METHODS TO IMPROVE PROCESS SAFETY PERFORMANCE THROUGH FLANGE CONNECTION LEAK PREDICTION AND CONTROL

A Thesis

by

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ABSTRACT

Process safety is a task of preventing leaks. Leak prevention is critical because pressure vessels and piping assets in chemical plants are fabricated from materials which have limited corrosion resistance. When corrosive compounds are processed in these assets, they may suffer degradation over time due to thinning, cracking, or loss of their material properties. This problem is partially controlled by applying a safety margin known called a corrosion allowance. The corrosion allowance is determined by predicting the asset's expected corrosion rate and its service life. However, this fixed safety margin does not consider the inherent uncertainty in an individual asset's degradation rate due to variability in the material's corrosion resistance, the operating parameters of the process, and the inspection techniques used to measure the progression of corrosion damage over time. Consequently, deterministic analysis is not capable of precisely estimating an asset's safe operating life during its design stage.

One of the most likely areas for leakage to occur in process equipment is at the flange connections that join assets together. Risk analyses for planning inspections of fixed equipment and piping usually treat flanges as components of their parent asset. This thesis focuses on methods to improve prediction and control of corrosion and leakage at flange connections in particular. Flange connection seal tightness can be monitored through vibration-based Non-Destruction Testing (NDT). The data gathered from this monitoring can be used to update risk models for flange connection leakage. Hierarchical Bayesian Network methods of modeling risk are demonstrated in this thesis to be capable of predicting probability of seal failure based on the mean and variance of failure rates in a population of flange connections. This allows for

prediction of the probabilities based on corrosion and leak events in the plant. The results of inspection techniques are used as inputs to this risk model, enabling probabilistic decision-making.

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NOMENCLATURE

API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
BFC	Bolted Flanged Connection
DNV	Det Norske Veritas
HSE	Health and Safety Executive
NDE	Non-Destructive Examination
QRA	Quantified Risk Analysis
RBI	Risk Based Inspection
SHM	Structural Health Monitoring
SWUT	Shear Wave Ultrasonic Testing
PTFE	Poly-tetrafluorethane

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1. INTRODUCTION

Flange connections play an important role in all process systems, allowing pressure equipment assets to be assembled and disassembled without making weld connections. Due to the large numbers of flange connections in a plant, they are often a failure point at which process leaks occur. Perhaps the most well-known incident related to the failure of a sealing connection was the Challenger Space Shuttle disaster. On January 28, 1986, seven crew members were killed when the space shuttle Challenger exploded at just over a minute into the flight. The failure investigation concluded that the explosion was caused by a failure of the solid rocket booster O-rings to seal properly. This allowed hot combustion gases to leak from the side of the booster and burn through the external fuel tank. Further analysis attributes this O-ring failure to faulty design of the solid rocket boosters which failed to take into account the insufficient low-temperature ductility of the O-ring material and of the joints that the O-ring sealed [1]. The key point is that the accident occurred despite the engineers being aware of the potential issue beforehand.

This tragic accident provides an invaluable lesson that failure of a component may have catastrophic consequences, even if the component was perceived to be insignificant to the overall system. In other words, this is a classic example of the proverb, "*For want of a nail, the Kingdom was lost*", occurring in the real world. The original rhyme goes as follows:

For want of a nail, the shoe was lost.

For want of a shoe, the horse was lost.

For want of a horse, the rider was lost.

For want of a rider, the battle was lost.

For want of a battle, the kingdom was lost.

And all for the want of a horseshoe nail.

Unfortunately, almost 30 years after the Challenger explosion, high consequence failures at flange connections continue to occur in the process industries as shown in Table 1.

Table 1 Several high consequence incidents related to flange connection leaks

No.	Year	Facility	Location	Consequence	Failure mode
1	1986	BASF [2]	Ludwigshafen, Germany	Large fire for 40 minutes due to depressurization.	Multiple gasket failures on NH3 synthesis loop due to vibration
2	1999	Rhone-Poulenc [3]	Charleston, WV	Release of 133 pounds of a toxic chemical.	Gasket failure in line leading to MIC unit.
3	2004	Huntsman Polymer Plant [4, 5]	Midland, Texas	Release of more than 100 tonnes of highly pressurized natural gas liquids	Metal gasket failure in a wellhead flange.
4	2004	Degussa Chemical Plant [6]	Theodore, Alabama	100 lb. release of gaseous ammonia	Malfunctioning gasket on tank nozzle.
5	2005	Fermi Nuclear Power Plant [7]	Newport, Michigan	Leak of non-radioactive cooling water, plant shutdown	Damaged gasket on inlet to one of 14 air cooling units.

Table 1 Continued

No.	Year	Facility	Location	Consequence	Failure mode
6	2005	BP Amoco [8]	Whiting, Indiana	Free hydrocarbon product detected in monitoring wells	Evidence of a prior leak on the fiber ring joint gasket. Flange faces had evidence of possible leak at two different locations.
7	2009	Columbia Gas Transmission Corp. [9]	Clendenin, WV	Uncontrolled gas discharge into compressor building, gas allowed to being vented from blowdown valves for 90 minutes.	Compressor head end gasket failure.
8	2010	Sunoco [10]	Philadelphia, PA	1700 barrel release of Vacuum Gas Oil (VGO) from the FM-1 pipeline into an open in-ground valve pit.	Failure of flange connection in a deadleg leading to pig trap.
9	2012	Citgo Refinery [11]	Corpus Christi, Texas	300-500lb release of Hydrofluoric Acid (estimated)	Metal gasket failure on a HF Alkylation unit piping flange

The recent nature of several of these releases associated with flange connection failure indicate that the problem of maintaining flange connection integrity is still an issue. The causes of leakage are known, but effective risk management is not a reality for many process plants.

2. QUANTIFIED RISK ANALYSIS

Quantified Risk Analysis (QRA) is used to evaluate process plants and determine the risk associated with scenarios where a failure could cause a process safety incident. These models consider the likelihood of failure events which may only occur less than once in ten thousand to one million operating years. Therefore, the models must account for random failure which happens independently of time and also degradation of the plant over time which leads to increased probability of a failure. After calculating this probability and the associated consequences, process safety management proscribes mitigation activities to reduce the likelihood for the failure to occur. Of these mitigation activities, inspection may be planned, which has the effect of reducing the uncertainty in the condition of the asset, which in turn reduces the probability that a failure will occur.

Industry standards for risk-based inspection use models to approximate the change in probability of failure over time due corrosion kinetics, along with a variance to account for the uncertainty in the effect that the corrosion will have an asset's condition. This parameter is called a damage factor, and it is combined with a generic failure frequency to determine an asset's probability of failure. Based on the probability and consequences of a failure, a risk is calculated and a mitigation event such as an inspection is scheduled before the vessel is predicted to exceed an acceptable risk level [12]. The industry standard codes for risk-based inspection are intended to calculate point value probabilities, and they are not currently capable of considering the likelihood distribution of outcomes from a failure. They also do not represent a system approach, because each vessel's risk is assessed independently of the population of vessels to which it is connected and with which it shares the causes of corrosion and material degradation.

2.1. *Data Sources for QRA*

A list of the typical generic failure frequencies for various flange connections is shown below. These generic failure frequencies were calculated based on unpublished sources of failure rates in assets. In addition, the incidents were screened against the causes of their failures to determine an expected failure rate independently of specific degradation mechanisms. According to the American Petroleum Institute, the generic failure frequency is intended to be representative of an expected failure frequency excluding “any specific damage occurring from exposure to the operating environment [12].” As can be seen, there is a wide variety of generic failure rates. This is due to the scatter in the sample that was used to construct the dataset, and also the subjectivity involved in screening out specific damage factors.

Table 2 Comparison of Generic Failure Frequencies Between Selected QRA Datasets

Data Source	Pressure Vessel Small Leak (10mm Ø)	Flange Connection Leak
HSE Failure Rate and Event Data (UK) [13]	$5.6 * 10^{-4}$	Gasket: $5 * 10^{-5}$
OGP RADD: Process Release Frequencies [14]	$5.6 * 10^{-4}$	
Handbook of failure frequencies for safety reports [15]	$1.2 * 10^{-4}$	Unspecified
Reference Manual Bevi Risk Assessments [16]	$1 * 10^{-4}$	Unspecified
API RP 581 [12]	$8 * 10^{-6}$	Unspecified
Handbook of Mechanical Reliability [17]	Unspecified	Static Seal: $2.1 * 10^{-2}$

2.2. *Bayesian Methods for QRA*

Bayesian Networks are capable of combining the probability distributions of multiple assets to infer the life expectancy of one flange connection based on the average life and variance in average life of the population [18]. Covariance models exist to predict the failure rate of flange connections, based on information about the flange connection that is generated during design, assembly, and operation [17, 19]. In the Bayesian Network approach, variable which is not known can be defined as probability distribution based on the range of expected values, and the expected mean value. The mean is known as the first moment of the distribution, and the variance is known as the second moment. Additionally, relationships between random variables may also be defined through their covariance [20].

