CHAPTER 1: INTRODUCTION

1.1 Background of Study

Heat Recovery Steam Generator (HRSG) is a machine that is widely used in chemical and gas processing plant. HRSG which can operate in either cogeneration or combined-cycle mode is essential to the processing plant depending on the mode their working on. HRSG works as a massive heat exchanger in which exhaust gas energy is converted into steam for other uses. "In cogeneration mode, steam produced from the HRSG is mainly used for application, whereas in the combined-cycle mode, power is generated via a steam turbine generator" (Ganapathy, 1996).

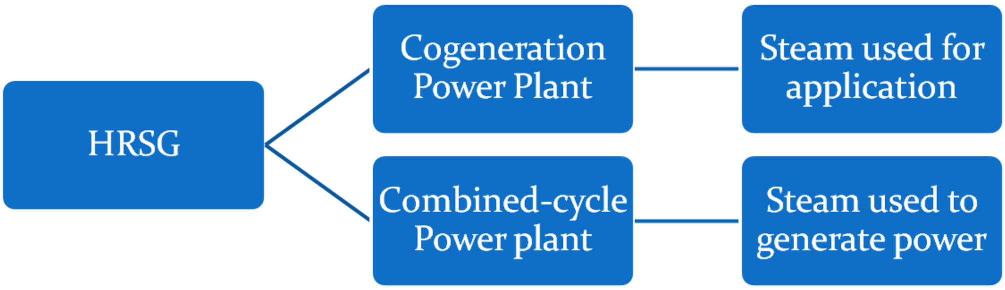

Figure 1: HRSG application in cogeneration and combined-cycle power plant.

In this research, HRSG used in a case study by Jaske and Shannon (2002) operates in cogeneration mode which provides steam for chilled water production. The chilled water will be used for refrigeration purpose. Carazas et al. (2010) points out that "in case of HRSG failure the steam cycle is shutdown, reducing the power plant output". Since HRSG works as a tool to reduce environmental impact of the high temperature exhaust gas from the gas turbine, its availability in the gas processing plant is crucial. In studies by Srikanth et al. (2003) and Shin et al. (2002) show that HRSG is capable to reduce exhaust gas temperature from 550^{o}C to 150^{o}C.

According to Carazas again, “in case of HRSG failure, the power plant has two possible operation conditions:

i) The gas turbine coupled to the failed HRSG may operate in open cycle if the power plant has an environmental license for that specific operation.

ii) The gas turbine coupled to the failed HRSG is shutdown”.

Due to its high impact on plant operation and environment, a thorough reliability analysis should be done to HRSG unit to foresee the performance of the power plant on long-term basis which according to Carazas et al. (2010) is affected by low-cycle thermal fatigue, corrosion and creep problems.

1.2 Problem Statement

HRSG which is a massive heat exchanger which operates at elevated temperature. High temperature operation will lead to structural failure in addition to other failures that may affect the reliability of the HRSG. According to analysis by Carazas, et al. (2010), reliability of a HRSG based on structural failure is affected by low-cycle thermal fatigue, corrosion and creep problems occurred in the tubing system.

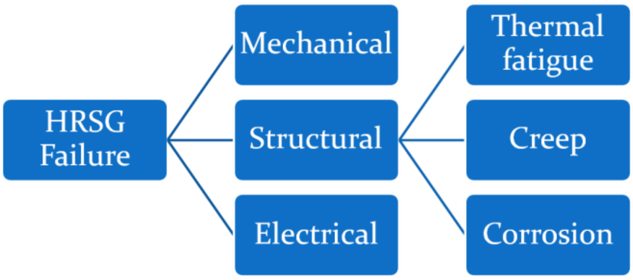

Figure 2: Structural and other failure associated with HRSG

With regards to the HRSG in the case study, it is a need for us to assess the reliability of the HRSG and due time constraint; the reliability will be based only on creep rupture failure. The result from the project can be used for maintenance purpose and further reliability assessment.

1.3 Objective

i) To assess the reliability of the HRSG tubing with subject to creep.

ii) To conduct sensitivity analysis in order to determine parameters that greatly affects HRSG reliability.

1.4 Scope of the Study

The project objective is to assess the reliability of the HRSG subjected to structural failure. Due to the time constraint, the project will focus on the creep rupture failure. According to Carazas et al. (2010), creep failure most likely to occur in superheater and reheater tubing systems since the tubes operates at a very high temperature.

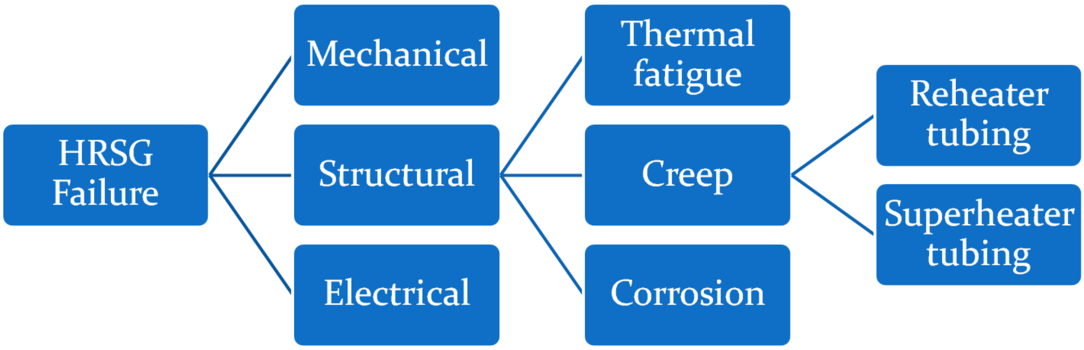

Figure 3: Creep failure occurrence in an HRSG

This is supported by According to ASM Handbook Volume 11, Failure Analysis and Prevention, where it says creep rupture can occur within a thin-section component such as steam pipes and boiler tubes with a uniform stress and high temperature. In this project, reliability analysis for the HRSG in the case study will focus on creep rupture failure at superheater and reheater tubing systems.

1.5 Relevancy of the Study

With the learning of optimizing manufacturing system as the core objective in Manufacturing subjects, reliability analysis of Heat Recovery Steam Generator will provides a good learning medium for identifying root cause of failure in a system. The result obtained from the project will serve as basis for maintenance worker to make improvement. The improvement made will optimize the power plant in terms of cost and quality.

CHAPTER 2: LITERATURE REVIEW

2.1 Heat Recovery Steam Generator

Heat Recovery Steam Generator (HRSG) is a massive heat exchanger that is usually coupled with a gas processing power plant. The main function of HRSG is to produce steam by extracting the waste energy of the gas turbine exhaust gas (Carazas et al. 2010). According to Ganapathy (1996), HRSG can operate in two different types of power plants; cogeneration and combined-cycle power plant. In cogeneration mode, steam produced by the HRSG is used for process applications; whereas in combined-cycle power plant, steam produced by the coupled HRSG will be used to generate electricity through steam turbine generator. HRSG operating conditions in both types of power plant is clearly described by the following figures.

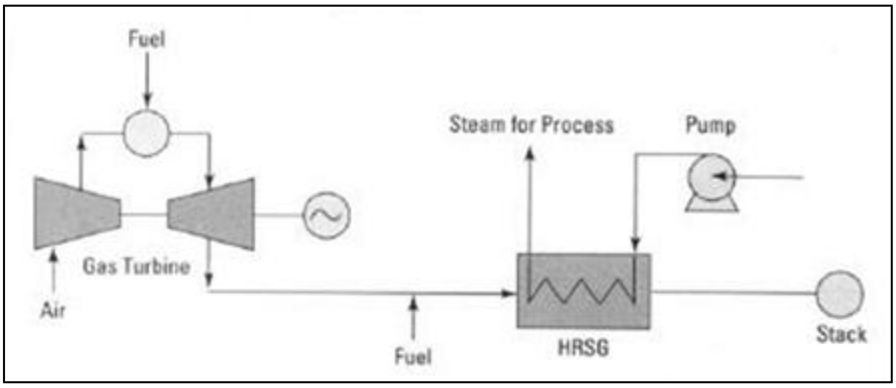

Figure 4: Schematic diagram for HRSG in cogeneration power plant (Ganapathy, 1996).

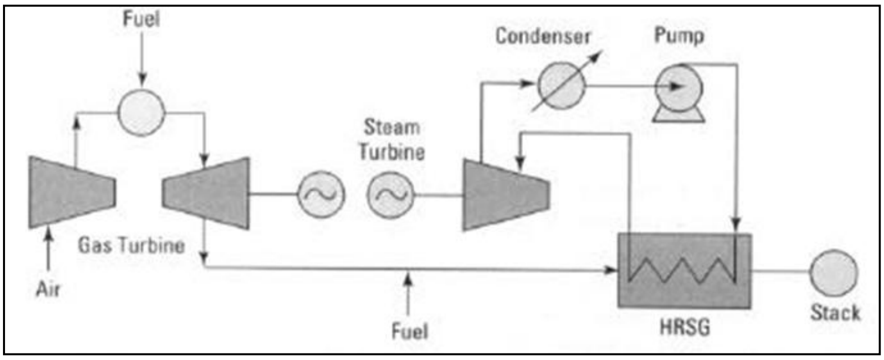

Figure 5: Schematic diagram for HRSG in combined-cycle power plant (Ganapathy, 1996).

Apart from producing steam for applications or generating electricity, HRSG also serves as a damage controller. In gas power plant, the exhaust gas produced can reach up to 600^{o}C which may affect and harm the environment and nearby inhabitants if the exhaust gas is directly released to the atmosphere. Extensive analysis by Srikanth et al. (2003) clearly shows that the temperature of flue gas released to environment is reduced to around 150^{o}C. Analysis by Shin et al. (2002) also supports the idea where stack emission temperature is reduced to 164^{o}C.

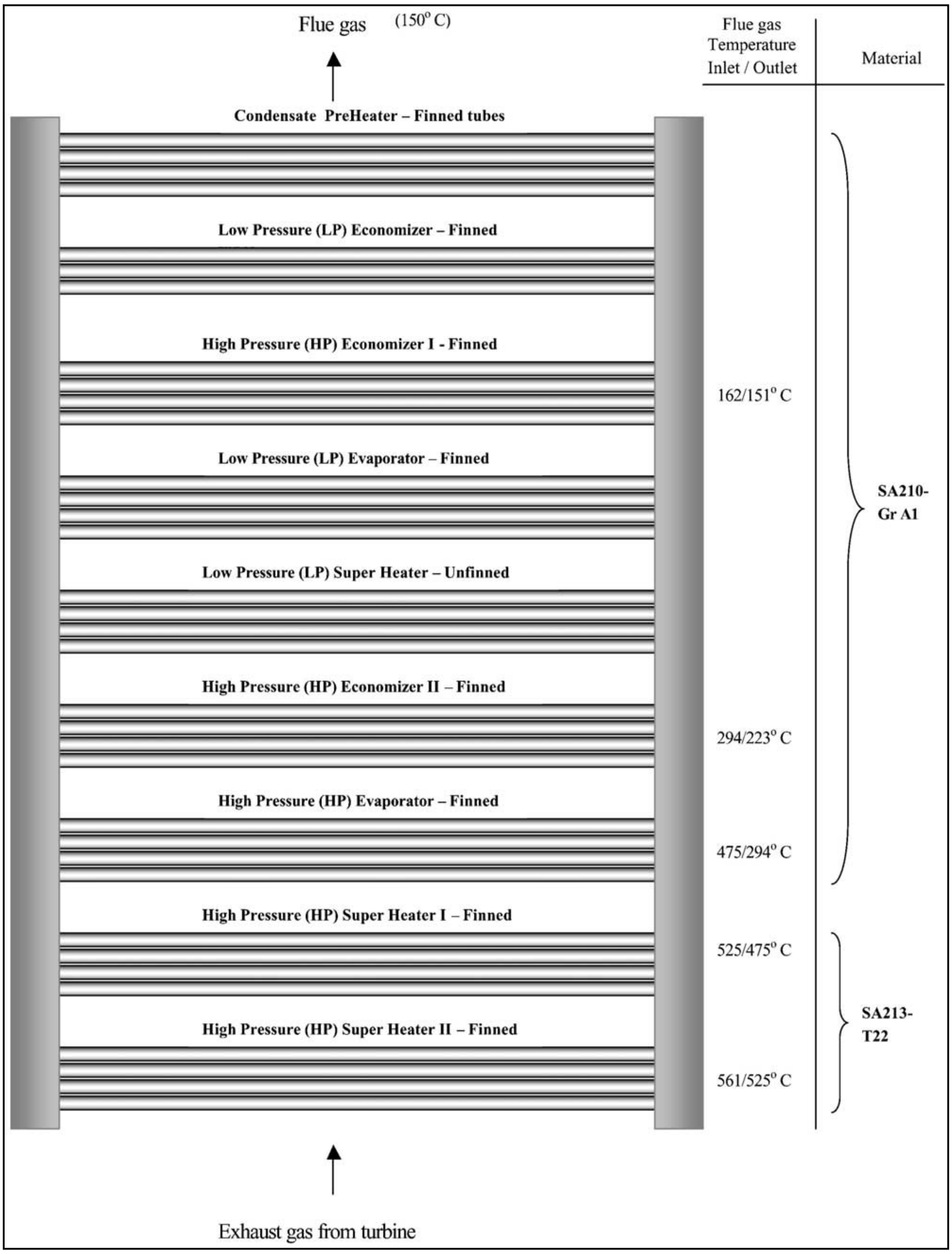

Figure 6: Exhaust gas temperature reduction by HRSG (Srikanth et al. 2003).

Gas turbine	Siemens KWU 64.3	
	Power output	61 MW
	Efficiency	34.6%
	Exhaust mass flow	684.2 ton/h
	Exhaust gas temperature	535°C
HRSG	Single pressure type	
	Pinch temp difference	15°C
	Approach temp. difference	9°C
	Stack temp.	164°C
	Deaerator pressure	2.0 bar
	Feed water temp.	36°C
	LTE exit temp.	100°C
Steam turbine	Two pressure condensing with	
	One-row governing stage	
	Power output	26 MW
	HP inlet pressure	42.2 bar
	HP inlet temperature	506°C
	LP inlet pressure	7.34 bar
	LP inlet temperature	286°C
	Working flow rate at throttle	85.2 ton/h
	Vacuum pressure	0.0588 bar

Figure 7: Exhaust gas temperature reduction by HRSG (Shin et al. 2002).

Due to the reduction of the exhaust gas, it can be released safely to the environment without causing any major environmental impact to the surrounding. Carazas et al. (2010) says that, due to prevent any accidental release of the hot exhaust gas, a power plant coupled with a failed HRSG must be shutdown unless the power plant has an environmental license to operate in open cycle.

HRSG has 3 main components which act as heat exchanger between the feed water or steam and the hot exhaust gas. The components are economizer, evaporator and superheater. The components and the flow of the working fluid are illustrated in the following figure.

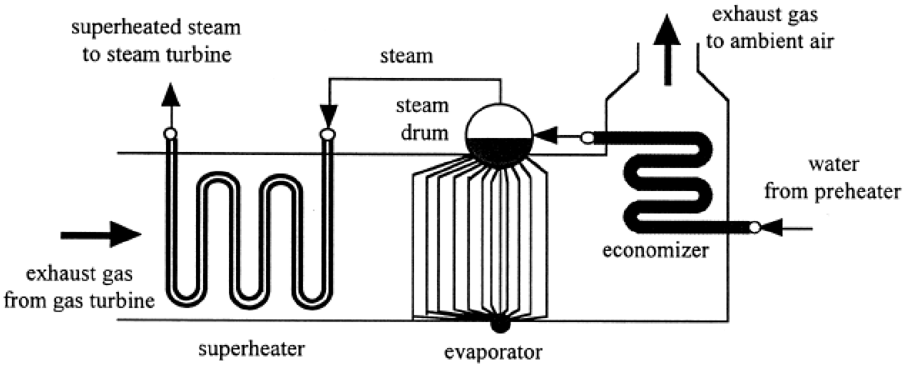

Figure 8: Schematic diagram of HRSG components (Kim et al. 2000).

