Chapter 1

INTRODUCTION TO PIPELINE SYSTEMS

1.1 INTRODUCTION

Pipelines affect the daily lives of people in most parts of the world. Modern-day life is based on structures in which energy fulfills a prevailing role. Oil and gas are major participants in this energy supply [1]. The ever shifting emergence and decline of other forms of energy (such as coal, nuclear, hydrogen, biomass, etc., Fig. 1-1) will continue to dominate energy usage in the future, depending on the acceptability, safety, technical, environmental, and economic issues. However, pipelines are means by which many hydrocarbon-based forms of energy are transported. It is no coincidence that wherever there is the largest pipeline network, there is also the highest standard of living and technological progress.

Compared with other forms of transport, pipelines allow a more continuous, stable, and high-capacity supply of hydrocarbons to reach end-users. Pipeline transportation has the advantages of being well established, efficient, cost-effective, and readily expandable. Its technology is mature and well understood. The capital cost of a pipeline project is largely a function of its diameter and length, although other factors, such as geography and topography, are also significant. Operating expenditures and self-consumption of product are relatively minor and predictable. Economic feasibility of a pipeline is limited by variables, such as volumes to be transported, supply–demand distance relationships, operating pressure, projected reserve life, and various risk factors. These limitations are more restrictive offshore than onshore.

The relative transportation cost for various petroleum products is depicted in Fig. 1-2. Although pipelines have been the most cost-effective mode of energy transportation, it can be inferred from Fig. 1-2 that cost of energy transportation by pipeline is distance- and location (offshore versus onshore)-dependent [3].

Pipelines are mostly buried. In virtual silence, pipelines supported by pumping and compression stations carry billions of cubic meters of our energy needs. Unattended pumping stations push oil and petroleum products in large volumes and under high pressure. Similarly, natural gas transmission systems supported by compressor stations move large volumes of gas to various destinations.

1.2 LIQUID PIPELINES

1.2.1 Liquid Pipeline System

The liquid pipeline transportation system applies to a variety of liquid hydrocarbons, including crude oil, refined petroleum products, liquid petroleum gas, gas to liquids, anhydrous ammonia, alcohols, and carbon dioxide. Liquid pipelines, including generally
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consist of laterals and mainlines which include tank farms, measurement facilities, pumping systems, pressure reduction, control systems, and pipeline appurtenances (scraper traps, valves, etc.). Scopes defining the limit of the pipeline system are well defined by applicable codes, an example of which is shown in Fig. 1-3 [4]. Also included within the scope of the system are:

- primary and associated auxiliary liquid petroleum and liquid anhydrous ammonia piping at pipeline terminals (marine, rail, and truck), tank farms, pump stations, pressure-reducing stations, and metering stations, including scraper traps, strainers, and prover loops;
- storage and working tanks, including pipe-type storage fabricated from pipe and fittings, and piping interconnecting these facilities;

![Figure 1-1](image1.png)

*Figure 1-1.* Energy market share, 1860 to 2060 [2].

![Figure 1-2](image2.png)

*Figure 1-2.* Representative costs of oil and gas transportation (US$/MBTU) (Mohitpour et al. [3]).
1.2.2 Liquid Pipelines and Pumping

Liquid pipelines are used to transport liquids, such as crude and refined oil, from the source of supply, such as a production area to the market/demand locations, an export-loading terminal, or to a processing unit (a refinery). Booster stations are installed along the transmission pipelines at variable distances to compensate for the pipeline pressure losses and elevation changes and to ensure a constant flow of liquid.

Pipeline pumps are used for boosting pressures and for transferring product in both gathering and mainline transmission systems. Centrifugal, reciprocating, and rotary-positive displacement pumps are generally used for such pipeline application.

In a booster station located on larger transmission lines, usually one or more high-capacity, single, or multi-stage centrifugal pumps are installed. They can be driven by a gas turbine, diesel engine, or an electric motor up to a unit power range of about 30 MW.
Of importance are the fluid characteristics when selecting a pump. The type of fluid to be transported affects pipeline design and facility requirements and configuration, including pumping systems. The properties of fluid to be transported have significant impact on pipeline system design. For liquid lines, the liquid properties which affect pipeline design are:

- viscosity,
- density, and
- specific heat.

