RISK-BASED ANALYSIS OF A THERMAL POWER PLANT UNAVALIABILITY DUE TO NATURAL GAS PIPELINE SUPPLY

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Abstract. *Fuel supply failure is one of the most common causes of power plant unavailability. Due to the great fuel consumption, usually large diameter pipelines supply fuel to the plant. The failure of a pipeline implies a reduction of fuel availability, impacting the power plant operational availability.*
This paper intends to apply the concepts of risk analysis to estimate the effects of a pipeline failure of natural gas supply to a thermal power plant.
The methodology is based on the application of failure modes and effects analysis method to list all possible failures (caused by aging phenomena or by accidents related to natural and non-natural phenomena) of large diameter pipelines and their consequences over the natural gas supply. Those consequences are measured in terms of the leakage magnitude and the time to restore the natural gas steady flow.
Taking in view the risk estimate due to the lack of fuel supply, the frequency of occurrence for the critical failures and their time to repair are defined based on databases related to pipelines failure considering the operational profile of a specific pipeline. Those values allow the estimation the pipeline unavailability.
The consequences of the gas supply failure for the power plant are estimated taking in view the reduction of the power generation capacity and are dependent on the power plant operational profile. Those consequences are expressed in monetary values.
A qualitative risk matrix is proposed and used to select the most critical failures for natural gas lack of supply. For those failures, the risk of power plant forced unavailability is expressed by the product of the unavailability of the pipeline times the consequences.
The proposed method is used to evaluate the risk of forced unavailability of a 200 MW nominal power plant.

Keywords*: Risk Analysis, Natural Gas, Pipeline, Power plant*

1. INTRODUCTION

Determination of the unavailability of thermal power plant is necessary in order to estimate the overall reserve capacity required in national generating and transmission systems as a compensation for the total unavailable capacity in all power generating plants. It is therefore of very great importance for public electricity utilities. Errors made in assessing the amount of reserve capacity required result either in excessive capital investment or in shortfalls in supplies to final consumers.

To increase the availability of a power generation plant and consequently to increase the energy offer for the subsystem in which this plant is inserted, it is fundamental to carry out a risk analysis. The aim of any risk analysis is to define a relation between the probability of the failure of a system(or component) and the consequences of that failure, usually expressed in monetary values.

For the present study, the failure events are characterized by the natural gas feeding pipeline failures and the failure consequences are defined by the impact on the thermal power plant generation capacity.

That analysis allows the plant manager to establish mitigation actions to reduce the lack of gas supply consequences on the plant availability.

2. RISK ANALYSIS CONCEPTS

According to Molak, (1996), risk analysis is a body of knowledge (methodology) that evaluates and derives a probability of an adverse effect of an agent (chemical, physical, or other), industrial process, technology, or natural process. Definition of an "adverse effect" is a value judgment. It could be defined as death or disease (in most cases of human health risk analysis); it could be a failure of a thermal power plant, or a chemical plant accident, or a loss of invested money. Although there are many types of risk analysis, some common elements are necessary to qualify the process as risk analysis. Those elements are: 1. Hazard (agent) identification; 2. Dose-response relationship (how is quantity, intensity, or concentration of a hazard related to adverse effect); 3. Exposure analysis (who is exposed? to what and how much? how long? Other exposures?) 4. Risk characterization (reviews all of the previous items and makes calculations based on data, with all the assumptions clearly stated; often the conclusion is that more data and/or improvement in methodology is needed and that no numerical risk number can be derived to express accurately the magnitude of risk)

Deciding WHAT is an adverse effect (and to some extent hazard identification) is a value judgment that can be made by well-informed citizens. The consideration of other components of risk analysis is a complex process, which in order to be properly conducted requires extensive training. Risk analysis may be a risky business if performed by untrained people. Because of its interdisciplinary nature and complexity, risk analysis requires an appropriate amount of time to evaluate all pertinent data, even when one deals with problems of less ocurrence.

