovation or safety protocol (refer to the first level) contributed in some ways to Sempra Energy's (as the SoCal Gas's parent company) corporate neglect and its lack of a strong safety culture (refer to the second level). This factor resulted in having no established risk management plans prior to the accident (refer to the third level), which made mitigation difficult and prolonged the kill procedure timeline. The existence of no specific risk management plan contributed to not continuously monitoring the well operations (refer to the fourth level), which resulted in the absence of well records for mechanical integrity (another factor in the fourth level). This factor in conjunction with complex sub-surface flow paths as well as load fluctuations in the system, which were often beyond legal upper limits, caused by changes in demand (two other factors in the fourth level), led to technospheric (mechanical) breakdown in the system (refer to the fifth level), including a ruptured 7-inch casing of injection well SS-25 (another factor in the fifth level), which itself contributed to the above-mentioned hole in the casing. Through examination of the relationships between each factor as seen in this example, the AcciMap becomes a powerful tool for accident analysis and tracking the contributing factors of the accident in different analyzed levels.

DOI: 10.7569/JSEE.2017.629515

Another important advantage of the AcciMap is highlighting the interactions, communication and interoperability within and between the captured levels of the framework, which each of them represents a group of decision-makers or players in the context of a studied problem. This way, it is possible to analyze and identify ineffective communication and interoperations in each level and between levels, which according to many references, they themselves are root causes of several accidents.

The interesting, yet disturbing part of this case study is that the technological aspect was not as big of an issue as one may have thought; in fact, an accident of this scale was highly likely at a site like this considering the limits the company was pushing this well to with high gas demands and outdated technology. This alludes to the fact that human factors and insufficient safety culture are the leading contributing factors to accidents like these, a trend cross-cutting through many other industries as well. This accident could have been avoided and we hope to illuminate a system that creates a better procedure for preventing and preparing for such disasters. This paper complements the findings and recommendations of the Interagency Task Force Report [11] on Natural Gas Storage Safety on how accidents in this industry can be prevented. The government report states that "while incidents at U.S. underground natural gas storage facilities are rare, the potential consequences of those incidents can be significant and require additional actions to ensure safe and reliable operation over the long term" [11, p.3].

4.2 Some Taken Actions and Connection to Model Analysis

On February 5, 2016, PHMSA suggested facilities upgrade their operating, maintenance and emergency response procedures. The issued Advisory Board ADB-2016-02 advised operators to follow 12 steps to ensure integrity of underground natural gas facilities. They recommended to verify the pressure required to inject natural gas volumes does not exceed the design pressure limits; monitor all wells for the presence of annular gas or liquids; inspect the wellhead assembly and attached pipelines; conduct functional tests of all surface and subsurface safety valve systems and wellhead pipeline isolation valves to assure proper function and ability to shut-off or isolate wells; perform risk assessments that reviews the American Petroleum Institute's criteria on new, removed or replaced tubing strings or production casing; verify and demonstrate mechanical integrity; implement a corrosion monitoring and integrity evaluation program for piping, wellhead, casing and tubing with appropriate well log evaluations; evaluate facilities that include analysis of facility flow erosion, hydrate potential, individual facility component capacity and fluid disposal capability at intended gas flow rates and pressures; identify potential threats and hazards associated with operations of the facility; verify the integrity of the reservoir with monitoring techniques for integrity changes such as monitoring of pressure and periodic pressure surveys, inventory (injection and withdrawal of all products), product levels, cavern subsidence

DOI: 10.7569/JSEE.2017.629515

and the findings from adjacent production and water wells; ensure emergency procedures are reviewed, conducted and updated annually; and ensure records of the procedures, processes, assessments and mitigation measures are maintained for the life of the well [43]. Several of these issues are among the captured factors in our developed AcciMap framework in Figure 5.

