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ACHIEVING DEPENDABILITY VALUE FOR PIPELINES AND FACILITIES

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ABSTRACT

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 provides practical means and measurable targets for achieving value, which are then implemented by sound operational risk assessment practices. Dependability management is needed to present viable business success options on risk avoidance, prevention, and mitigation; and where applicable, provides cost-effective risk treatments to support pipeline operation and enhance facility management. Characterizing the value of dependability focuses on two key issues: (1) what is the value of dependability, and (2) what is required to achieve it. This paper establishes a unified approach for understanding the dependability principles and practices, and enunciates how dependability value can be ascertained and assured in real life situations. It presents a general framework and provides implementation guidelines for ensuring that dependability value can be achieved in practical application for pipelines and facilities.

INTRODUCTION

Ultimately all enterprises are about creating value for their stakeholders. Dependability is a critical aspect of value creation and this paper attempts to clarify the nature of the value that dependability brings to pipelines and facilities.

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.

WHAT IS DEPENDABILITY

Definition of Dependability

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 Figure 1. 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 [1]. 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.

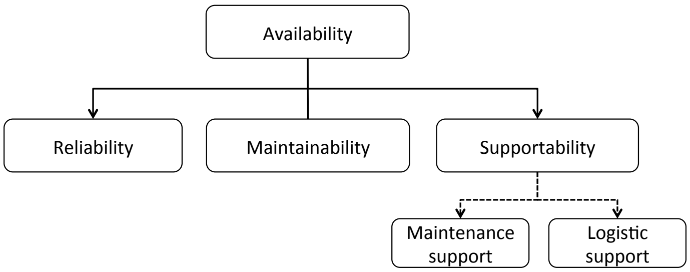

Figure 1 – Interrelationship between dependability characteristics

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 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 Figure 2.

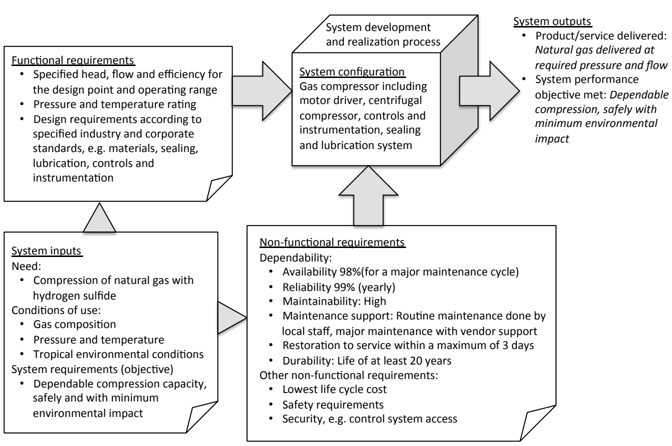

Figure 2 – Functional and non-functional requirements

Evolution of Dependability

The genesis of *dependability* evolves from the first use of the word "reliability" by Samuel Taylor Coleridge who bestowed the word on his friend, the poet Robert Southey to praise his steadfastness [2]. From this seemingly insignificant usage of the term, reliability has grown enormously to a broadly accepted, if not entirely understood, property that everyone expects for a wide range of situations. The main pillars of reliability are the concepts of probability and statistics which emerged earlier from the work of two Frenchmen, Blaise Pascal and Pierre de Fermat. Reliability came into further prominence in the 1960's when many Mil-standards and specifications were developed to meet the needs of design and implementation for defence production in the USA. Worldwide industry acceptance of these Mil-standards became noted as the leading source of reliability knowledge [3].

Reliability engineering now encompasses statistical methods, techniques such as FMEA and Fault Tree Analysis, physics of failure, hardware, software and human reliability, probabilistic or quantitative risk assessment and reliability prediction, to name only a few. Databases of information have been established and their use has increased dramatically. Practically every engineering discipline has a focus on these aspects as a key component of business success.

