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INTRODUCTION

A pipeline is a closed channel (mostly circular cross-section) used to transport fluids like water, petroleum products, etc. Globally, there are trillions of kilometres of pipelines, and this number is exponentially increasing. Pipelines are considered the cheapest and fastest medium to transport fluids over long distances. Another advantage of pipelines is their flexibility; a pipeline could pass underground or on the seabed. Uncomfortably, leakage or blockage in a pipeline might result in massive losses (man and material), such as in the interstate pipeline incident in Sabah-Sarawak, Malaysia, in 2014. Thereby, there are increasing concerns regarding pipeline monitoring and maintenance systems to ensure safety. This chapter briefly discussed the use and importance of pipelines in fluid transportation. Pipeline faults and the reasons behind the faults are also addressed. An overview of pipeline monitoring is also presented. Though the discussion in this book is specific to gas pipelines, water and oil pipelines also faced similar challenges.

PIPELINES IN OIL AND GAS PROCESSING

Pipelines are one of the essential components of oil and gas processing and transport. A simplified transport process of oil and gas from wells to the consumers is presented in Figure 1.1 [1], it is extracted from the Pipeline Safety report by U.S. Government Accountability Office (GAO), published in 2017. From the wells to the consumers, various

types of pipelines are used. Pipelines can be classified according to the material of manufacturing, type of fluid to be transported, the diameter of a pipeline, maximum allowable pressure, length of a pipeline and finally, the function of a pipeline. Here, let us discuss the type of pipelines used in the oil and gas industry based on their functionality.

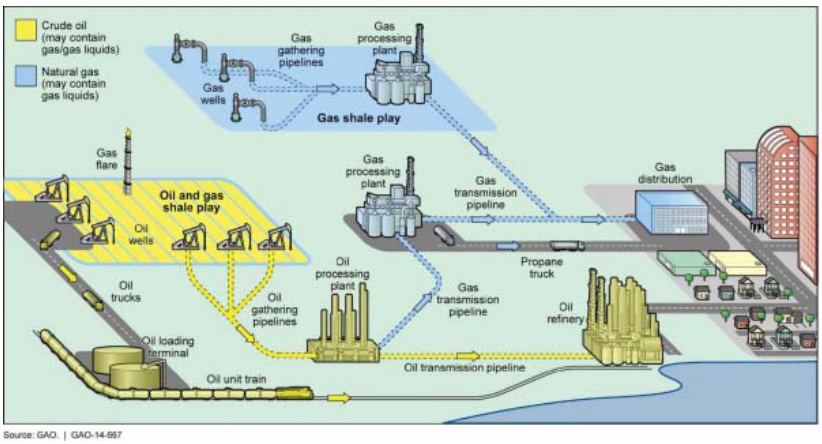

Figure 1.1 Transportation of oil and gas from production wells to consumers by GAO [1]

Gathering Pipelines

Oil and gas are transported from the production site (wellheads) to the collection unit by gathering pipelines. Usually, in several wells that produce oil or gas, the gathering lines are used to deliver commodities from the well top and send them to a main collection point/ pipeline called trunk.

Distribution Pipelines

Distribution pipelines can be classified as mains and service lines. Mains are the lines between high-pressure transmission pipelines and low-pressure service pipelines. As the name defines, service pipelines in the distribution system deliver the commodity to individual customers.

Feeder Pipelines

Feeder pipelines in the oil and gas processing units are the lines that feed processed products to the transmission pipelines.

Transmission Pipelines

Transmission pipelines transport oil or gas or refined petroleum for long distances (hundreds of kilometres and to cover long distances, these lines operate at high pressures.

GAS TRANSMISSION PROCESS AND PIPELINES

The compressor stations aid distribution and transport pipelines in the gas processing unit. Figure 1.2 presents a typical pipeline network from a gas processing plant to the consumers. After the gas is processed in a plant, a feeder pipeline is used to send gas to the compressor station. The compressor increased the energy of the gas. Pressurised gas from the compressor is sent to the industries or transmitted to other areas or cities through transmission pipelines. Another compressor station might be installed for long distances to obtain the required gas pressure. After that, the gas is delivered to various customers like small industries and our homes. All the black lines in Figure 1.2 indicate the pipeline connection between the two units, and the line width shows the comparative pipeline diameter.

