Reliability Analysis of Pressure Relief Valve

by

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CERTIFICATION OF APPROVAL

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Approved by,

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

ZURHAZRIN AZUREEN BINTI ZULKIFLI

ABSTRACT

Pressure relief valve (PRV) is a reclosing-type pressure relief device. Pressure Relief Devices are used to protect pressurized equipment from exceeding the maximum allowable working pressure. PRD is considered as the "last line of defense" to save human lives and property. Therefore, it is extremely important to perform reliability analysis on pressure relief valve system.

The aim of this study is to assess reliability of pressure relief valve by using proof test data. The reliability analysis will use Weibull models to fit data obtained from available public data approved by the Center for Chemical Process Safety Process Equipment Reliability Database (CCPS PERD). The purpose of this dissertation is to outline research that has been done about the topic and review existing literatures related to the topic. The calculated failure rate of PRV by using Weibull++ is consistent with existing literature.

This dissertation has five chapters: (1) Introduction, (2) Literature Review, (3) Methodology, (4) Results and Discussion, and (5) Conclusion and Recommendation. The first chapter describes background study, problem statement, objectives, and scope of the study. The second chapter explains previous literatures related to reliability analysis and pressure relief valve system.

The third chapter outlines the methodology used to complete the project. The Gantt chart and required tools for the study are also mentioned. The fourth chapter records the findings of the project and the final chapter concludes this dissertation report.

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CHAPTER 1

INTRODUCTION

This chapter describes background of study, problem statement, objectives, scope of study, and significance of this project.

1.1 BACKGROUND OF STUDY

Pressure relief devices (PRD) are used to protect pressurized equipment from exceeding the maximum allowable working pressure. A pressurized system is a closed container designed for the containment of pressure, either internal or external such as pressure vessels and power boilers. When the pressure inside the vessel increases and excess pressure threatens to blow up the vessel, PRD release the pressure at predetermined set point to protect the vessel. PRD are considered as the "last line of defence" to save human lives and property [13]. They are extensively used in nuclear systems, transport tanks, and petroleum industries.

The main types of PRD are reclosing-type, vacuum-type, and nonreclosing-type. Pressure relief valves (PRV) are reclosing-type PRD. PRV are a spring-loaded pressure relief device. They are designed to open to relieve excess pressure and to reclose and prevent further flow of fluid after normal conditions have been restored. Purposes of PRV are to prevent pressure in the system from increasing beyond safe design limits and to minimize damage to other system components as a result of operation of the PRV itself [13]. PRV is a general term and it includes safety relief valves, relief valves, and safety valves as shown in Figure 1 on the next page.

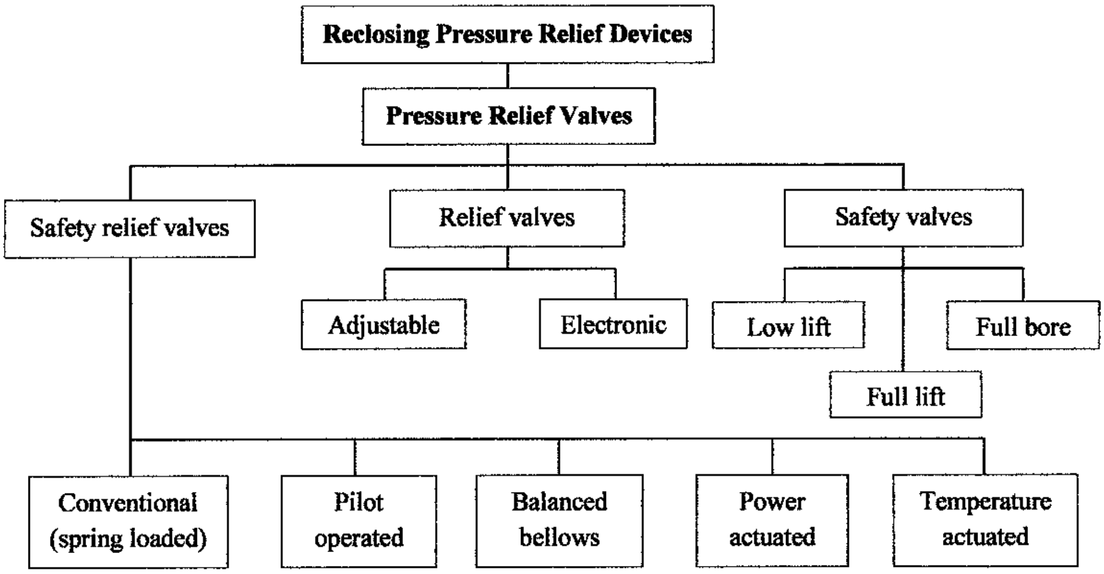


Figure 1: Types of reclosing pressure relief devices [13].

PRV are important safety devices used extensively in the chemical process industry to reduce the risk of accidents caused by overpressure events [5]. It is necessary to ensure that PRV are always in good condition by conducting periodic inspection, maintenance, and testing. A number of guidelines exist for recommending the basic structure of an effective PRV inspection and maintenance program [14]. For example, API Recommended Practice 510: Pressure Vessel Inspection Code and API Guide for Inspection of Refinery Equipment provide excellent guidance for reviewing PRV.

Major incidents like fire and explosion may happen if PRV are not functioning properly. For instance, March 1979 nuclear accident at Three Mile Island in USA. During the accident, the pressure in the primary system which is the reactor vessel began to increase due to failure at other section of the plant. Figure 2 shows the simplified schematic diagram of the plant. The pilot-operated relief valve at the top of the pressurizer opened to prevent that pressure from becoming excessive. The relief valve should have closed when then pressure fall by a certain amount, but it stayed open and apparently stuck due to mechanical fault. The open valve permitted coolant water to escape from the system, and was the principal mechanical cause of the true coolant-loss meltdown crisis that followed [1] [3]. Therefore, high reliability of PRV is extremely important to avoid accident from occurring.

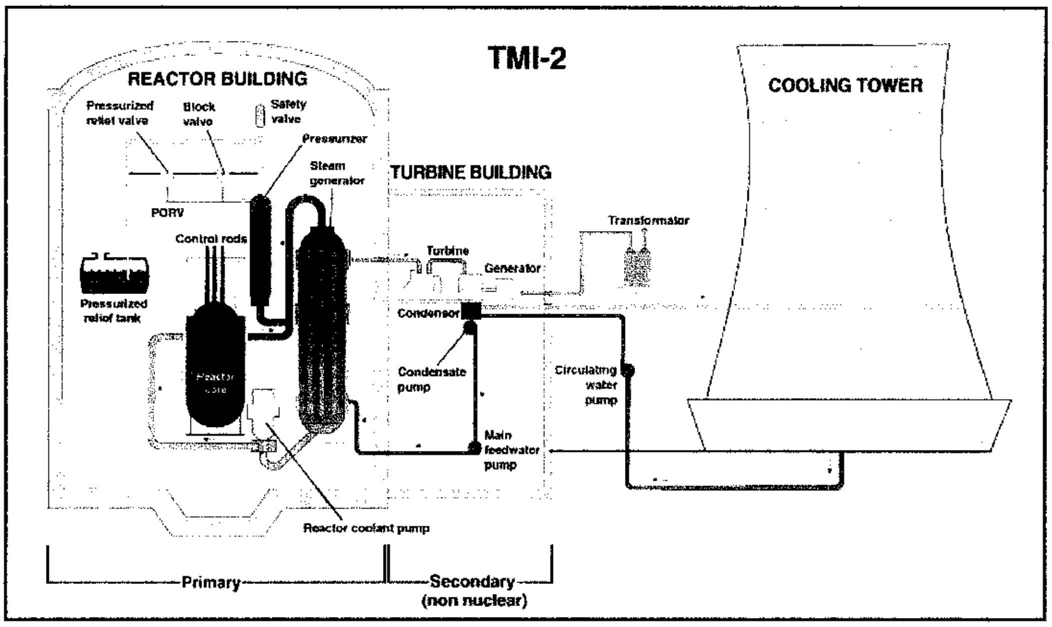


Figure 2: Simplified Schematic Diagram of the Three Mile Island Nuclear Plant [3]