This probabilistic approach allows the effect of the uncertainty of input variables to be reflected in the degree of uncertainty of the overall system. The end goal of a probabilistic model is to provide the decision maker with a distribution for the range of expected outcomes. From this, the decision maker can determine whether there is enough information to make a decision or whether the circumstances warrant collecting additional information. Therefore, the probabilistic model is especially useful for dealing with complex systems such as flange connections.

3. RISK MODELS FOR LEAK PREDICTION

3.1. *Inspection Data for Risk-Based Decision Making*

The problem of the process operator is making decisions that optimize the reliability of the plant. Often the decisions must be made with a limited amount of information, because the time and expense of acquiring exact data cannot be justified. There are two potential options for making decisions in this case. The decision maker can either choose the most conservative option available to them, or they can create prognostic models of the potential outcomes based on the available information and determine whether they have enough information to make a decision. The latter approach to decision making has the advantage of allowing measurement of the uncertainty, risk, and consequences of the potential outcomes.

3.2. *Decision Analysis Methods Utilizing Sparse Datasets*

The main difficulty in making decisions that affect process safety is in quantifying the likelihood that an unsafe condition could exist. The tools and data for doing this are rarely robust enough to feed directly into deterministic models and product decisive answers. Therefore, probabilistic approaches are favored. As can be seen in Table 3, the precision of a model is related to the amount of data that can be measured and correlated in a model[21].

Table 3 Effect of Sample Size On % Error In Distribution Estimates

mean estimator $\left(\frac{r}{T}\right)$	$mean\ (\mu)$	$stdev\ (\sigma)$	$\frac{\mu - \frac{r}{T}}{\mu}$	% Error
1/5 = 0.2	0.288	0.163	0.306	31
3/15 = 0.2	0.236	0.101	0.153	15
5/25 = 0.2	0.222	0.080	0.099	10
15/75 = 0.2	0.208	0.047	0.038	4.0
30/150 = 0.2	0.203	0.034	0.015	1.5
60/300 = 0.2	0.202	0.024	0.010	1.0

The approach proposed in this research is to use vibration-based NDE as a method for establishing the amount of integrity remaining in a flange connection before failure due to unacceptable leakage occurs. Other methods could be utilized for this purpose, such as measuring strain in each of the bolts to estimate a contact pressure at the gasket. However, these methods are more time consuming and do not account for the flange flexing. A vibration-based NDE approach would give the overall picture of how much pressure existed across the overall flange.

Decision making models could be created to varying degrees of detail. A superficial model could be created based on observed correlations and trends in the plant. This type of model would be vulnerable if it does not capture causal relationships, or if it assumes linear correlations where nonlinear correlations exist. Such models are also observed in practice to produce many false alarms because they have no way of differentiating between the variability in the data caused by normal operations (e.g., startup and shutdown) and that caused by damage progression [22].

An improved model is one that offers predictions based on physical correlations between variables that are known to affect failure rates. Because the model is based upon physical parameters, an observed failure can only have an effect on a subset of the parameters, so future performance extrapolations will be less influenced by false signals. Such a model has been established for flange connection leakage by the US Navy [17]. This particular deterministic model accounts for the factors leading to gasket failure, such that the life expectancy of a flange connection's seal could be predicted if all of the variables were measured and/or controlled. Because variability is expected, a more robust model has been produced by this research.

A Bayesian Network model is used in this research to predict the point in time when a flange connection's leak rate will exceed acceptable limits. It is based on the API 581 industry standard risk model which predicts the change in the probability of pressure boundary failure on a vessel or pipe over time [12]. This industry standard model is referenced for the sake of establishing a flange connection leakage risk model that is relatable to the widely accepted notions of how often failures occur and the degree of risk associated with those failures in the chemical process industries. The mechanics of the flange connection model are independent of the pressure vessel risk model, and the base assumptions about generic failure frequencies can and will be changed as the model incorporates new information. One model for flange connection failure is published by the US Navy in the Handbook of Mechanical Reliability. This model uses algebraic multipliers to relate input parameters and predict a seal failure rate. The experiments underlying this particular model were performed for the Air Force Research Laboratory, and appear to have more in common with sealing air and spacecraft, than with sealing process piping.

The input parameters are defined over ranges that are more stringent than the expectations in the process industries. One example is the parameter for mean surface roughness of the flange face. In the ASME Boiler Pressure Vessel Code, the expected range of average (RMS) roughness is 125-250μin. The US Navy model parameter is defined over a 25-150μin range. See Appendix A – Flange Requirements in Pressure Vessel Design Codes for further details.

Uncertainty of input data is a common limitation of deterministic corrosion models. The dynamic nature of field operations means that there is not always an opportunity to analyze the full complement of input variables needed to construct a full analytical model. In practice, the corrosion engineer must make educated judgments about likely values of certain parameters and emphasize the use of "conservative assumptions." This is less than ideal, as shown by the improved approach that Bayesian Networks provide.

Limited data is still useful if a system approach is used to extrapolate the risk from the basis of one model to another. This system approach uses the expected range of variables as input for measuring the problem's range of variables. A probabilistic model is created from a deterministic model by defining a Probability Density Function (PDF) for each of the model parameters. This can be done based on a parameter's mean and variance values. Skewness can also be factored into the distribution. Data or observations from a population of flange connections can be used to adjust and extend the original distribution. Since the PDF is a continuous function, it can be extrapolated to make predictions about low probability events.

More importantly, the uncertainty of an event's probability can be measured by the variance in the PDF.

The probabilistic failure frequency distributions for a large population of flanges can be modified based on the observations about the population. If a particular flange connection shares similar risk drivers with other connections, the PDF of each individual connection can be aggregated into a population likelihood PDF. This is useful because the failure rate model for each individual flange has a base failure frequency term in it, which is generic. After each iterations of inputting observations into the model, these generic failure frequencies (gff) can be updated to be specific about that particular flange at that particular moment in time.

The model generated from this research is based on a combination of the known physical properties of flange connections, and it also allows for missing data to be accounted for with the use of parameter learning and Bayesian updating of the probability distributions. The correlations between the parameters are set up as prior probability distribution nodes in a Bayesian Network. These groups of parameters are modeled for a population of flange connections in a process plant. Observations in the plant, such as failures or accelerated corrosion events, are then used to update the values of the other flange connections in the population. By the same token, absence of failures can be used to update the expected remaining life of the flange connection seals. This can be used to determine which flanges should be broken during shutdowns for inspection. The model used in this work does not explicitly capture the probability of failure due to non-routine operation; such as during startup, shutdown, and upset conditions. While these operating modes may have a different effect on the remaining life of the flange connection seal, the probabilistic nature of the model allows it to capture rare events.

In this way, a progressively updated model is generated from generic, but accurate, physical data and updating with observations. At the same time, the PDF of unmeasured parameters are inferred based on the observed performance of the system, or population of flange connections.

3.3. *Results of Deterministic Calculation for a Typical Flange Connection Scenario*

Table 4 shows the inputs to the seal failure rate model. Table 5 shows the resultant coefficients and calculated probability of failure.

Table 4 Typical Inputs Used in Deterministic Model

Parameter	Value	Justification for Value
Qf	0.031	assuming Qf (allowable leakage) > 0.03in^3/min
Dsl	2	assuming Dsl (seal inner diameter) = 2"
M (Meyer hardness, psi)	3870	PTFE (from AD0470462)
C (contact pressure, psi)	5000	
f (surface finish, μn RMS)	125	
T (temperature °F)	100	
N10	0.008	assuming cylinder (from US NAVY HMR)
GPMr	10	

Table 5 Covariance Model Factors and Results

Parameter	Value	Justification for Value
λ_{SEB}	2.4	failures/million hours
Cp	0.25	Assuming pressure <= 1500psi
Cq = 0.055/Qf	1.774193548	
Cdl = 1.1*Dsl + 0.32	2.52	
Ch = ((M/C)/0.55)^4.3	4.345368043	
Cf = (f^1.65)/353	8.168208522	
Cv	3.847	assuming diesel fuel at 100°F
Ct	0.21	assuming T_{rated}-T_{op} > 40°F
Cn = (Co/C10)^3 * N10 * GPMr	0.08	assuming Co=C10
λ_{SE}	6.2	failures/million hours
Base Probability of Failure (λ_{SEB} * 0.00876)	2.10E-3	failures/year
Scenario 1 PoF (λ_{SE} *0.00876)	5.40E-3	failures/year

The probability of failure calculations for this scenario indicate an unacceptable probability of leakage. However, there are two factors that affect the outcome of this scenario. First, these calculations are based on data from lab samples, which was measured in a way that does not allow its variance to be accounted for in predictions. In other words, the tests which were used to make these multipliers has an unknown uncertainty. The uncertainty of the actual performance can be characterized, depending on how narrow the window of operating parameters is, and the spread of observed failure rates. Second, the data is calibrated for a specific application (flange connection seals on space rocket motors). The translation of these observations to seals in a process plant will be necessary. This may be accomplished over time by aggregating test data. The inputs to the model will be the same for process plant equipment, but the resulting seal life expectancy (equivalently, seal failure rate) may be different due to the variance in the operating parameters of a plant over a relatively long time scale compared to a rocket engine.