The term "reliability" now has a much broader and commonly understood meaning that includes not only of the specific meaning of reliability as the probability that something may fail within a certain time period but also related concepts of availability, maintainability, supportability, maintenance, safety, integrity and a host of other terms. This has led to a proliferation of aggregate terms 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 responding to a German proposal in 1962 and later approved by the IEC Committee of Action in 1964 [4]. 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, according to its Strategic Business Plan approved in 2009, 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 and Risk

It is quite important to recognize the close relationship between dependability and risk. Whereas dependability is mainly associated with the prevention of failure, risk is the estimate of the probability of failure and its potential consequences. Evaluating risk is therefore an alternate means of characterizing dependability. It is no coincidence that many of the dependability techniques such as FMEA are also applicable to risk assessment as covered in a joint standard by ISO and IEC on risk assessment [5].

THE VALUE OF DEPENDABILITY

Value Creation

Value is the relative worth of something desirable or significant. The worth of something may be expressed as monetary or material worth, or interpreted as its usefulness or importance to a desirable outcome. The economic value of an item reflects the value in use or utilization in terms of goods and services. Ultimately all enterprises are about creating value for their stakeholders. In narrow financial terms, value is benefit minus cost since profit is a major goal for most organizations. For others such as public services, profit is not a requirement but the balancing of benefit and cost is, not to mention a necessity for economic survival. Value also has other meanings such as safety and service, some of which can be quantified and others not very easily, if at all.

The concept of value creation has been a focus of management theory. Kaplan and Norton's work on the Balanced Scorecard [6] is a strategic management tool for tracking managerial performance in task assignments and monitoring the consequences arising from their execution actions and results. The task performance activities are measured from four perspectives: financial, customer, internal business processes, and learning and growth, with respect to established targets of the assigned tasks. The performance measurements permit objective setting and alignments of the organization's goals and strategic priorities by focusing on a balanced set of performance measures. The Balanced Scorecard does not replace the traditional financial statements, which address the organization's tangible assets. But it complements the development of intangible assets to enhance value for the organization.

The generalization of Kaplan and Norton's work has been adopted by many organizations in developing strategic maps for corporate management [7]. The objective of the strategic map is aimed at converting intangible assets into tangible outcomes.

The Value Chain

The concept of value chain was introduced by Michael Porter, Professor at Harvard Business School in his 1985 book on *Competitive Advantage* [8]. The value chain describes a set of coordinated activities that run efficiently to add value to the organization's products and services. Porter highlighted the competitive advantage and distinct capabilities of value to improve profit margin and enhance customer satisfaction. The value chain allows alignment of processes with customers to generate quality advantage by focusing on cost management efforts supported with efficient processes to sustain and improve operations. The value chain thus helps managers identify the activities that are especially important for competitiveness attainment of the organization's overall strategy.

Since its introduction, the value chain has taken various forms and is extensively used and has been adopted by industry for value engineering, supply chain management, and value-added service applications. In the context of technological systems, the value chain 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. In this respect, the value chain process has become the delivery system in support of value creation. Figure 3 illustrates the general value creation framework for the system life cycle as applied to pipelines and facilities.

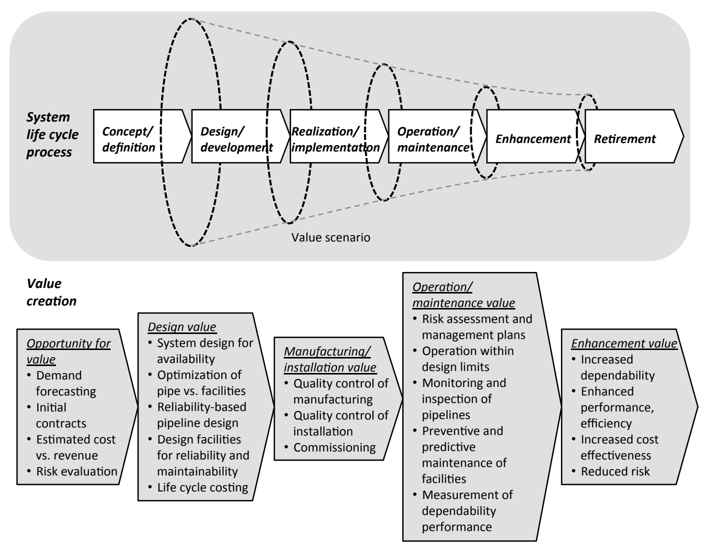

Figure 3 – Dependability value framework for system life cycle application

The value scenarios are shown in the framework overview as circles encircling the sequence of system life cycle stages. Each circle portrays a view of the value creation opportunities reflecting the potential system performance value status at the time of appraisal. It should be noted that for dependability value application, these circles decrease in size to indicate the narrowing of the scope of value creation possibilities as they approach the end of the system life cycle process.