1.2 PROBLEM STATEMENT

The sole purpose of PRV is to protect life and plant property. The only times we know the PRV work are when the occurring of overpressure event and when they are tested and maintained [19]. During the plant normal operation, we cannot notify the PRV is fail or not, unless the failure is visible defects that can be seen during periodic visual inspection. Generally, the testing and maintenance intervals are formed based on plant past performance data. The intervals may be safely extended when supported by the quality test data, statistical tools, and failure analysis [8].

If there is insufficient data exist to provide a decision on optimum intervals, confidence may be improved by shortening the PRV's time in service [11]. However, it is not a cost-effective solution because there is probability that the particular PRV is reliable for another year. In addition, if the primary failure mode is neither corrosion nor high stress in service, shortening time in service provides little valve performance improvement [11]. Thus, it is extremely important to perform reliability analysis of PRV so that the optimal time in service (or useful life) can be estimated.

1.3 OBJECTIVES

The objectives of this project are as the following:

- To use the proof test failure data to assess the reliability of PRV.
- To develop and establish a reliability model to predict useful life.

1.4 SCOPE OF STUDY

Proof test data is used to estimate the time-to-failure of PRV. Then, the data is fit into appropriate distribution by using Weibull++. The results of this project would be the reliability and failure rate function. The proof test data is obtained from available literature that has been approved by Center for Chemical Process Safety Process Equipment Reliability Database (CCPS PERD) [5]. The results are to be compared with the existing literatures.

1.5 SIGNIFICANCE OF STUDY

Reliability analysis of pressure relief valve would really help to estimate proper maintenance and testing intervals of PRV. Furthermore, the current state of industry relief valve reliability information is not adequate. The available literature is often inconsistent in definition, contradictory in results, and in large part consists of data collected for non-oil/chemical industries [12].

CHAPTER 2

LITERATURE REVIEW

This chapter explains literature review and theory on pressure relief valve, proof test for PRV, reliability concept, life data analysis, and quantal response data analysis of PRV proof test data.

2.1 PRESSURE RELIEF VALVE (PRV)

A pressure relief device is a safety device used on pressurized equipment to protect life and property when all other safety measures fail [13]. A pressure relief valve is a pressure relief device. Its primary purpose is to prevent pressure in the system from increasing beyond safe design limits. Secondly, it is to minimize damage to other system components as a result of operation of the PRV itself. Table 1 shows the advantages and disadvantages of pressure relief valves. They are many types of pressure relief valves, based on design and construction. They are generally classified as safety relief valves, relief valves, and safety valves.

Table 1: Advantages and disadvantages of pressure relief valves.

Advantages	Disadvantages
• Most reliable if properly sized and operated.	• Relieving pressure is affected by back pressure.
• Versatile – can be used for many services.	• Subject to chatter if built-up back pressure is too high.

2.1.1 Safety Relief Valves

A safety relief valve is a PRV that may be used either a safety or a relief valve, depending on the application. Safety relief valves are classified as: (1) conventional type, (2) pilot operated, (3) balanced bellows, (4) power actuated, and (5) temperature actuated [13]. Table 2 summarized further description on each of the types of safety relief valves.

Table 2: Description of types of safety relief valves.

Types of Safety Relief Valves	Description
Conventional PRV	• Used for applications where excessive variable or built-up back pressure is not present in the system. • The spring load is preset to equal the force exerted on the closed disk by the inlet fluid when the system pressure is at the set pressure of the valve. • The disk remains seated on the nozzle in the closed position when the inlet pressure is below the set pressure. The valve opens when the inlet pressure exceeds set pressure, overcoming the spring force. The valve recloses when the inlet pressure is reduced to a level below the set pressure.
Pilot-operated PRV	• The major relieving device is combined with and is controlled by a self-actuated auxiliary PRV. • It uses process pressure to keep the valve closed instead of a spring. A pilot is used to sense process pressure and to pressurize or vent the dome pressure chamber which controls the valve opening or closing.
Balanced bellows PRV	• A spring-loaded safety valve which incorporates a bellows or other means of balancing the valve disk to minimize the effects of back pressure on the performance characteristics of the valve.

	• The term 'balanced' means the set pressure of the valve is not affected by back pressure. It should be selected where the built-up back pressure is too high for a conventional relief valve. • It works by the same principle as the conventional relief valve.
Power-actuated PRV	• The major relieving device is combined with and controlled by a device requiring an external source of energy. • The movement to open or close is fully controlled by a power source such as electricity, air, steam, or water (hydraulic). • Used mostly for forced-flow steam generators with no fixed steam or waterline and also nuclear power plants.
Temperature-actuated PRV	• Actuated by external or internal temperature or by pressure on the inlet side. It is also called a T&P safety relieve valve. • It incorporated two primary controlling elements: a spring and a thermal probe to prevent both temperature and pressure from exceeding the specified limits.

2.1.2 Relief Valves

A relief valve is a spring-loaded pressure relief valve actuated by the static pressure upstream of the valve [13]. Normally, the valve opens in proportion to the pressure increases over the opening pressure. It is generally used for liquid service. Liquid-service valves do not pop in the same manner as vapour-service valves because the expensive forces produced by the vapour are not present in liquid flow.

2.1.3 Safety Valves

A safety valve is a direct spring-loaded pressure relief valve that is actuated by the static pressure upstream of the valve and is characterized by rapid opening or pop action [13]. It is used to prevent overpressure in steam plants. It operated by releasing a volume of fluid from within the plant when a predetermined maximum pressure is reached, thereby reducing the excess pressure in a safe manner.

Safety valves are installed wherever the maximum allowable working pressure (MAWP) of a system or pressure vessel is likely to be exceeded [13]. It typically used for boiler overpressure protection and other applications such as downstream of pressure-reducing controls. Safety valves are also used in process operations to prevent product damage due to excess pressure [13].

2.2 PROOF TEST FOR PRV

Proof test data is widely used for predicting pressure relief valve reliability in several literatures. Proof test is conducted to detect fail-to-open failure. This failure mode cannot be detected while the plant or equipment is in operation. The PRV would normally close and would open only in the case of overpressure event [4]. If the valve is actually stuck in the closed position, this would be undetectable in operation unless an overpressure event is occurred and the valve failed to open. It is preferable to discover this failure mode before overpressure event occurs.