On February 24, 2016, California Senator Fran Pavley introduced a set of amendments to Senate Bill SB380 in response to the natural gas accident. The existing bill assured that DOGGR will regulate drilling, operations, maintenance and the abandonment of oil and gas wells in California as well as authorize the Public Utilities Commission to supervise and regulate all state public utility companies. The proposed bill has five additional specifications the community and other involved stakeholders hope to be enacted. First, the bill would enact an immediate moratorium of any further natural gas injection into the Aliso Canyon reservoir. Secondly, it would impose restrictions on production of natural gas in wells that were drilled before 1954, unless to ensure regional energy reliability. Third, it would require that each individual well must have quantitative and objective evaluations performed using the most innovative technology, as well as all possible risks by well failure examined prior to the moratorium being lifted. These specifications involve well age, history and conditions be inspected, particularly when a well is 10 years or older; a supervisor must evaluate all technical methods involved with input from independent experts as well as the public through a public process; any wells posing an increased chance of failure must be repaired or properly abandoned; a supervisor must determine the overall risk of well failure in order to lower any possible health, property, life or natural resources damages; and the Public Utilities Commission and the State Energy Resources Conservation and Development Commission will be in correspondence with all risk assessments. The fourth addition requires state regulators and the public Utilities Commission to assess the feasibility of minimizing or eliminating the use of the Aliso Canyon storage reservoir entirely while still sustaining regional energy demands. And lastly, the amendment includes an urgency section for any enduring harm within the community.

On May 23, 2016, SoCal Gas provided their final report to DOGGR in regards to the well inspections [9]. This issue was one of the main captured factors in our developed AcciMap framework in Figure 5. At the time, 90% of the wells completed phase one inspections, which include temperature and noise tests [9]. Additionally, 72 wells have moved on to phase two of the inspection protocol [9]. Only wells that pass the six phases of inspection required by DOGGR will be considered for storage in the Aliso Canyon operations [9]. The remaining wells will be taken out of service and only after all the active wells meet the requirements can the field be put back in service [10]. The SoCal Gas Company is monitoring each well at the facility using infrared technology for leak detection. Additionally, SoCal Gas publically supports SB 380, a moratorium which requires implementing regulations and criteria for a comprehensive safety review that the company

DOI: 10.7569/JSEE.2017.629515

must abide by. DOGGR and the California Public Utilities Commission Safety and Enforcement Division (SED) remain onsite at the facility to oversee the investigation into the cause of the gas leak. Well SS-25, because it is an older well with little technological updates, was more likely to have "single point of failure" designs. These designs, as stated by the Department of Energy, offer less protection against leaks and should be replaced with modern designs to better combat failures [11, p.54]. If there were a second barrier between the metal casing and the production tubing, the leak could have likely been avoided [11, p.54]. The first barrier prevents unintentional flow to the surrounding environment, and the second line of defense is intended to prevent unintentional flow if the primary barrier fails [11, p.83]. The two layers must be able to be independently tested for failure of the lines of defense to work effectively and be verified it is working as intended [11, p.83]. It is noteworthy that most of these addressed technical issues were the captured factors in the Physical Events, Processes and Conditions level of the AcciMap framework in Figure 5. It is however needed to state that although the physical final barrier of defense might have been the single point of failure design in the well, there were several layers beyond the physical well that contributed to the system failure as well.

Another stated factor (in the Government and Regulators level) in our developed AcciMap framework was the fact that the PIPES act was not mandatory in California till 2016. On June 22, 2016, the Protecting our Infrastructure of Pipelines and Enhancing Safety Act of 2016 became a law [43]. The law implements standards for operation, environmental protection and integrity management; considers economic impacts of the regulations on customers; ensures there is no significant economic impact on the end users; and considers the recommendations from the Task Force Report [11] that followed the Aliso Canyon leak [43]. The PHMSA mandates that these regulations are enforced within two years from the enactment date [43].

California has responded to this accident with regulatory changes and state laws. As of August 2016, California was only one of three states that had regulations addressing well construction, well maintenance and plugging and abandonment [11, p.14]. This highlights the need for nationwide criteria to be implemented to assure proper well protocol on well integrity, mandatory state regulations in these areas, as well as additional sectors such as emergency response protocol and operator certification training.