The gasket life expectancy can be modeled as an exponential curve, with a hazard rate of 1.0E-3. Suppose the contact stress distribution did not have a significant amount of variance, and was approximated as a point value. Then on-stream measurement of bolt strain or joint stiffness could be used to measure the contact stress and estimate the remaining life of the flange connection seal.

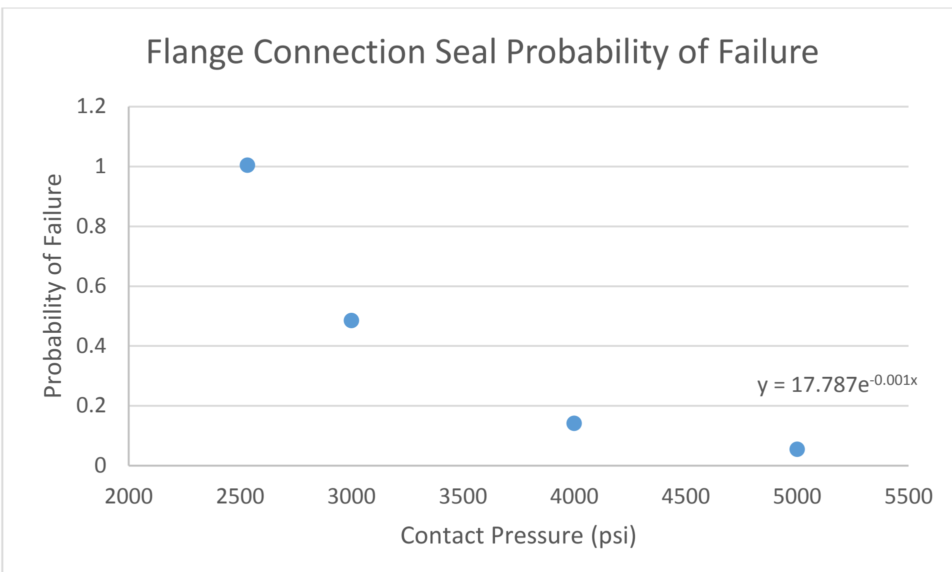

Figure 1 Calculated Correlations Between Contact Pressure and Probability of Failure

The conversion from event frequency to probability of failure is based on the assumption that the seal will degrade in an exponential fashion. The probability of failure can be related to a risk matrix, along with the consequence of failure, to identify action levels. Action levels are points at which the utility cost of a potential seal failure exceeds the cost of a mitigating event such as an inspection or repair.

However, the above first moment calculations do not have any way of accounting for the variance of the distribution, so a second moment method is proposed which makes use of the mean and the variance of the distribution.

3.4. *Beta-Binomial Bayesian Network for Typical Flange Connection Leakage Scenarios*

One possible method of estimating the failure frequency would be using a beta binomial conjugate distribution. The beta probability density function is represented by a beta expression which measures the likelihood of a particular failure frequency in a normal distribution (1).

$$f(\lambda) = \frac{\Gamma(\alpha+\beta)\lambda^{\alpha-1}(1-\lambda)^{\beta-1}}{\Gamma(\alpha)\Gamma(\beta)} \tag{1}$$

The conditional likelihood of n failures out of a population of k flanges would be represented by a binomial distribution.

$$p(\lambda|f) = \binom{n}{k} p^k (1-p)^{n-k} \tag{2}$$

An example of a beta binomial Bayesian Network is shown in Figure 2.

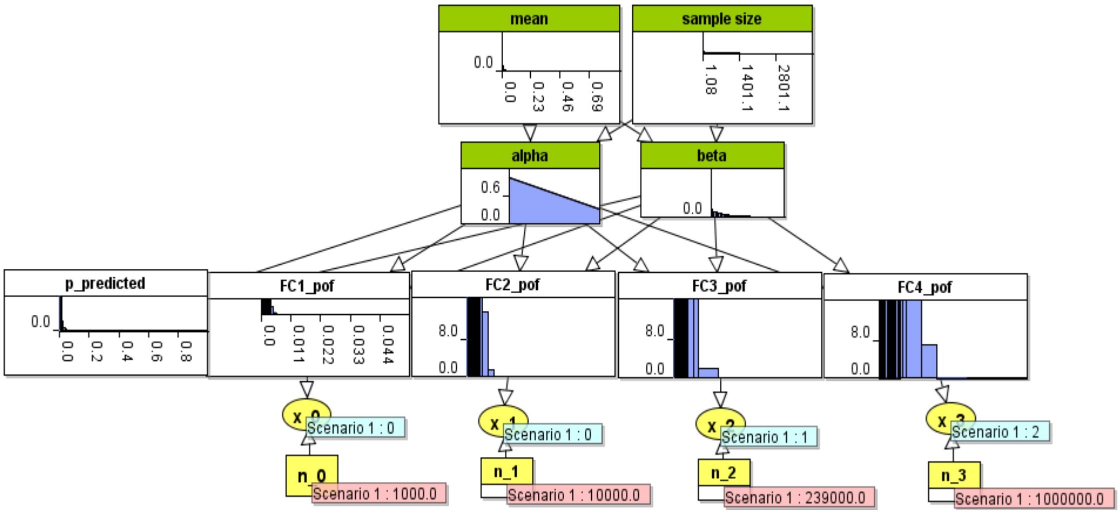

Figure 2 Predicted λ Based On Four Measured Flange Connection Failure Rates in a Beta Binomial Bayesian Network

The effect of this network is to treat base failure rates as a normal distribution in a population (API 581 assumes their generic data to be lognormally distributed, but does not give a justification for it). Then the known failure rates are used to construct a weighted average failure rate for the population. This failure rate can then be extrapolated to an estimate of a posterior failure rate, such as for a particular flange that has no known performance data. As can be seen from Table 6, Table 8, and Table 10, the average failure frequency of the population converges to the mean as the amount of time in service increases. Adding additional unknowns to the population does not affect the predicted probability, which implies that the technique could be applied to populations with arbitrarily large quantities of unknown elements. It does change the properties of the prior distribution, however, this has a limited effect on the precision of the predicted probability of failure. Adding elements reduces the percent error in the predicted probability, consistent with the characteristics of a normal distribution.

Table 6 Properties of Beta-Binomial Hierarchical Bayesian Network for Four Flange Connection Population With Known Failure Rate

Flange	Hours	Failures	median PoF	variance
FC1	1000	0	4.33E-04	6.18E-07
FC2	10000	0	6.52E-05	9.90E-09
FC3	239000	1	7.05E-06	3.68E-11
FC4	1000000	2	2.68E-06	3.30E-12
Sum(FC1-4)	**1250000**	**3**	**2.40E-06**	
predicted aff			1.45E-03	6.27E-03

Table 7 Properties of Associated Prior Distribution

Sample Size		Prior Mean		Beta	
Median	509.47	Median	0.001428	Median	508.93
Variance	394790	Variance	0.00748	Variance	409730

Table 8 Properties of Beta-Binomial Hierarchical Bayesian Network for Five Flange Connection Population With Known Failure Rate

Flange	Hours	Failures	median PoF	variance
FC1	1000	0	4.33E-04	6.18E-07
FC2	10000	0	6.52E-05	9.90E-09
FC3	239000	1	7.05E-06	3.68E-11
FC4	1000000	2	2.68E-06	3.30E-12
FC5	1000000	2.4	2.68E-06	3.30E-12
Sum(FC1-5)	2250000	5.4	2.40E-06	
predicted aff			1.45E-03	5.65E-03

Table 9 Properties of Associated Prior Distribution

Sample Size		Prior Mean		Beta	
Median	509.79	Median	0.001431	Median	509.25
Variance	398870	Variance	0.008152	Variance	399070

Table 10 Properties of Beta-Binomial Hierarchical Bayesian Network for Five Flange Connection Population With Known Failure Rate For Four Flanges

Flange	Hours	Failures	median PoF	variance
FC1	1000	0	4.33E-04	6.18E-07
FC2	10000	0	6.52E-05	9.90E-09
FC3	239000	1	7.05E-06	3.68E-11
FC4	1000000	2	2.68E-06	3.30E-12
FC5	1000000	unknown	1.45E-03	6.27E-03
Sum(FC1-5)	2250000	5.4	2.40E-06	
predicted aff			1.45E-03	5.65E-03

Table 11 Properties of Associated Prior Distribution

Sample Size		Prior Mean		Beta	
median	509.79	Median	0.001428	Median	508.93
variance	394790	Variance	0.00748	Variance	409730

3.5. *Gamma-Exponential Bayesian Network for Typical Flange Connection Leakage Scenarios*

In a similar fashion, the gamma-exponential conjugate distribution could be used to estimate an average time to first failure, given the time to first failure of other flanges in the population.