To conduct the proof test, the PRV is removed first from the process. Then, it is pressurized on a test bench until the valve opens. The pressure needed to open the valve is the Test Pressure (TP). Each PRV has a Set Pressure (SP), which the valve should open in normal operation at this pressure. The ratio of TP/SP is recorded. The valve is considered 'fail-to-open' when TP/SP value ≥ 1.5, which means the pressure required to open the PRV during testing is 50% or more above its Set Pressure.

The proof test data is then used to perform reliability analysis by using statistical tools. Bukowski & Goble (2009) used quantal response analysis. Three independent data sets obtained from 500 operating companies were analysed by three independent analysis groups in the paper. Data Set I consisted of 3403 proof tests performed on 1949 individual PRV resulting in 48 ''fail-to-open'' test results. Data Set II consisted of 2578 proof tests which included 57 failures. Data Set III consisted of 3282 proof tests which included 24 failures. Data Set III is unique in that the 3282 proof tests include 2377 proof tests that were performed prior to initial installation and these tests include 10 initial failures [4]. Table 3, 4, and 5 on the next page show the quantal reponse data used in the above-mentioned literature. Quantal response data analysis is further described in the next section.

Table 3: Data Set I [4]

i	T_i (years)	q_i	$-\ln(1-q_i)$
1	0.64658	0.01205	0.01212
2	1.58904	0.01015	0.01020
3	1.96301	0.01166	0.01173
4	2.10753	0.01351	0.01360
5	2.41699	0.01295	0.01303
6	2.96301	0.00416	0.00417
7	3.28082	0.01176	0.01183
8	3.54795	0.01674	0.01688
9	3.73863	0.01799	0.01815
10	4.20913	0.00894	0.00898

Table 4: Data Set II [4]

i	T_i (years)	q_i	$-\ln(1-q_i)$
1	0.16	0.00519	0.0052
2	0.57	0.00717	0.0072
3	0.79	0.03169	0.0322
4	0.88	0.01193	0.0120
5	0.93	0.02635	0.0267
6	0.98	0.00797	0.0080
7	1.03	0.00995	0.0100
8	1.13	0.00608	0.0061
9	1.31	0.03449	0.0351
10	1.53	0.01538	0.0155
11	1.91	0.02732	0.0277
12	2.21	0.02049	0.0207
13	2.83	0.01568	0.0158
14	3.83	0.00896	0.0090
15	5.10	0.01646	0.0166
16	6.15	0.04715	0.0483
17	6.58	0.08625	0.0902
18	7.46	0.04065	0.0415
19	9.04	0.13886	0.1495

Table 5: Data Set III [4]

i	T_i (years)	q_i	$-\ln(1-q_i)$
1	0.00	0.00419	0.0042
2	0.82	0.01617	0.0163
3	2.60	0.02410	0.0244
4	3.15	0.01124	0.0113
5	4.41	0.00866	0.0087
6	5.18	0.01114	0.0112
7	8.12	0.03844	0.0392

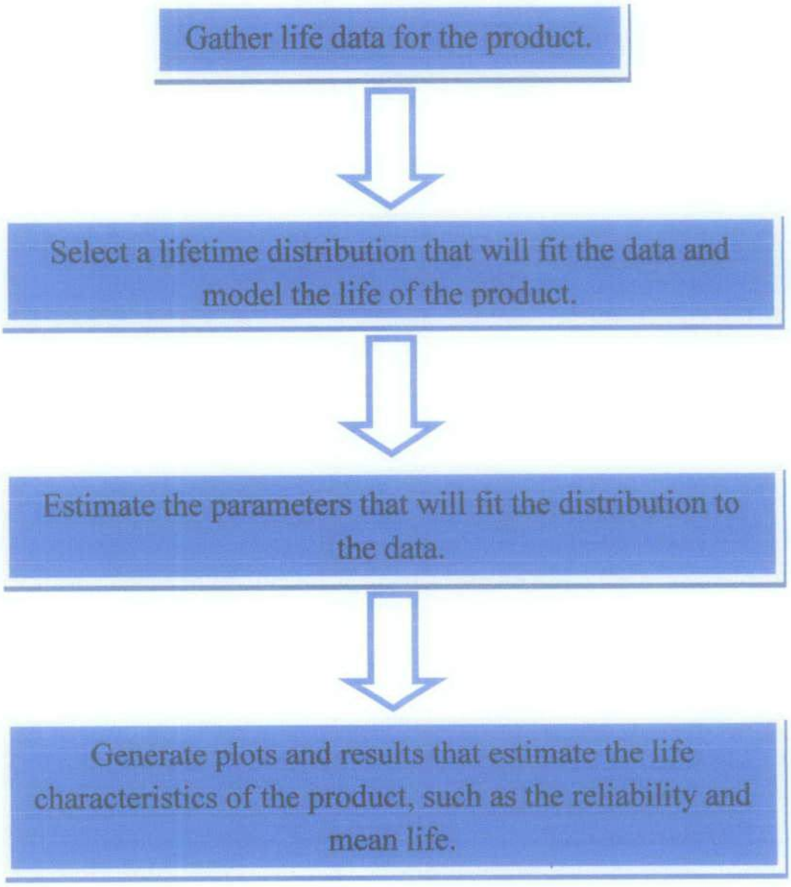
2.3 RELIABILITY CONCEPT

Reliability of a product (system) is the probability that the product (system) will perform its intended function for a specified time period when operating under normal (or stated) environmental conditions [15]. The basic of reliability is the reliability function. This function gives the probability of an item operating for a certain amount of time without failure. Every reliability value has an associated time value and thus, this function is a function of time. To come out with the desired reliability value, one must specify a time value [2]. For example, 95% reliability at 100 hours. In other words, after operating for 100 hours, the system has 5% probability of failure may occur.

To perform reliability analysis, data of the system to be measured is needed. Most problems in reliability engineering deal with quantitative measures and the data is in form of numbers. For example, time-to-failure of a component and whether a component fails or not fails [2]. The quantitative measures are random variables that can be used in reliability analysis. Types of random variables are: (1) discrete random variables and (2) continuous random variables. Discrete random variable is the variable that can take only two discreet values, for instance defective = 0 and non-defective = 1. Continuous random variable consists of range of data. For example, in the case of time-to-failure data that can be in a range from 0 to infinity.

2.4 LIFE DATA ANALYSIS

The term 'life data' refers to measurement of product life [17]. Product life is measured in hours, cycles or other metric that represents to the period of successful operation of a particular component or system. Life data points are often called 'time-to-failure' because time is a common measure of component life. In life data analysis, the practitioner attempts to make predictions about the life of all products (or components) in the population by fitting a statistical distribution to life data from a representative sample of units [17]. From the resulted distribution from the data set, it can be used to estimate reliability, probability of failure at specific time, the mean life, and the failure rate [17]. The general steps in life data analysis are shown in Figure 3.



Gather life data for the product.