The Value of Dependability

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 Proposition

As a part of strategy and planning, organizations may use a value proposition to explain what benefit it is providing to customers, partners, society, employees and suppliers [9]. Even if there is no formal value proposition, the different stakeholders will have a perception of value although they will often not have the same perspective on value.

The actual value proposition adopted by an organization operating a pipeline will vary with its stakeholders. Starting with its customers, value is created by dependable delivery of the product being transported. The target will be 100% availability of the design capacity with no interruptions in service. By its very nature, a pipeline needs to consider the public as a major stakeholder. Their value proposition is focused on safe and environmentally acceptable operation and preventing any incidents that can lead to personal, property or environmental damage. The value for shareholders is not only financial gain but also reputation and avoidance of major consequences that could threaten the ability to continue operation. Finally, employees have a stake in personal safety and work satisfaction. Figure 4 combines these value propositions into a balanced approach that points to the necessity to compromise between them which then leads to risk management as a fundamental means of ensuring that they can be met. It is clear that dependability is a critical factor in most of these value propositions.

CUSTOMERS 100% availability of design capacity No service interruptions Product quality	PUBLIC/SOCIETY No personal incidents/ accidents No damage/loss of property No environmental damage
SHAREHOLDERS Financial gain No loss of reputation No loss of capacity	EMPLOYEES No personal incidents/ accidents Work satisfaction

Figure 4 – The value proposition for pipelines according to the balanced approach

ACHIEVING DEPENDABILITY FOR PIPELINES

Pipeline System Dependability Requirements

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 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.

Complex systems require a more sophisticated approach to dependability analyses and various methods are available to accomplish this. Probably the most common is the Reliability Block Diagram (RBD). A larger system or network is divided into blocks that are connected in series and/or parallel. The availability or reliability of each block is defined by an average failure rate (or MTBF) or a Weibull characteristic and the resultant system availability or reliability can then be calculated. It is a practical and useful technique that is widely used in analyzing networks including electrical systems [10]. Availability and reliability modeling is best handled by Monte Carlo simulation techniques [11] and [12].

Another technique is fault tree analysis, which is applicable to large, complex systems [13] but is more time-consuming since the fault trees can grow to a very large size. Even more flexible but also more complicated is Markov analysis that can handle multiple states [14].

Compressor unit and station availability studies play a fundamental role in providing information that will support decision making in terms of defining a criterion for installing stand-by units. One such study [15] presented two methods adopted for the Bolivia-Brazil Gas Pipeline Project - Gasbol transmission system that has 4 compressor stations in Bolivia side and 10 compressor stations in Brazil side. It adopted two methods to evaluate the availability of the gas pipeline: (1) scheduled and unscheduled maintenance and (2) Monte Carlo simulation. Additionally, compressor unit unavailability was calculated by using a binomial distribution for the purpose of comparing its results with the other two methods. The objective of the study was to quantify the availability of the transmission system and to identify the required quantity of the stand-by compressor units to be installed to fulfill contractual obligations for firm capacity. An optimum number of stand-by compressor units where defined, taking into account contractual liabilities (as a result of failure to provide total required firm capacity) and also the total investment and operating cost for the new stand-by compressor units.

The availability values for the compressor station units were defined based on the following criteria:

a) Obtained from the EPRI Report No. RP 4CH2983 as 0.971 for installed compressor stations with centrifugal compressor and gas turbine driver.

b) Obtained by the following equation and without stand-by units:

Reliability = 1 - FOF
Availability = 1 – (FOF + SOF)
FOF = FOH / PH
SOF = SOH / PH

FOF = Forced Outage Factor
FOH = Forced Outage Hours
PH = Period Hours
SOF = Scheduled Outage Factor
SOH = Scheduled Outage Hours

The values of FOF and SOF presented below were taken from the North American Electric Reliability Council – NERC Report of January 2005 for gas turbine drivers.