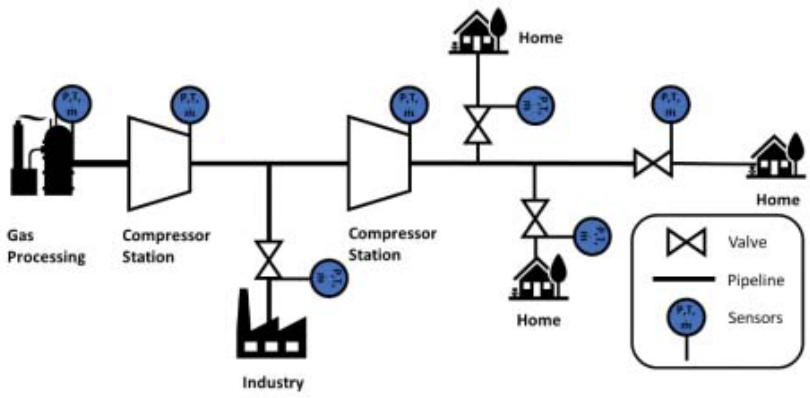

Figure 1.2 Typical representation of gas transportation from processing to customers

ENERGY DEMAND AND PIPELINES

Energy demand or consumption are the terms used interchangeably to reflect on the utilisation of energy by humans. We need the energy to

run our cars, trains, aeroplanes, ships, industrial machines, bulbs, fans, smartphones, and even wristwatches. There are various sources (for instance, gasoline, diesel, coal, natural gas, wind, water, nuclear and solar etc.) to generate and meet the global energy needs. As a matter of fact, global energy consumption is continuously increasing with time, and it is still strongly reliant on petroleum products as its primary energy source. According to the report by B.P. (British Petroleum) [2], overall global energy consumption increased by ~3% in 2018. In the same year, natural gas consumption increased by more than 5%.

Nowadays, natural gas is widely used in domestic to industrial applications. The core advantage of using natural gas is its lightweight and high calorific value (energy generation capacity). As per the U.S. Energy Administration Department report [3], it is predicted that the demand for natural gas will significantly grow by 2050 compared to other sources (Figure 1.3). Likewise, referring to the CEIC website (regarding past consumption of natural gas) [4], it can be deduced that the demand for natural gas is continuously increasing in almost every country.

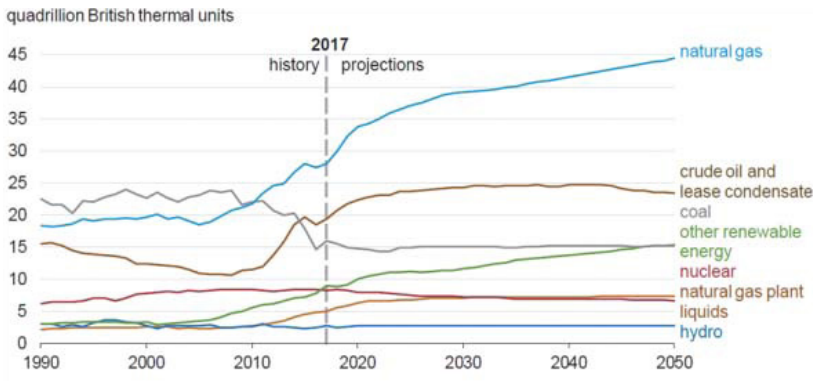

Figure 1.3 Projected energy production using various sources [3]

Pipelines are considered the fastest and most economical means of transport for natural gas, gasoline, diesel and water, particularly long distances [5]. There are millions of kilometres of pipelines worldwide, and the number is continuously increasing. Specific to the natural gas pipeline, Sovacool [6] mentioned that 60% of the pipelines in the world transport only natural gas.

CAUSES OF PIPELINE ACCIDENTS

Leakage and blockage are the two main defects in pipelines that lead to pipeline incidents if not addressed on time [7]. There are plenty of reasons pipelines may block or leak, such as corrosion, land sliding, manufacturing fault, chemical reaction, digging and vandalism. This book does not focus on addressing or assessing the factors that lead to pipeline leakage but discusses the strategies to detect leakages in pipelines once it occurs. As a fact, a fault can not be fully eliminated. That is why there is a need to time and accurately detect faults to avoid tragedies and minimise risks.

Blockage

The blockage is reduces the nominal pipeline area due to internal or external reasons. Internal issues begin as a minor increase in wall roughness that accumulates over time for physical or chemical processes, eventually blocking a significant amount of the cross-sectional pipe area. The pipeline could be contracted due to external reasons like throwing garbage into the pipeline, using heavy machinery near the underground pipeline and ground movement. These blockages are wasting energy and are responsible for the blast caused by high pressures. Recognising the obstructions as soon as possible is critical to address the blockage. Sometimes blockage may lead to leakages.

Leakage

Leakage is fluid emission from the pipeline due to cracks and holes. A pipeline leakage could be occurred due to various reasons like corrosion, manufacturing defects, digging above underground pipelines, welding defects etc. Among them, corrosion is one of the significant and uncontrollable factors that cause pipeline leakage. Corrosion, both internal and external, leads to the degradation of pipeline material which causes leakage after some years. Fluids like natural gas contain sulfur which is responsible for speeding up the corrosion process. These leakages in natural gas pipelines resulted in huge explosions and massive losses.