As of October 7, 2016, 27 wells at Aliso Canyon have passed DOGGR's comprehensive safety review [44]. Another 9 wells are currently in the second phase of testing, and 76 have been sealed off from storage [44]. Wells that are sealed are filled with fluid, are mechanically sealed off and are isolated from the pressure in the field to assure they do not succumb to leaking before being tested [44]. After renovations to many of the wells, SoCal Gas requested regulatory approval on November 1, 2016 after completing the Fitness-for-Service Analysis evaluation DOGGR and the CPUC requested [40]. Over 40 miles of new steel piping has been replaced on wells that have completed approval for injection. Alongside the new

DOI: 10.7569/JSEE.2017.629515

metal piping, the surrounding casing was tested and ensured to hold up against large forces of pressure, to provide the intended secondary barrier of protection [44]. In total, a well must pass tests regarding temperature, noise, ultrasonic imaging, cement bond verification, magnetic flux leakage, multi-arm, caliper, hydro pressure test of well casing and hydro pressure test of the inner tubing [44]. After the wells are verified and begin storing natural gas again, they must also have improved monitoring. This includes an infrared fence-line methane detection system with 16 infrared methane monitors, pressure monitoring that occurs 24-7, operators patrolling and examining wells 4 times a day, thermal imaging that scans and detects leaks and enhanced training for employees. These measures are important for operators and their daily procedure, but must be enforced at the managerial level and endorsed throughout the company culture. Systematic protocol such as these monitoring examples are a step towards safer management practices that can prevent or allow for quicker responses to accidental leaks. SoCal Gas and other companies moving forward should enforce mandatory evaluation training programs to baseline the status of the wells they are looking after [11, p.55].

Mechanical Integrity Testing (MIT) is used to assure that wells conform to their design specifications [11, p.82]. The set of tests verify there are no leaks in the casing, tubing or packer system, or vertically around the outside of the cement casing. Tests that have been used include annulus pressure tests and radioactive tracer surveys, to demonstrate mechanical integrity [11, p.82]. After this accident, California is proposing a maximum pressure level of 2,926 psi, which is lower than the 3,595 psi SoCal Gas proposed as a safe upper limit [45].

On December 16, 2016 the PHMSA revised the Federal pipeline safety regulations for all facilities in the United States [43]. The Interim Final Rule (IFR) addresses safety issues related to downhole facilities and was enacted in response to the PIPES Act of 2016. It will be effective January 18, 2017 [43].

On January 23, 2017, before all well testing was complete and the Aliso Canyon site was still recognized as offline, SoCal Gas issued a statement that natural gas would be withdrawn from the reservoir in response to high energy demands resulting from cold weather. This shows that the need for natural gas to assure electricity reliability is still necessary and in the face of demand we cannot shy away from using it as an energy source. However, companies must be implementing the new regulations quickly to assure the transition is smooth and as fast as possible.

On February 15, 2017, the SoCal Gas VP of Gas Emissions and Storage wrote to the director of the energy division of CPUC Gas regarding the storage safety enhancement plan [46]. The letter outlines the company's plan to reconfigure wells at their La Goleta, Honor Rancho and Playa Del Rey site to only use flow gas through the inner casings and how they have already installed real-time pressure monitoring on all wells [46]. All changes should be accompanied with corresponding employee training to assure the new technology is being utilized to its greatest accident-preventing potential. Testing regarding feasibility for well conversion is

DOI: 10.7569/JSEE.2017.629515

being conducted and starting March 1, wells will start to undergo the conversion process. Converting a well to tubing flow only involves using a close sliding sleeve between the inner and outer casing [46]. If the outer casing cannot be isolated, a mechanical plug must be implemented along with the injection of fluids to reinforce isolation until a workover rig can do integrity testing on a new tube that will then be installed [46]. Only wells that have completed this conversion protocol by April 1 will be used for withdrawal [46]. This process will reduce injection and withdrawal capacity anywhere from 0-79% depending on location and inventory levels [46]. SoCal Gas will want to undergo this changeover as quickly as possible considering the peak summer load period begins around August 1 every year [46]. It is noteworthy that SoCal Gas needs to utilize all lessons learned from the Aliso Canyon gas leak in its future operations in order to make sure that such an accident will not occur in any of its other gas storage facilities, which some of them were stated above.