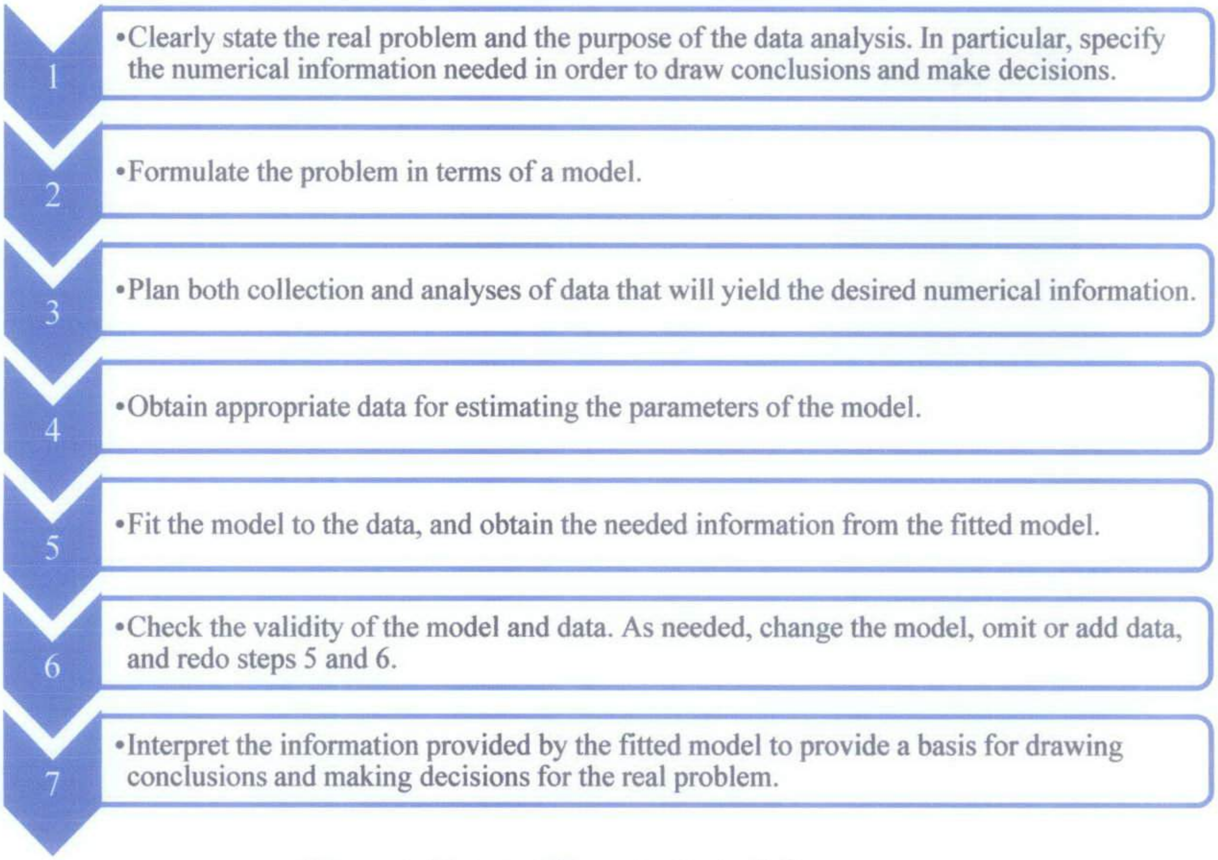
Select a lifetime distribution that will fit the data and model the life of the product.

Estimate the parameters that will fit the distribution to the data.

Generate plots and results that estimate the life characteristics of the product, such as the reliability and mean life.

Figure 3: Life Data Analysis [17].

According to Nelson (2004), the solution of a real problem involving data analysis consists of seven steps. Figure 4 below describes the seven steps of nature of data analysis.



1. Clearly state the real problem and the purpose of the data analysis. In particular, specify the numerical information needed in order to draw conclusions and make decisions.
2. Formulate the problem in terms of a model.
3. Plan both collection and analyses of data that will yield the desired numerical information.
4. Obtain appropriate data for estimating the parameters of the model.
5. Fit the model to the data, and obtain the needed information from the fitted model.
6. Check the validity of the model and data. As needed, change the model, omit or add data, and redo steps 5 and 6.
7. Interpret the information provided by the fitted model to provide a basis for drawing conclusions and making decisions for the real problem.

Figure 4: Nature of Data Analysis [16].

2.5 QUANTAL RESPONSE DATA ANALYSIS OF PRV PROOF TEST DATA

Most literatures are using quantal response data to evaluate maintenance intervals for pressure relief valves. To define quantal response data, suppose each unit is inspected only once. If a unit is found failed, one knows only that its failure time was before its inspection time. If a unit is found unfailed, one knows only that its failure time is beyond its inspection time. This inspection data is called quantal-response data as depicted in Figure 9. If the inspection time when a failure is found is treated as the failure time, it is totally wrong [16]. One must keep in mind that the failure occurs before the inspection and this must be properly taken into account.

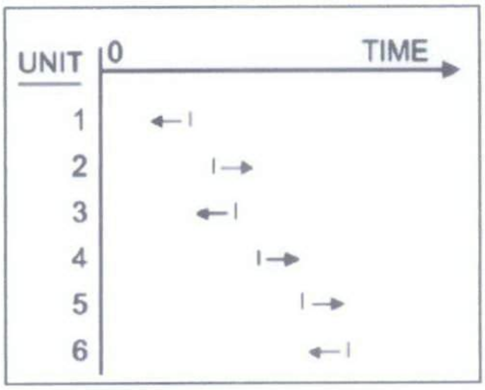


Figure 5: Quantal-response Data [16].

Proof tests are normally conducted during periodic inspection and maintenance. Thus, when a PRV failure is discovered during proof test, the actual time is not known [4]. The relief valve systems fall into the classification of standby systems because the only times we know they are working is when the process challenges them, and when they are tested and maintained [19]. By doing the proof test, it is conformed that the failure occurred sometime between the last proof test and the current proof test. As a consequence, the usual method of time-to-failure analysis used to estimate failure rates cannot be used on proof test data [4]. In addition, one can wrongly treat the proof test data as a failure rate data. The quantal response analysis is an appropriate analysis method to estimate failure rates from proof test data [4].

The steps of the quantal response method are summarized as follows [4]:

1. Arrange the valve data in ascending order of in-service hours since last proof test without regard to whether the valve passed or failed the proof test.
2. Divide the data into *m* non-overlapping intervals each containing some suitable nonzero number of failures.
3. For each intervals i, $i = 1,2, \ldots, m$, let n_i = number of valve tested and k_i = number of valves failed and t_p = in-service hours since last proof test, $p = 1,2, \ldots, n_i$.
4. Form the ratio $q_i = k_i/n_i$, $i = 1,2, \ldots, m$.
5. Compute $T_i = 1,2, \ldots, ni$ as

$$T_i = (1/n_i) \sum_{p=1}^{n_i} t_p \qquad \text{or} \qquad T_i = (1/k_i) \sum t_f$$

6. Plot q_i vs T_i and estimate F(t) and λ(t).

By using the same public data group from Bukowski (2007), a quantal response analysis was performed by the same author to determine the useful life interval of PRV. That study resulted three plots of $-\ln(1- q_i)$ vs. T_i along with power curve fits for respective three data sets, as shown in Figure 5. Table 1 indicates estimated values for parameters of power curve fits and error information.