There could be various reasons that a pipeline starts leaking or blocked. This situation ultimately leads to incidents. EGIG [8] reported

that the causes of European pipeline incidents are external interference, corrosion, construction defects, material failure and ground movement. Figure 1.4 shows that corrosion and external interference are the most common causes of incidents in Europe, contributing 55% of the incidents. External interference includes digging near the pipeline and intentionally destroying the pipe (vandalism). The remaining factors are failure of pipeline components due to manufacturing defects (16%) or improper assembly, bypassing the pipeline (taping) accounts for 6%, and ground movement where a pipeline is resting is responsible for 16% of the time.

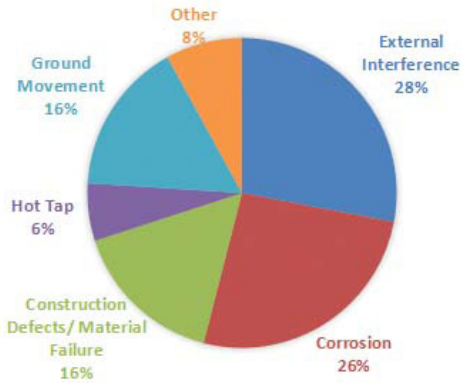

Figure 1.4 Reasons for significant gas pipeline incidents in Europe within ten years [8]

EFFECTS OF PIPELINE ACCIDENTS

Besides many advantages, pipelines are not immune to incidents. Pipeline incidents are caused due to the explosion in the pipeline. Specifically, gas pipelines are more prone to catching fire. The blast in a line results in various issues and losses like a waste of earth's natural resources, cut off the supply, damage at the nearby station, buildings or vehicles, and sometimes life losses. The broken pipe not only interrupts the gas supply to the site but also leads to massive material losses and human deaths [9]-[10]. Alberta Energy, Canada, observed pipelines for ten years and concluded that gas pipelines suffer more from such incidents as compared to other pipelines [11]. Thus, other countries are pushing companies through strict policies and standards to ensure the pipeline's safety.

According to the U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration (PHMSA), in 2018 alone, around 300 significant pipeline incidents were reported [9], as can be seen in Figure 1.5. Each year from 1999 to 2018, more than 250 incidents are reported except for 2001.

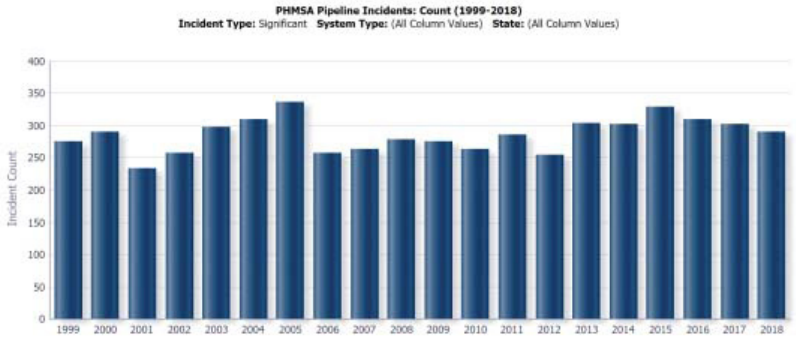

Figure 1.5 Number of significant incidents that occurred per year [9]

Figures 1.6 shows the associated cost incurred due to pipeline incidents [9]. This cost includes wasted fuel, damaged houses, furniture, cars etc. In the most recent year, 2018, the price was around 1000 million U.S. dollars.

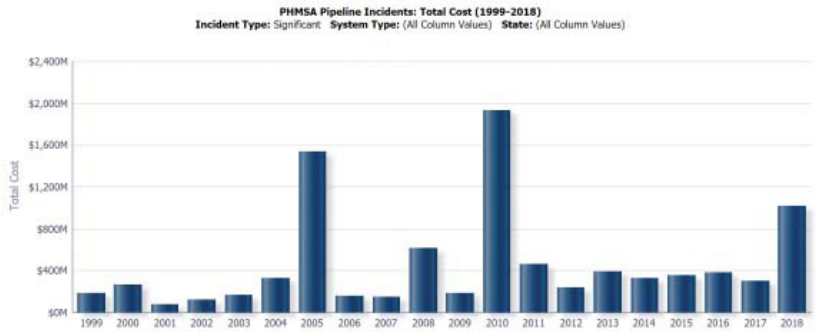

Figure 1.6 Total cost incurred due to significant incidents per year [9]

According to the U.S. Department of Transportation report, around 6000 incidents occurred between 1988 to 2008 related to pipelines and a large proportion of these incidents were related to gas pipelines.