In March 2017, the CPUC released an update on the status of the "Aliso Canyon SS25 Well Leak Investigation Overview" being conducted by Blade Energy Partners [47]. Blade Energy Partners is an independent third party conducting a root cause investigation that is supplementary to the two state investigations being conducted by the CPUC and DOGGR [47]. These three investigations are interdisciplinary and all necessary before Aliso Canyon's investigation can be considered complete. Blade Energy's investigation consists of 5 phases. This investigation was in phase 2 as of March 2017 [47]. The preliminary phase 0 began in January 2016, which consisted of data collection and analyses. Following, phase 1 consisted of site evidence collection and documentation, which began after the well kill procedure was certified. As of March, phase 2 has been active and underway [47]. Its aim is to assure SS-25 site restoration to rig readiness. This phase involves finalizing the phase 3 protocol, which has been completed and has gone through 4 revisions as of July 31, 2017, and includes plans for the beginning of phase 3 [48]. Additionally, in phase 2, SoCal Gas must file a Notice of Intent (NOI) with DOGGR for phase 3 to begin [47]. And lastly, SS-25 must complete rig construction on-site. These steps are necessary for the preparation of phase 3, which involves tubing and casing extraction at well SS-25. Phase 3 is a multistep process that includes fluid loss remediation, well logging and tubing extraction, tubing recovery and logging, pressure tests and repair, and lower casing recovery and tieback [47]. Phase 3 is expected to take anywhere between 178 and 276 days. Once these are successfully accomplished, phase 4 can begin. Phase 4 is the nondestructive and laboratory metallurgical examination. In this phase, Blade Energy has selected two labs to perform testing [47]. Among the several examinations, there will be a visual, metallographic examination, a corrosion examination, a connection testing assessment and a fractographic examination (SEM) [47]. Phase 5 is the final report, which includes an integration and interpretation analysis. This investigation strives to achieve transparency and has set up a viewing facility and video surveillance for interested parties [47].

DOI: 10.7569/JSEE.2017.629515

Throughout these investigations, the Aliso Canyon facility has undergone major renovations and safety overhauls to assure compliance with new regulations enacted after this disaster [49]. However, there still needs to be intensive safety checks before Aliso Canyon will know where they stand moving forward regarding meeting natural gas demands. As of July 29, 2017, the facility had closed over half of its wells and a judge has allowed SoCal Gas to reopen Aliso Canyon at a 28% capacity [49]. The CPUC stated they were prepared to shut down the facility within 10 years.

On July 31, 2017, despite opposition from local residents, Aliso Canyon resumed well injection after a temporary ban was lifted [50]. This was allowed so the facility would be able to maintain reliable natural gas supplies in the region [50].

4.3 Recommendations

Moving forward from this accident, the question is how can we prevent this from happening again? LA City Councilman Mitch Englander spoke out against SoCal Gas' negligence saying "the community is now left with two unacceptable options: a safety risk to local residents or power losses in a region known for extreme summer temperatures" [51]. The solution moving forward has to balance keeping residents safe while supplying energy demands. State officials have predicted that the partial shutdown of Aliso Canyon could result in short-term power outages for up to two weeks in the summer of 2016 [41]. Residents are now burdened with either having to worry about breathing in unsafe air, or having to deal with unexpected energy blackouts. Mayor Garcetti has asked the community to conserve energy wherever they can and officials are planning accordingly for the expected shortages, but making up for the lost power is not an easy solution. One main recommendation of this study is to apply human factors characteristics within the utility companies to move towards a culture that focuses on quality without compromising quantity.

The culture of the utility companies comes from the top and flows down, setting the tone for how workers will conduct their profession. Having a strong leader with safety values and actions is the best way to set an example for operators to conduct their work with integrity. The Sempra Energy Foundation was created with the goals of supporting public charities that benefit the community in areas of education, disaster response and safety, the environment and employee involvement. By fixing the culture on which the company is based on, the solution would be cross-cutting into worker safety, community health and environmental sustainability. By addressing only one of these at a time in a responsive way, a company is being less efficient and less economic.

SoCal Gas, a subsidiary of Sempra, follows with a similar tone. They have a sustainability initiative and on their website, they emphasize how "protecting the environment is part of our culture" [52]. The page goes on explaining how they focus on things like how they are reducing, reusing and recycling in their system

DOI: 10.7569/JSEE.2017.629515

operations, yet they do not discuss their emissions as the direct environmental degradation that is the most detrimental. There are different forms of green washing and this example above is a type known as green washing with hidden tradeoffs. By highlighting certain environmental attributes, you are distracting from the other parts of a product whose environmental impact is more important or damaging. SoCal Gas emphasizes their commitment to be LEED certified and other environmental efforts to be more sustainable, but none addresses the root issue of how past and possible leaks will be mitigated to offset the emissions that have been released. SoCal Gas is working to address mitigation plans that will make up for the amount of global warming equivalent to 1,735,404 cars for an entire year [6].