According to Carazas et al (2010)

> After a pre-heating step in the economizer, water enters into the drum, slightly sub cooled. From the drum, the water flows to the evaporator and returns as water-steam mixture to the drum where water and steam are separated. The saturated steam leaves the drum to the superheater where it reaches the maximum temperature.

HRSG in Jaske and Shannon (2002) case study has similar function with HRSG in UTP. In UTP, a Gas District Cooling (GDC) power plant is used to generate electricity for the whole campus. According to A. Karim and Yongo (2011), the GDC which operating as a cogeneration plant consists of a Gas Turbine Engine (GTE), an HRSG and a Steam Absorption Chiller (SAC) that produce both power and heat simultaneously. A schematic diagram by Baheta (2010) on GDCs HRSG is illustrated in the following figures.

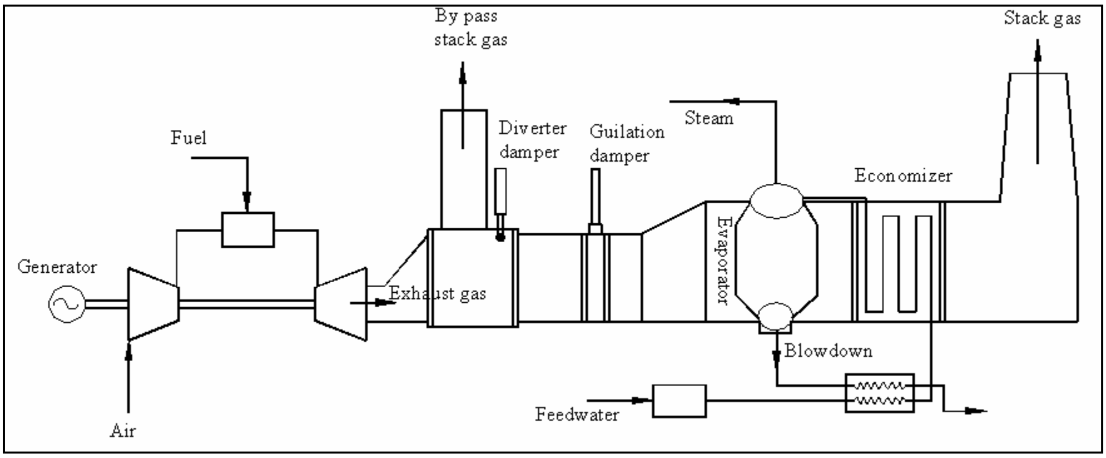

Figure 9: Schematic diagram of HRSG in GDC UTP (Baheta, 2010).

In UTPs GDC, HRSG produces steam from the exhaust of the gas turbine. The steam is then used to produce chilled water through steam absorption chiller.

According to A. Karim and Yongo (2011)

> The waste heat from the exhaust of the gas turbine is utilized for steam production that is used for heating in the steam absorption chiller. The chilled

water produced from steam absorption chiller is used for air conditioning of the buildings in UTP.

2.2 Creep in HRSG

HRSG works at elevated temperature. Due to the high temperature, HRSG components are subjected to many structural failures. Pearson and Anderson (2011) say that reliability of HRSG normally suffers from low-cycle thermal fatigue, corrosion-related problems and others thermal-mechanical problems. Carazas et al. (2010) also points out the same problem faced by the HRSG which are:

i. Low-cycle thermal fatigue
ii. Corrosion
iii. Creep

Due to time constraint, this project will focus on creep effect towards the reliability of the HRSG. Eti et al. (2007) define reliability as “the probability of the equipment or process functioning without failures”. Eti associates failures as “loss of function when that function is needed”.

According to Mao and Mahadevan (2000), creep is “one of the principal damage mechanisms for material operating at elevated temperature”. Mao and Mahadevan stated that significant creep damage of any metallic materials can accumulate if the temperature rise more than 30% of the materials melting temperature. Creep in metallic material can lead to strain deformation, stress relaxation which finally leads to crack initiation and growth.

In ASM Handbook Volume 11, Failure Analysis and Prevention, it states that creep rupture can occur within a thin-section component such as steam pipes and boiler tubes with a uniform stress and high temperature. For the HRSG, creep rupture will most likely to occur at tubes that operates at the highest temperature. Carazas et al. (2010) states that HRSG failure due to creep occur in superheater and reheater tubing system. The following figures will illustrate the area of the HRSG that are most probably affected by creep failure.

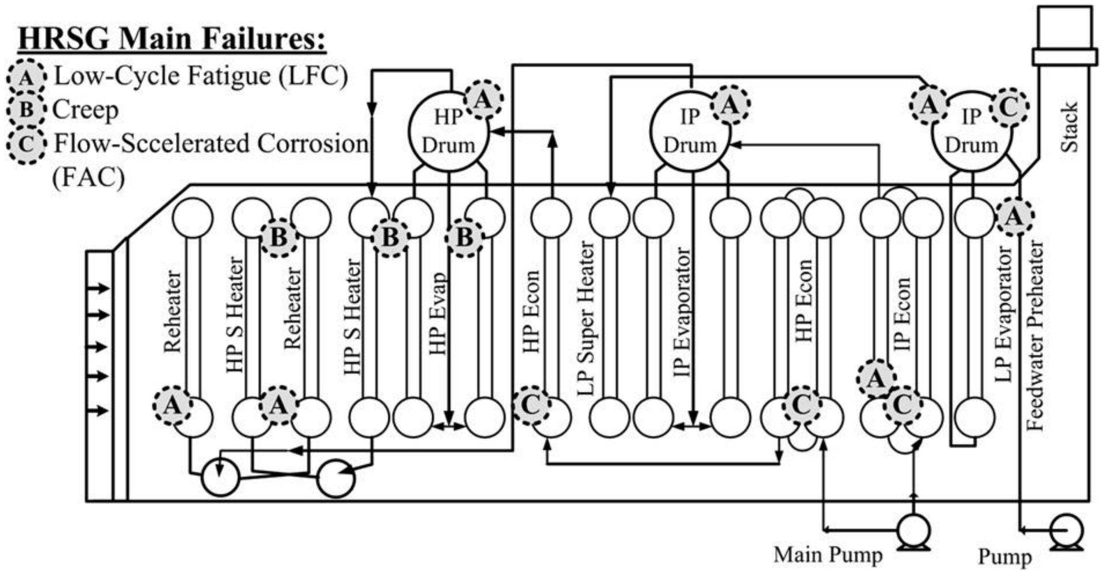

Figure 10: Structural failure in HRSG identified by Carazas et al. (2010).

In this situation, the superheater and reheater tubes act as a critical component towards the reliability of the HRSG. Jovanovic (2003) defines critical components as "component mostly contributing to risk"

2.3 Reliability Analysis of HRSG based on creep

Reliability analysis of HRSG based on creep rupture has been conducted by Carazas et al. (2010). In the project, he assessed two units of HRSG in a 500 MW combined-cycle power plant. Carazas identify that the creep rupture in HRSG occurred at the superheater and reheater tubing system. The following figures illustrates the work flow used by Carazas in coming up with the result.

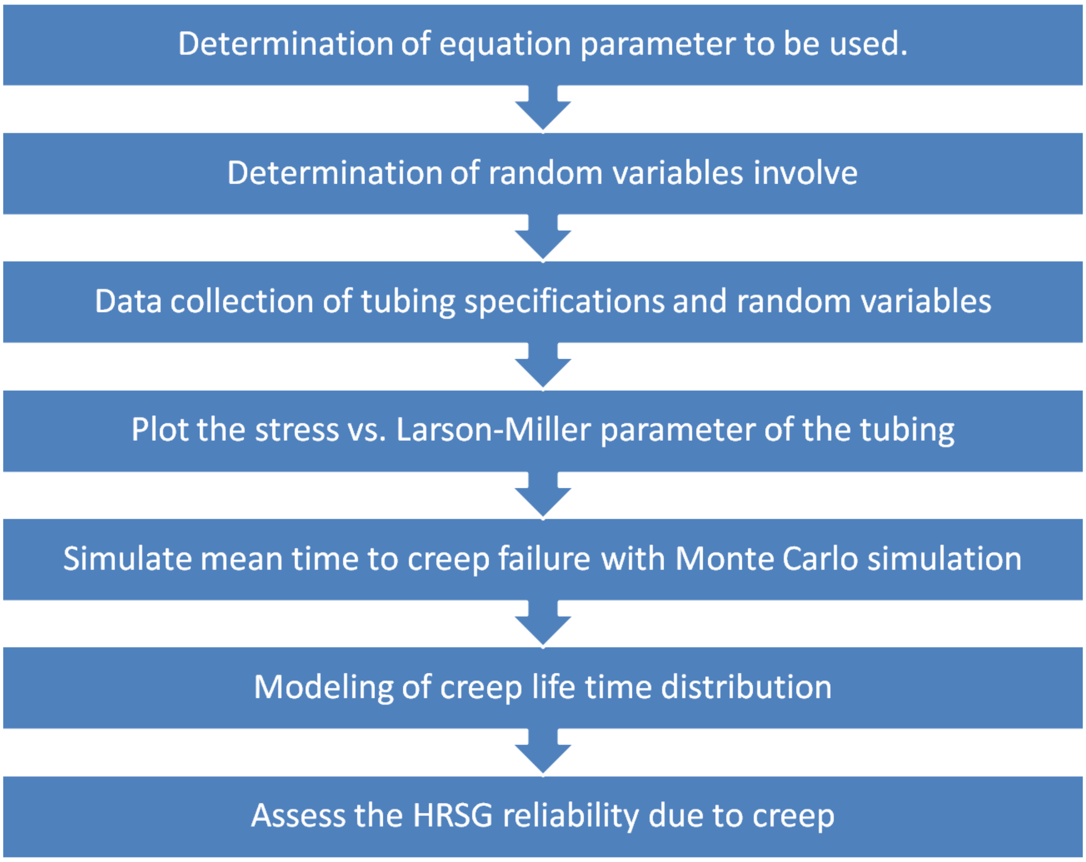

Figure 11: Work flow by Carazas et al. (2010) in assessing HRSG reliability.

There are many parameters that can be used to evaluate creep rupture. Common parameters used are the Larson-Miller and Manson-Haferd parameters. In the assessment, Carazas used the Larson-Miller parameter (LMP) which correlates between the temperature with the time to creep rupture. LMP is denotes by Eq. (1).

$$P(L.M) = T(\log t_r + C) \quad (1)$$

In reliability, random variables are variables that may affect the reliability or rate of failure of the machine. For the assessment, random variables determined are pipe geometry, internal pressure and model parameter. After parameters and random variables determined, the data is collected. The following figures illustrate the data collected by Carazas for the assessment.

Table 1: Tubing specification collected by Carazas et al. (2010).

Superheater tubing specification – SA213-T22 steel.

Property	Value
Chemical composition	C: 0.05–0.15 Si: 0.5 Mn: 0.3–0.6 P, max: 0.025 S, max: 0.025 Cr: 1.90–2.60 Mo: 0.87–1.13
Tube geometry	Inner radius: 16.3 mm Thickness: 4.0 mm

Table 2: Random variables used by Carazas et al. (2010)

Random variables and corresponding parameters.

Variable	Description	Mean value	Coefficient of variation	Probability distribution
Geometry of the tube				
R_{mean}	Mean radius	20.3 mm	0.02	Normal
h	Wall thickness	4.0 mm	0.05	Normal
Material property – parameter P				
f_{model}	Model uncertainty	1.0	0.02	Normal
Loading				
p	Internal pressure	10 MPa	0.1	Normal
T	Tube wall temperature	Depending on case under study (i, ii, or iii)	–	Constant

With the data collected, Carazas later plot the distribution of stress versus Larson-Miller parameter which is associated with the creep lifetime. Following figure shows how stress versus Larson-Miller parameter plot done by Carazas. Xing et al.(2006) state that “the remaining life can be assessed by extrapolating curves parallel to the material’s so-called master curve”.

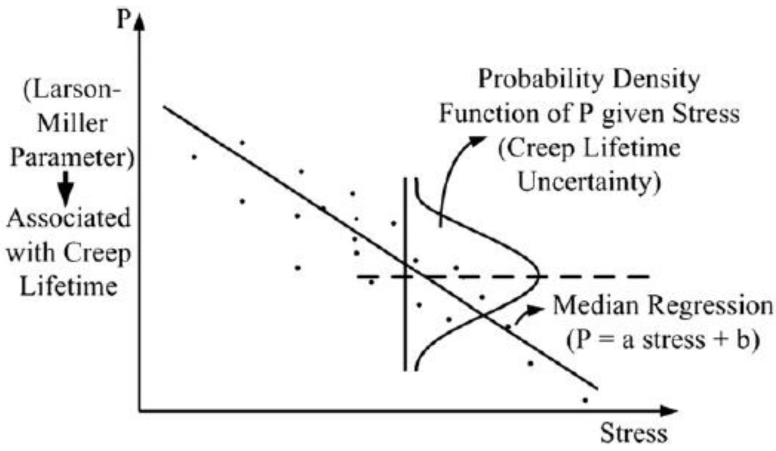

Figure 12: Stress vs. Larson-Miller parameter plot by Carazas et al. (2010).

By using Monte-Carlo simulation, an estimate of mean time to creep failure can be determined by using a number of trials. In the assessment, Carazas used more than 7000 trials and the Monte-Carlo simulation is shown below.

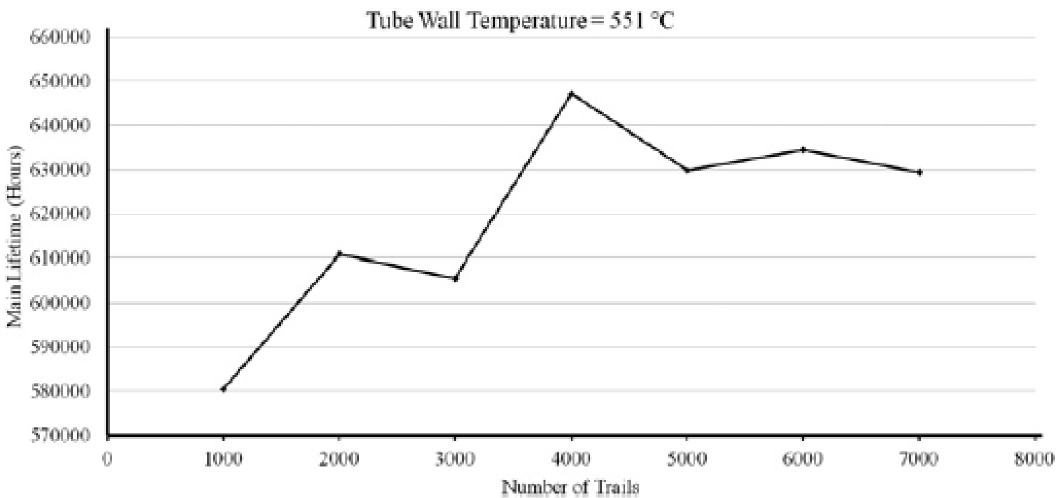

Figure 13: Monte Carlo simulation of mean time to creep failure (Carazas et al. 2010).

After the simulation, a creep lifetime distribution can be modelled by a lognormal probability distribution. By using mean 12.46 and standard deviation of 1.31, Carazas is able to obtain the creep lifetime distribution as shown in following figure.