The gamma pdf is given by (3), where $\alpha = mean * \left(\frac{mean}{variance}\right)$ and $\beta = \frac{variance}{mean}$.

$$f(\lambda) = \frac{\beta^{\alpha}\lambda^{\alpha-1}e^{-\lambda\beta}}{\Gamma(\alpha)} \tag{3}$$

The exponential pdf is given by (4).

$$f_x(x) = \lambda e^{-\lambda x} \tag{4}$$

An application of this type of conjugate distribution is shown in Figure 3 [18].

$$f_x(x) = \lambda e^{-\lambda x} \tag{5}$$

The effects of estimating average failure frequency using the gamma exponential conjugate distribution are similar to using a beta binomial, even though the approach is different.

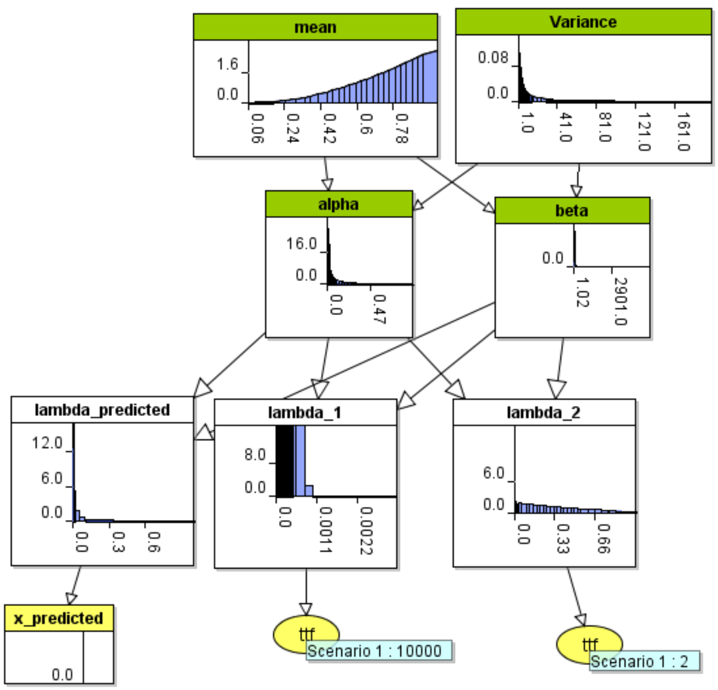

Figure 3 Prediction of aff Using Gamma Exponential Bayesian Networks

3.6. *Risk Modeling Using a System Approach*

Process safety performance management has a potential benefit from adopting a system approach to managing flange connection leak risk. The connection entity is not considered as a discrete risk driver by the current editions of the industry consensus risk-based inspection guidance documents. According to the EPA, this asset category has the second highest leak frequency in process plants [23]. A hierarchical Bayesian network which uses conjugate probability distributions for the population of flanges is useful for predicting the failure frequency of the population and of a single connection, and also for making decisions systematically. This approach to modeling risk enhances the visibility of the potential secondary effects of specific decisions on the system. It also provides pathways to confirm the risk drivers for observed events. Most importantly, a system approach is needed to improve process safety because it enables the measurement of long tail risk. This is characteristic of process safety incidents, which are rare events with high consequences. It also reveals interdependencies between apparently isolated events.

4. FLANGE CONNECTION MATERIALS, DESIGN, AND DEGRADATION

Large numbers of flange connections are present in a typical plant. They enable assets to be quickly connected and disconnected, without cutting or welding operations. Despite their apparent simplicity, flange connection seals are a complex system which changes over time. Most flange connections are made up of three components. The flanges are either welded or slip on type and are attached to associated asset. Typically bolts are used as fasteners to apply clamping force on the flanges. And in most cases, a gasket is installed between the flanges. The gasket forms a seal while compensating for the surface roughness of the flanges as well as variations in the clamping force applied by the fasteners [24]. A flange connection joint's design and performance is governed by its stiffness, which is limited by the stiffness of the gasket [25].

Since the transition away from asbestos, most gaskets are now made from three types of materials: 1) nonmetallic, such as elastomers, PTFE or compressed graphite, 2) metallic, including flat and spiral wound metal, or 3) composites, consisting of a nonmetal outer layer with a metallic core [26, 27]. The most important property of a gasket is its response to the fasteners' compressive stress. This response is governed by the gasket's stiffness. Metallic gaskets have an elastic stress response, and deform proportionally to the applied stress until they begin to plastically deform. The elastic modulus of a metal gasket determines its stiffness. Nonmetallic gaskets deform viscoelastically, and their stiffness is measured by their dynamic modulus, which is a function of temperature and the frequency of a cyclic loading applied to the test specimen [28]. Dynamic modulus can then be measured in a lab setting by vibrational response techniques [29]. Other materials-related properties of gaskets that are relevant to sealing performance include response to thermal and pressure cycling, relationship between the thickness of the gasket and its stiffness, and the degree of plastic deformation the gasket can withstand under compressive loading [30-32]. Another important property for nonmetallic and composite gaskets is the creep relaxation which they undergo while under compression. This creep results in a loss of the clamping load applied by the fasteners and a loss of the seal's integrity [33-38].

4.1. *Causes of Flange Connection Leakage*

A flange connection's leak rate is determined by material properties, assembly parameters, and process operating conditions. A leak rate is a measure of the conductance of fluid through the gasket membrane. In very low leak rate regimes, this conduction happens by molecular diffusion. At higher leak rates, this occurs by laminar flow. The sealing performance of the flange connection, and the leak rate or life expectancy for the flange connection over a time interval, are related. The leak rate is increased by a lower viscosity process fluid, but decreased by a tighter seal. Since the properties of the process fluid are constrained by the process design, the leak rate is most effectively controlled by the quality of the seal.

A seal is only formed when the pressure applied to the gasket by the flange is high enough to compress the gasket into any roughness that may exist on the flange face. If the flange surface is very rough, the gasket will be required to compress more in order to form a seal. If the gasket material has a high stiffness, a higher stress will be required to achieve the compression necessary to form the seal. This gasket property is known as high loadability [24]. The compressibility of the gasket affects how much pressure must be applied in order to form and maintain this seal. Therefore, flange connections made with highly loadable gaskets have a lower leak rate due to the higher contact stresses applied.

Surface pressure may be directly measured using pressure indicating films, but the pressure value cannot be known without disassembling the seal, and the film also affects the leak rate. The methods for indirectly measuring surface pressure include using elongation methods to measure the strain at the fasteners, but the strain is distributed unevenly across the flange surface because the flange elastically deforms. The ligaments between bolt holes in the flange will have a lower applied stress. Also, the flange will rotate and expand at the inside radius due to the moment applied by the fasteners at the outside of the flange radius.

Leakage at flange connections can occur through two routes: due to a lack of intimate contact between the gasket and the flange surface or due to diffusion through the gasket membrane. Membrane diffusion typically only occurs at appreciable rates when the gasket is in service at very high temperatures and pressures. In most cases leakage is due to a loss of sealing between the gasket and flange [39]. Originally, pressure vessel design codes assumed that properly designed and installed flange connections would not leak while in service. The older editions of these codes specified design calculations for the flanges and fasteners based on the seating and maintenance stress levels (Y and m factors) of the gaskets [40]. Seating stress is the initial amount of compression required to conform the gasket surface to the mating flange surfaces. It is applied before the flange is pressurized. The maintenance stress is a measure of the minimum required compression to keep the gasket compressed against the flange while internal or external pressure is applied to the flange. This maintenance stress represents a balance of forces between the fastener and the flange and gasket in the elastic loading regime for both. Ideally, the balance shifts when the hydrostatic pressure in the flange increases the end thrust on the bolts, such that the gasket can expand to compensate for the relaxation of the bolts while still maintaining a tight seal. Modern design guidelines recognize that leakage will always occur, and therefore include rules for flange connection design based on specific maximum leak rates [30]. A summary of flange design code details is given in Appendix A – Flange Requirements in Pressure Vessel Design Codes.