FOF = 0.0282
SOF = 0.0424
Reliability = 100 – FOF = 0.9718
Availability = 1 – (FOF + SOF) = 0.9294

(c) Obtained from a Binomial Distribution based on the availability value taken from NERC report for the gas turbine driver.

(d) Obtained from the scheduled maintenance as recommended by gas turbine manufacturer.

(e) Obtained from Monte Carlo simulation, and considering the availability number for the gas turbine drivers taken from the NERC report. The simulation considered the compressor stations operating initially without stand-by units and then defined a number of stand-by units to be installed to guarantee an adequate level of availability for the pipeline to cope with contractual obligations related to firm transportation capacity and also to mitigate liabilities.

A comparison between the binomial distribution and Monte Carlo simulation showed very little difference and the Monte Carlo approach was used for this evaluation. An availability value of 0.9294 for each compressor station unit was adopted and then Monte Carlo simulation applied to the gas pipeline compressor station model for three cases: (a) no stand-by units, (b) five stand-by units and (c) ten stand-by units. The criterion to evaluate the gas pipeline availability considered the available capacity taken from the thermo-hydraulic simulation software of the gas pipeline under different unavailability scenarios. Pipeline Studio® from Energy Solutions was used to run the scenarios. The maximum capacity taken from the simulation software for each scenario divided by the contractual firm transmission capacity provided the availability of the transmission system. From the average firm transportation capacity of 27.77, 29.36 and 29.99 MMm3/d calculated for each configuration, respectively, the availability of the gas pipeline transmission system was evaluated by simply dividing this capacity value by the firm contractual capacity of 30.08 MMm3/d with the following results:

- No stand-by compressor units: 0.9231
- 5 stand-by units (for the first 5 stations): 0.9761
- 10 stand-by units (1 to each station): 0.9971

Unavailability can also be estimated from the outage time associated with the quarterly, semi-annual and annual inspections and the turbine overhauls that occur at intervals of 30,000 running hours. Based on a schedule as recommended by the equipment manufacturer, the available capacity was determined as shown in Figure 5 which shows a significant reduction of 2.48 MMm3/d due to maintenance outages. This is well below the contracted firm capacity.

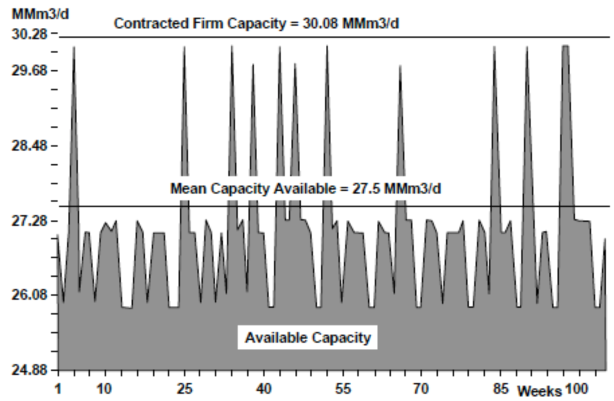

Figure 5 – Capacity loss due to maintenance services with no stand-by compressor units [15]

However, as additional units are installed as stand-by, the overall pipeline availability increases, as the stand-by units overrides the unavailable ones without causing capacity shortage on the stations where they are installed. Figure 6 presents the situation when five additional units are installed in five compressor stations (one per station). The gray area below graphic line now extends up, covering almost 100 % of the required firm gas transmission capacity. By this approach the expected average capacity is now very close to 30.08 MMm3/day.