In the other hand, (Muhlbauer, 2004) defines Risk as the probability of an event that causes a loss and the potential magnitude of that loss. By this definition, risk is increased when either the probability of the event increases or when the magnitude of the potential loss (the consequences of the event) increases. The definition of risk is often expressed as a mathematical relationship showed in Eq.(1).

$$Risk = (event\ likehood)x\ (event\ consequence) \tag{1}$$

According to Eq.(1) a risk is often expressed in measurable quantities such as the expected frequency of human fatalities or injuries, or economic loss. Monetary costs are often used as part of an overall expression of risk. However, the difficult task of assigning a monetary value to human life or environmental damage is necessary to use this as a metric.

A complete understanding of the risk requires that three questions should be answered: 1. What can go wrong? 2. How likely is it? 3. What are the consequences? By answering these questions, the risk is defined.

3. NATURAL GAS PIPELINE RISK ANALYSIS

The pipeline risk analysis is based on frequency determination of failures occurrence and on evaluation of consequences associated with those failures.

The identification and frequency determination of failures can be characterized by getting for the following questions: 1. What can go wrong? 2. How likely is it?

In order to answer the first question there are methodologies to identify the main failures modes of pipelines systems. According to Muhlbauer, (2004), the failure of gas pipeline can be simply defined as “the unintentional release”. Loss of integrity is another way to characterize pipeline failure. However, a pipeline can fail in other ways that do not involve loss of contents. A more general definition is the failure to perform its intended function.

As a first step it is necessary to define which are the failure modes that the gas pipelines can present. For the identified failure modes, it necessary to identify which of them can cause as consequence the unavailability of gas for the final consumer during a given period of time. In such a way, the unavailability period must not only be determined as the probability distribution of occurrence of a failure, but also by the time to repair probability distribution. The consequences of the failure for the final consumer, as function of the time, can be quantitatively evaluated.

Another complex point associated with the definition of failure is the fact that some pipeline systems like natural gas distribution systems tolerate some amount of leakage (unlike most transmission pipelines). Therefore, they might be considered to have failed only when the leakage becomes excessive by some measure.

The term leakage implies that the release of pipeline contents is unintentional. Distinguishing a failure from a venting, de-pressuring, blow down, flaring, or other deliberate product release.

Failure occurs when the structure is subjected to stresses beyond its mechanical capacities, resulting in reduction of structural integrity. Internal pressure, soil overburden, extreme temperatures, external forces, and fluctuating loading are examples of loads that must be resisted by pipelines. Failure or loss of strength leading to failure can also occur through loss of material due to corrosion or to mechanical damage.

By the commonly accepted definition of risk, it is apparent that the probability of occurrence of a failure is a critical aspect for all risk assessments. Some estimate of the probability of failure will be required in order to assess risks. This addresses the second question of the risk definition: “How likely is it?”

Statistical analysis requires failure data associated with past observations from which inferences can be drawn. Data interpretation becomes more and more necessary to obtain meaningful estimates. As systems become more complex, more variable in nature, and where failure observations are less available, the historical frequency approach will often provide answers that are highly inappropriate estimates of probability.

3.1. Hazard Identification. “What can happen?”

Considering the pipeline failure definition: “incapacity of transport gaseous fluid from the producer to its final destination with specified pressure and outflow”, several failures modes can be indentified, as for example, not intentional gas release, loss of structural integrity and blockage.

For the present study failure modes such delivered gas pressure and flow in disaccordance with the specified value and the gas chemical properties out of the standards must be taken in consideration, once their occurrence can compromise or make impracticable the operation of the power plant.

According to Naval Surface Warfare Center Carderock Division (2006), most failures of a pipe assembly occur at or within the interconnection points. The life of a pipe system depends not only on the material, but on the installation quality and on the surrounding environment. The following failure modes need to be considered when evaluating a pipe assembly as for reliability studies:

- Burst failure caused by internal pressure,
- Buckling caused by external pressure (not relevant for buried pipelines),
- Bending failure,
- Stress related failure from applied loads, and
- Excessive leakage at the interconnection points.

Table 1, provides a summary of potential failure modes of a pipeline assembly.