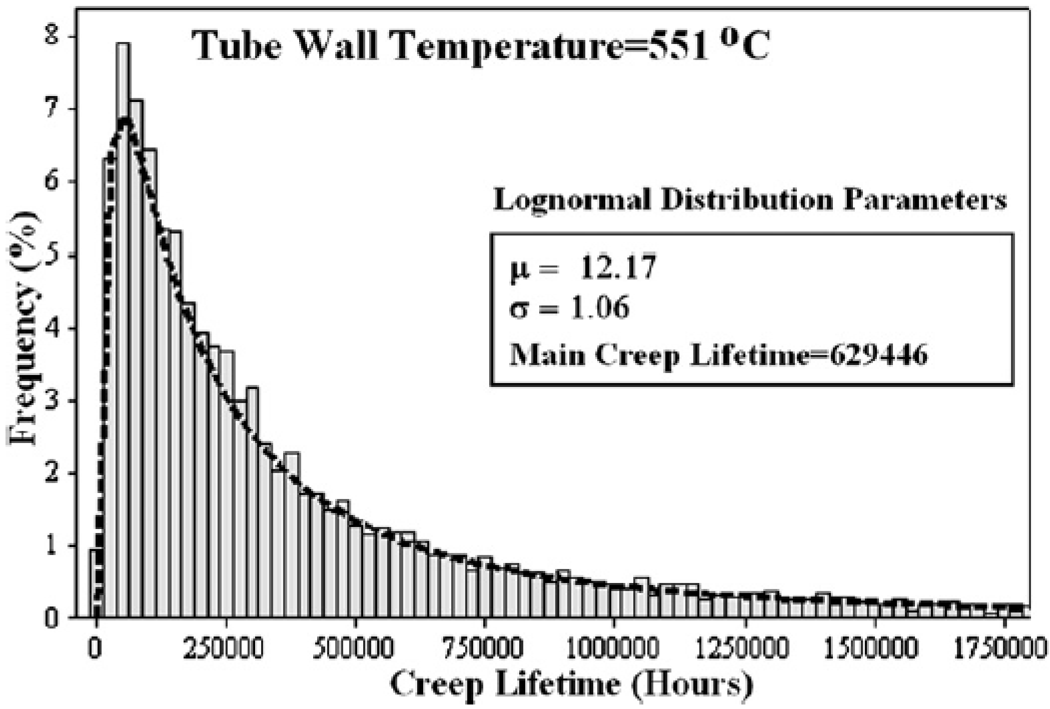

Figure 14: Creep lifetime distribution by Carazas et al. (2010).

After modelling the creep lifetime distribution, the reliability of the HRSG can be assessed with the following equation.

$$R_{HRSG}(t) = 1 - p_{creepfailure}(t) \quad (2)$$

CHAPTER 3: METHODOLOGY

3.1 Project Activities

To assess the reliability of the HRSG in the case study, similar approach used by Carazas et al. (2010) will be used. The following figures will illustrate on how the project will be conducted.

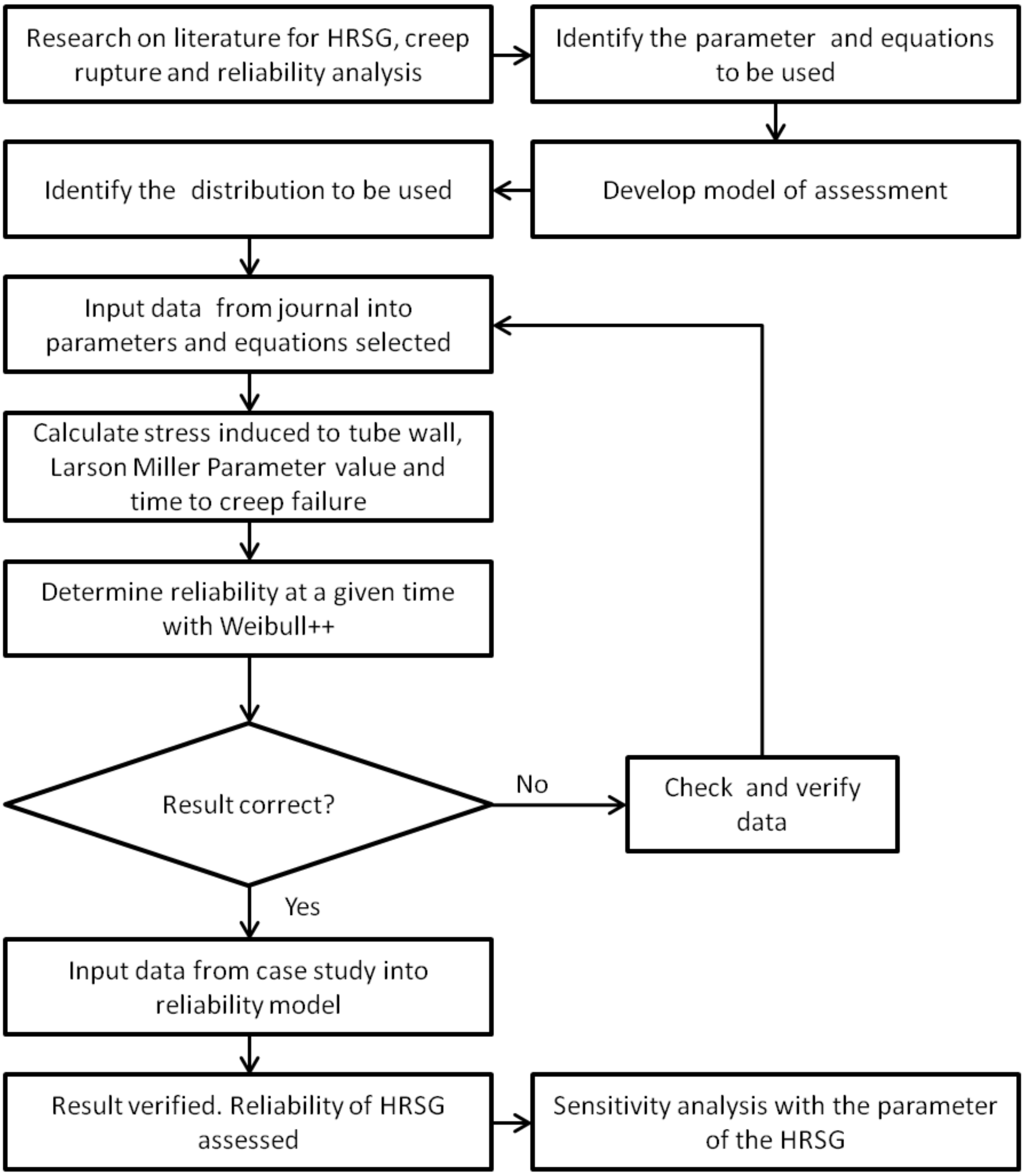

Figure 15: Work flow of the project.

3.2 Gantt Chart

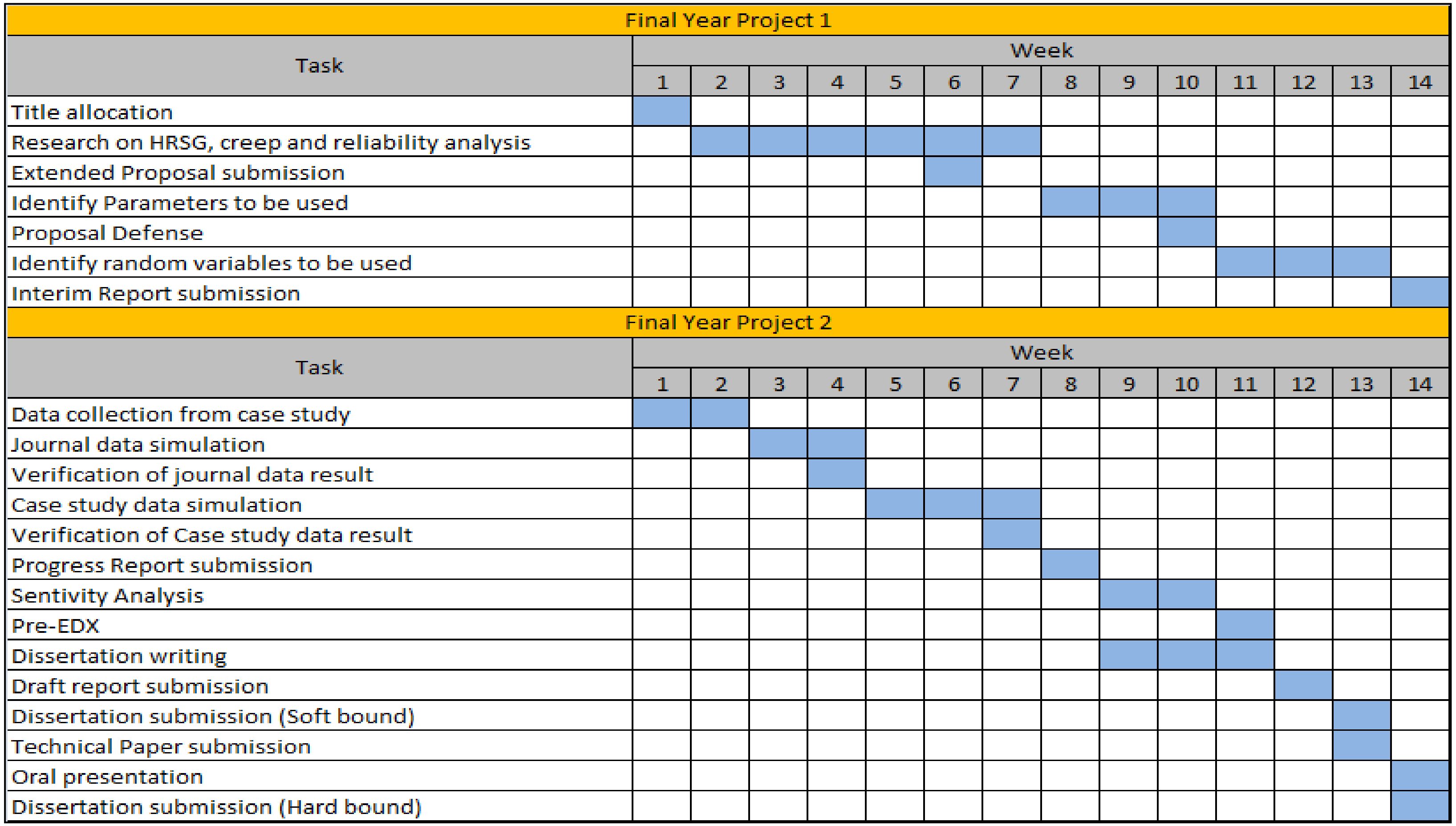

Figure 16: Gantt chart for the project.

3.3 Reliability Methodologies

3.3.1 Research on HRSG, Creep and Reliability Analysis

In understanding the concept of HRSG working principle, creep rupture in machine working at elevated temperature and reliability analysis conducted to assess the rupture failure, extensive research has been conducted by referring to books, lecture notes, journals and publications from experts of the respective field. The knowledge gained during the process is elaborate as literature for this project in the Literature Review section (Chapter 2) of this report.

3.3.2 Identifying Parameter to be used

In his assessment, Carazas et al. (2010) used the Larson-Miller parameter (LMP) to evaluate the stress and creep lifetime distribution. LMP is derived from Arrhenius equation by F.R. Larson and J. Miller. LMP correlates between the time to failure with the material temperature and is chosen for the project since its application is suitable in evaluating creep lifetime in HRSG. LMP is denoted by Eq. (1)

$$P(L.M) = T(\log t_r + C) \quad (1)$$

Where;

T = temperature, K or °R

t_r = creep-rupture time, h

C = constant usually of order 20

The stress acting on the tubes can be expressed by Eq. (3)

$$\sigma_{\text{mech}} = \frac{\mathrm{p}R_{mean}}{h} \quad (3)$$

3.3.3 Identifying Random Variable to be used

By referring to Eq. (3) and Eq. (4), we can determine the random variables to be used in the assessment. In both equations, variables such as tube geometry, internal pressure and temperature is needed. The variables needed for assessing the HRSG reliability are:

i. Tube mean radius
ii. Tube wall thickness
iii. Internal pressure
iv. Tube wall temperature

The data for the variables will be collected from GDC management team during data collection phase.

3.3.4 Assessing the Reliability of the HRSG

For this project, the method of assessing the reliability of the HRSG will be made based on the method used by Carazas et al. (2010). In his research, Carazas used a linear regression method by defining a relationship between Larson-Miller parameter and the stress induced at the tube wall. The relationship is shown in the following Eq. (4):

$$\mathrm{P} = -7.899\,\frac{\sigma_{\mathrm{mech}}}{6.895} + 44557 \qquad (4)$$

Rearranging Eq. (1), (3) and (4) will yield time to creep failure that will enable us to determine the reliability and probability of creep failure at a given time. The time to failure is denoted by Eq. (5).

$$\log tr = -1.146\,\frac{\mathrm{p}R_{mean}}{hT} + \frac{44557}{T} - 20 \qquad (5)$$

With time to creep failure determined, the data will be used in Weibull++ to generate random number through Monte-Carlo data generation wizard. A distribution can be obtained where mean time to creep failure can be obtained and reliability at a specific time can be determined.

3.4 Tools Required

To simulate the mean time to failure and creep lifetime distribution, certain software must be used. Based on the methodology used, two softwares are needed which is Microsoft Excel 2007 and Reliasoft Weibull++ 7. In the project, Microsoft Excel 2007 will be used to calculate and tabulate random numbers for the parameters used and to determine the corresponded time to creep failure. The generated time to failures will be analyzed in Weibull++ 7 to determine the distribution that will allow us to calculate the reliability of the HRSG at a given time.

CHAPTER 4: RESULT AND DISCUSSIONS

4.1 Model Validation with Data from Journal by Carazas et al. (2010)

After determining the equation, parameters and the distributions that are going to be used in the project, verification is needed by computing the data obtained from Carazas et al. (2010) research. Table 3 lists all parameters used by Carazas and the distribution for each of the variables.

Table 3: Value of the Parameters used in the Trial Calculation

Variable	Description	Mean Value	Coefficient of Variation	Probability Distribution
R_{mean}	Mean radius	20.3 mm	0.02	Normal
h	Wall thickness	4.0 mm	0.05	Normal
f_{model}	Model uncertainty	1.0	0.02	Normal
P	Internal Pressure	10 MPa	0.1	Normal
T	Wall temperature	551^{o}C	-	Constant

By using Eq. (5), the time to creep rupture, t_r is tabulated by using Excel spreadsheet. Random number is generated by using the mean and standard deviation values for each parameter. Standard deviation can be calculated by following Eq. (6) according to Mokhtar (2011).

$$COV = \frac{\sigma}{\mu} \tag{6}$$

Where COV is the Coefficient of Variation, σ is the standard deviation and μ is the mean value. The time to creep rupture is tabulated where 100 random numbers is generated for each parameter with given mean and standard deviation by using Microsoft Excel 2007. The generated number is tabulated in appendix A1.

By computing the generated time to failure in Weibull++ 7, the probability density function (PDF) of the failure can be evaluated by using lognormal distribution. Figure 17 shows the PDF of the creep failure.

By using Weibull++, the reliability and probability of failure (POF) at a given time can be determined. The following table shows the reliability of the HRSG at a given time.

Table 4: Reliability and POF at a given time based on Carazas et al. (2010) data.

Time (hours)	Reliability (%)	Probability of failure (%)
8760	100.00	0.00
10000	100.00	0.00
100000	100.00	0.00
200000	100.00	0.00
300000	52.66	47.34

Figure 18 shows the relationship of the system reliability with respect to time.

From the plot we can determined the mean time to creep failure which is at 300,400 hours of operation with a mean of 12.6127 and standard deviation of 0.0175. The standard deviation is relatively small compared to the one obtained by Carazas et al. (2010) but it is still with an acceptable range. The result obtained is conclusive since the mean time to failure is close to time to failure obtained by Carazas which is 353,510 hours. The method will be used to assess the reliability of the HRSG based on case study data in section 4.2.