5. FLANGE CONNECTION INSPECTION

The integrity of flanges is determined by NDT inspection. Many techniques are available for flange inspection, but they do not ensure that a seal will be maintained across the connection formed by the two flanges, fasteners, and the gasket [41]. Some of the techniques that are commonly used in industry are listed below in Table 12 [22].

Table 12 Strategies for Assessing Flange Connection Integrity While In Service

Strategy	Implementation	Limitations of Strategy
Material Balance Monitoring	Loss of product between flow sensors calculated as a leak rate.	Insufficient sensitivity to detect low leak rates. Requires flow in system in order to make measurements.
Pressure monitoring	Pressure monitoring to detect leakage. Gaskets which have an annulus space and taps allow pressurized gas to be applied to the sealing surface before the entire flange is pressurized.	Does not indicate whether a potential leak is caused by flange loosening or gasket damage, which affects the mitigation strategy.
Acoustic leak detection	Baseline acoustics of a pipe in service are compared to inspection data to determine if a leak is present. Can use microphones as well as fiber optics or MEMS to localize damage [42].	Requires microphone to be positioned very close to leak. Passive technique, precision is limited by background noise filtering effectiveness. Requires active process fluid release for detection.
Infrared leak detection	Infrared absorption is used to detect the presence of volatile emissions from flange connections [43].	Requires active process fluid release for detection. Calibrated to absorption wavelengths of specific chemicals, not capable of detecting generic releases.

Table 12 Continued

Strategy	Implementation	Limitations of Strategy
External strain measurement	Time-of-flight measurement of ultrasonic signal along the length of a bolt to determine the extension and stress level in the bolt. This is then converted into a bolt stress.	Accuracy depends on the precision datum faces machined each end of the bolt, and operator skill. Adequate bolt tightness may not prevent leak paths from forming on the flange face (if the flange geometry is not in-spec).
Strain indicating fasteners	Strain gages installed inside the bolt shaft, or washers which emit an indicator fluid at a specific stress level.	Adequate bolt tightness does not rule out the presence of leak paths on the flange face ligaments between bolts.

Vibration-based NDT is capable of detecting a change in the stiffness of a bolted joint, in particular a flange connection [35, 44]. Microphones or accelerometers are coupled with an impulse signal source, or each other, to measure the systems' vibrational response. The input and output time signals may be converted to frequency spectra with a Fourier transform if the system's vibration response is approximately linear over the measured frequency range. The data must also be stationary, or not changing within the time interval over which the DFT is sampled [45, 46]. This means that time-domain signals which change over the time that they are measured, or with respect to the location of the sensor, will have increased error in the frequency spectra. The Empirical Modal Decomposition technique using the Huang-Hilbert Transform has been used to measure nonlinear vibration systems, in particular during continuous monitoring [47-49].

Vibration data may be used to detect changes in the integrity of a flange connection by modal parameters such as the position and amplitude of the system's resonance frequencies. These parameters are affected by a change in the stiffness of the flange connection [44, 50-56]. Leakage may also be detected by a change in impedance parameters such as the reflection coefficient of longitudinal waves impacting the flange surface [57]. In the ultrasonic frequency range, reflection coefficients may be used to non-intrusively measure the flange surface's contact pressure directly under the transducer [44, 55, 58-60].

Prior data is useful to plant operators for determining the remaining life of pressure assets. These risk models are commonly used to schedule outages [61]. The purpose of the outages is to detect damage that may have occurred while the asset was in service, and to repair that damage. While the inspection itself does not reduce existing damage to the vessel, it does reduce uncertainty in the condition of the vessel.

5.1. *Vibration-Based Inspection for Measuring Seals of Flange Connections*

Because flange connections are distinct locations, an inspection can be focused within the vicinity of the flange connection and can exclude adjacent vessels and piping. A flange connection inspection could also be primarily focused on evaluating the integrity of the seal. A secondary goal may be to detect mechanical damage that could lead to catastrophic collapse of the components.

A method of measuring the seal is to examine the vibrational properties of the connection. The vibration spectrum offers more signal bandwidth than even the optical spectrum, as can be seen by the effect of opaque materials in blocking light, whereas vibrations can be conducted through almost all materials at some frequency. Therefore, vibration testing is a suitable option for evaluating seals of flange connections.

Since the flange connection is generally composed of different materials, and these materials have different characteristic vibration impedances due to their stiffness and damping coefficients, a plane wave vibration which encounters the flange will be partially reflected as it passes through the flange to the gasket. This reflection is a function of the impedance drop, which is also a factor of the degree of contact area between the different flange and gasket materials. Therefore, the reflection coefficient parameter is relatable to the conductance parameter of the leak rate equation.

5.2. *Governing Equations for Vibration Inspection*

In the experiments for this thesis, the speed of sound in the steel was calculated using the elastic modulus and the density. The formulas are as follows.

$$c = \sqrt{\frac{E}{\rho}} = \sqrt{\frac{205\ GPa}{7800\,\frac{kg}{m^3}}} = 5126\,\frac{m}{s} \tag{6}$$

The wavenumber was then calculated as a function of frequency to determine the optimal spacing of the accelerometers.

$$k_L = \frac{2 * pi * f}{c_o} = \frac{\omega}{c_L} \tag{7}$$

The accelerometer spacing was set at 7cm. The bounds on the spacing between measurement sensors are due to the error introduced into the signal by phase mismatch on the higher end and the finite difference limit on the lower end. The graph below shows the minimum wavenumber for various spacing.

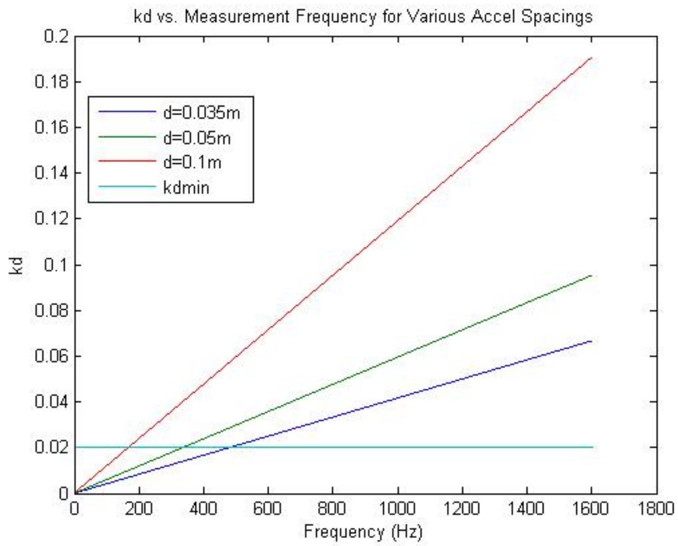

Figure 4 Minimum Wavenumber For Various Accelerometer Spacing

An upper frequency limit is set by the impact hammer's excitation frequency range. In this case, the amplitude of the impact hammer (B&K Type 8206-001) starts to fall off around 1300Hz. The coherence is still acceptable up to 1600Hz.

5.3. *Reflection Coefficient*

The following equations explain how a reflection coefficient is calculated. It is adapted from Kinsler [62]. A propagating plane wave in a bar or a small diameter pipe will have two axial vibration modes. One will be forward going and the other reflected. Their intensity can be represented as the ratio of reflected to incident wave amplitude, as shown below in Figure 5.