Table 1 - Typical Failure Modes of Pipe Assemblies. (Naval Surface Warfare Center Carderock Division, 2006)

Failure Modes	Failure Cause	Failure Effect
Damaged connector	• Corrosion • Improper torque on fitting • Gasket failure • Operation error • Ground movement • External interference	Gradual increase in system leakage
Burst failure	• rapidly applied load • pressure transients • Ground movement • External interference	Catastrophic pipeline assembly failure
Bending failure	• Bend radius less than allowable	Immediate leakage above system requirements
Crack in rigid pipe	• External interference	System leakage
Leakage	• Chemical incompatibility with fluid (corrosion) • Chemical attack/improper thread sealant • Ultraviolet deterioration	Gradual increase in system leakage
Fatigue failure	• Water hammer from upstream component	System fluid leakage

3.2. Frequency, statistics, and probability

Historical failure frequencies-and the associated statistical values- are usually used in a risk assessment. Historical data, however, are not generally available in sufficient quantity or quality for most event sequences. Furthermore, when data are available, they are usually rare-event failure data in many years of service on a specific pipeline.

The European Gas Pipeline Incident Data Group (EGIG) has developed an European gas pipeline incident database of fifteen European countries on almost 3.15 million km of pipelines.

The Tab. 2. shows the percentage proportion of failures causes presented on that reference.

Extrapolating future failure probabilities from small amounts of information can lead to significant errors. However, historical data are very valuable when combined with all other information available to the evaluator.

Table 2 – Pipeline incident causes. (European Gas Pipeline Incident Data Group, 2008)

Cause	Overall Percentage [%]
External interference	49.6
Construction defect / Material failure	16.5
Corrosion	15.4
Ground movement	7.3
Hot-tap made by error	4.6
Other and unknown	6.7

3.3. Failure rates

According to Souza (2003), the failure rate, $\lambda(t)$, can be defined as the system failure probability $(\lambda(t)\ \Delta t)$ in a time $t<t+\Delta t$, considering that the system is performing normally at the time $t = t$". The elementary product $\lambda(t) * \Delta t$ is a conditional failure probability, given by Eq. (2).

$$\lambda(\mathrm{t})\ \Delta t = \mathrm{P}\ (\boldsymbol{t} < t + \Delta t \mid \boldsymbol{t} > t\ ) \tag{2}$$

On the other hand, according to Muhlbauer (2004), a failure rate is simply a count of failures over time. It is usually a frequency observation of how often the pipeline has failed over some previous period of time. A failure rate can also be a prediction of the number of failures to be expected in a given future time period. The failure rate is normally divided into rates of failure for each failure mechanism.

The historical rate of failures for a particular pipeline system may tell an evaluator something about that system. Figure 1 presents a graph that illustrates the well-known "bathtub" shape of failure rate changes over time. This general shape represents the failure rate for many manufactured components and systems over their lifetimes.

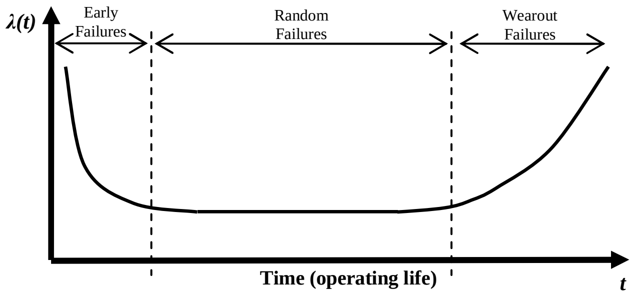

Figure 1 - Common failure rate curve - bathtub curve. (Lafraia, 2001)

The modes in which a pipeline can fail can be categorized according to the behavior of the failure rate over time. When the failure rate tends to vary only with a changing environment, the underlying mechanism is usually random and should exhibit a constant failure rate as long as the environment stays constant. When the failure rate tends to increase with time and is logically linked with an aging effect, the underlying mechanism is time dependent.

There is certainly an aspect of randomness in the mechanisms labeled time dependent and the possibility of time dependency for some of the mechanisms labeled random. The labels point to the probability estimation protocol that seems to be most appropriate for the mechanism.

3.4. Pipeline failure frequency

An important risk analysis stage is the potential hazard frequency determination. This frequency must be determined in the form of a probability distribution.

There are several ways to obtain the mechanical system probability distribution. The following ones are distinguished:

- Analyzing historical data failures of the system in study,
- Analyzing historical data of similar systems,
- Reliability tests, mainly the accelerated tests of life, and
- Reliability prediction mathematical models based on chemical composition, geometric parameters, mechanical loads, among others.

In many cases, due to absence of historical data and the impossibility to plan and to execute reliability tests, failure frequency prediction models are used. These models can be based on similar pipeline historical data.