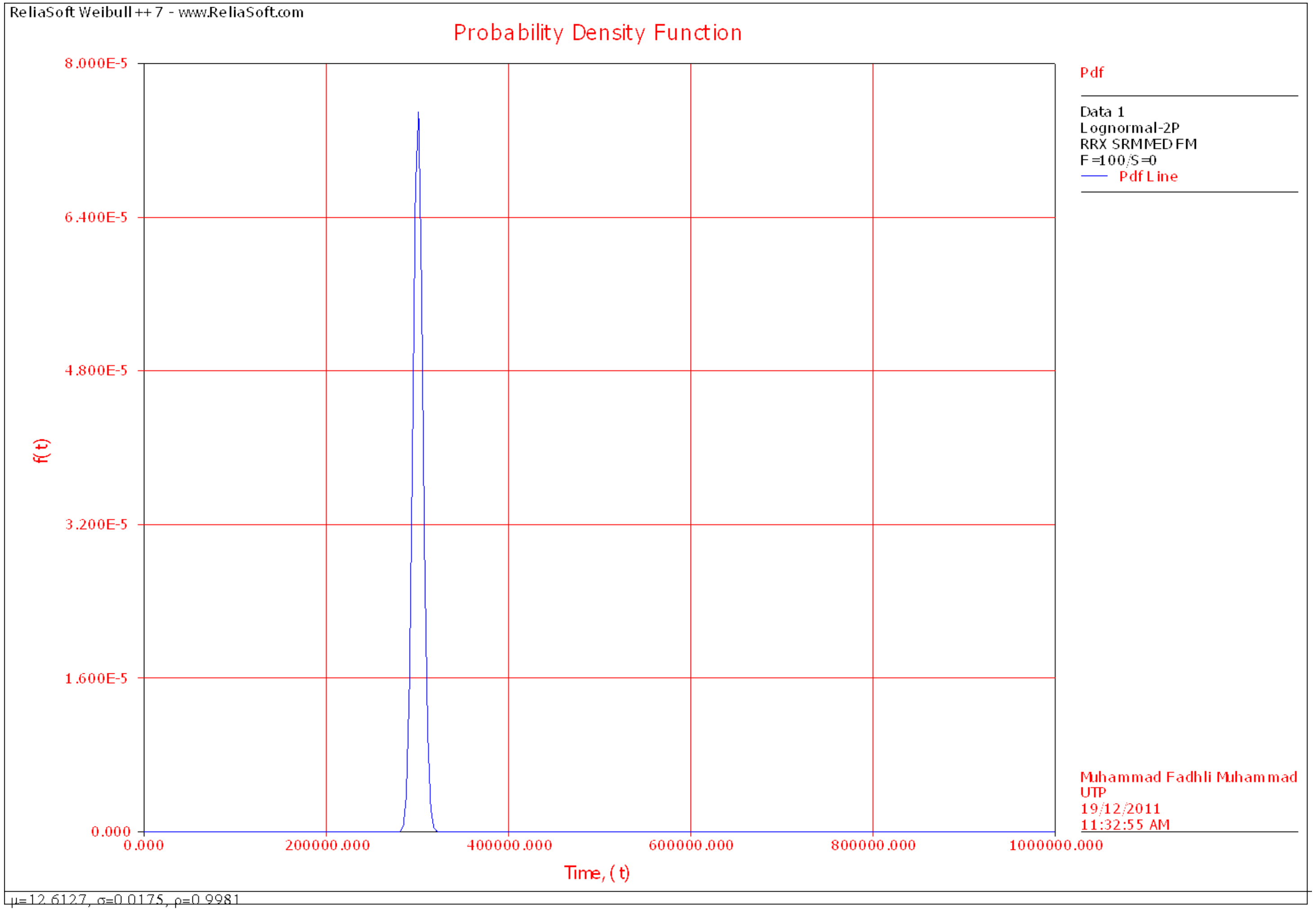

Figure 17: PDF plot based on Carazas et al. (2010) parameters data.

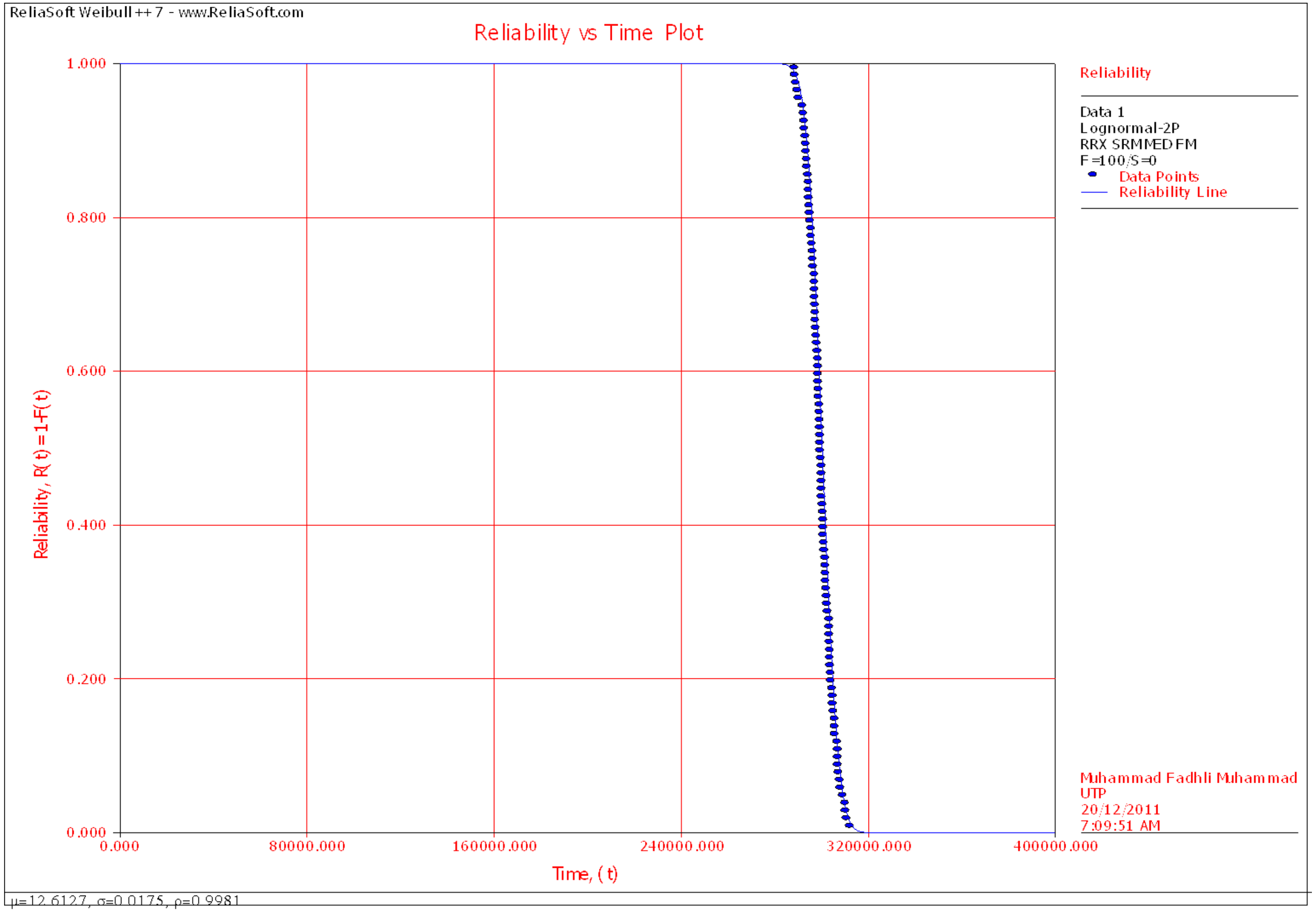

Figure 18: Reliability vs time plot for Carazas et. al (2010) data.

4.2 Reliability of HRSG Based on Case Study Data

By using the method in section 4.1, the reliability of a HRSG from a case study can be determined. Based on Jaske and Shannon (2002), the value of the parameters of the HRSG is tabulated in the following table.

Table 5: HRSG parameter data and distributions form Jaske and Shannon (2002) case study.

Variable	Description	Mean Value	Coefficient of Variation	Probability Distribution
R_{mean}	Mean radius	87.122 mm	0.02	Normal
h	Wall thickness	17.018 mm	0.05	Normal
f_{model}	Model uncertainty	1.0	0.02	Normal
P	Internal Pressure	3.45 MPa	0.1	Normal
T	Wall temperature	926.67^{o}C	-	Constant

For the assessment, the COV and probability distribution are assumed to be the same as the one used by Carazas et al. (2010). The distributions of the parameters are assumed to be normal with reference to Melchers (1999). According to Melchers (1999):

- The variation in material property is typically assumed normally distributed for it is a reasonable model for many natural processes or physical properties.
- Variation in pipe diameter and thickness is assumed to follow a normal distribution since many processes are assumed to follow this distribution.

The time to creep failure is tabulated by using 100 random values of the parameters in Table 5 as shown in appendix A2. From the time to creep failure obtained, the PDF of the failure can be analyzed with Weibull++ by using lognormal distribution. The PDF is shown in following figure.

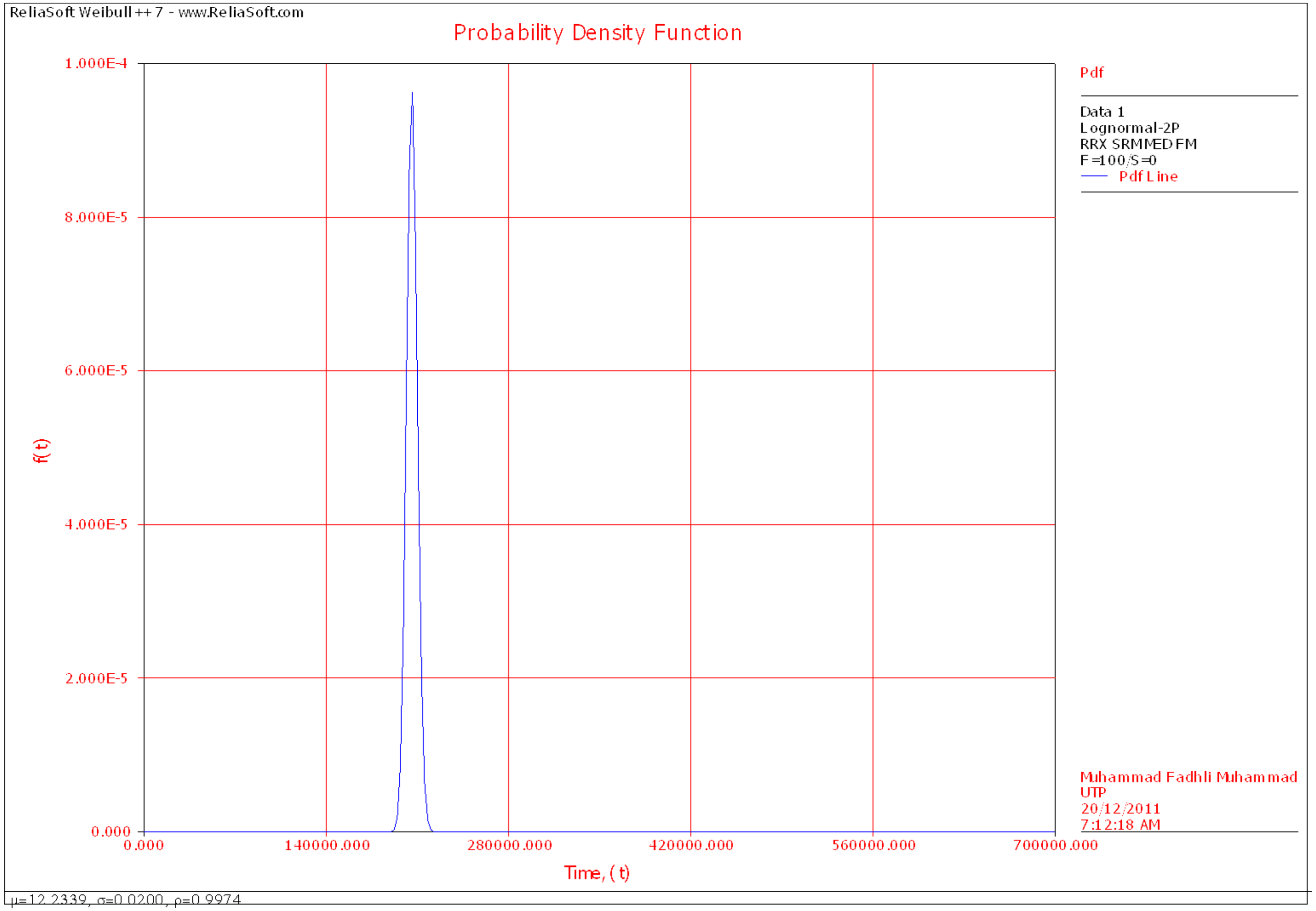

Figure 19: PDF plot based on case study by Jaske and Shannon (2002).

By using Weibull++, the reliability and probability of failure (POF) at a given time can be determined. The following table shows the reliability of the HRSG at a given time.

Table 6: Reliability and POF at a given time based on case study by Jaske and Shannon (2002).

Time (hours)	Reliability (%)	Probability of failure (%)
8760	100.00	0.00
10000	100.00	0.00
100000	100.00	0.00
200000	91.75	8.25
300000	0.00	100.00

The following Figure 20 shows the reliability versus time plot of the HRSG.

From the plot we can determined the mean time to creep failure which is at 205,680 hours of operation with a mean of 12.2339 and standard deviation of 0.02. The mean time to creep failure for the case study is shorter since the HRSG operate at extreme temperature which is 926.67^{o}C compared to the HRSG evaluated by Carazas et al. (2010) which is at 551^{o}C.

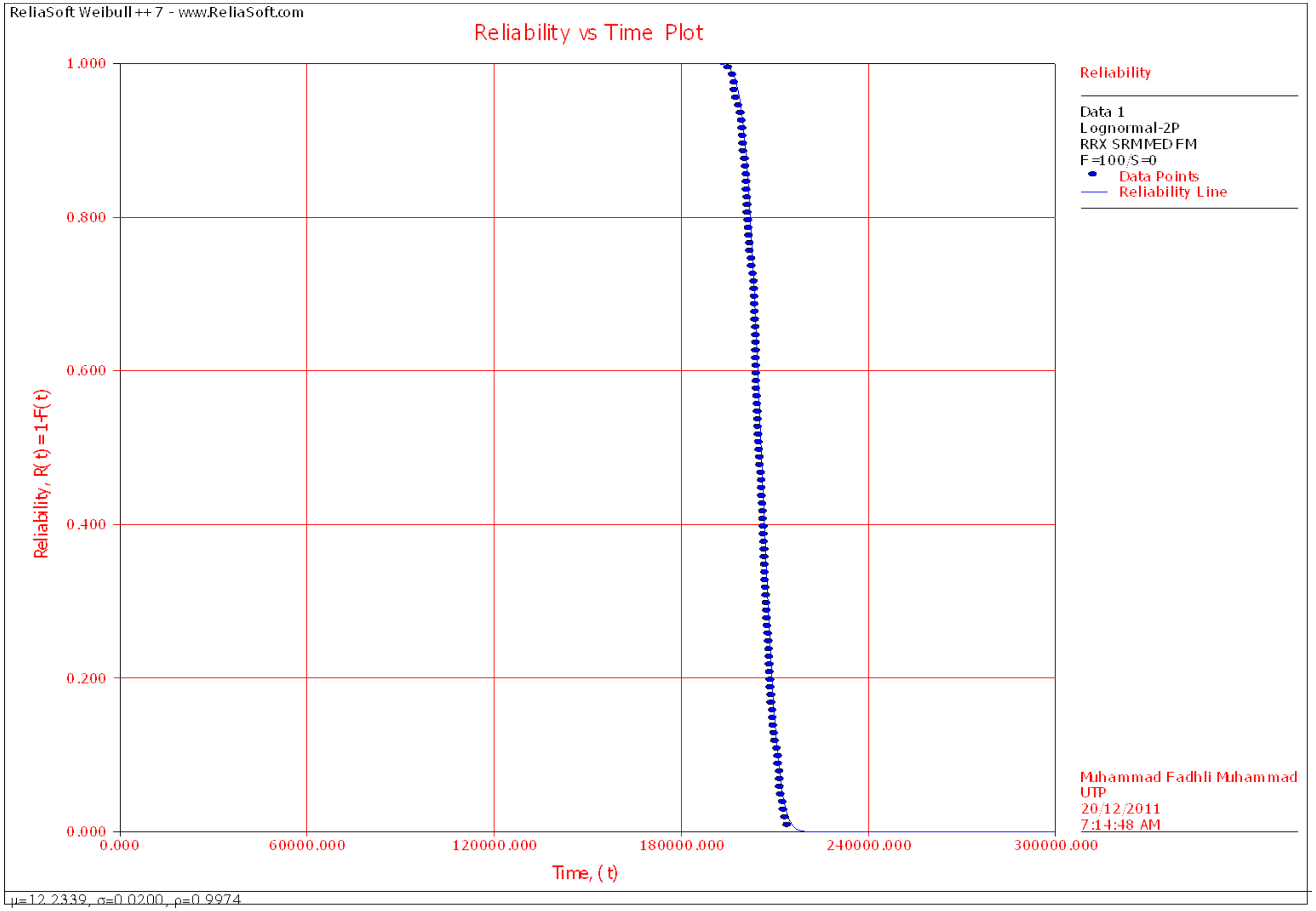

Figure 20: Reliability vs time plot based on case study by Jaske and Shannon (2002).