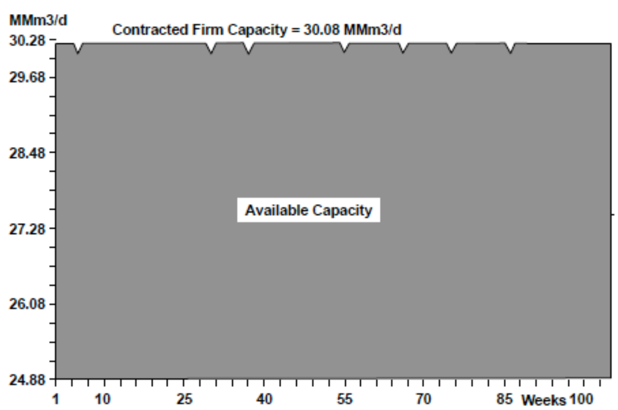

Figure 6 – Capacity recovery with the installation of five stand-by compressor units [15]

An economic analysis to define the right number of stand-by units was done for the three scenarios identified above. The objective was to identify the adequate quantity of stand-by units to provide a manageable level of risk exposure to contractual liabilities due to non-delivered capacities. The discounted cash flow was used and compared for the three configurations to identify the one that would give the better net present value – NPV. The avoided losses and liabilities were considered as revenues and the stand-by units as capital investments. No additional costs related to fuel gas plus operation and maintenance were accounted for since the units will operate as stand-by units.

The evaluation results pointed to an opportunity to install stand-by units for all compressor stations as follows:

(a) No Stand-by Units – Base Case
- System availability: 0.9231
- Potential loss of capacity 2.28 MMm^3/d
- Potential loss of revenue: 182.8 MMUS$
- Potential loss in liabilities: 182.8 MMUS$

(b) 5 Stand-by Units
- System availability: 0.9761
- Remaining Loss of capacity: 0.85 MMm^3/d
- Remaining yearly exposure: 136.3 MMUS$
- Recovered capacity: 1.43 MMm^3/d
- Avoided loss of revenue: 114.7 MMUS$
- Avoided contractual liability: 114.7 MMUS$
- Capex for stand-by units: 64.5 MMUS$
- NPV: 164.8 MMUS

(c) 10 stand-by units (1 at each 10 compressor station)
- System availability: 0.9971
- Remaining Loss of capacity: 0.07 MMm^3/d
- Remaining yearly exposure: 11.2 MMUS$
- Recovered capacity: 2.21 MMm^3/d
- Avoided loss of revenue: 177.2 MMUS$
- Avoided contractual liability: 177.2 MMUS$
- Capex for stand-by units: 129 MMUS$
- NPV: 225.4 MMUS$

The highest NPV is for the case where one stand-by unit is installed at all 10 compressor stations.

Dependability Framework for Pipelines

Even though there are certainly similarities, there are fundamental differences in approaches to dependability between machinery/equipment and structures or static equipment. For the oil and gas industry, the most important structures are pressure-containing such as pressure vessels, piping and pipelines. The essential dependability-related features of pipelines are that:

- pipe has only a few dominant failure modes to consider;
- failure rates are very low for most of their life;
- other than for valves and cathodic protection equipment, regular preventive maintenance of the pipe itself is not needed and replacement or refurbishment is condition-based;
- monitoring and inspection is the major form of maintenance;
- consequences may be very high (fire for gas pipelines and spills for oil pipelines);
- public safety is a primary concern;
- environmental damage may be substantial;
- regulatory requirements have to be met;
- failures can affect company reputation.

These attributes dictate that a risk assessment approach is common for pipelines and subsequently the use of risk assessment techniques is well developed for liquid and gas pipelines. In order to promote a positive view, this is often referred to as integrity management. The emphasis is especially on mitigating consequences related to safety of the public and the environment when a leak or rupture occurs. It is now common for pipeline companies to be required to prepare Integrity Management Plans (IMP). The objective of the integrity management program – executed in conjunction with other, general maintenance tasks – is to make the likelihood of a pipeline failure so remote within the life-cycle of the pipeline system, that the risk of failure can be considered to be controlled [16].