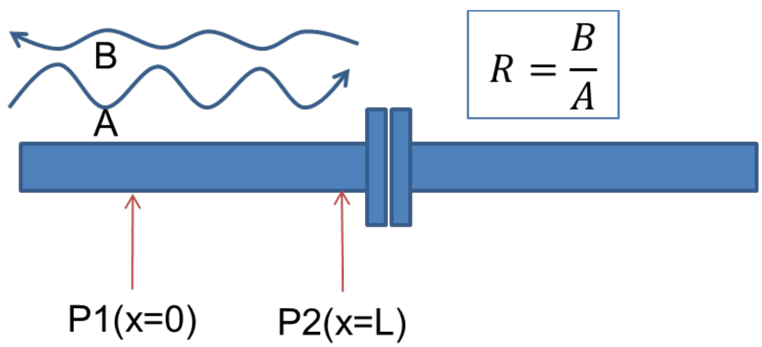

Figure 5 Schematic of Reflection Coefficient Measurement

$$P(x) = Ae^{ikx} + Be^{-ikx} \tag{8}$$

At the first accelerometer reference point, pressure is given by (9).

$$P_1(x = 0) = A + B \tag{9}$$

And at the axial position of the second accelerometer, pressure is given by (10).

$$P_2(x = d) = Ae^{ikd} + Be^{-ikd} \tag{10}$$

The expectation value of the pressures is given by their complex conjugate (11), which is also known as the autospectrum for location 1.

$$(P_1^* P_1) = S_{11} = (A + B)^*(A + B) \tag{11}$$

The crossspectrum (12) is the covariance between the pressure amplitude at two locations.

$$(P_1^* P_2) = S_{12} = (A + B)^*(Ae^{ikd} + Be^{-ikd}) \tag{12}$$

The ratio of autospectrum to crossspectrum can be used to find the reflection coefficient, or the fraction of energy that is dissipated by the barrier that the wave impacts (13, 14).

$$\frac{S_{11}}{S_{12}} = \frac{A + B}{Ae^{ikd} + Be^{-ikd}} = (1 + R)/(e^{ikd} + Re^{-ikd}) \tag{13}$$

$$|R| = \frac{|B|}{|A|} = \left|\frac{S_{11}e^{ikd} - S_{12}}{S_{12} - S_{11}e^{-ikd}}\right| \tag{14}$$

In order to reduce the amount of input noise to the system, autospectra can be filtered against the input signal using the following relations (15-20).

$$S_{xx} = E[X^*X] \tag{15}$$

$$S_{xy_1} = E[X^*Y_1] \tag{16}$$

$$S_{xy_2} = E[X^*Y_2] \tag{17}$$

$$S_{12} = E[Y_1^*Y_2] \tag{18}$$

$$S_{y_1y_2} = \frac{S_{xy_1}^* S_{xy_2}}{S_{xx}} \tag{19}$$

$$S_{y_1y_1} = \frac{S_{xy_1}^* S_{xy_1}}{S_{xx}} \tag{20}$$

A comparison between the reflection coefficient calculated from the same signal data with and without using this filtering technique is shown in Figure 6.

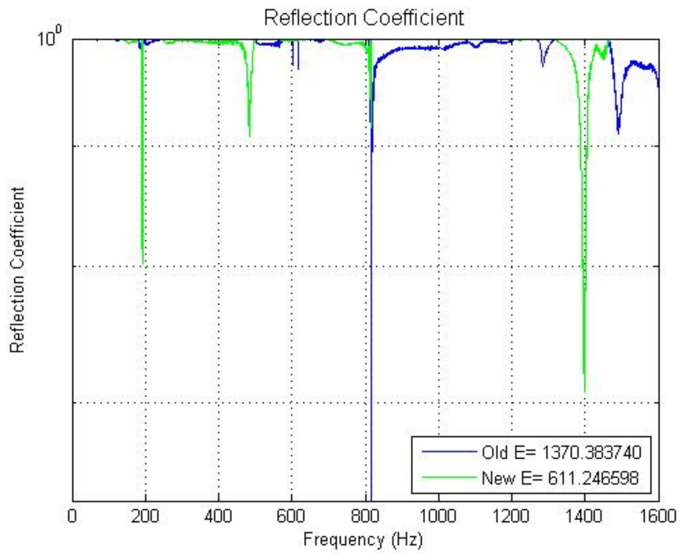

Figure 6 Comparison Between Unfiltered and Filtered Reflection Coefficient Spectra

The reflection coefficient may also be thought of as the ratio of impedances between the two materials which are carrying the vibration wave. Neglecting the effect of phase lag, the reflection coefficient using the acoustic impedance of the materials reduces to (21).

$$|R| = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 \tag{21}$$

A transfer function (below) may be thought of as a measure of the impedance of the vibration carrier, which governs the input/output ratio of vibrations at each frequency.

$$H_{12} = \frac{S_{12}}{S_{11}} \tag{22}$$

Since $H_r - H_{12} = \left(\frac{S_{11i}}{S11}\right)(H_r - H_i)$ and $H_{12} - H_i = \left(\frac{S_{11r}}{S_{11}}\right)(H_r - H_i)$, the reflection coefficient becomes indeterminate when Hr=Hi, which occurs at half wavelength accelerometer spacing

[56]. The suggested spacing to avoid this condition is given by $s < \frac{c_o}{2f_{upper}}$, which for 1600Hz would be 2m.

5.4. *Metrics for Estimating Remaining Life of a Flange Connection Seal*

In the signal data, the most useful measurements of the remaining life are comparisons between the undamaged vs. damaged states. The metric chosen to make this comparison is the norm of the reflection coefficient. This norm is implemented by taking the square root of the trace of the standard deviation of the reflection coefficient [63]. From this, a damage index measurement is used, which compares the reflection coefficient norm measured in a known good condition (such as immediately after assembly) with a measurement after some time has passed. If loss of contact pressure (i.e., tightness) has occurred, the norm will increase due to a higher vibration/acoustic impedance drop across the flange-gasket interface. Marshall [54] and others [44] have theorized that, on a microscopic scale, this change in the reflection coefficient can also represent the loss of vibrational energy across the joint due to the change in contact stiffness. This contact stiffness is due to roughness and asperities at joint which act as dampeners. The outcome is the same; reflection coefficient is inversely correlated with tightness. This can be considered as the major contributing factor to a loss of sealing. Therefore, the damage index is useful as a metric for the amount of sealing capability left in the flange connection.

The graphs below show the change in reflection coefficient as well as the numerical integration values for the reflection coefficient.

5.5. *Flange Connection Resonance Experiment Setup*

The vibration NDT experimental setup consists of two pieces of 2" Sch40 carbon steel pipe joined together by 150# class flanges. Different gaskets are used to evaluate their effect on the vibrational characteristics of the flange connection. The modal analysis is performed on the position and amplitude of the resonance peaks to relate tightness of the connection with its stiffness. The resonance frequencies and amplitudes are measured using an impact hammer coupled to a microphone.

The reflection coefficient testing is performed on the same flange connection, but with accelerometers used to measure the axial acceleration caused by the impulse signal. The acceleration wave is decomposed into incident and reflected components to determine how much energy is absorbed by the connection. A more intimate contact at the flange gasket interface will theoretically reduce the impedance drop and reduce the reflection coefficient.

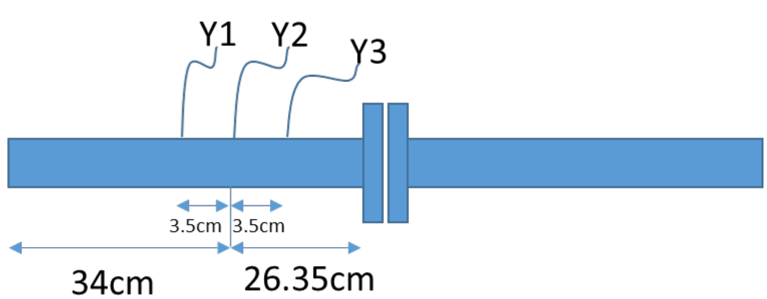

Figure 7 Flange Connection Layout with Accelerometers Positioned

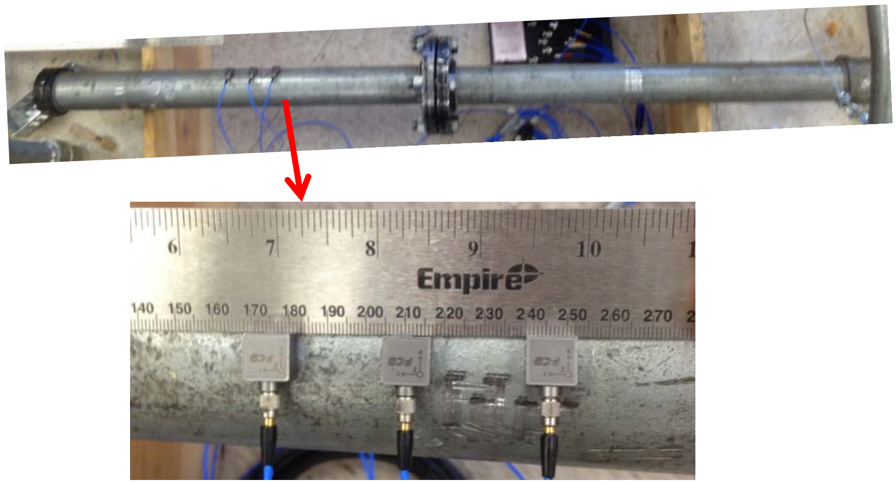

Figure 8 Flange Connection with Accelerometers Positioned

5.6. *Reflection Coefficient Experiment Results*

Different bolt torque levels were used to produce different contact stresses. The objective of the vibration experiment was to correlate a change in the reflection coefficient with the applied contact stresses.