4.3 Sensitivity Analysis

According to Xu and Gertner (2007), sensitivity analysis (SA) is conducted to determine how the variation of the independent parameter can contribute to the variation of the model output. For this project, we can see that parameters such as wall temperature, wall dimension and internal pressure can affect the mean time to creep failure of the HRSG. Pannell (1997) suggested that two values of the parameters (higher and lower) should be used for the analysis in order to determine the variation produced between those changes. For this project, SA will be conducted to evaluate mean time to creep failure by the following condition:

- Variation in COV for model uncertainty
- Variation in temperature
- Variation in internal pressure

4.3.1 Variation in COV for model uncertainty

According to Mokhtar (2011), Coefficient of Variation, COV is a normalized measure of dispersion of a probability distribution. COV which is a ratio of mean and standard deviation will change the shape of the distribution and ultimately yield different result. In this project, SA will be used to calculate mean time to creep failure for different COV of the model uncertainty. The following table lists all of the parameters used for all values of COV.

Table 7: Parameters used for all values of COV.

Variable	Description	Mean Value	Coefficient of Variation	Probability Distribution
R_{mean}	Mean radius	87.122 mm	0.02	Normal
h	Wall thickness	17.018 mm	0.05	Normal
P	Internal Pressure	3.45 MPa	0.1	Normal
T	Wall temperature	926.67^{o}C	-	Constant

The value of COV for the SA is tabulated in the following table:

Table 8: COV values for the sensitivity analysis.

Description	Mean Value	Coefficient of Variation	Probability Distribution
Lower COV	1.0	0.015	Normal
Case Study COV	1.0	0.020	Normal
High COV	1.0	0.025	Normal
Higher COV	1.0	0.050	Normal

All of the parameters are then calculated in Microsoft Excel. Time to creep failure for lower COV, high COV and higher COV are shown in appendices A3, A4 and A5 respectively. The time to creep failure value is then analyzed with Weibull++ to determine the mean time to creep failure. From Weibull++, the PDF and reliability plot is analyzed and are shown in the following figures.

The following table show the mean time to creep failure for each COV analyzed.

Table 9: Mean time to creep failure acquired for each COV values.

Description	Mean Value	Coefficient of Variation	Mean Time to Creep Failure
Lower COV	1.0	0.015	206,570 hours
Case Study COV	1.0	0.020	205,680 hours
Higher COV	1.0	0.025	206,970 hours
Higher COV	1.0	0.050	206,400 hours

From the result obtain, we can see that the variation in COV does not change the mean time to failure greatly. Even at double COV, which is 0.05, the mean time to failure only deviates at 0.35% from the time to failure at COV 0.02. This shows that COV does not affect the HRSG reliability greatly since the time to creep failure follows lognormal distribution.

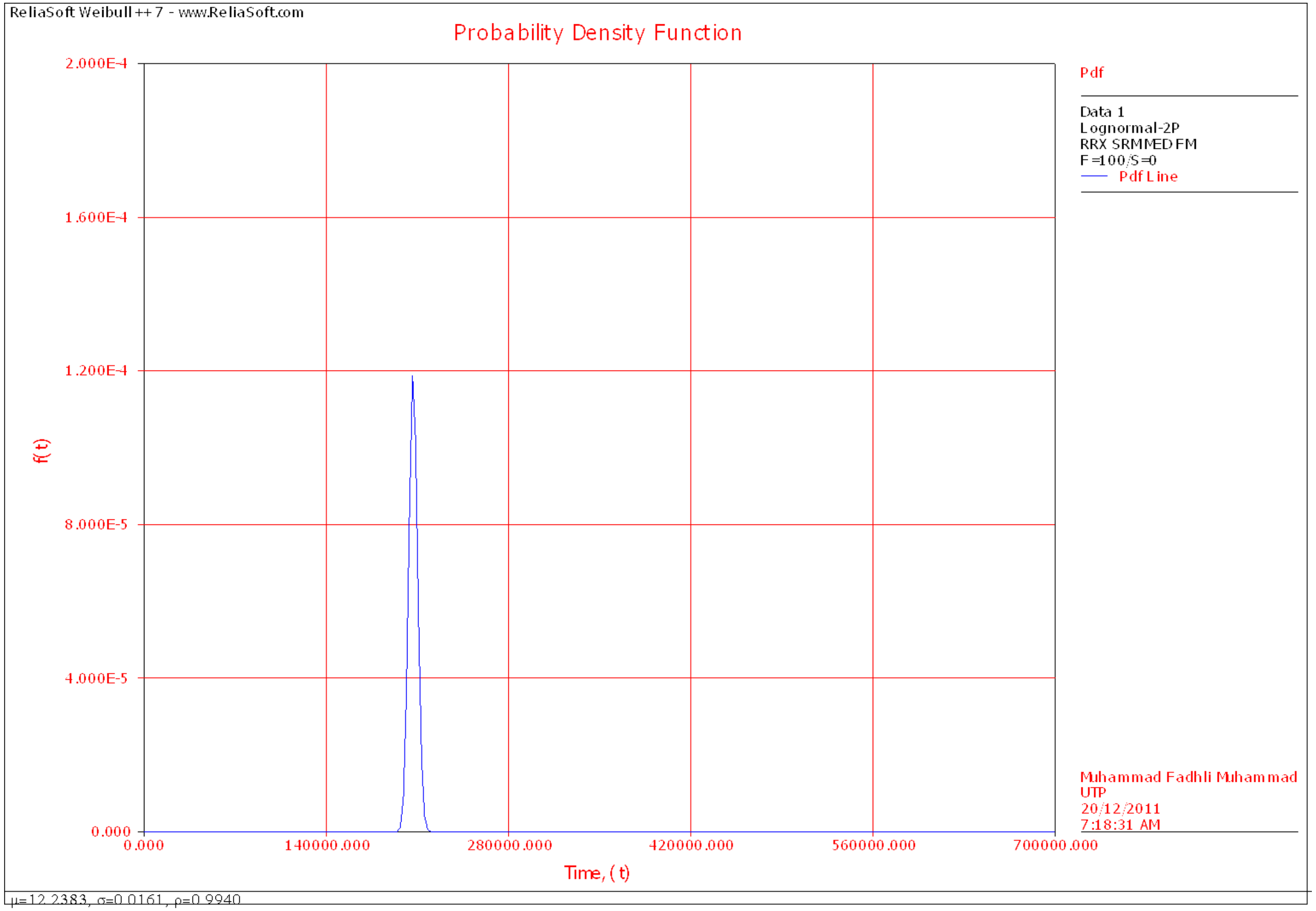

Figure 21: PDF plot for 0.015 COV value.

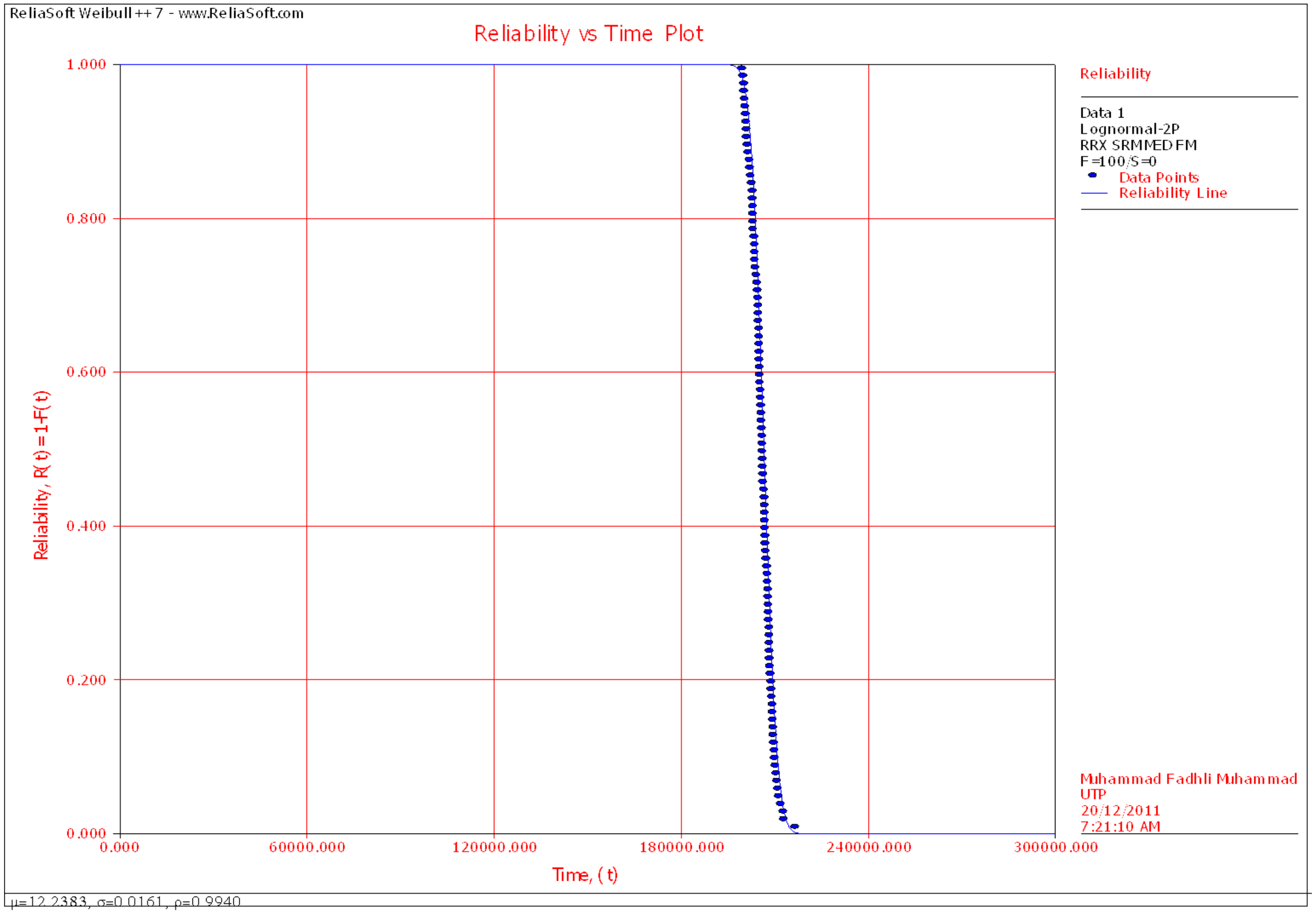

Figure 22: Reliability vs time plot for 0.015 COV value.

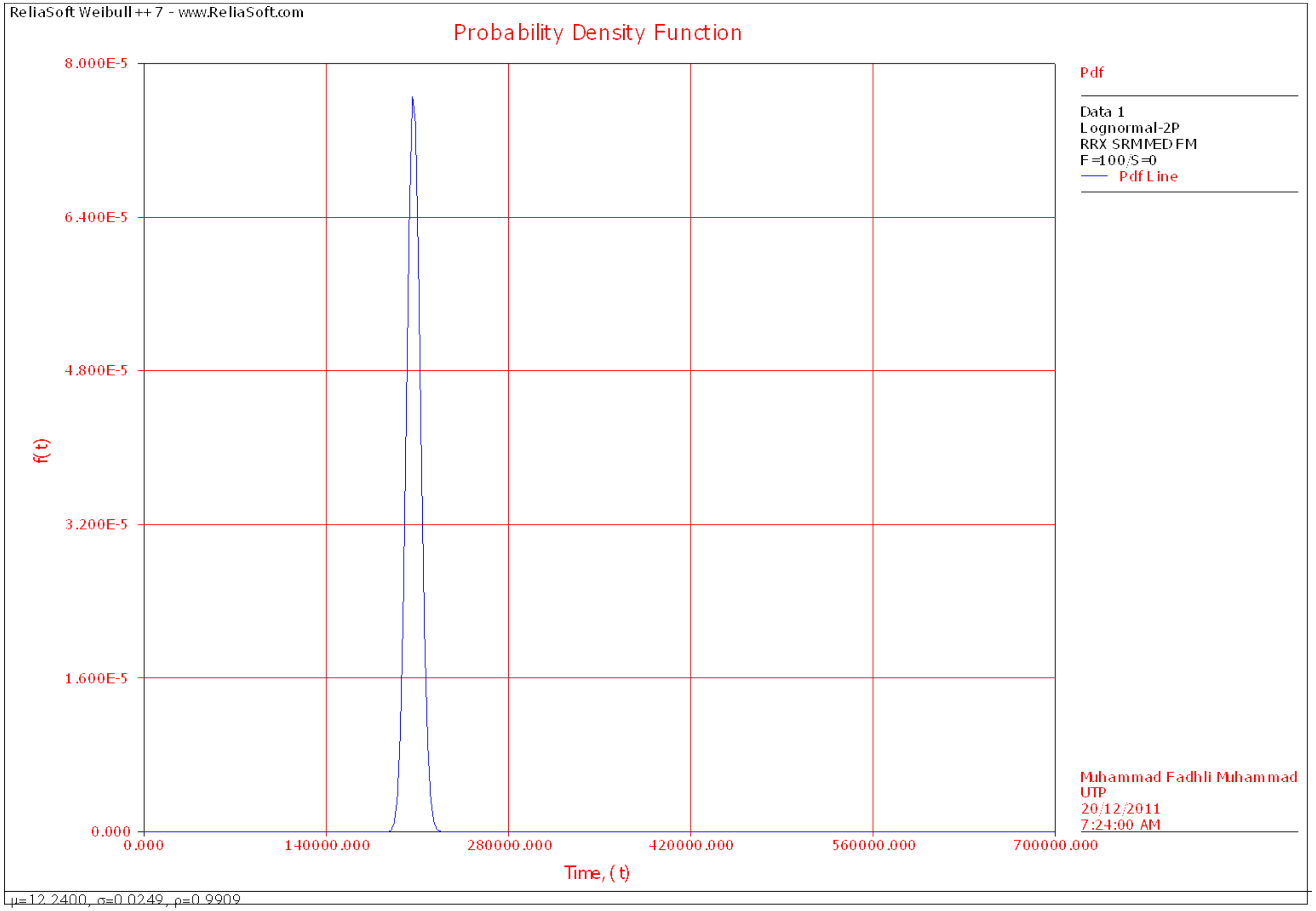

Figure 23: PDF plot for 0.025 COV value.