The estimation of pipeline reliability or failure rate is best done by quantitative methods, referred to as Quantitative Risk Assessment or QRA, in which the probabilities of failure are expressed as classical probabilities (a number between 0 and 1.0) and the consequences are measured by a common measure (e.g., number of casualties or a monetary value). Much effort is spent on producing models for estimating failure probabilities for different scenarios, for example, for offshore pipelines [17]. The resultant risk is commonly determined using a risk matrix such as the one in Figure 7.

				<1E-06	1E-06 to 1E-04	1E-04 to 1E-03	1E-03 to 1E-01	>1E-01
Potential Severity	Service Interruption	H&S Effect	Environmental Damage	Virtually impropable and unrealistic (Improbable)	Not anticipated to occur (Remote)	Occurrence considered rare (Rare)	Expected to occur at least once in 10 years (Probable)	Occurs several times a year (Frequent)
1 Slight	$100K to <$1M impact.	Slight injury requiring first aid only	Only minor cleanup required	L	L	L	L	M
2 Minor	$1M to <$10M impact.	Minor injury or restricted work only (reversible)	Clean up 100% achievable, no latent effect to environment	L	L	M	M	M
3 Moderate	$10M to <$100M impact.	Major injury i.e., single LTI with permanent disabilities	Localised environmental damage	L	M	M	S	S
4 Major	$100M to <$1B impact.	Single fatality or multiple LTI with permanent disabilities	Major environmental damage	L	M	S	S	H
5 Severe	>=$1B impact.	Multiple fatalities	Massive environmental damage	M	S	S	H	H

Figure 7 – Example of a risk matrix for a pipeline [16]

This methodology is also utilized during design of a pipeline known as Reliability-Based Design and Assessment, now incorporated in several standards, ASME B31.8 [18] and CSA Z662-11 [19]. This results in consistent safety/risk levels, optimizes resources to achieve the desirable safety level, can be used to objectively and quantitatively evaluate pipeline integrity performance and communicate this to regulators and the public. RBDA has been shown to be appropriate and practical for making operational decisions [20].

Dependability Value for Pipelines

The value of dependability is centered around ensuring safety of the public, employees and contractors as well as environmental protection while minimizing total cost over the long-term.

Being proactive in mitigating risk is especially critical toward the end of a pipeline's life. The risk for pipeline increases substantially as corrosion advances and begins to show up in more sections of the pipeline. At some point, replacement of major sections is needed and it is desirable from a cash flow point of view to spread these over a longer time period. The pipeline may even face being shutdown by the regulator. For oil pipelines, environmental damage from major leaks or ruptures may cause extended shutdowns of the line due to public pressure and cleanup can be extremely costly financially and in corporate reputation.

An example of the development of a Pipeline Integrity Program can be seen for a 14,000 km gas transmission system [21]. Prior methods for determining maintenance expenditures and their relative priority were based on non-quantitative methods. With emerging trends in the industry, the pipeline company recognized the benefits of developing a system integrity program that implemented a proactive strategy using both probability and consequence as the basis for inspection and maintenance decisions and a program that was entirely risk-based. The risk management strategy required that two fundamental steps be taken: (1) completion of a qualitative pipeline risk assessment for risk ranking purposes, and (2) the subsequent completion of quantitative assessments for the purpose of identifying actual risk levels and determining the appropriate maintenance actions.

A quantitative risk assessment tool, PIRAMID™ was used to calculate the failure rate, failure consequences and risk level along each pipeline and to facilitate the maintenance optimization process. The software calculates the level of risk associated with a specific pipeline segment and quantifies the expected reductions in the risk level that would result from carrying out various possible maintenance actions. It then develops cost comparisons for candidate maintenance actions in which the total annual cost for a line segment is presented. This information can then be used as the basis for integrity maintenance decisions and to develop maintenance plans for each segment in the pipeline system. The basic premise used in developing these plans is to ensure that acceptable safety standards are met and maintained (i.e. safety risk is kept at or below tolerable levels) at the lowest possible total cost.

Risk profiles were used to display variation in risk along the length of a pipeline segment and identify high-risk areas. An example profile of the variation in financial risk along an example pipeline segment is shown in Figure 8.