One aspect that can assist in the changing of the culture around cleaner, safer energy production is regulation. The PHMSA is the authority on regulating natural gas storage units, yet they often leave regulation standards for facilities to the states. This inequality and lack of urgency to get on the same page to be proactive in protecting our communities and our energy needs is discouraging. In the United States, 2-4% of natural gas is lost as an emission in production, transmission, transportation or distribution. This inefficient process should motivate us to want to do more and become more proactive in our energy sources and the safety that comes with it. We should be taking the lead on clean energy practices to become the energy leader in a world that is coming to the quick realization that we need to change our current ways.

The Company's cost-benefit analysis did not account for the possibility of such extreme repercussions, emphasizing the managerial team's lack of concern for preventative and precautionary measures. Beyond the company's financial burdens, this leak is costing millions in the customers' pockets and wellbeing, as well as environmental damages that will continue to live on and magnify even though the well has been securely stopped. This is an example of poor planning and questionable decision-making on a managerial level. The company's lack of leadership, absence of a questioning attitude and weak effective safety communication accumulate to highlight the weak preventative and responsive measures they, or any company in the natural gas industry, have prepared. Accidents like these cannot be blamed on one single person or one single failure, instead they are a concatenation of failures; however, the operators and workers are usually the ones who take the fault while the customers pay the consequences of health risks and added costs, and the executives who set the tone of the company walk away without repercussions. There was a direct conflict between money and demand pressures versus foresight, respect and care for safety, with disregard for personal accountability. Pumping gas through a well and its lining to support gas demands is known to be unsafe, yet companies take actions like this due to lack of maturity in their safety culture. Based on this analysis, improving the culture of safety and moving towards a positive safety culture through nurturing its traits is vital.

DOI: 10.7569/JSEE.2017.629515

The natural gas industry, federal and state regulation and local agencies must work together in a preventative safety culture to lower the chance of future leaks [11]. Gas storage facilities across the US ought to conduct risk assessments, develop and implement transition plans that address high-risk infrastructures and apply procedures to maintain safety and reliability throughout all facilities until the transition towards modern well design standards are recognized [11, p.60]. The Task Force Report [11, p.1] focuses on three areas of study: well integrity, public health and environmental effects, and energy reliability concerns in the case of future leaks. Regarding well integrity, the key recommendations include emphasizing new well designs that prevent single point of failure accidents that cause leaks and uncontrolled flow, and wells that do not assure this satisfaction and do not follow this design should be phased out of service. Well integrity should also assure that operators follow risk management protocols that include monitoring programs, well integrity evaluation, leakage surveys, mechanical integrity tests and conservative assessment intervals. This recommendation does not fall on the operators alone, but should be integrated throughout the upper management as part of the company safety culture that flows from regulatory bodies and government legislation to assure the system as a whole is strong against failure. Finally, well integrity can be addressed by the Department of Energy and Department of Transportation conducting joint studies of subsurface safety valves at facilities across the US. By having these agencies working together and creating a united front of safety protocols, the industry can be made safer.

Reducing public health and environmental effects from natural gas storage leaks is an integral part on how recommendations should be enacted to assure the best outcome for the public. The Task Force Report [11, p.2] recommends some key steps to prevent and mitigate the impact of future leaks. First, if leaks, such as the one at the Aliso Canyon, require a response from multiple jurisdictions, a unified command should be defined early. Leaders from each agency should coalesce to provide a clear communication channel between agencies, and with the company and the public. This will help move all stakeholders towards a communal goal of controlling the leak and addressing possible health risks. Second, state and local agencies should establish emergency air monitoring protocols. In the case of an accident, air sampling will be able to begin immediately which will help in understanding the leak and its effects. By having advance mandatory preparation in order, emergency response can help mitigate potential impacts. Lastly, states should review their requirements regarding greenhouse gas mitigation plans and individualize a plan that best fits their legislation.