The graphs below show the change from snug bolts (finger tight) to properly tightened bolts (120 ft. lb. torque incrementally tightened to 36 ft. lb. and 84 ft. lb.) for flange connections made using two different types of gaskets. The ePTFE is a soft gasket which has a lower loadability and is less sensitive to the contact pressure required to make a seal. The PTFE gasket is harder and has a higher loadability.

The norm of the reflection coefficient was measured at 105.2 (tight) vs. 110.4 (loose) for the hard PTFE gasket and 79.4 (tight) vs. 80.7 (loose) for the soft ePTFE gasket. Again, the values for numerical integration are only meaningful as relative changes from a known good condition to a known level of damage, since they are based on averages of a noisy signal which includes a large band of spectrum with reflection coefficient exceeding unity. The change in the reflection coefficient is calculated by the following equation.

$$loosening = \frac{\left||R_{loose}|\right| - ||R_{tight}||}{||R_{loose}||} \tag{23}$$

For the PTFE gasket, this amounts to a 4.7% change, and for the ePTFE gasket a 1.6% change.

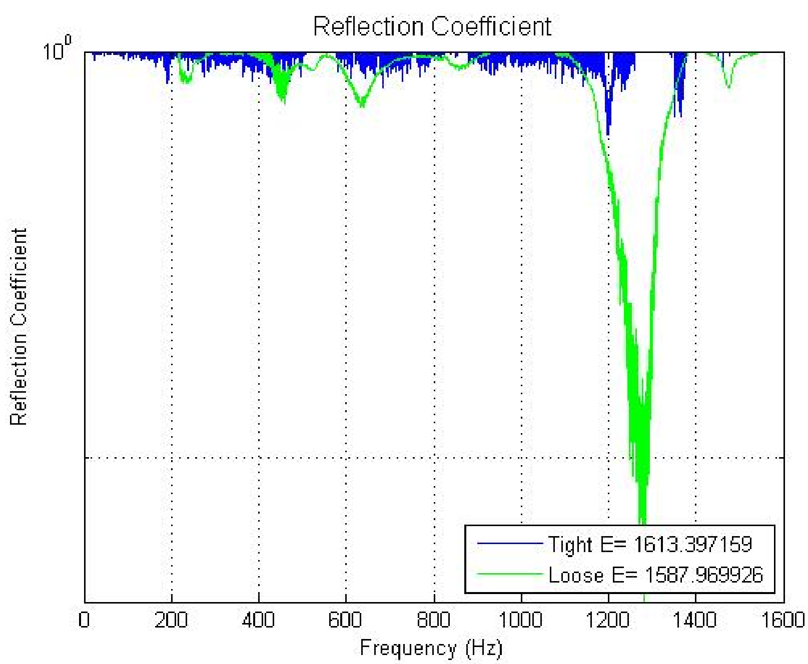

Figure 9 ePTFE Gasket: Change in Reflection Coefficient with Bolt Loosening

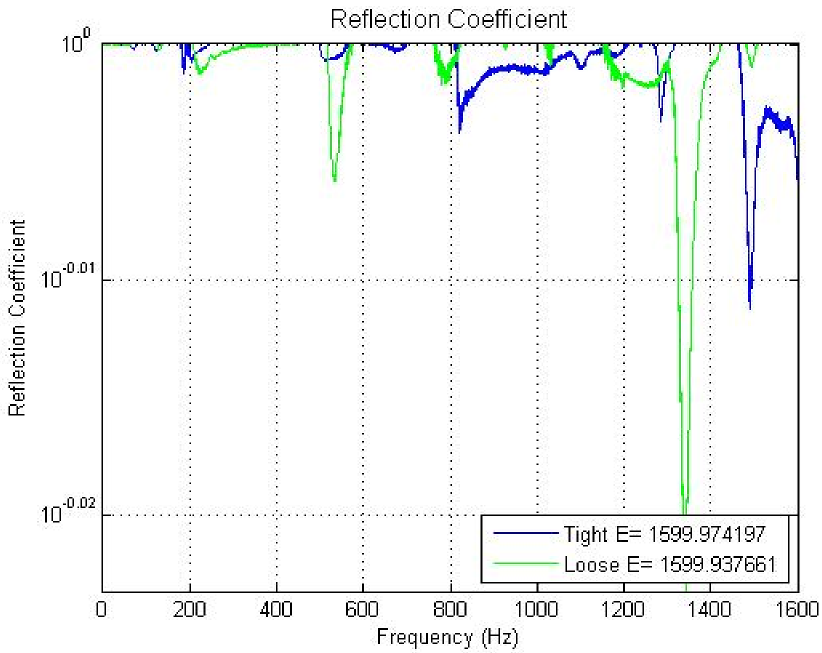

Figure 10 PTFE Gasket: Change in Reflection Coefficient with Bolt Loosening

A further comparison of the reflection coefficient between the snug (0 ft. lb. torque), 36 ft. lb., and 120 ft. lb. cases are shown below. An ePTFE gasket was used in the tests. As can be seen from the graph, the position of the accelerometers affects the shape of the reflection coefficient, which is unexpected. It is possible that the mass of the accelerometers could be affecting the propagation of the wave. Also, the signal could be discontinuous with respect to position on the pipe, which would require comparison measurements to be taken at the same locations relative to a flange.

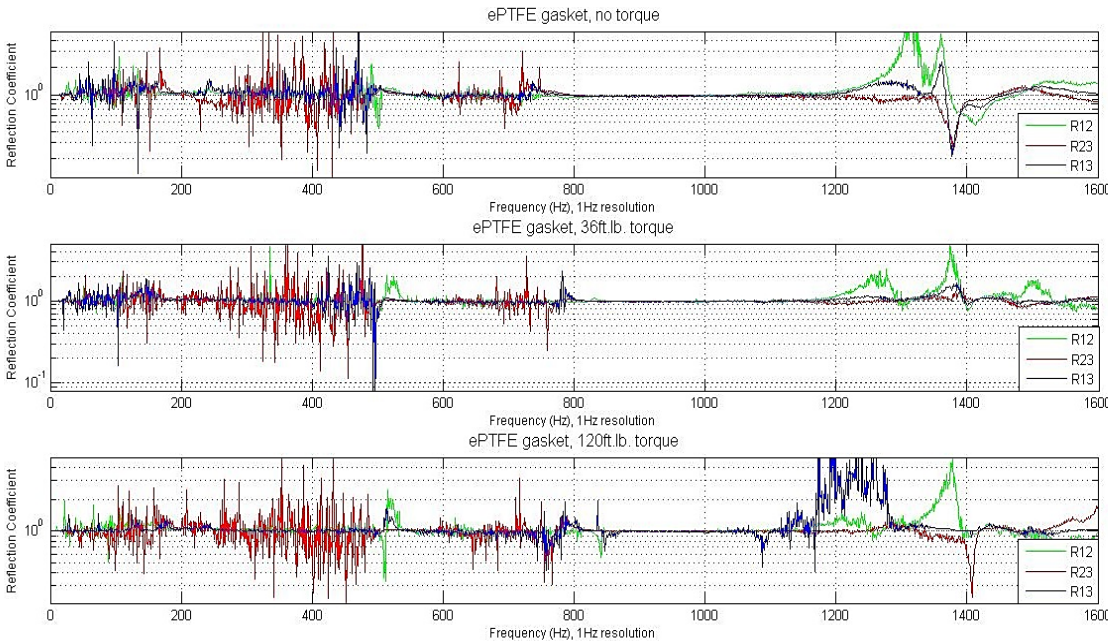

Figure 11 |R| Compared with Different Accelerometer Positions and Torque Levels, ePTFE Gasket

5.7. *Variance in Flange Connection Tightness Measured by Bolt Strain*

While vibration testing was performed, other parameters related to the flange connection were measured. One of the highest sources of variability was in the application of contact pressure through bolt torque. The elongation of the bolts was measured after torque was applied. Using the parameters shown below, a target theoretical elongation of 0.8% was expected. The equations were taken from Bickford [25].