To evaluate maintenance alternatives the total expected cost for a pipeline segment was calculated for existing conditions and for each candidate maintenance option. The total expected cost is the sum of two components: 1) the average annual expected cost; and 2) the amortized maintenance cost.

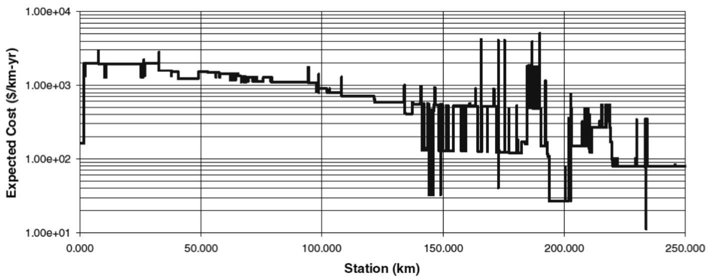

Figure 8 – Example of an expected cost risk profile [21]

Calculating the total expected cost for a range of time periods (i.e., one to fifteen years) for a scenario, the cost curve will generally start at a high value, drop with time until it reaches a minimum, and then increase again. The high initial value reflects the initial cost associated with implementing the scenario. This value drops with longer periods of time because as the useful life of the scenario increases, the initial cost is amortized over a longer period of time. At a certain time period, the rate of increase of the risk-related costs with time will exceed the rate of decrease of the initial cost, and the total cost will start to increase again. The optimal useful life (or optimal time to next maintenance event) for a given scenario is the lowest point on the total cost plot for that scenario. For the example shown in Figure 9, the optimal useful life is 6 years (2008) for the MFL inline inspection option and 7 years (2009) for the hydrostatic test scenario. Since the status quo does not involve any initial expenditure for maintenance activities, the corresponding cost curve does not have the decreasing portion.

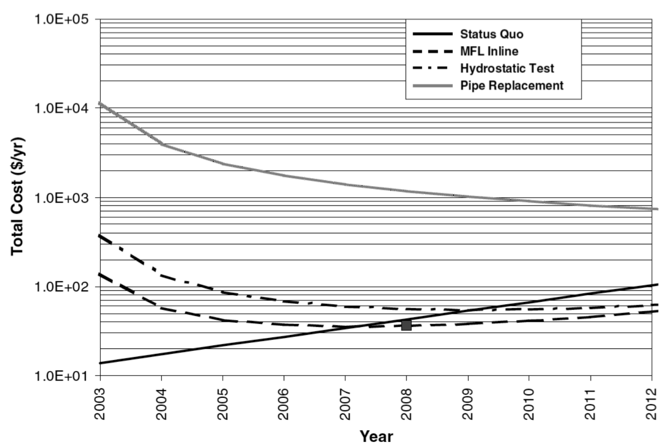

Figure 9 – Example of a cost profile for various scenarios [21]

The concept of an individual risk ratio (IRR), the ratio of calculated individual risk to the tolerable individual risk [21], was used to facilitate evaluation of life safety risk along the length of a pipe segment that includes variations in tolerable risk level. Where the IRR is greater than 1.0, the calculated individual risk exceeds the tolerable level at that location. If the individual risk ratio exceeds a value of 1.0 at any point along its length, it is said to violate its individual risk constraint.

Cost optimization analyses were carried out for each line segment found to have a maximum IRR greater than 1.0. The recommended maintenance plan for each segment was the minimum cost option that at the very least meets the criteria for tolerable individual risk level. The cost optimization analysis resulted in recommended maintenance actions that were implemented through a multi-year program.

Dependability Framework for Compression/Pumping Facilities

For machinery or equipment, the major dependability-related features of facilities are that:

- equipment consists of may 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 is particularly important and quite a few techniques exist to facilitate these as well as extensive standards, including international ones by IEC/TC56 [22]. A large body of literature exists to support this.

Design reliability studies use many techniques but in a recent survey [23], the most common ones used in industry are failure modes and effects analysis (FMEA/FMECA): 80%, reliability life data analysis (Weibull): 60%, FRACAS (Failure Reporting, Analysis and Corrective Action System): 56%, general statistics and Six Sigma: 53% and risk/safety analysis: 51%.