These properties are influenced by the pressure and temperature. Temperature considerably affects the above properties in liquid pipelines and, specifically, crude oil or heavy crude oil pipelines. Viscosity is also affected by the liquids’ shear rate. Liquids that have a constant shear rate with respect to shear stress at any given temperature are termed Newtonian fluids, and the viscosity is a function of temperature only. It increases with decreasing temperature. Non-Newtonian fluids have viscosities which are not only a function of temperature but also of shear rate (Fig. 1-4) [5]. Non-Newtonian fluids which are time-dependent are classified as thixotropic (fluids that require a decreasing stress to maintain a constant strain rate) and rheopectic fluids (ones that need an increasing shear stress to maintain a constant strain rate).

Other time-independent ones are pseudo-plastic, yield pseudoplastic, dilatants, and Bingham fluids shown in Fig. 1-5. As can be seen from Fig. 1-5, when transporting non-Newtonian products through the pipeline, a definite minimum stress must be applied to the product (to reach its yield point) before any flow of the product takes place.

When the product being transported is always a low viscosity liquid such as water, gasoline, diesel oil, or very light crude oil, centrifugal pumps are cost-effective, reliable, and efficient. However, as the liquid viscosity increases, the frictional losses within a centrifugal pump quickly reduce pumping efficiency dramatically (Fig. 1-6). For this reason, rotary, positive displacement pumps are often used when products such as heavy crude oil, bunker fuels (no. 6 fuel oil), low sulfur fuels, asphalt, Orimulsion (a manufactured boiler fuel emulsion of 30% water and 70% bitumen), and similar products are to be transported.

![Figure 1-4. Viscosity characteristics for a typical non-Newtonian heavy crude oil [5].](image-url)
Pumping capacity and power requirement must therefore consider the fluid condition over time because pumping operation will be influenced by any changes in liquid viscosity and density that may occur. Such change can affect

- net-positive suction head,
- priming flexibility,
- fluid condition and corrosion,
- useful life,
- maintenance,
- quantity pumped,
- pumping head,
- power source, and
- transportation economics.

Figure 1-5. Flow curves illustrating shear characteristics for various products.

Figure 1-6. Rotary versus centrifugal efficiency (light versus heavy products, 100 US GPM, 75 psig discharge).
1.3 Gas Pipelines

1.3.1 Gas Pipeline Systems

Gas is usually considered to be any hydrocarbon-based gas or mixture of gases suitable for domestic or industrial fuel that is transmitted or distributed to the user by a pipeline/piping system. The most common types are various compositions of natural gas but other gases such as hydrogen and carbon dioxide are becoming more prevalent. A gas transmission and distribution system (Fig. 1-7) consists of the following components:

- gas processing and treatment facilities to remove objectionable materials and constituents
- gathering pipeline facilities
- production plants/compression
- receipt meter stations
- lateral lines
- mainlines
- mainline control valves to regulate pressure or flow
- mainline compression facilities
- delivery meter stations/custody transfer/city gate stations
- storage facilities used for peaking requirements (usually the pipeline itself)

The components include production wells, gathering lines within the production fields, processing plants, transmission pipelines, compressor stations (periodically along the transmission pipelines), storage wells and associated gathering pipelines, metering stations and city gate at distribution centers, distribution piping, and meters at distribution sites (residential or industrial).

Compression is required in gas pipeline systems to overcome friction losses, which increase as the rate of gas flow increases. Gas is received from receipt points along the pipeline and delivered to delivery/sales stations at specified flows and pressures. In between these points, pressure drop occurs because of expansion, friction loss, change in elevation,
or change in temperature. Three methods can be used to maintain the required pressure at an existing delivery point when there is an increase in flowrate beyond the design point (Fig. 1-8):

- looping the pipeline (i.e., add a parallel pipeline, connected to the existing pipeline); this reduces the flow in each line, thereby decreasing velocity and, hence, pressure loss due to friction;
- adding a compressor station to boost the pressure sufficiently to maintain the required pressure at the delivery point;
- a combination of loop and compression; and
- line pack usage based on diurnal gas delivery fluctuations.