3.5. Similar Systems Failure Data Historical

In order to quantify the pipeline frequency failure the use of specific units that take in account the number of failure for unit of length per unit of operational time is common. The units most commonly used by are the frequency of specific incident per:

- 1000 kilometers per year (per km.yrs) which is equivalent to per meter per million years (x 10^{-6} per year)
- or per kilometer per thousand years (x 10^{-3} per year)

Among the databases regarding failures in pipelines the one organized by the European Gas Pipeline Incident Data Group (2008) is distinguished. This database presents no intentional incidents in gas pipelines that caused significant volume losses. That report deals with steel tubing, designed to operate with at least 15 bar of internal pressure and excludes from the analysis ground handling equipment, such as, valves, compressors among others.

The report analyzed failure data collection between the years of 1970 and 2007 from various companies in 20 European countries of the Europe totalizing 3.15 million km of gas pipelines, concluding that the statistics of incidents collected in the database give reliable failure frequencies. The overall incident frequency is equal to 0,37 incidents per year per 1,000 km over the period 1970 to 2007.

Through the data presented in Tab. 3 it is possible to determine the equivalent failure rate of each one of the failure causes. These independent failure rates can be assumed if exponential distribution of the time to failures con be used and if assume that the events are mutually exclusive. Thus a distribution of this failure rate becomes in accordance with the percentage of the observed events. The results for the failure rates of each one of the causes of failures in the European gas pipelines are shown in Tab. 3. These data are presented graphically in Fig. 2.

Table 3 - Failure rates of incident causes by percentage

Cause	Overall Percentage [%]	Failure rate [incidents per year per 1,000 km]
External interference	49.6	0.18
Construction defect / Material failure	16.5	0.06
Corrosion	15.4	0.06
Ground movement	7.3	0.03
Hot-tap made by error	4.6	0.017
Other and unknown	6.7	0.025
Total	100	0.37

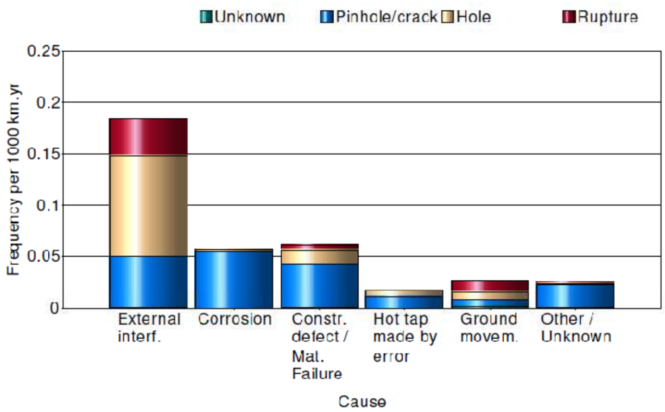

Figure 2 - Relationship between cause and size of leakages (European Gas Pipeline Incident Data Group, 2008)

3.6. Consequences

Inherent in any risk evaluation is a judgment of the potential consequences. This is the last of the three risk-defining questions: If something goes wrong, what are the consequences? Consequence implies a loss of some kind. Many of the aspects of potential losses are readily quantified. In the case of a major hydrocarbon pipeline accident (product escaping, perhaps causing an explosion and fire), we could quantify losses such as damaged buildings, vehicles, and other property; costs of service interruption; cost of the product lost; cost of the cleanup; and so on. Consequences are sometimes grouped into direct and indirect categories, where direct costs include property damages, damages to human health, environmental damages, loss of product, repair costs and cleanup and remediation costs.

Indirect costs can include litigation, contract violations, customer dissatisfaction, political reactions, loss of market share, and government fines and penalties.

The monetary value of losses is frequently used to quantify the consequences. That value is a basic information in the determination of how much it is disposed to spend to prevent that accident.

In this article the risk of accidents, losses of human lives or any deriving loss directly related to the failure incident of the gas pipeline will not be analysed. Only the consequences for the final consumer of the gas pipeline will be considered. In such a way the quantification of the consequences in this analysis is limited to the unavailability costs on the power plant.