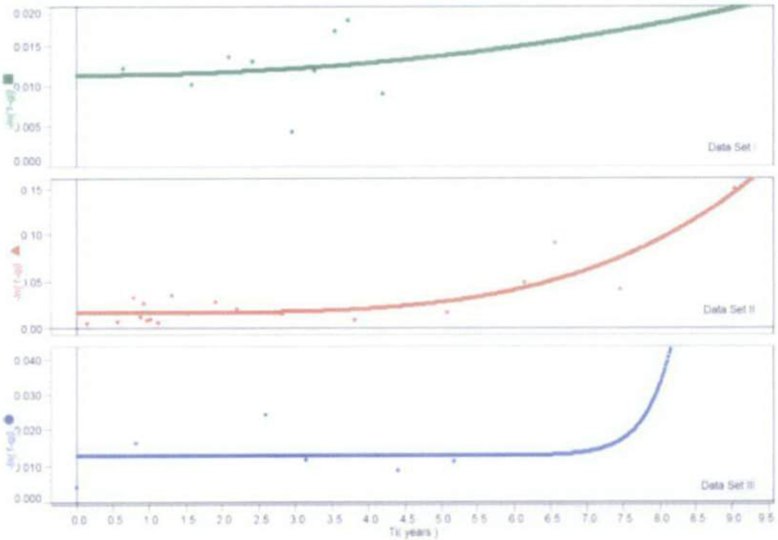


Figure 6: Plots of $-\ln(1- q_i)$ vs. T_i along with power curve fits [5].

Table 6: Estimated values for parameters of power curve and error information [5].

Data Set	*A* (Scale Factor)	*n* (Power)	*b* (y intercept)	Mean Square Error	Root MSE
I	7.89E-5 ± 2.03E-3	2.12 ± 16	0.0113 ± 4.7E-3	1.37E-5	3.70E-3
II	152E-5 ± 3.2E-5	4.11 ± 0.99	0.0164 ± 4.5E-3	2.23E-4	0.0149
III	1.46E-22	22.3	0.0127	3.46E-5	5.88E-3

By using linear regression, a straight line of the form $mt + b$ is fit to the useful-life data for each data set [5]. Table 2 indicates the estimated values for m (in failures/year) and b with their standard deviation along with the sample correlation coefficient, r, and the man squared and root mean squared errors.

Table 7: Estimated value for parameters of linear fits and error information [5].

Data Set	*m* (Failures/year)	*b* (y intercept)	*r* (Sample Correlation Coefficient)	Mean Square Error	Root MSE
I	4.39E-4 ± 1.3E-3	0.0109 ± 3.6E-3	0.1230	1.37E-5	3.70E-3
II	5.31E-4 ± 3.0E-3	0.0158 ± 5.2E-3	0.0507	1.65E-5	9.82E-3
III	1.90E-4 ± 1.7E-3	0.0122 ± 5.6E-3	0.0547	4.03E-5	6.35E-3

All the results are summarized in Table 3. To further support the linear regressions and the information derived from them, the failure rate values are compared with that values derived from failure modes, effects, and diagnostics analysis (FMEDA) analysis. The FMEDA predicted failure rate of 8.4×10^{-8} failures/h, and it is consistent with the estimates for failure rates obtained [5].

Table 8: Summary of results along with general conclusions drawn [5].

Data Set	Estimated Useful-Life Interval	Estimated PIF from		Estimated λ Failures/h
		B	*b*	
I	4.2 years	1.13%	1.09%	5.0×10^{-8}
II	4-5 years	1.64%	1.58%	6.1×10^{-8}
III	5.2 years	1.27%	1.22%	2.2×10^{-8}
General conclusions	4-5 years	1-1.6%		10^{-8} to 10^{-7}

CHAPTER 3

METHODOLOGY

This chapter consists of four sections: (1) Project Flow, (2) Project Development, (3) Gantt Chart, and (4) Tools and Equipment.

3.1 PROJECT FLOW

This section described steps taken by the author to complete this project.

1. Background of Study & Problem Statement

When the project title is finalized, initial research is conducted to understand the topic. It leads to problem statement identification to make this project to be more significant. The objectives and scope of the study are also identified to create boundary of the project.

2. Literature Review

Extensive research on the project topic is conducted to further understand underlying concepts of reliability analysis and pressure relief valves. Related existing researches are reviewed to understand the current state of reliability analysis on PRV.

3. Weibull++ Software Skills

As the main tool to complete this project, the author needs to have adequate skills to use Weibull++. The software is used for data plotting and calculations of results.

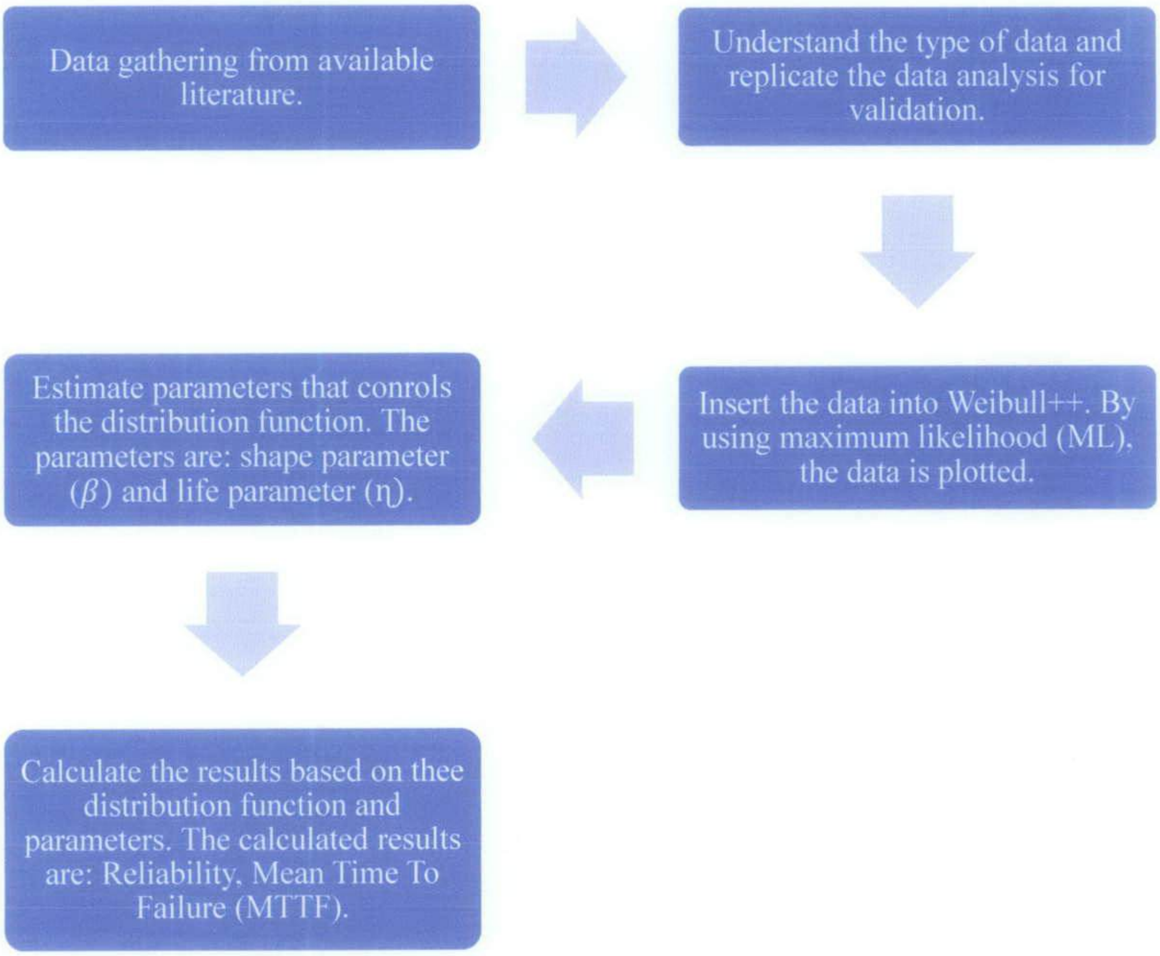
4. Results Analysis

The data used for this project are from Bukowski & Goble (2009). After the data is input to Weibull++, the generated plots are analysed to be compared with existing literatures.