**Figure 1-8.** Pipeline looping versus compression.
The evaluation of which method will be economically more feasible depends on many factors such as:

- capital expenditures
- fuel cost
- emissions
- maintenance
- future expansions

1.3.2 Gas Pipelines and Compression

Compression facilities are the heart of gas pipeline systems. Compressor stations push natural gas through a pipeline by compressing the gas at intervals along the system. Gas flows by expanding in the pipe from the discharge side (high pressure point) from one station to the suction side (low pressure point) of the next. An average station may compress as much as 830 million cubic feet of gas per day. A typical gas pipeline network schematic is shown in Fig. 1-9 [6], while a typical natural gas processing and transmission/distribution system, which involves compression, is shown in Fig. 1-10.

The use of compression equipment on or related to pipelines covers a wide field, ranging from a small manually operated field compressor up to a large computer-controlled installation involving many thousands of kilowatts. Compression equipment performs one or more of the following major functions with respect to the gas pipeline industry in general:

Transmission. Long-distance mainline transmission is designed with compressor stations spaced at intervals along the pipeline. The compression ratio across a station, resulting from pipeline friction losses, is established by the compressor units as they are placed into operation or varied in load. These stations are usually designed for fully automatic, remotely controlled operation to enable a complete pipeline system to be operated from a central location.

Lateral Compression. Lateral pipeline transmission is designed to carry gas from one or more sources to a main pipeline, or from a pipeline to a sales point or distribution system. Operation varies from base load to “on–off” depending on the situation and can be subject to large changes. Compression ratios are often higher than for a main line station, with flows and power requirements being much less.

Figure 1-9. Typical gas pipeline network (Energy Information Administration 2008 [6]).
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Field Compression. Field compression and gas gathering stations involve the boosting of gasfield well-head pressures up to a required plant inlet pressure or directly to a pipeline-operating pressure. Compression ratios are often high, with a slowly declining suction pressure (and therefore increasing ratio) as the gasfield becomes depleted.

Interchange Compression. Interchange compression is often required to transfer gas between different pipeline systems. The operating conditions include variable suction and discharge pressures, which may vary at random, unaffected by the compressor operation.

Gas Storage Compression. Gas storage compression is designed for injection and withdrawal of gas from peak shaving or storage reservoirs. These compressor units operate under a continually changing compression ratio, both on injection and withdrawal, and would be considered as high-ratio, high-flow, and high-power units.

Booster Compression. Booster compression is designed to raise the pressure from a low pressure transmission line, for example, to a high pressure line. The units would basically be considered as transmission units but operating under higher compression ratios.

Gas Recovery Compression. Gas recovery compression is used to raise associated gas (gas in solution with crude oil) from very low pressures (down to almost atmospheric pressure) up to pipeline transmission pressure. This is a very high-ratio service.

1.4 Dependability of Pipeline Systems

1.4.1 Dependability

In today’s competitive and changing environment, it is crucial that pipelines and associated facilities create and sustain value for their stakeholders. This value can only be achieved by incorporating dependability into the pipeline system, in whole or in part. Dependability characteristics address not just availability and reliability as the probability of successful performance, but also identify other potential risk exposures such as degradation and wear-out that advocate the need for maintenance and logistic support to sustain “problem free” pipeline and facility operation. Dependability engineering [8] provides practical means and measurable targets for achieving value, which are then implemented by sound operational risk assessment practices.

The term “reliability” has the specific meaning as the probability that something may fail within a certain time period but is also commonly used in a broader sense for the combined and related concepts of availability, maintainability, supportability, maintenance, safety, integrity, and a host of other terms. This has led to a proliferation of aggregate terms.

Figure 1-10. Typical natural gas processing and transmission/distribution system.
such as R&M (Reliability and Maintainability), RAM (Reliability, Availability and Maintainability), RAMS where the additional “S” is safety, and Dependability, which is used by international standards.