Analyzing the impact of the failures on the gas pipelines it is possible to associate the causes of failures with leakage size (Pinhole, hole or rupture). The (European Gas Pipeline Incident Data Group, 2008) presents this relation also shown in Fig. 2. Table 4 shows the values of failure rates related to the causes of failures and to the size of leak.

Analyzing the consequences of the failures for the thermal power plant it is possible to evaluate the impact over the final consumer. The main consequence on the thermal power plant is the occurrence of forced unavailability due to lack of fuel supply.

The power plant down time associated with forced outage or forced de-rating state must be estimated from the failure data collected on the power plant. Owing to the lack of data, the down time and the number of maintenance personnel involved in the pipeline repair are estimated by interviewing the maintenance personnel.

Table 4 - Failure rates of incident causes by percentage

Cause	Failure rate [incidents per year per 1,000 km]			
	Pinhole /crack	Hole	Rupture	Total (Percentage)
External interference	0,05	0,1	0,03	0,18 (48,6%)
Construction defect / Material failure	0,04	0,02	0,01	0,07 (18,9%)
Corrosion	0,05	0,005	<0,001	0,055(14,9%)
Ground movement	0,005	0,005	0,015	0,025(6,7%)
Hot-tap made by error	0,01	0,005	<0,001	0,015(4,1%)
Other and unknown	0,021	0,001	0,003	0,025(6,8%)
Total (Percentage)	0,176 (47,5%)	0,136 (36,8%)	0,058 (15,7%)	0,37 (100%)

The production loss cost can be estimated using Eq. (3).

$$PLC = DT \bullet PWP \bullet SP \tag{3}$$

where:
PLC: production loss cost [$],
PWP : Power (warranty physics) [MW],
SP : selling price of generated electricity [$],
DT : power plant down time [h].

For the Brazilian electrical energy market, the evaluation of the production loss cost due to power plant unavailability depends on the bilateral agreement between the electrical energy generator agent (power plant owner) and the Brazilian Electricity Regulatory Agency (ANEEL). Those agreements determine prices and sales volume of electrical energy during certain periods.

If the amount of delivered energy is smaller than the sales volume defined in the agreement, the generator agent may suffer penalties including fine payment or reduction of sales volume in future contracts. Those penalties affect production loss cost.

In order to avoid those penalties the generator agent can buy electrical energy in a spot market to accomplish with the contracted sales volume. The spot market is a segment of the wholesale electrical energy market in which energy not contracted for bilaterally and surpluses over those amounts contracted for are brought and sold. The price varies on-demand and greatly affects the power plant production loss cost.

3.7. Down Time and Repair Time

It is now necessary to introduce Mean Down Time and Mean Time to Repair (*MDT*, *MTTR*) concepts. There is frequently confusion between the two form and it is important to understand the difference. Down time, or outage, is the period during which equipment is in the failed state. According to Smith (2001), a formal definition is usually avoided, owing to the difficulties of generalizing a parameter which may consist of different elements according to the system and its operating conditions.

It is necessary to define the down time as required for each system under given operational conditions and maintenance arrangements. *MTTR* and *MDT*, although overlapping, are not identical. Down time may start before repair. Repair often involves an element of checkout or alignment which may extend beyond the outage. The definition and use of these terms will depend on whether availability or the maintenance resources are being considered.

The significance of these terms is not always the same, depending upon whether a system, a replicated unit or a replaceable module is being considered. According to Smith (2001), the main components of down time and repair time are: *a) Realization Time; b) Access Time; c) Diagnosis Time; d) Spare part procurement; e) Replacement Time; f) Checkout Time; g) Alignment Time; h) Logistic Time; i) Administrative Time.*

Activities (b)–(g) are called Active Repair Elements and (h) and (i) Passive Repair Activities. Realization time is not a repair activity but may be included in the *MTTR* where down time is the consideration. Checkout and alignment, although utilizing manpower, can fall outside the down time. The Active Repair Elements are determined by design, maintenance arrangements, environment, manpower, instructions, tools and test equipment. Logistic and Administrative time is mainly determined by the maintenance environment, that is, the location of spares, equipment and manpower and the procedure for allocating tasks.

The distribution most commonly used to describe the actual distribution of system repair time is the lognormal because it reflects short duration repair-time, a large number of observations closely grouped about some modal value, and long repair-time data points.