5. Conclusions & Recommendation

Based on the results, overall findings of the analysis are concluded. Several recommendations are suggested for future improvement in subsequent study.

3.2 PROJECT DEVELOPMENT



Data gathering from available literature.

Understand the type of data and replicate the data analysis for validation.

Insert the data into Weibull++. By using maximum likelihood (ML), the data is plotted.

Estimate parameters that conrols the distribution function. The parameters are: shape parameter (β) and life parameter (η).

Calculate the results based on thee distribution function and parameters. The calculated results are: Reliability, Mean Time To Failure (MTTF).

3.3 GANTT CHART

The following Table 9 and 10 describe the timelines for FYP I and FYP II activities in order to complete this project successfully.

Table 9: Gantt Chart for FYP I.

No	**Activities**	**Week**													
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1.	Selection of project topic	■													
2.	Preliminary research work		■	■	■	■									
3.	Submission of extended proposal						■								
4.	Proposal Defence								■	■					
5.	Project work continues										■	■	■		
6.	Submission of interim draft report													■	
7.	Submission of interim report														■

Table 10: Gantt Chart for FYP II.

No	**Activities**	**Week**														
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
1.	Project work continues	■	■	■	■	■	■	■								
2.	Submission of progress report								■							
3.	Project work continues									■	■	■	■	■		
4.	Submission of poster												■			
5.	Submission of draft report													■		
6.	Submission of dissertation (Soft bound)														■	
7.	Submission of technical paper															■
8.	Oral presentation (Viva)															■
9.	Submission of project dissertation (Hard bound)															■

Table 13: Data Set I

i	T_i (years)	q_i	Percentage Failed (%)	Cumulative Percentage Failed (%)
1	0.64658	0.01205	1.205	1.205
2	1.58904	0.01015	1.015	2.22
3	1.96301	0.01166	1.166	3.386
4	2.10753	0.01351	1.351	4.737
5	2.41699	0.01295	1.295	6.032
6	2.96301	0.00416	0.416	6.448
7	3.28082	0.01176	1.176	7.624
8	3.54795	0.01674	1.674	9.298
9	3.73863	0.01799	1.799	11.097
10	4.20913	0.00894	0.894	11.991

Table 14: Data Set II

i	T_i (years)	q_i	Percentage Failed (%)	Cumulative Percentage Failed (%)
1	0.16	0.00519	0.5187	0.5187
2	0.57	0.00717	0.7174	1.2361
3	0.79	0.03169	3.1687	4.4048
4	0.88	0.01193	1.1928	5.5976
5	0.93	0.02635	2.6347	8.2323
6	0.98	0.00797	0.7968	9.0291
7	1.03	0.00995	0.9950	10.0241
8	1.13	0.00608	0.6081	10.6322
9	1.31	0.03449	3.4491	14.0814
10	1.53	0.01538	1.5380	15.6194
11	1.91	0.02732	2.7320	18.3514
12	2.21	0.02049	2.0487	20.4001
13	2.83	0.01568	1.5676	21.9677
14	3.83	0.00896	0.8960	22.8637
15	5.10	0.01646	1.6463	24.5100
16	6.15	0.04715	4.7152	29.2252
17	6.58	0.08625	8.6252	37.8503
18	7.46	0.04065	4.0651	41.9154
19	9.04	0.13886	13.8862	55.8016

Table 15: Data Set III

i	T_i (years)	q_i	Percentage Failed (%)	Cumulative Percentage Failed (%)
1	0.00	0.00419	0.4191	0.4191
2	0.82	0.01617	1.6168	2.0359
3	2.60	0.02410	2.4105	4.4464
4	3.15	0.01124	1.1236	5.5700
5	4.41	0.00866	0.8662	6.4362
6	5.18	0.01114	1.1138	7.5500
7	8.12	0.03844	3.8442	11.3942

4.2 RESULTS AND PLOTS

By using Weibull++ software, the data is fitted into 2-parameter Weibull distribution. Probit (free-form) data plotting is selected to input the data into Weibull++. The X-axis value is represented by the time intervals, *i* and the Y-axis value is represented by the cumulative percentage of failures at each time intervals.

Data Set I

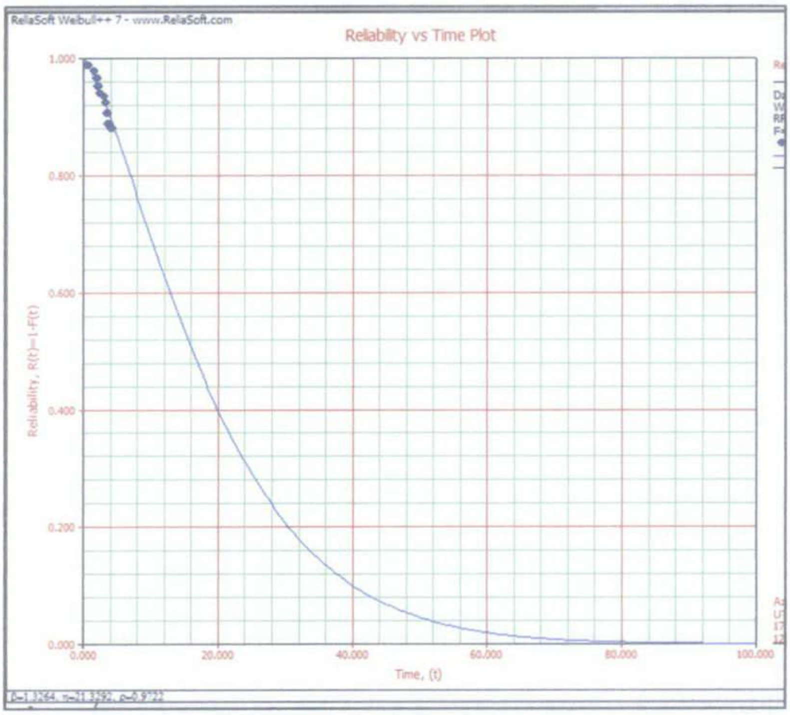


Figure 7: Reliability vs. Time Plot for Data Set I

Based on the above Figure 7, the resulted parameters are:

1. Beta, $\beta = 1.3264$
2. Eta, $\eta = 21.3293$ years

By using Quick Calculation Pad (QCP) application in Weibull++, the following results are obtained:

1. Mean Life = 19.6219 years
2. Failure Rate = 0.0609 failures for 20 years mission end time, and thus 3.045E-3 failures/year
3. Reliability = 0.3392 for 20 years mission end time

Options for Calculations
○ Std. Prob. Calculations
○ Conditional Calculations
○ Failure Rate
○ Warranty (Time) Information
○ BX Information
● Mean Life

Results Options
● Results as Reliability
○ Results as Probability of Failure

Required Input from User

Results
Mean Life 19.6219

Folio: Folio1 (Plot of Data 1)

Figure 8: QCP for Mean Life of Data Set I.