Table 13 Predicted Bolt Strain

Parameter	Value	Unit
E: carbon steel modulus of elasticity	2.99E+07	Pa
D: Diameter	0.625	in
T_h: Head Height	0.380	in
T_n: Nut Height	0.538	in
A_b: Area of bolt	0.307	in^2
A_s: Area under thread	0.278	in^2
L_b: Length of bolt	2.804	in
L_t: Length of thread	1.800	in
L_{be}: Effective length of body and head $L_{be} = L_b - T_h/2$	2.614	in
L_{se}: Effective length of body and thread $L_{se} = L_t + T_n/2$	2.069	in
Reciprocal of spring constant of joint $(1/k_{be}) = L_{be}/(E*A_b) + L_{se}/(E*A_s)$	5.33E-07	in/lbf
k_{be}	1.87E+06	lbf/in
σ: seating stress	50000	psi
F_b: applied load ($F = \sigma * A_b$)	15339.808	lbf
Δ_b: change in bolt length due to applied load $\Delta_b = F_b/(1/k_{be})$	0.0082	in

Table 14 Measured Elongation of Lubricated Bolts (Aramid fiber gasket)

	Round 0 (snug)	Round 1 (36 ft-lb)	Round 2 (84 ft-lb +/- 5)	Round 3 (120 ft-lb)	Total elongation %
Bolt 1 (in)	2.804	2.8045	2.8055	2.8065	0.089158
Bolt 2 (in)	2.795	2.7955	2.797	2.7995	0.161002
Bolt 3 (in)	2.8	2.8005	2.8015	2.8024	0.085714
Bolt 4 (in)	2.803	2.8045	2.8061	2.8068	0.135569

As can be seen, at the target torque, none of the bolts achieved the specified elongation to provide the required contact pressure on the gasket. After lubricating the bolt threads with a silicon compound, the following elongation values were observed.

Table 15 Measured Elongation of Lubricated Bolts (ePTFE gasket)

	Round 0 (snug)	Round 1 (36 ft-lb)	Round 2 (84 ft-lb +/- 5)	Round 3 (120 ft-lb)	Total elongation %
Bolt 1	2.80355	Not measured	Not measured	2.81225	0.310321
Bolt 2	2.7955	Not measured	Not measured	2.803	0.268288
Bolt 3	2.8005	Not measured	Not measured	2.81225	0.419568
Bolt 4	2.804	Not measured	Not measured	2.8085	0.160485

This represented a significant improvement, but was still not at the required contact pressure. In a probabilistic risk model, this dispersion of measurements across a single flange, let alone a population of flanges, would increase the variance of the distribution substantially. Ultrasonic measurement of the elongation would reduce the measurement variance, but the underlying error due to differences in friction on each fastener's mating surfaces (bolt and nut threads, nut and bolt contact with the wrench, and nut and bolt head contact with the flange body). Therefore a more precise fastening tool would be required in order to reduce the variance in contact pressure.

5.8. *Vibration Signal Variance Due to Accelerometer Spacing*

The recommended setup for measuring reflection coefficients was originally based on the ASTM procedure for reflection coefficient measurement in an acoustic impedance tube [64]. This test guideline is intended for measurement of a vibration wave propagating through air, but in the case of a flange connection, the reflection coefficient of interest is related to the vibration wave propagating through the flange itself. From the measurements taken in this research, it is inconclusive whether the reflection coefficient was truly affected by the spacing of the accelerometers. This could be an issue if the accelerometers were placed on a node line, such as a half wavelength of the signal frequency of interest. As long as the measurements were taken at the same spots on the pipe consistently, there should not be a significant variation in the reflection coefficient due to the accelerometer spacing.

6. CONCLUSION

Loss of containment events in the process industry are rare. The consequences of a failure are high, which justifies a Quantified Risk Analysis. The various data sources which may be used for predicting probabilities of failure have large differences in parameters that should be comparable. This variation is due to differences in the way the data has been sampled, censored, and categorized by the authorities who gathered it. Expert judgment can be used to rationalize the differences in probability predictions that are based on different data sources. However, the judgment and decisions based on the experience of an individual or a group of individuals in an industry are by nature heuristic. They are not capable of accounting for unknowns for which the expert group has no awareness.

In order to make predictions about rare events that are relatable to event scenarios with other priors and that can be extrapolated beyond the timescale of the priors, the degree of uncertainty in the priors should be considered. Hierarchical Bayesian methods provide a tool for doing so. With these probabilistic techniques the unknown or incomplete distribution of likelihoods for a prior can be updated as data is gathered about a specific scenario. This enables predictions to be made without censoring data, and without including data which may have priors that are not correlated to the scenario under consideration.

In order to maintain mechanical integrity, fixed assets in the process industries are managed based on their estimated remaining life. The primary causes of degradation in these fixed equipment assets are corrosion reactions between the asset's material of construction and the process chemistry. The remaining life predictions for these assets typically use a generic failure frequency that is modified based on the expected corrosion rate. The sources of uncertainty in these models are population-wide and asset-specific.

Population-wide variance includes the uncertainty in the accuracy of the generic failure frequencies used to conduct the analysis. This affects the predicted failure rate of each asset in the plant. On a specific level, there is uncertainty in the actual corrosion rate due to 1) variation within the material of construction's specified composition, 2) control of the fabrication process, where welding, forging, application of corrosion resistant linings, and other heat treatment operations could produce microstructures which have unexpected mechanical properties and corrosion resistance, 3) control of the process operating conditions which govern the chemical activity of the corrosive components of the stream, and 4) precision of the inspection techniques used to quantify the structural integrity and amount of remaining life in the vessel, including the sample amount of the vessel that is inspected and the probability of detection of any Non-Destructive Evaluation techniques which are used.

Asset-specific uncertainties have historically been addressed with empirical safety factors, which have no physical basis or statistical measurement of their uncertainty. A new approach has been proposed in this thesis for predicting the probability of failure based on the average failure frequency (aff) of a specific population of assets in a process plant. This aff is determined by a hierarchical Bayesian network which combines a covariance model with a generic failure frequency and then updates as failures are observed at different operating times. In this way, remaining life predictions of a population of assets can be tied to their actual performance, even where they have different corrosion resistance, operating conditions, and inspection history. The use of an aff also enables a system approach which updates the predictions for the remaining life of other assets when an observation is made in a single asset.

A specific application of this probabilistic method for flange connection leak risk has been demonstrated. Flange connections are present in large numbers in a process plant, but their risk as discrete elements of a process system is typically not considered. The prior factors that drive the failure frequency were developed from an existing static seal covariance model and the generic failure frequency was updated using the averaging technique described above.

In order to update the expected failure rate prior to observing a failure, an inspection technique for flange connections was also investigated. Flange connection seal failures are generally due to a loss of clamping force at the flange face. This loss of clamping force can be caused by degradation of the gasket material, corrosion of the flange face, or loss of tightness at the fasteners. A vibration-based NDE method may be capable of detecting all of these forms of degradation by measuring the loss of tightness in the sample. Although there are many measurements that may be performed from a vibration frequency spectrum, the experiments in this thesis focused on the shift in the resonance frequencies of the transfer function and changes in the reflection coefficient. The resonance frequency shift is a function of the stiffness of the system. As expected, decreasing bolt torque shifted the resonance frequencies lower, indicating a loss in the flange connection system's stiffness. The reflection coefficient is a function of the amplitudes of the forward and reverse propagating components of plane waves in the pipe. Also as expected, the reflection coefficient decreased with increasing bolt torque, due to the increase of contact stress causing the surface area between the flange face and gasket to increase and the overall stiffness of the system to increase.

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APPENDIX A

FLANGE REQUIREMENTS IN PRESSURE VESSEL DESIGN CODES

6.1. *ASME Boiler Pressure Vessel Code Approach*

The ASME Boiler Pressure Vessel Code (BPVC) Section VIII Nonmandatory Appendix S specifies a seating stress *y* and a maintenance factor *m*. However, these constants are only applicable for a statically loaded connection. Once the pressure or temperature have cycled, the seal of the connection will be less effective.

For flange gasket seating surfaces, a typical roughness recommendation is 125-250µin (ASME PCC-1 Appendix C). A defect depth limit is given by the following table (ASME PCC-1 Appendix D).

Table 16 Allowable Defect Depth vs. Width Across Face

Measurement	Hard-faced gaskets	Soft-faced gaskets
rd <w/4	<0.030 in.	<0.050 in.
w/4 <rd <w/2	<0.010 in.	<0.030 in.
w/2 <rd <3w/4	Not allowed	<0.005 in.
rd >3w/4	Not allowed	Not allowed

6.2. *DIN EN 13555 Approach to BFC Design*

EN 13555 uses a leak rate based approach. An acceptable volumetric leak rate is specified, based on the process fluid viscosity at operating temperature. The EN 13555 approach provides for the case that the BFC will experience cycles of pressure and temperature while it is in operation. Therefore, it is a more realistic test of the seal's ability to resist these challenges.

A tightness parameter is given by (24), where P = internal pressure (MPa), P* = atmospheric pressure (MPa), Lrm = mass leak rate per unit diameter (mg/sec-mm), and L*rm = reference leak rate per unit diameter [150L*rm = 1 mg/sec] (mg/sec-mm).

$$T_P = \frac{P/(L_{rm})^{0.5}}{P^*/(L_{rm}^*)^{0.5}} \tag{24}$$