The repair times t_i for any unit are observed and registered. Using log normal distribution to estimate the *MTTR* of the unit, the value of *MTTR* can be calculated through the use of in Eq. (4).

$$MTTR = \int_0^\infty t \frac{1}{S.t\sqrt{2\pi}} exp\left(-\frac{1}{2}\left(\frac{\ln t - \bar{t}}{S} \right)^2 dt \right) \tag{4}$$

where:
$\bar{t}$ is the mean value in the logarithm domain, and
S is the standard desvaiton value in the logarithm domain.

3.8. Risk Matrix

One of the simplest risk assessment structures is the decision matrix analysis. A risk matrix is a twodimensional presentation of likelihood and consequences using qualitative metrics for both dimensions. According to this method, risk is characterized by categorizing probability and consequence on the two axes of a matrix. Risk matrices have been used extensively for screening of various risks. They may be used alone or as a first step in a quantitative analysis.

This approach may simply use expert opinion or a more complicated application might use quantitative information to rank risks. Figure 3 shows a matrix model. While this approach cannot consider all pertinent factors and their relationships, it does help to crystallize thinking by at least breaking the problem into two parts (probability and consequence) for separate examination.

Likelihood	Consequences				
	I None	II Significant	III Minor	IV Major	V Extreme
Likely	High	High	High	Extreme	Extreme
Unlikely	High	High	High	High	Extreme
Very Unlikely	Medium	Medium	High	High	High
Doubtful	Medium	Medium	Medium	Medium	High
Highly Unlikely	Low	Medium	Medium	Medium	High
Extreme Unlikely	Low	Low	Low	Medium	Medium

Figure 3 - Simple risk matrix. (adapt. of SMITH, 2001)

According to Kreith & Yogi (2007), the likelihood metric can be constructed using the categories shown in Tab. 5, whereas the consequences metric can be constructed using the categories shown in Tab.6. These consequence categories focus on production loss aspects of consequences and the economic impact, and should be adjusted to meet specific needs of industry and/or applications.

Table 5 - Likelihood Categories for a Risk Matrix (Kreith & Yogi, 2007)

Category	Description	Annual Probability Range
A	Likely	> 0.1 (1 in 10)
B	Unlikely	> 0.01 (1 in 100) but < 0.1
C	Very Unlikely	> 0.001 (1 in 1,000) but < 0.01
D	Doubtful	> 0.0001 (1 in 10,000) but < 0.001
E	Highly Unlikely	> 0.00001 (1 in 100,000) but < 0.0001
F	Extremely Unlikely	< 0.00001 (1 in 100,000)

Table 6 - Consequence Categories for a Risk Matrix (adp. Kreith & Yogi, 2007)

Category	Description	Examples	Cost
I	Extreme	Extreme economic impact	≥ \$ 10,00,000 but < \$ 100,000,000
II	Major	Major economic impact	≥ \$ 1,000,000 but < \$ 10,000,000
III	Significant	Significant economic impact	≥ \$ 100,000 but < \$ 1,000,000
IV	Minor	minimal economic impact	≥ \$ 10,000 but < \$ 100,000
V	None	No significant consequence.	< \$ 10,000

3.10. Unavailability determination of the Thermal Power Plant due to fuel supply

The unavailability frequency of the gas pipeline must be associated with the plant natural gas consumption profile. Depending on the consumption profile of the thermal power plant a different scenario of risk is characterized. The worst scenario can occur when an failure in the pipeline occurs at the moment where the thermal power plant is being requested to generate power by the Brazilian Electricity Operator Agency (ONS)

The unavailability frequency of the plant can be determined through a conditional probability. Thus, the probability of the plant to be unavailable is the probability of the gas pipeline unavailability given that the plant is generating electric power.