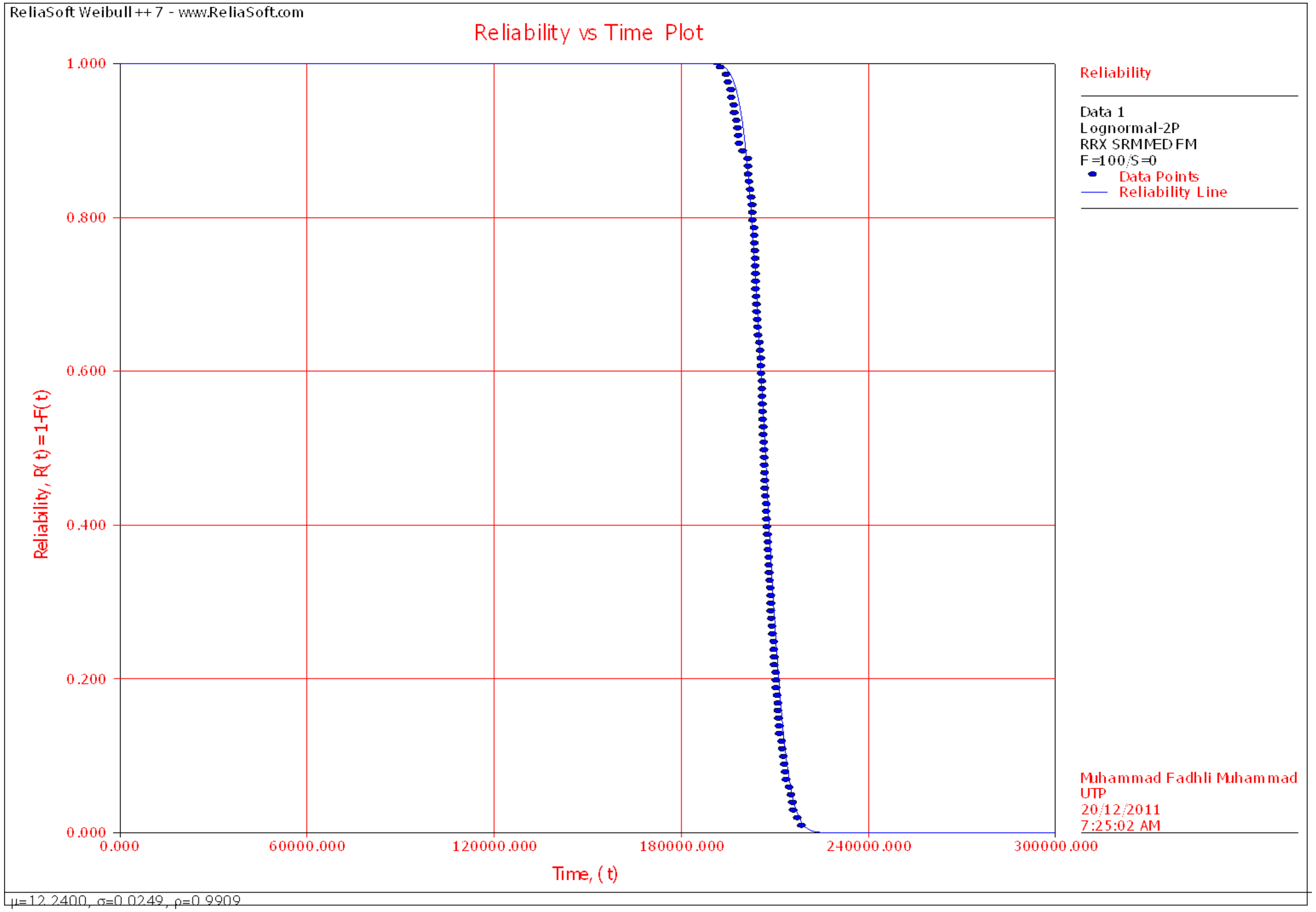

Figure 24: Reliability vs time plot for 0.025 COV value.

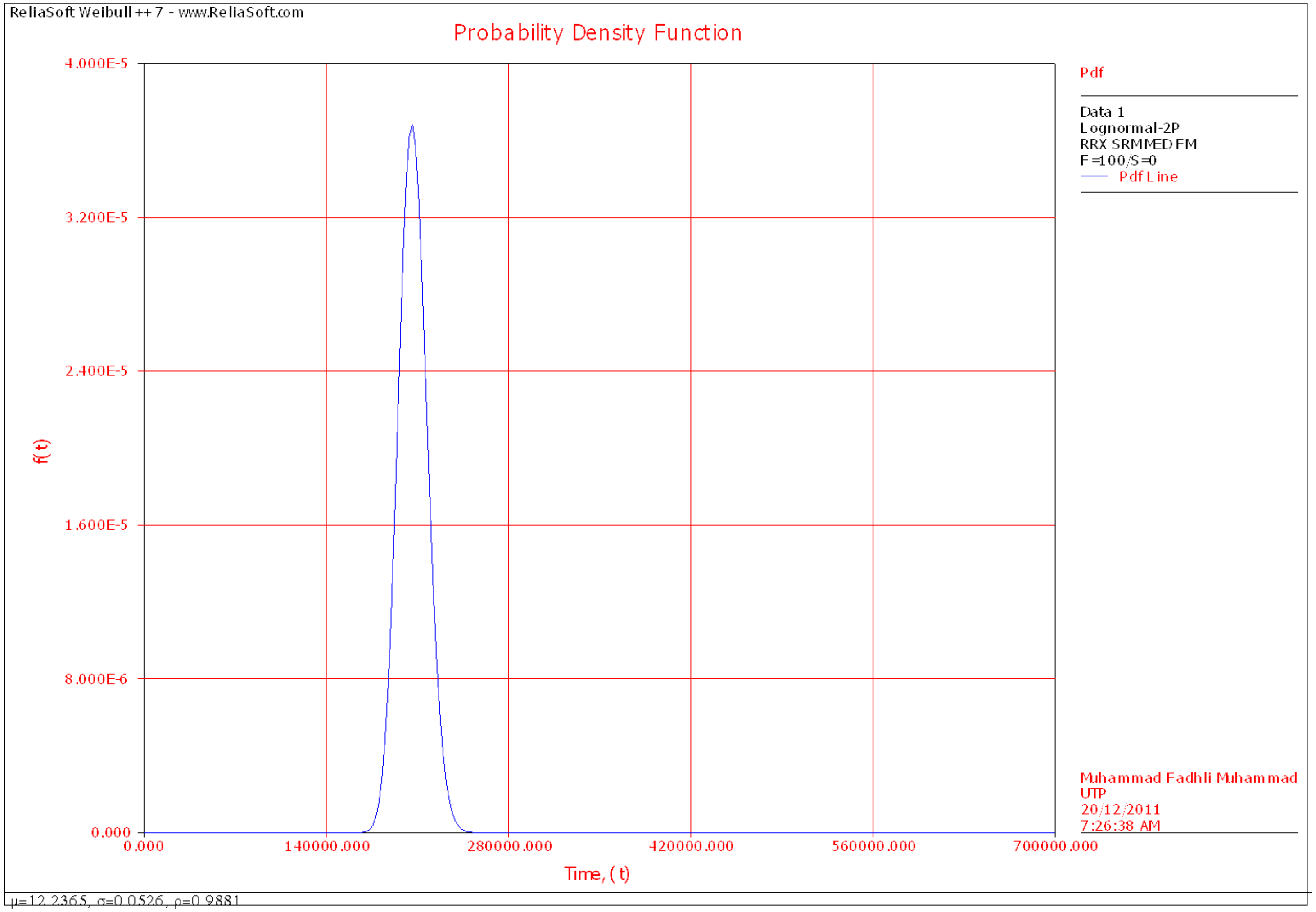

Figure 25: PDF plot for 0.05 COV value.

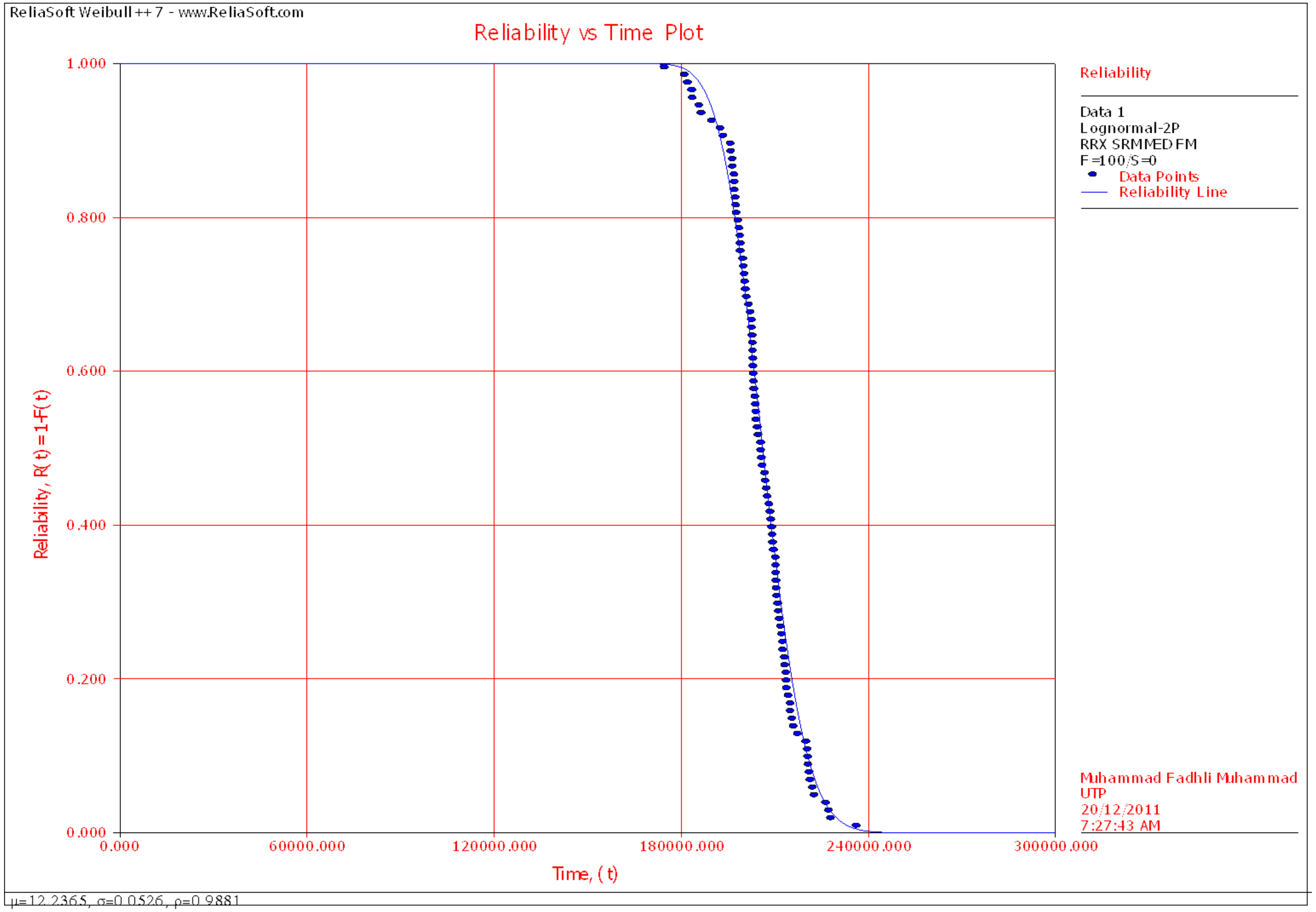

Figure 26: Reliability vs time plot for 0.05 COV value.

4.3.2 Variation in temperature

According to Carazas et al. (2010), creep is always associated with material operates at elevated temperature. Creep in HRSG which mainly occurs at superheater and reheater tubing system that operates up to 1,000^{o}C. With temperature as one of the parameter that defines creep failure, it is natural to do SA in terms of temperature variation. Similar approach will be used as in section 4.3.1 where higher and lower temperature values will be used to see the effect of temperature towards time to creep failure. The following table lists the parameters used for the SA.

Table 10: Parameters used for all values of temperature.

Variable	Description	Mean Value	Coefficient of Variation	Probability Distribution
R_{mean}	Mean radius	87.122 mm	0.02	Normal
h	Wall thickness	17.018 mm	0.05	Normal
f_{model}	Model uncertainty	1.0	0.02	Normal
P	Internal Pressure	3.45 MPa	0.1	Normal

The value of temperature used in the SA is tabulated in the following table.

Table 11: Temperature values for the sensitivity analysis.

Description	Mean Value	Coefficient of Variation	Probability Distribution
Lower Temp	850^{o}C	-	Constant
Case Study Temp	926.67^{o}C	-	Constant
Higher Temp	1,000^{o}C	-	Constant

All of the parameters are then calculated in Microsoft Excel. Time to creep failure for lower temperature and higher temperature are shown in appendices A6 and A7 respectively. The time to creep failure value is then analyzed with Weibull++ to determine the mean time to creep failure. The following figures illustrate the PDF and reliability plot for both lower and higher temperature.

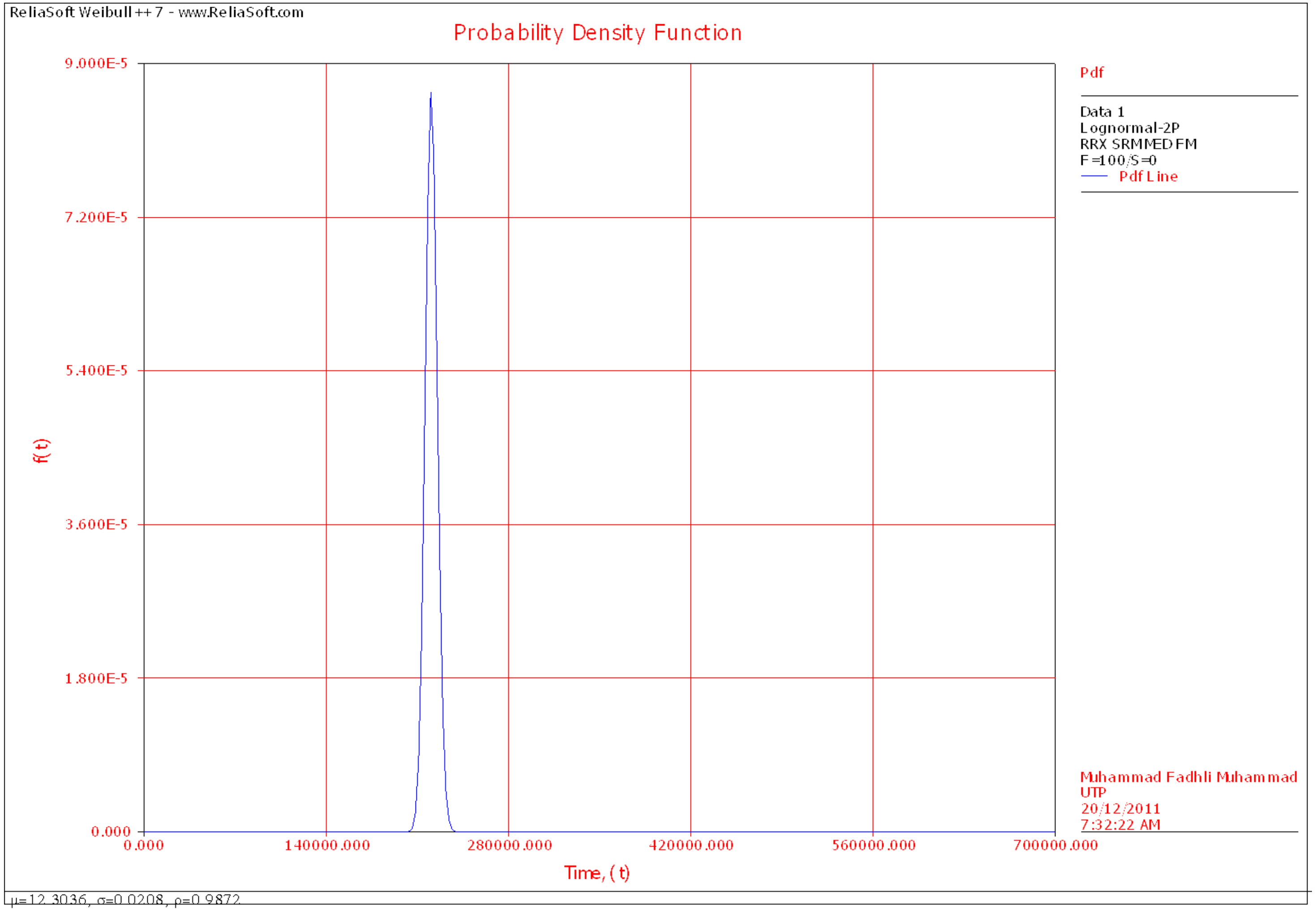

Figure 27: PDF plot at 850°C.