The final key area of focus is energy reliability. The United States' 400 facilities has the capacity to store four trillion cubic feet of natural gas, which would run one-third of the nation's electricity [43]. When large accidents such as the one at the Aliso Canyon happen, millions of people are indirectly affected by the natural gas emission. The probability of electricity shortages in Southern California was increased long after the leak began and ended. The natural gas storage industry is

DOI: 10.7569/JSEE.2017.629515

responsible for providing energy to households and businesses year-round, and this is increasingly important during times of high demand such as the winter. The Task Force Report [11, p.75] recommends strengthening planned and coordinated efforts to lower possible future impacts of prolonged disruptions in infrastructure. It also suggests including optional back-up strategies to reduce reliability risk in the case of supply failures [11, p.76]. As for power plant systems, planners and operators must better understand how natural gas disruptions affect the electric system and how they must adapt in the case of an absence of methane available [11, p.75].

These key factors interrelate and affect the way that the Task Force Report [11] suggests certain recommendations as well as how companies should react to such regulations. The findings of the Task Force Report [11] build on the recommendations suggested in the 2015 Quadrennial Energy Review [53]. The overarching goal behind the findings of all agencies emphasizes the urgency to replace, expand and modernize natural gas transmission, storage and distribution infrastructure [11]. The report does not suggest lowering the use of natural gas as an energy source, as these facilities are a large component of providing the US with electricity. Additionally, companies need to be held accountable for ensuring the safety of workers. Prevention and safety culture are crucial to the company and the public, but operators at the front line of defense during an accident must be aware of proper conduct that assures no harm is caused.

These recommendations give a comprehensive protocol on how technology should be updated, environmental and health effects should be minimized, and energy reliability should be ensured. However, by using the AcciMap methodology the recommendations go beyond the operator working at the time of the accident, or the steps that can be taken after an accident. The AcciMap allows us to see how every level in the methodology impacts and concatenates on creating the environment in which an accident can happen or be prevented. The root cause is not a single point of failure on the operator's end. It is the executives creating the safety culture in which risk management protocol is created. Management needs to provide the training, improve the monitoring and data collecting technology and give the tools to the operators to succeed in this safety-critical industry.

To go beyond the recommendations of the Task Force, steps need to be put in place to ensure there are continuous improvements and updates that coincide with technological advances. New protocols and operator training should be updated when new federal standards are issued to assure compliance with legislation and improvement in safety culture. As updates are being implemented, proper transition plans and guidelines must be outlined to assure no discrepancy between types of systems and no inconsistencies within the company. Another characteristic is that these recommendations are being adapted in a way that are properly addressing the issues that have led to accidents in the past. By using Rasmussen's AcciMap methodology, the analysis of an accident such as the Aliso Canyon can better enable the natural gas industry to know how to be compliant in

DOI: 10.7569/JSEE.2017.629515

the future. These systems established with the help of utilizing frameworks such as the AcciMap should be robust enough to address new scenarios that could succumb to possible vulnerabilities we have never seen before. Systems should be put in place that have the flexibility to address engineering factors, physical disruptions such as weather, technological complications and human errors to assure it can stand up to unforeseen possible failures. There are some procedures that are only capable of handling planned changes, called Management of Change (MOC) procedures. Companies that do not have proper safety protocols often adopt MOC procedures. This is while these procedures are not capable of handling unplanned and unexpected changes such as changes in human behavior over time or changes in the environment, which increases the risk of accidents. In this regard, a commitment to resilience can be aided by a culture that focuses on detecting unexpected errors and problems, developing methods to contain those errors and problems, and devising processes for reacting to those problems – without reverting to the all-too-common practice of "fixing the blame but not the problem" [54].

Finally, there should be a systematic framework on how companies can mitigate the environmental effects they have caused that align with a national regulations baseline. This will assure that there is a price to pay beyond lowering energy reliability and endangering the community. The framework will assure the environmental mitigation plan is comparable to the damage from the accident, as well as assure the financial burden is placed within the company and not on its customers.

Acknowledgments

The authors would like to express their gratitude to Dr. Curtis Oldenburg, senior scientist at the Lawrence Berkeley National Laboratory, for his advice and comments on this manuscript. This work however, should not necessarily be construed as his representative position or be endorsed by him.

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