Options for Calculations
○ Std. Prob. Calculations
○ Conditional Calculations
● Failure Rate
○ Warranty (Time) Information
○ BX Information
○ Mean Life

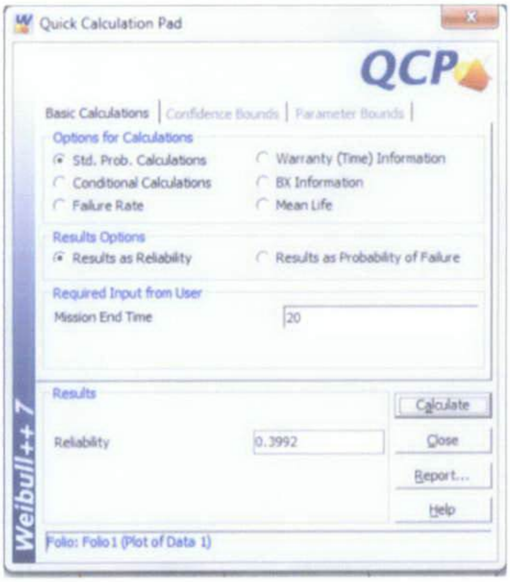
Results Options
● Results as Reliability
○ Results as Probability of Failure

Required Input from User
Mission End Time 20

Results
Failure Rate 0.0609

Folio: Folio1 (Plot of Data 1)

Figure 9: QCP for Failure Rate of data Set I.



Options for Calculations

● Std. Prob. Calculations
○ Conditional Calculations
○ Failure Rate
○ Warranty (Time) Information
○ BX Information
○ Mean Life

Results Options

● Results as Reliability
○ Results as Probability of Failure

Required Input from User

Mission End Time: 20

Results

Reliability: 0.3992

Folio: Folio1 (Plot of Data 1)

Figure 10: QCP for Reliability of Data Set I.

Data Set II

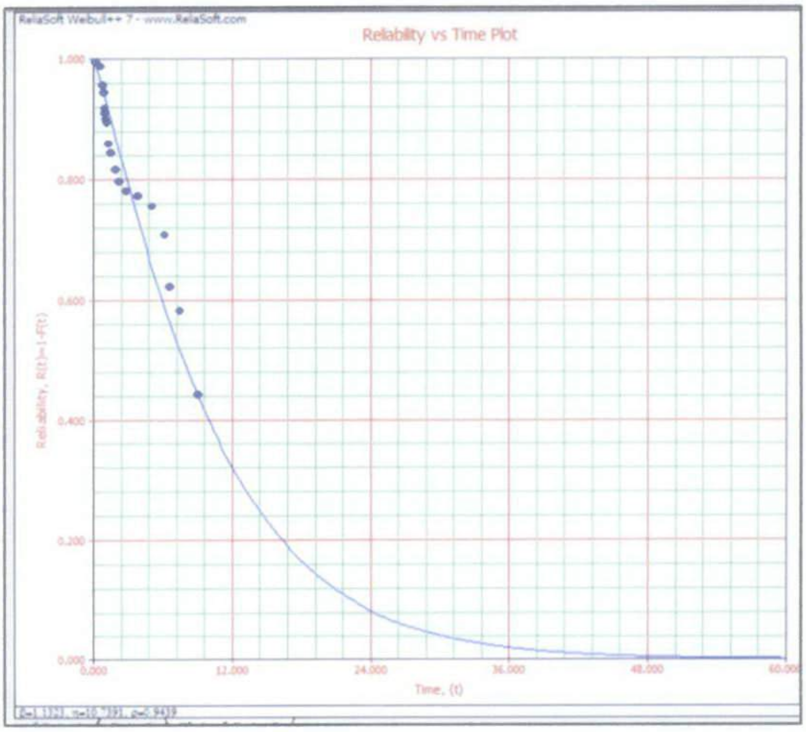


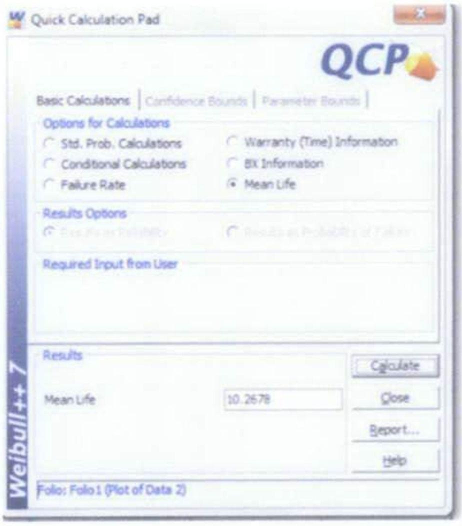
Figure 11: Reliability vs. Time Plot of Data Set II

Based on the above Figure 11, the resulted parameters are:

1. Beta, β = 1.1323
2. Eta, η = 10.7391 years

By using Quick Calculation Pad (QCP) application in Weibull++, the following results are obtained:

1. Mean Life = 10.2678 years
2. Failure Rate = 0.1145 failures for 20 years mission end time, and thus 5.725E-3 failures/year
3. Reliability = 0.1324 for 20 years mission end time

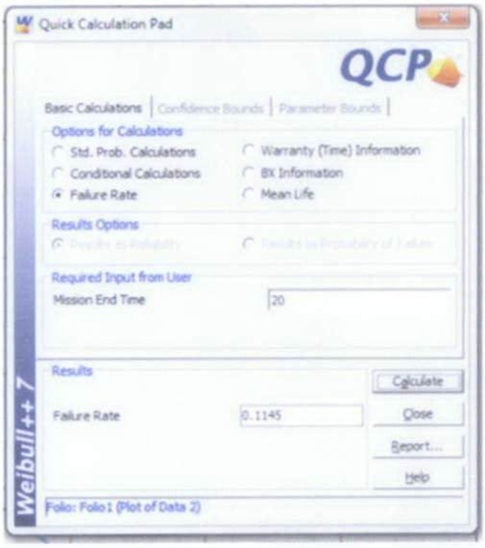


○ Std. Prob. Calculations
○ Conditional Calculations
○ Failure Rate
○ Warranty (Time) Information
○ BX Information
● Mean Life

Mean Life: 10.2678

Folio: Folio1 (Plot of Data 2)