On the international scene, the IEC (International Electrotechnical Commission) established a TC (Technical Committee) 56 in 1965 to address reliability standardization. The initial title of IEC/TC56 was “Reliability of electronic components and equipment.” In 1980, the title was amended to “Reliability and Maintainability” to address reliability and associated characteristics applicable to products. In 1989, the title was changed to “Dependability” to better reflect the technological evolution and business needs on a broader scope of applications based on the concept of dependability as an umbrella term. In 1990, following consultations with ISO (International Organization for Standardization), it was agreed that the scope of TC56’s work should no longer be limited to the electrotechnical field, but should address generic dependability issues across all disciplines. The scope of IEC/TC56 covers the generic aspects on dependability program management, testing and analytical techniques, software and system dependability, life cycle costing and technical risk assessment. This includes standards related to product issues from component reliability to guidance for engineering dependability of systems, standards related to process issues from technical risk assessment to integrated logistics support and standards related to management issues from dependability management to managing for obsolescence.

Dependability provides critical value at the pipeline system level by ensuring that the combination of pipe and pump/compressor stations can provide the capacity and availability to satisfy contractual requirements. For the pipe portion, dependability is normally couched in terms of risk management or integrity management with the objective of public, employee and contractor safety, avoidance of environmental damage, satisfying regulatory requirements and managing cost. For facilities, dependability value is obtained by high availability and reliability and low life cycle costs.

Due to fundamental differences in these assets — pipe being a structure and facilities consisting of many types of equipment — it is natural that different approaches and techniques are needed to ensure effective and dependable operation over their life cycle.

Dependability is the ability to perform as and when required. It applies to any physical asset such as a system, product, process, or service and may involve hardware, software and human aspects. Dependability is a collective set of time-related performance characteristics that coexist with other requirements such as output, efficiency, quality, safety, and integrity. The main dependability characteristics of a system consist of:

- availability for readiness of operation;
- reliability for continuity of service provision;
- maintainability for ease of preventive and corrective maintenance actions;
- supportability for provision of maintenance support and logistics to perform maintenance tasks.

The interrelationship between these characteristics is shown in Fig. 1-11. Availability is the operational result of a combination of reliability, maintainability, and supportability. It is directly related to production capability and assurance in the oil and gas industry [9]. Reliability is inherent in the system design and must be sustained through the manufacturing and installation to provide dependable operation. Maintainability is dependent on the system design architecture and technology implementation guided by the maintenance strategies to enhance reliable operation. Supportability is enabled by available maintenance support resources to permit flexibility in logistic support management and outsourcing provision.
Performance requirements of equipment or a system can be divided into functional and non-functional components where the functional requirements denote fundamental objectives of the system and the non-functional ones are essential criteria needed to establish other requirements, such as safety, dependability, and usability. Dependability is associated with the time-dependent aspect of the requirements of a system. For example, the compression of natural gas is based on certain conditions of use to provide dependable compression capacity, safely and with minimum environmental impact. The resultant functional requirements become performance specifications, such as head, flow, and efficiency at a certain design point and operating range with the design carried out according to specified standards. Non-functional requirements relate to safety requirements and local and national regulations. The dependability characteristics relate to how this performance can be maintained over time, such as a pump producing the required pressure for a regulated flow to sustain operation without interruption or degradation with minimum downtime. A system configuration and design example is shown in Fig. 1-12.
1.4.2 The Value of Dependability for Pipelines

The general value of dependability is related to the ability of functional requirements to be satisfied from a time perspective. The value created by dependable operation is both positive in enhancing availability and reliability but also negative in the sense of avoidance of the consequences caused by cessation of required functions.

In general, dependability value can be expressed in the following ways:

1. Safety is enhanced: In many industries such as transportation, safe execution of the service is of paramount importance. Great lengths are taken to ensure no injuries or deaths are incurred although hopefully no one is under the illusion that all risk is eliminated. Moreover, there may be different acceptable safety levels for the public as opposed to employees.

2. Customer or user satisfaction is achieved: In particular for customer products and services, satisfaction is the measure of success even though likely not everyone will be equally satisfied. This satisfaction will be linked to the performance of the product or the service and whether any product failures or service interruptions are experienced. Availability upon demand is also important to the user or customer.

3. Life cycle cost is minimized: Life cycle cost is influenced by initial acquisition costs and the cost of operation and downtime or unavailability due to failures and the need for maintenance. Some costs may be inherent to the design while others can be minimized by good operating and maintenance practices. Sometimes long-term life cycle cost is compromised in the short term to achieve objectives. Costs and benefits may include not only those of the actual asset but ones related to achieved or lost production.