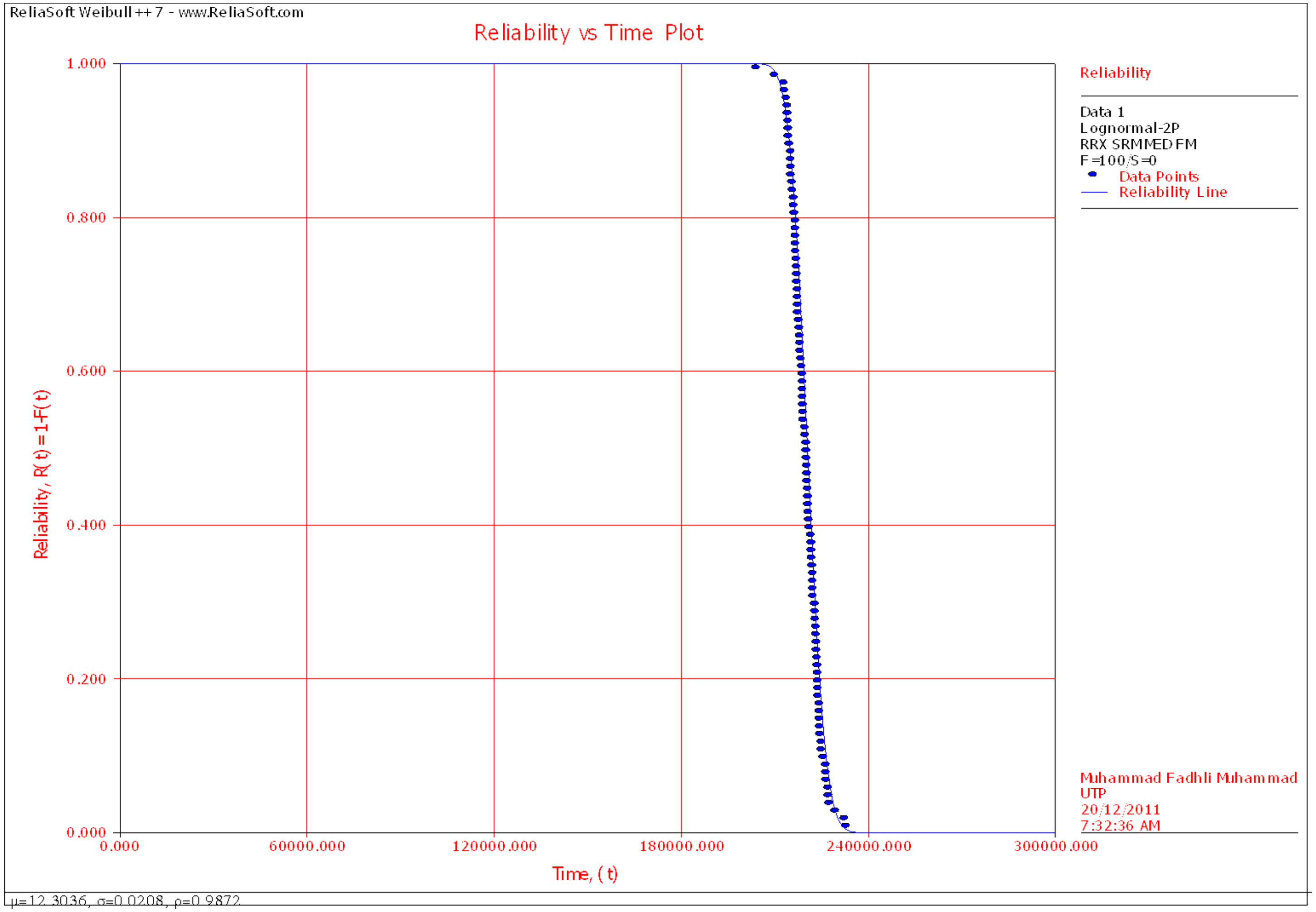

Figure 28: Reliability vs time plot at 850^{o}C.

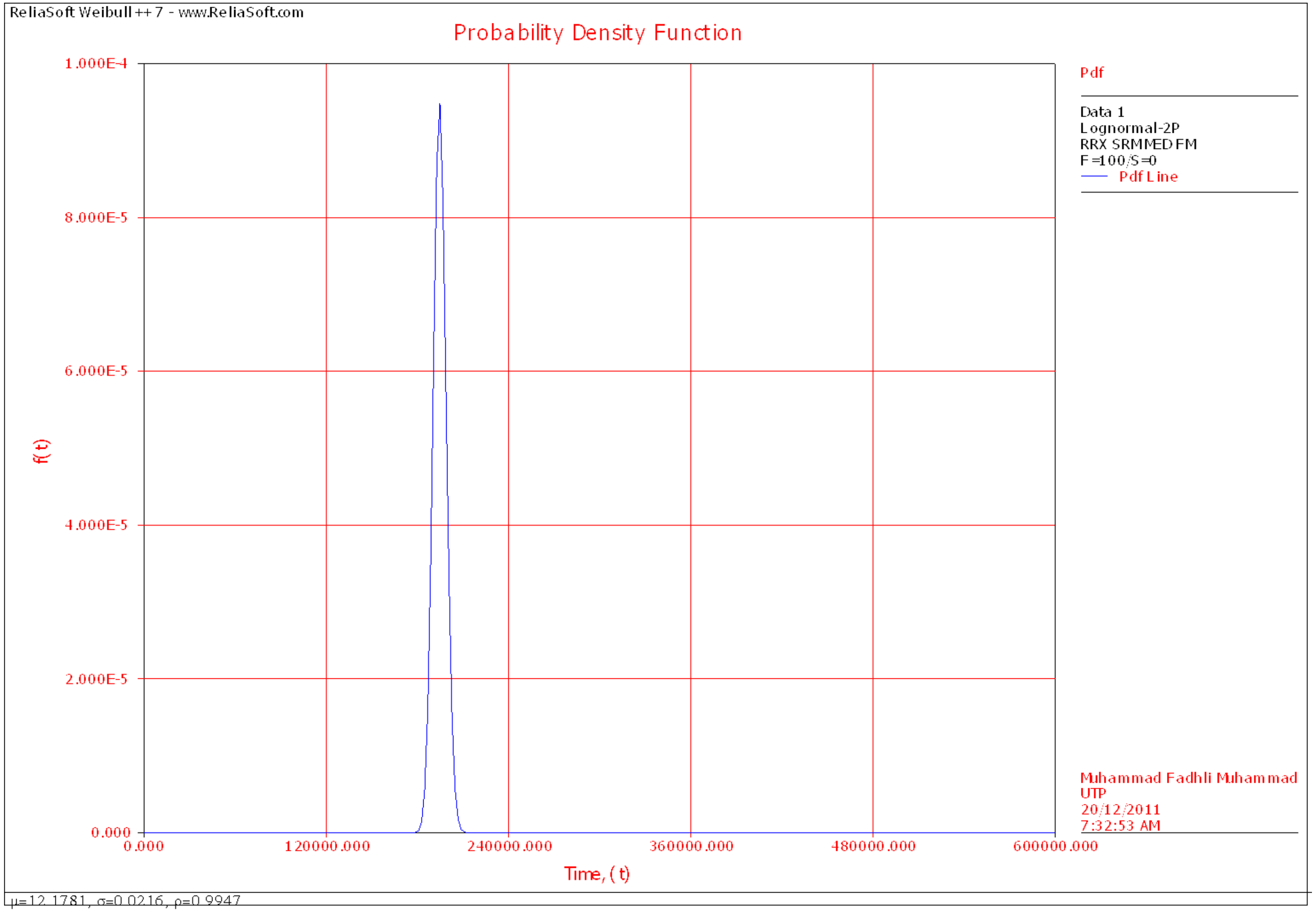

Figure 29: PDF plot at 1000^{o}C.

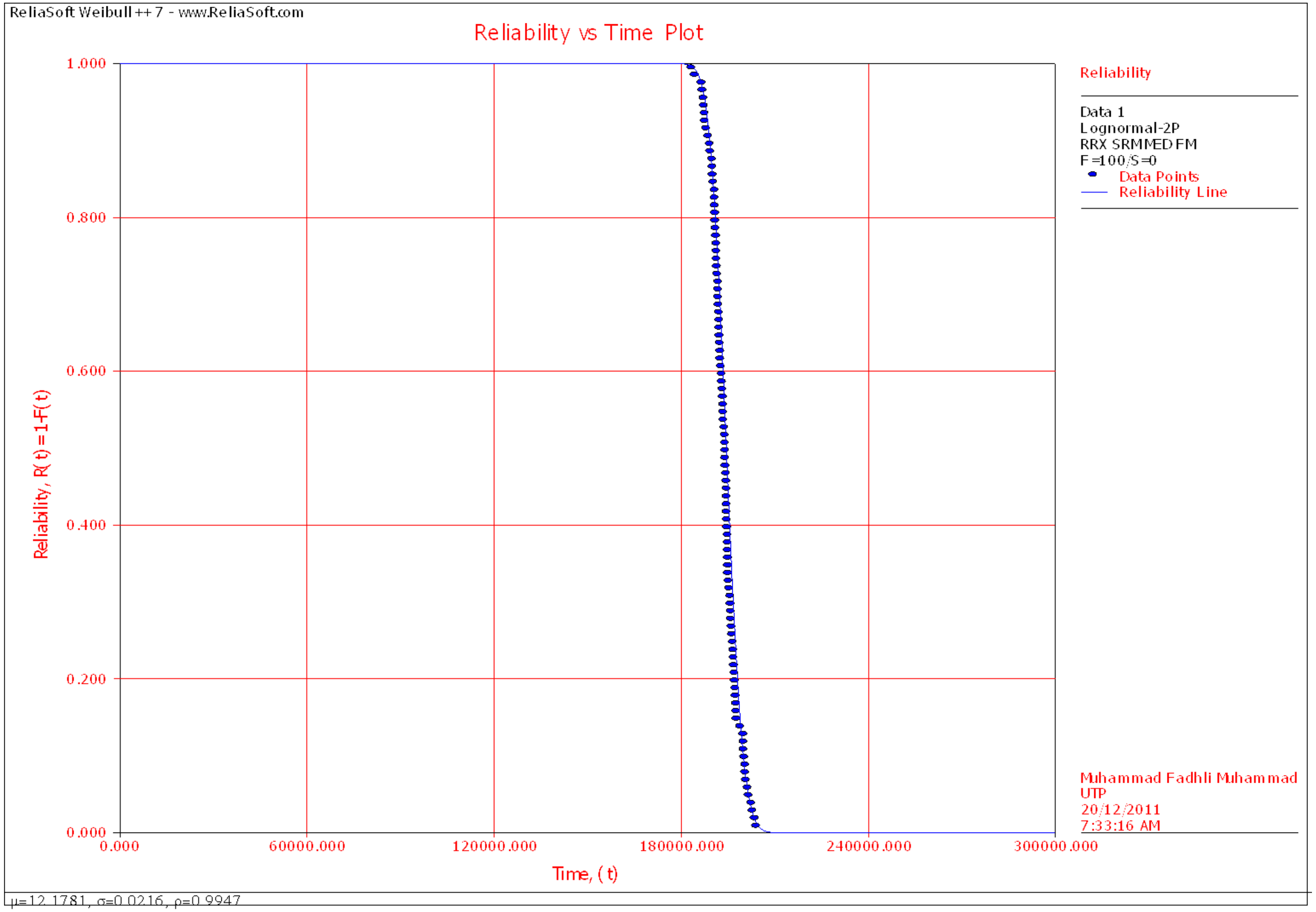

Figure 30: Reliability vs time plot at 1000°C.

The following table show the mean time to creep failure for each temperature analyzed.

Table 12: Mean time to creep failure acquired for each temperature values.

Description	Mean Value	Mean Time to Failure	Percentage of Difference
Lower Temp	850^{o}C	220,540 hours	7.22 %
Case Study Temp	926.67^{o}C	205,680 hours	0.00 %
Higher Temp	1000^{o}C	194,540 hours	5.42 %

Based on Table 12, we can see that changes in temperature yield a significant change in mean time to creep failure. Reducing operating temperature by 75^{o}C will significantly increase time to failure by 7.22 % which gives about 14860 longer operating hours. The situation is reverse with higher temperature where time to failure is reduced and failure will occur earlier.

4.3.3 Variation in pressure

According to Eq. (5), time to creep failure is also affected by pressure. From the equation, we can estimate that higher internal pressure will result in lower time to creep failure and vice versa. By using the same method used in section 4.3.1 and 4.3.2, one higher and lower values of pressure will be used in SA to analyze the effect of pressure towards the time to failure of the HRSG. The following table lists all the parameter used for each internal pressure evaluated.

Table 13: Parameters used for all values of pressure.

Variable	Description	Mean Value	Coefficient of Variation	Probability Distribution
R_{mean}	Mean radius	87.122 mm	0.02	Normal
h	Wall thickness	17.018 mm	0.05	Normal
f_{model}	Model uncertainty	1.0	0.02	Normal
T	Wall temperature	926.67^{o}C	-	Constant

The value of pressure used in the SA is tabulated in the following table.

Table 14: Pressure values for the sensitivity analysis.