The probability of the gas pipeline to be unavailable is given by Eq. (5)

$$\bar{A}_{Pipeline} = 1 - A_{pipeline} \cong \lambda_{pipeline}.MTTR_{pipeline} \tag{5}$$

To determine the probability of the thermal power plant to be unavailable the unavailability must be multiplied by the generation probability. This probability can be found through the generation data of the power plant. Equation (6) can be used estimate the probability of the plant to be generating in one day any of one year operational.

$$P(generation\ of\ power\ plant) = \frac{Number\ of\ days\ of\ annual\ generation}{365\ days} \tag{6}$$

And the power plant unavailability is calculated as showed in the Eq. (7).

$$\overline{A_{power\ plant}} = \overline{A_{pipeline}}\ .P(generation\ of\ power\ plant) \tag{7}$$

3.10 Risk Function of thermal power plant

For the risk of gas supply failure, the thermal power plant probability is estimated by the unavailability of the thermal plant and the consequence can be estimated by the addition of the cost of the purchase of energy and the cost of the penalties and fines imposed by the ONS.

Then, the expression of the risk in study can be express for Eq. (8)

$$Risk = \overline{A_{Power\ plant}} * PLC \tag{8}$$

4. CASE EXEMPLE: 200 MW NOMINAL RATE THERMAL POWER PLANT

The example used as an application of the proposed methodology is a combined cycle gas power plant with nominal power around 200 MW and gas natural consumption close to 750 thousand of m^3 day.

The natural gas is delivered by the Bolivia-Brazil gas pipeline (Gasbol), possessing 3150 kilometers of extension since the production field until the final consumer (case example).

For determination of the probability of the plant to be generating in a give time the following hypotheses are made:

- Every day of generation requested for the ONS are considered.
- The average of the daily consumption will be considered as 700,000 m^3 day for all days that the power plant is requested.
- It is assumed that consumption distribution during this year is equal to the distribution of ONS request, therefore any operational unavailability of the plant is not considerate.

This power plant operates about 80 days per year, then the probability of being operational when the pipeline failures is obtained from Eq. (6). Thus the probability that the plant is operational at the moment that occurs a failure in the gas pipeline is approximately 22%.

The risk matrix for gas pipeline in study can be found from the study of the likelihoods and the consequences on the system. The probabilities can be found through the knowledge of the length of the gas pipeline and for the analysis of failure rates with each one of the respective causes of the failures presented in the Tab. 4. The consequences the same ones must take in to consideration the time of repair of the gas pipeline and the power plant scenario of generation.

Aiming at evaluating the frequency of occurrence of events that can cause the unavailability of the gas pipeline the values of failure rate presented in the Tab. 4 are considered. Those data are considered for a 1,000 km gas pipeline, however the gas pipeline in study possess a total length of 3,150 km. Thus all the values presented in the Tab. 4 must be multiplied by a factor of 3.15. Then, the corrected data are presented in Tab. 7.

Table 7 also present the causes of the failures with the respective occurrence rates. Aiming at fully defining the risk concept and conceiving a risk matrix it is necessary to quantify each one of the consequences associated with main pipeline failure modes. Through hypothetical data of MTTR of the gas pipelines, used here only for the demonstration of the methodology, the procedure is presented for calculating the risk which is summarized in the Tab. 8.

Table 8 also presents the values of failure rates for each one of the failure modes in failures per hour. The values of *MTTR* and the failure rate of the gas pipeline are used to calculate the unavailability. This is made in agreement with Eq. (5).

From the unavailability of the gas pipeline and from the profile of fuel consumption of the thermal power plant under study, the unavailability of the power plant due to gas shortage for generation is calculated by using Eq. (6). The results also are shown in Tab. 8.

Table 7 - Failure rates of incident causes by percentage from 3,150 km pipeline

Cause	Failure rate [incidents per year per 3,150 km]			
	Pinhole /crack	Hole	Rupture	Total (Percentage)
External interference	0,158	0,315	0,095	0,567 (48,6%)
Construction defect / Material failure	0,126	0,063	0,032	0,221 (18,9%)
Corrosion	0,158	0,016	0,000	0,173(14,9%)
Ground movement	0,016	0,016	0,047	0,079(6,7%)
Hot-tap made by error	0,032	0,016	0,000	0,047(4,1%)
Other and unknown	0,066	0,003	0,009	0,079(6,8%)
Total (Percentage)	0,554 (47,5%)	0,428 (36,8%)	0,183 (15,7%)	1,166 (100%)

For the calculation of consequences of the unavailability of the plant Eq. (3) is used. This one aims at quantifying monetarily the consequences of the failures. Assuming the physical warranty of the plant as 76 MW average and the price of the electricity at the spot market as $ 330/MWh the cost of unavailability for one hour can be calculated as:

PLC = DT•PWP•SP= 1•76•330=25,080 $/hour

For each one of the consequences the causes the gas pipeline failure an unavailability of the gas pipeline exists, and therefore, a proportional cost to the *MTTF*, which accounts reflects in the plant as power plant down times (*DT*). Thus, in Tab.8 the calculation of production loss cost estimate in each one of the possible failure modes is presented.