4. Maximum asset life can be attained: Dependable products and systems are much more likely to have a long life, something that is most important for infrastructure and very expensive assets. As long as the failure rate is not increasing dramatically, longer operation reduces life cycle costs.

5. Environmental impact is minimized: Failures can seriously impact emissions and environmental damage due to loss of containment of hazardous substances.

6. Reputation is maintained or enhanced: This is more problematic to quantify but a loss of reputation can impact business value such as the stock price and may result in a loss of market for products that could even lead to the end of an organization.

The value of pipelines can be represented by the sequence of life cycle stages, which constitutes the primary process for value creation. Each life cycle stage from concept initiation to in-service operation adds value to the process. Figure 1-13 illustrates the general value creation framework for the system life cycle as applied to pipelines and facilities.

1.4.3 Dependability for Pumping and Compression

Satisfying dependability performance for a pipeline happens at several levels, starting with the pipeline system as a whole and being supported by specific and different approaches for the pipe portion and the compression or pumping facilities. The pipeline system level is essentially a network consisting of pipe and facilities with input and delivery points. The delivery is naturally also dependent on adequate supply volumes but this has to be assumed so it will not be considered further.

Delivery from a pipeline system is measured by availability as a function of flow with expectation by the customer that contracted volumes will be met. For a gas pipeline, even with loss of compression, expected volumes can often be made up due to changeable
linepack and delivery requirements satisfied unless downtime is extensive. For oil pipelines, unless it is operating well below capacity, this may not be possible. For this reason, redundancy for pumping is more crucial than for compression.

Compared to pipe, compressors are less reliable and require downtime for maintenance. This would argue for less compression and larger pipe diameters except for the fact that installing pipe is considerably more costly than compression. Determining the most effective tradeoff options can be conducted by dependability analyses.

For pumping and compression facilities, the major dependability-related features are that:

- equipment consists of many different types of components with differing failure modes and failure rates;
- failure rates are relatively higher;
- consequences are generally from low to medium;
- regular preventive maintenance is needed along with condition-based maintenance;
- public safety or environmental damage is a not primary concern;
- regulatory requirements are less stringent;
- maintenance and replacement are technology driven and are continuously being improved.

During the design phase, considering reliability and maintainability are particularly important and quite a few techniques exist to facilitate these as well as extensive standards, including international ones by IEC/TC56 [11]. A large body of literature exists to support this.

Figure 1-13. Dependability framework over the life cycle for pipelines [10].
Detailed pipeline system operational capability, reliability, and availability assessment of a system are described by Mohitpour et al. [7]. In this reference, applicable codes and standards providing guidelines for assessment of pipeline systems reliability, and availability/dependability are provided. Fundamentals and techniques are described, and typical pipeline component failure data are provided. Reliability/availability assessment application is then detailed.

Creating value from dependability for compression or pumping facilities leads primarily to these benefits: improved safety, high availability, and reduced costs. Improved safety applies mainly to employees and contractors and not so much the public so it is less critical than for pipelines.

Availability is linked to meeting delivery contract requirements and providing customer satisfaction. The impact of compressor/pump downtime is very dependent on the number of stand-by units installed and, especially for gas pipelines, the flexibility of the pipeline itself in handling short term downtime which will guide the tradeoff between availability and capital and operating costs.

Reduced costs may range from short-term cost comparisons to long-term life cycle costing (LCC is also known as TCO or total cost of ownership). LCC studies are best done during equipment acquisition and used to compare alternatives.

The major steps in a LCC analysis are:

- preparing a breakdown structure for applicable costs;
- determining costs for each breakdown element;
- collecting failure and repair data (MTBF/MTTR or Weibull) from industry sources or actual experience;
- analyzing system availability and reliability;
- selecting an LCC model (e.g. \( LCC = \text{Acquisition cost} + \text{Operating cost} + \text{Failure cost} + \text{Support cost} - \text{Net disposal value} \));
- estimating costs for each component of the LCC model;
- applying discounting over the time period of the study;
- determining the final LCC based on Net Present Value (NPV);
- comparing alternatives.

REFERENCES