The main purpose of considering maintainability during design is to minimize the time to perform maintenance, both preventive and corrective, or even eliminating the need for maintenance, and thereby to reduce the cost of maintenance. There are several design activities that assist with these objectives [24] and these can be broken down into the following groups.

- Modularization
- Parts standardization and interchangeability
- Accessibility and disassembly/reassembly
- Reparable or throwaway
- Diagnosis and fault isolation
- Maintainability prediction and verification.

A major part of the responsibility rests with the manufacturer as illustrated in this paper about how maintainability was actively taken into consideration for the Solar Mercury™ 50 power generation package [25].

On the maintenance side, RCM (Reliability Centered Maintenance) has become very popular as a risk-based technique for determining the most effective maintenance tasks with the functional analysis based on a modified FMEA. Using reliability techniques such as Weibull analysis, the link can be made to Life Cycle Costing (LCC) and financial optimization and justification for preventive maintenance and replacement [26]. Other areas for reliability focus are spare parts optimization [27] and condition monitoring [28].

Dependability Value for Compression/Pumping Facilities

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 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 presented.

- Prepare a breakdown structure for applicable costs
- Determine costs for each breakdown element
- Collect failure and repair data (MTBF/MTTR or Weibull) from industry sources or actual experience
- Analyze system availability and reliability
- Select an LCC model (e.g. LCC = Acquisition cost + Operating cost + Failure cost + Support cost - Net disposal value)
- Estimate costs for each component of the LCC model
- Apply discounting over the time period of the study
- Determine the final LCC based on Net Present Value (NPV)
- Compare alternatives.

An example of a LCC comparison for pumps [29] is shown in Figure 10. This challenges the common practice of basing equipment selection on acquisition cost. The primary cost is that of operation with energy costs being the largest component. This is the main reason why the smart pumping system which uses a variable speed drive and better controls to stay in the optimum operating range has a lower life cycle cost.

Pump Type	Cost Element	Cost	Percent of LCC
Conventional Pumping System	Initial Cost	$ 20,600	3.0%
	Operating Cost	$ 636,900	92.5%
	Maintenance Cost	$ 31,000	4.5%
	Life Cycle Cost	$ 688,500	100%
Smart Pumping System	Initial Cost	$ 19,800	4.40%
	Operating Cost	$ 410,700	91.44%
	Maintenance Cost	$ 18,600	4.16%
	Life Cycle Cost	$ 449,100	100%
Parallel ANSI Pump	Initial Cost	$ 13,500	8.5%
	Operating Cost	$ 110,715	70.19%
	Maintenance Cost	$ 33,503	21.31%
	Life Cycle Cost	$ 157,718	100%
Multistage Centrifugal Pump (Present Study)	Initial Cost	$ 31,000	3.5%
	Operating Cost	$ 838,750	94%
	Maintenance Cost	$ 21,346	2.5%
	Life Cycle Cost	$ 890,265	100%

Figure 10 – Example of a cost profile for various pump scenarios [29]

CONCLUSION

It has been shown that dependability value is evident at three distinct but interrelated aspects of the pipeline operation: the pipeline system, the pipeline, and the compression/pumping facilities.

At the overall level of the pipeline system, the primary measure of dependability is availability, which is directly related to meeting delivery requirements for the customers. The example illustrates that cost optimization can be achieved by evaluating the tradeoff between the value of using redundant compression to increase delivery volumes versus the needed capital investment cost to realize the redundancy scheme.

The achievement of dependability for the pipeline portion is focused on risk assessment using qualitative and quantitative techniques to characterize pipeline reliability to minimize risk exposures to the public. Dependability value is assessed in terms of risk avoidance and risk prevention for the pipeline.

The dependability characteristics of availability, reliability, maintainability and supportability of the compression/pumping facilities affect safety and pipeline operational performance. The value of dependability drives the pipeline life cycle process in balancing acquisition and ownership costs.

The importance of dependability in creating value for pipeline organizations is a significant factor affecting major pipeline business decisions. Dependability has far-reaching implications and influences many aspects of achieving successful pipeline operation.

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