Figure 12: QCP for Mean Life of Data Set II



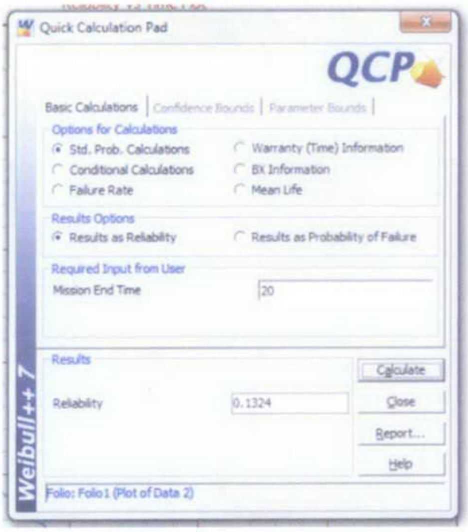
○ Std. Prob. Calculations
○ Conditional Calculations
● Failure Rate
○ Warranty (Time) Information
○ BX Information
○ Mean Life

Mission End Time: 20

Failure Rate: 0.1145

Folio: Folio1 (Plot of Data 2)

Figure 13: QCP for Failure Rate of Data Set II



Options for Calculations

● Std. Prob. Calculations
○ Conditional Calculations
○ Failure Rate
○ Warranty (Time) Information
○ BX Information
○ Mean Life

Results Options

● Results as Reliability
○ Results as Probability of Failure

Required Input from User

Mission End Time: 20

Results

Reliability: 0.1324

Folio: Folio1 (Plot of Data 2)

Figure 14: QCP for Reliability of Data Set II

Data Set III

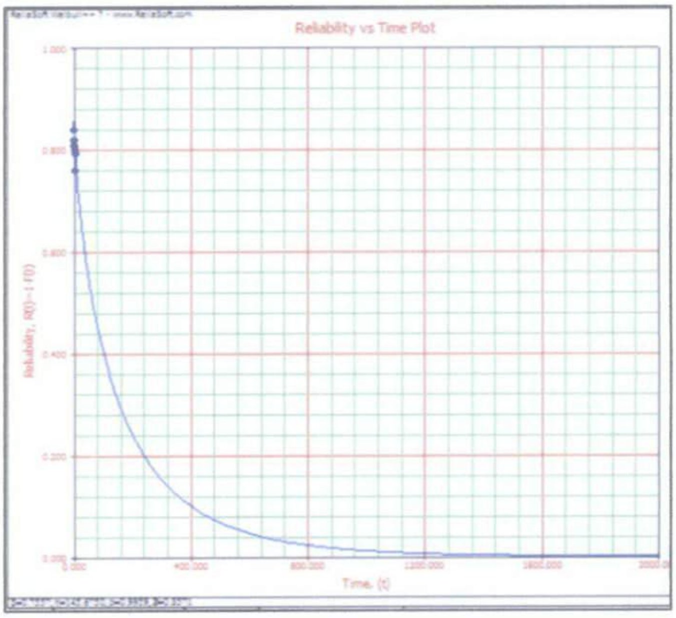


Figure 15: Reliability vs. Time Plot of Data Set III

Based on the above Figure 11, the resulted parameters are:

1. Beta, β = 0.757
2. Eta, η = 145.675 years

By using Quick Calculation Pad (QCP) application in Weibull++, the following results are obtained:

1. Mean Life = 147.7429 years
2. Failure Rate = 0.0084 failures for 20 years mission end time, and thus 4.2E-4 failures/year
3. Reliability = 0.6858 for 20 years mission end time

● Mean Life

Mean Life 147.7492

Folio: Folio1 (Plot of Data 3)

Figure 16: QCP for Mean Life of Data Set III

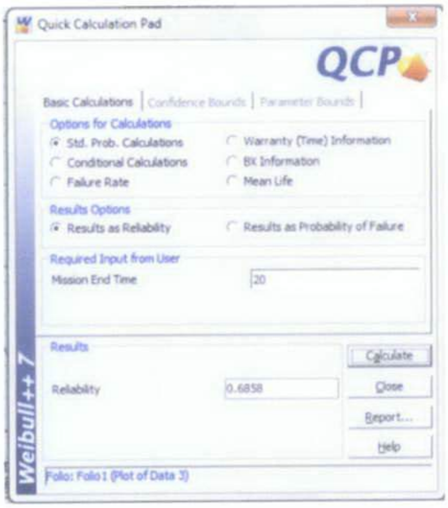
● Failure Rate

Mission End Time 20

Failure Rate 0.0084

Folio: Folio1 (Plot of Data 3)

Figure 17: QCP for Failure Rate of Data Set III



● Std. Prob. Calculations
○ Conditional Calculations
○ Failure Rate
○ Warranty (Time) Information
○ BX Information
○ Mean Life

● Results as Reliability
○ Results as Probability of Failure

Mission End Time: 20

Reliability: 0.6858

Folio: Folio1 (Plot of Data 3)

Figure 18: QCP for Reliability of Data Set III

4.3 DISCUSSION

The resulted distribution is two-parameter Weibull. Reliability (R) is defined as the probability at time *t* that failure will not occurred by that time [11]. The reliability at time *t* year is calculated by:

$$R(t) = 1 - F(t)$$

The probability of failure at *t* years is defined as:

$$F(t) = 1 - \exp\left[-\left(\frac{1}{\eta}\right)^{\beta}\right] \qquad t \geq 0$$

By using Weibull++, the calculations for results are done by QCP application. Table 16 summarizes all calculated results for three data sets.

Table 16: Result Summary for Three Data Sets

Data Sets	Mean Life (Years)	Failure Rate (failures/year)	Reliability for 20 years
I	19.6219	3.045E-3	0.3392
II	10.2678	5.725E-3	0.1324
III	147.7429	4.2E-4	0.6858
Average Value	59.2109	0.00306	0.3858

Based on Table 16, the average failure rate value is 0.00306 failures per year. To compare with the paper done by Bukowski & William (2009), the failure rate unit is converted to total failures per hour.

Assuming 1 year = 8760 hours,

The average failure rate for three data sets = **3.4970E-7 failures/hour**

The estimated failure rate by Bukowski & William (2009) is 10^{-8} to 10^{-7} failures/hour. The failure rate value by using Weibull++ is consistent with the existing literature.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

For reliability analysis of pressure relief valve, the suitable type of data is quantal response data. It is because the data source is obtained from inspection. It must not be treated as time-to-failure data because the exact failure time is uncertain. For example, if one PRV fails a proof test, the failure occurred between the last proof test and current proof test. If a PRV is found unfailed, one knows only that its failure time is beyond its inspection time. Thus, reliability analysis of PRV is important to estimate the life of the equipment.

Based on this project, two-paramater Weibull distribution is used to fitting the quantal response data. The resulted average failure rate is 3.4970E-7 failures/hour and it is consistent with research done by Bukowski & William (2009).

Reliability analysis of PRV should be further analysed because the role of PRV is very crucial in order to protect plant property and also human beings. Thus, more research on this equipment should be encouraged by developing more reliable and complete data source.

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APPENDIX-A: Pressure Relief Valves Failures Mode [18]

API RBI	CCPS PERD
Complete Failures	
Fail to open	Fail to open
Stuck open (fails to reseat)	Fail to close (reseat)
Spuriously opens	Spuriously open
	Equipment rupture
Partial Failures	
Opens above set pressure	Opens above set pressure
Fail to relieve required capacity	Fail to relieve required capacity
	Opens below set pressure
	Fails to completely reseat
Leakage	Seat leakage
	External leakage
	Opens too slowly
	Erratic opening