Of the 6000 incidents, 1,074 resulted in more than 30 fatalities, 100 injuries, and property damage, amounting to USD551 million [12]. As per the findings of the 9th Report of the European Gas Pipeline Incident Group (EGIG), there were around 1300 gas pipeline issues addressed from 1970 to 2013. The overall incident frequency is reported to be 0.33 incidents per year per 1,000 km of pipeline [8].

The explosion of a gas pipeline in Malaysia (Figure 1.7) located somewhere between Laws and Long Sukang in the Northernmost district of Sarawak resulted in an estimated loss of R.M. 4 billion due to a temporary shutdown. The same incident also affected nearby villagers, with some houses and vehicles reportedly destroyed [13].



Figure 1.7 Sabah-Sarawak, Malaysia Pipeline Incident [14]

In another instance, Figure 1.8, a pipeline ruptured with a massive blast in San Burno, California, taking the life of eight people, injuring 58 others and numerous damaging houses, which led to an evacuation of 300 people. Around 48 MCF of gas burned in the explosion. The estimated cost of the losses was 13.7 million USD [15].



Figure 1.8 California Pipeline Incident in USA [16]

PIPELINE MONITORING FOR CONDITION ASSESSMENT AND FAULT DETECTION

Pipeline monitoring can assess pipeline condition (health) or/and detect faulty lines. Corrosion, valve malfunction, reduction in pipeline thickness, cracks and fungus can be monitored to state the health of a pipeline. At the same time, pipeline monitoring for fault detection is to identify leakage and blockage. Usually, a pipeline assessment to check the integrity of a pipeline is performed once a year or two to three times a year. Unlikely, a fault like a leak will likely happen after the health check and will remain undetectable until the subsequent check. The techniques to continuously monitor pipelines for faults like leakage are of great interest to avoid this issue. Pipeline monitoring specifically for fault detection aims to timely and accurately detect and diagnose the faults like leakage and blockage.

Various techniques have been developed to monitor pipelines for fault detection and diagnostics (FDD) and ensure the safety of the process. FDD in pipelines can be broadly divided into hardware and software-based methods [7]-[17]. These two approaches can be further divided into many techniques. Each technique has its advantages and disadvantages. In general, software-based techniques are cost-

effective but require accuracy and fault detection time improvements. Considering this challenge, this book can contribute to improvising one of the software-based leak detection techniques for gas mixture pipelines by understanding system monitoring and control terminologies here.

Basic Terminologies

Several terminologies such as transient flow, fault, and failure, are commonly used in system monitoring and control. Transient flow or transient conditions refers to the dynamic or changing nature of the system. For instance, if the pressure at a point in a pipeline change over time, it is called unsteady or transient conditions. This book considers transients due to varying customer demand causing pressure fluctuations, temperature changes (atmosphere), and gas compressibility. In contrast, transients due to pipeline elastic behaviour, vibrations, compressor start-up and compressor shutdown are ignored.

Fault detection is the determination of the presence of abnormal conditions. In this book, we have presented leak detection in pipelines. Fault or leak diagnosis deals with the detected leak's time, location, type, and size [18].

The following table summarises the basic definitions of terminologies repeatedly used in system monitoring and control writings [19].

Table 1.1 Terminologies used in fault detection and diagnostics papers

Terminology	Definition
Fault	An unpermitted deviation of at least one characteristic property or parameter of the system from the acceptable/ usual/standard condition.
Failure	A permanent interruption of a system's ability to perform a required function under specified operating conditions.
Malfunction	An intermittent irregularity in the fulfilment of a system's desired function.
Monitoring	A continuous real-time task of determining the conditions of a physical system by recording information, recognising and indicating anomalies in the behaviour.

Table 1.1 (cont.)

Terminology	Definition
Residual	A fault indicator based on a deviation between measurements and model-equation based computations.
Quantitative model	Use of static and dynamic relations among system variables and parameters to describe a system's behaviour in quantitative mathematical terms.
Qualitative model	Use of static and dynamic relations among system variables and parameters to describe a system's behaviour in qualitative terms such as causalities or if-then rules.
Fault detection	Determination of the faults present in a system and the time of detection.
Fault isolation	Determination of the kind, location, and time of detection of a fault. Follows fault detection.
Fault identification	Determination of the size and time-variant behaviour of a fault. Follows fault isolation.
Fault diagnosis	Determination of the kind, size, location, and time of detection of a fault. Follows fault detection. Includes fault isolation and identification.

Natural gas fulfils most of the energy demand to its lightweight and high heating capacity. Pipelines are the fastest and most economical medium to deliver natural gas to consumers. Due to growing energy needs, pipeline networks are multiplying over time. Unfortunately, this vast system is not free from faults like blockage and leakage. Sometimes these faults may lead to catastrophic losses. There is a need to monitor pipelines in real time (continuously) to mitigate these losses. Various pipeline fault detection and diagnostics techniques have been developed to monitor and detect faults.