Table 8 – Pipeline and Power Plant Risk Calculation

	Pinhole /crack	Hole	Rupture
MTTR (hours)	2,37	22,20	524,92
$\lambda_{pipeline}$ (failure/hour)	6,32.10^{-5}	4,89.10^{-5}	2,09.10^{-5}
$\overline{A_{pipeline}}$	0,015%	0,108%	1,097%
$\overline{A_{power\ plant}}$	0,003%	0,023%	0,241%
PLC [$/hour]	59,439	556,776	13,164,994
Risk [$/hour]	1.96	133	31,800

$P(generation\ of\ power\ plant) = 0{,}22$

Without considering the cost of the contract penalties, the production loss cost can be used as cost of the consequences in the risk analysis. Thus, from Eq. (8) the Risk of unavailability of the plant is determined. The results also are presented in the Tab. 8. This risk can be understood as an operation cost that must be saved for eventual unavailability due to fuel supply failures. As a strategic decision, this value could be considered as a fixed cost of operation of the plant.

For example, in an operational period of 8,760 hours, the power plant approximately possesses a cost associated to the risk of natural gas lack of supply in the order of $ 1,165,000 per year in the case of failures due to the presence of holes in the gas pipeline.

For identification of the cases of extreme and high risk it is necessary to calculate the probability of occurrence of each one of the failures that lead to the three consequences scenarios. For this it is necessary to assume an exponential distribution in which the failure probability can be calculated through the Eq. (9).

$$F(t) = e^{-\lambda . t} \tag{9}$$

The Tab. 9 presents the probability of each one of the failure modes studied for one year operational.

Table 9 - Failure probability of gas pipeline failure modes

	Pinhole /crack	Hole	Rupture
F(t)	42,53%	34,81%	16,72%

In accordance with the classification of established by Kreith & Yogi (2007) and presented in the Tab. 5, all the events are classified as likely.

The consequences can be classified in accordance with Tab.6. Thus “pinhole/crack” presents “minor” consequence, the consequences proceeding from “holes and ruptures” can be classified as significant and extreme, respectively.

Thus, the events that present higher frequency and greater consequences must be prioritized. In this case the events that cause rupture must be mitigated. Analyzing Tab. 7 one can conclude that the biggest cause of rupture in the gas pipelines is the external interference. These analyses are taken as a base for taking decisions in investments in safety of the installations of gas pipelines or even for the possibility of the alternative fuel use in the energy generation.

4. CONCLUSIONS

In order to determine the national capacity of electrical energy generation, knowledge of the availability of its generating units is fundamental. Aiming at estimating this availability and planning the future operations of the plant, the availability of the fuel is used for the thermal power plant availability estimation. To evaluate the availability of the transport systems the risk analysis concepts are used. This methodology is based on the evaluation of the pipeline failure frequencies and consequences that cause power plant unavailability. The main consequence on the power plant is the forced unavailability due to gas lack. The severity of the consequences on the thermal power plant can be estimated as being directly proportional the *MTTR (*Mean Times To Repair) of the gas pipeline.

Three types of consequences of failures on gas pipelines had been evaluated: Pinholes, Holes and Rupture. For them it was attributed statistical data: Failure rate (λ) and *MTTR*. Historical data of European gas pipelines was used for estimating the failure rate. The estimated failure rate used in this work was 0,37 failures per 1000 km per year. Also it was estimated values of *MTTR* depending on each one of the failures presented by the pipeline.

As main results of this article, one has the methodology to calculate the production loss cost, which can be understood as the monetary evaluation of the consequences of failures the gas pipeline and the quantitative evaluation of the risk plant unavailability due gas supply problems. These data can be used for a strategic investment decision.

It is distinguished that the data used in this paper was obtained through analysis of similar systems. Therefore the trustworthy application of the methodology depends on the collection of reliable data.

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6. RESPONSIBILITY NOTICE

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