Description	Mean Value	Coefficient of Variation	Probability Distribution
Lower Pressure	1.0 MPa	0.1	Normal
Case Study Pressure	3.45 MPa	0.1	Normal
Higher Pressure	6.0 MPa	0.1	Normal

All of the parameters are then calculated in Microsoft Excel. Mean time to creep failure for lower and higher internal pressures are shown in appendices A8 and A9 respectively. The time to creep failure value is then analyzed with Weibull++ to determine the mean time to creep failure. The following figures illustrate the PDF and reliability plot for both lower and higher pressure

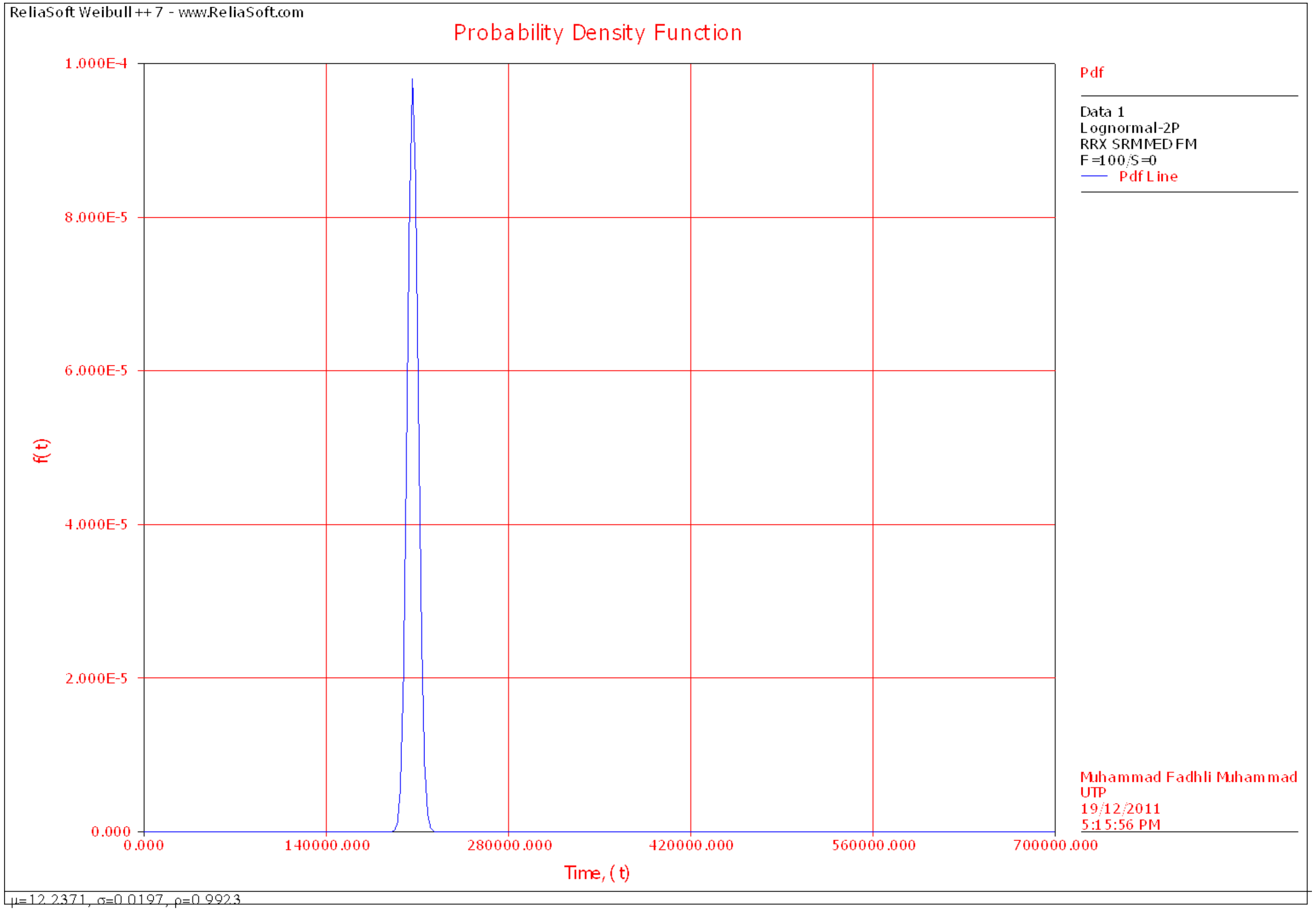

Figure 31: PDF plot at 1.0 MPa.

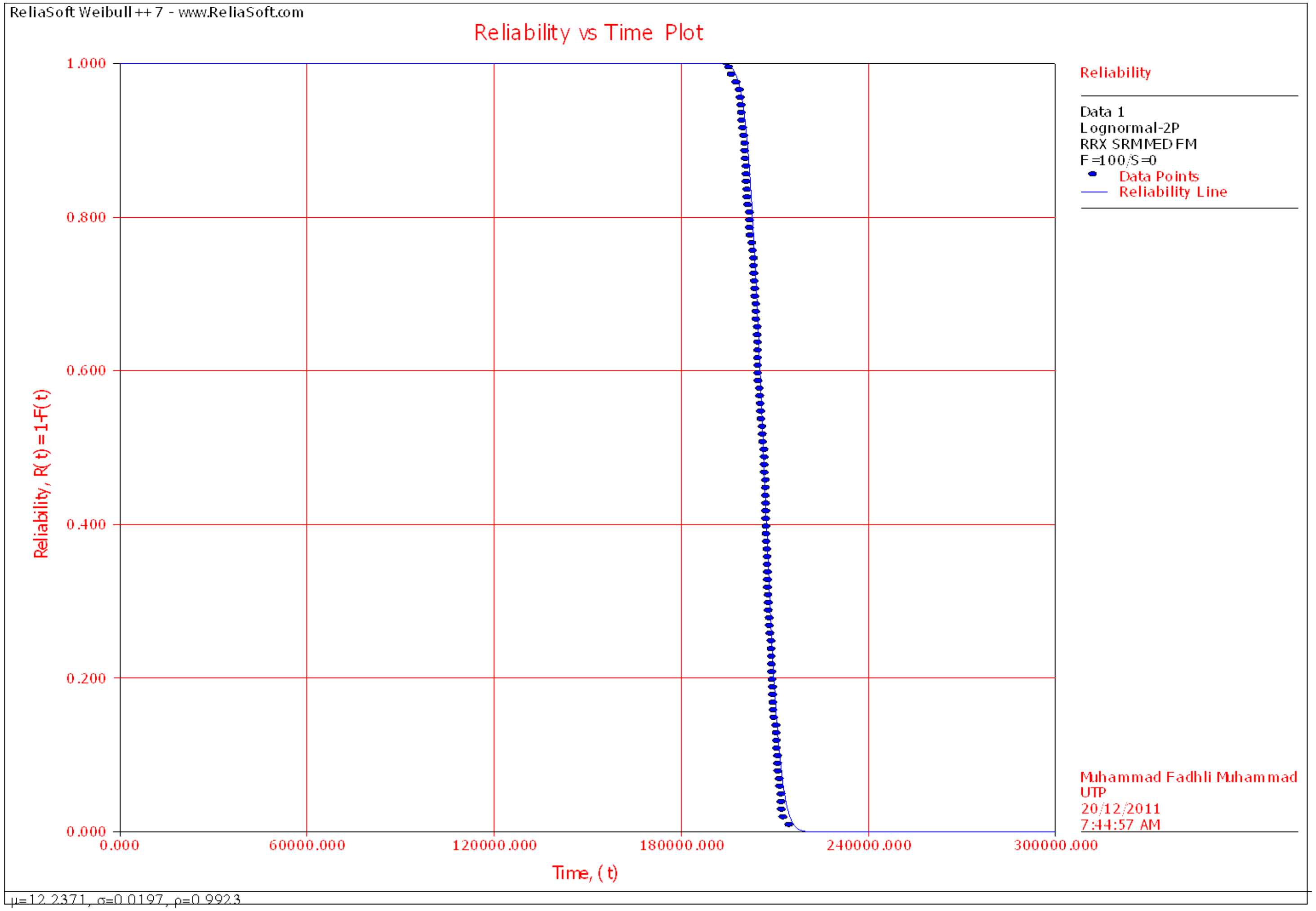

Figure 32: Reliability vs time plot at 1.0 MPa.

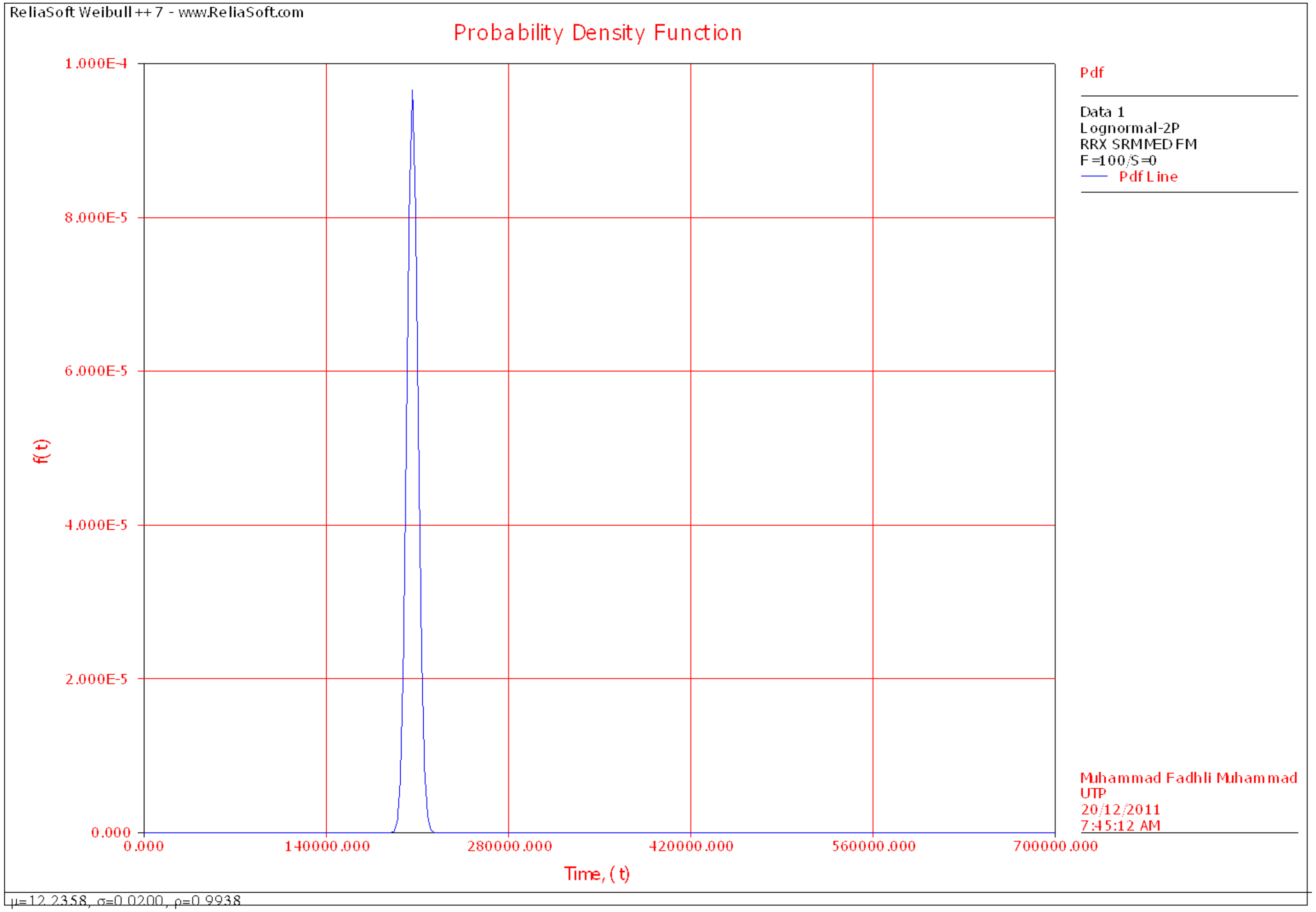

Figure 33: PDF plot at 6.0 MPa.

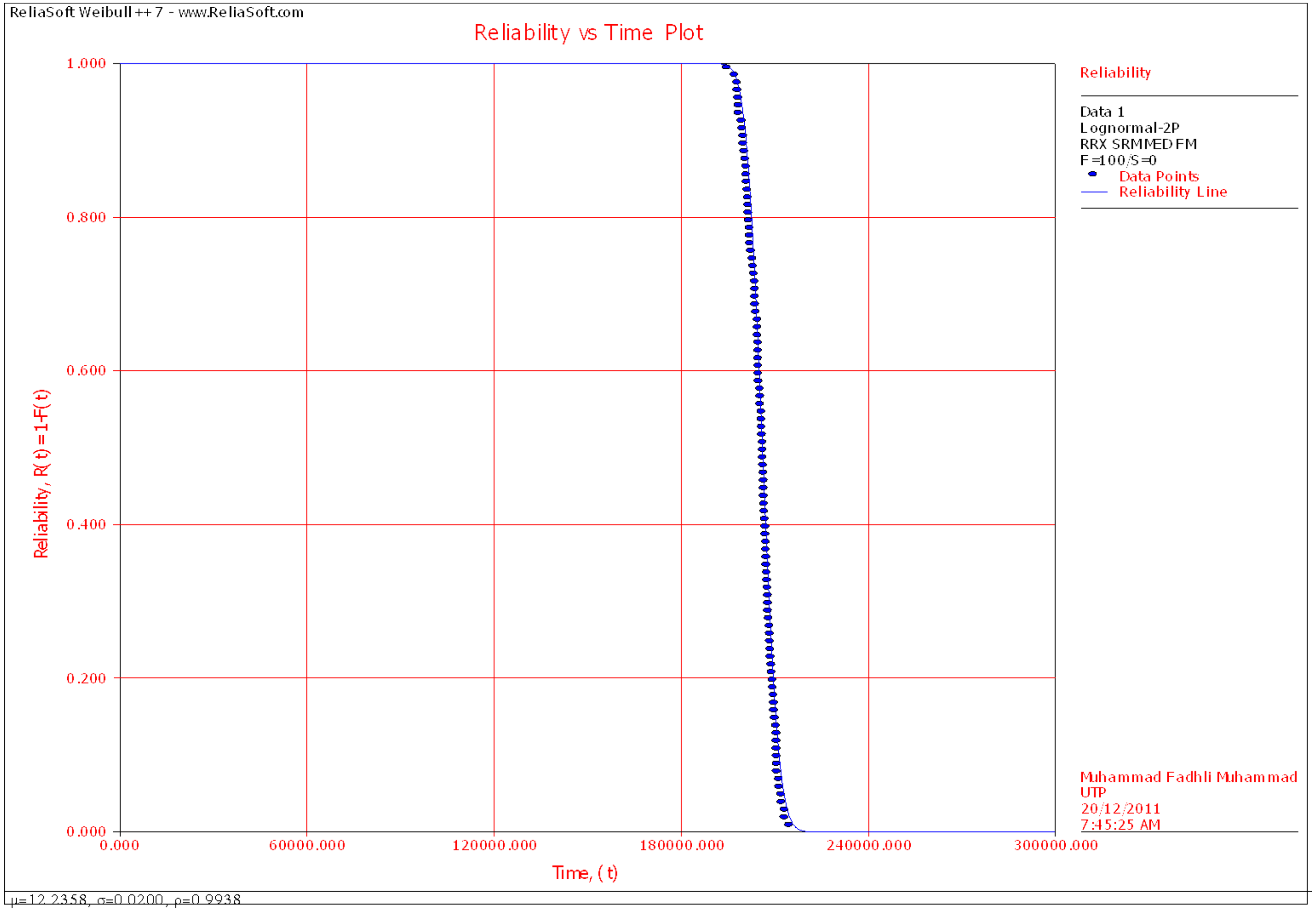

Figure 34: Reliability vs time plot at 6.0 MPa.

The following table show the mean time to creep failure for each internal temperature analyzed.

Table 15: Mean time to creep failure acquired for each pressure values.

Description	Mean Value	Mean Time to Failure	Percentage of Difference
Lower Pressure	1.0 MPa	206,340 hours	0.32 %
Case Study Pressure	3.45 MPa	205,680 hours	0.00 %
Higher Pressure	6.0 MPa	206,090 hours	0.20 %

Based on the result in Table 15, we can see that changes in pressure do not affect the time to creep failure as expected. Both higher and lower pressures only yield time to failure with an average difference of 0.3% from initial condition.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

By the end of the assessment, both objectives outlined at the beginning of the Final Year Project have been achieved. From the assessment, we can conclude that the mean time to creep failure for the HRSG assessed is estimated to be around 205,680 hours of operation. The model and method selected also enable us to evaluate the reliability and probability of failure at a given time.

From the assessment conducted, parameters that greatly affected HRSGs reliability are also determined. From the analyzed parameters, which are temperature and pressure, the wall tube temperature or operating temperature produce a significant effect towards the mean time to creep failure of the HRSG. With a mere change of 75^{o}C, the lifetime of the HRSG before failure can be either increase or decrease by approximately 12,000 hours. Aside from temperature, pressure and coefficient of variation are also analyzed however both parameters do not yield significant changes to mean time to creep failure.

From the result, we can see that a proper maintenance scheduling can be outlined since the mean time to creep failure has been estimated. With proper scheduling, the spare parts can be ordered beforehand thus reducing downtime of the HRSG and simultaneously increase the plant efficiency and productivity. The maintenance or management team can also use the result in plant optimization process where the operation of the HRSG can be optimized before downtime occurred. For example, the HRSG can operate on lower temperature if there is no demand of higher temperature from other machines. This will greatly improve the HRSG utilization and reducing both parts and labor cost at the same time.

This report also serves as a basis for a proper Reliability, Availability and Maintainability (RAM) model which can be constructed in the future and can be used for Universiti Teknologi PETRONAS (UTP) or PETRONAS applications such as to evaluate HRSG in GDC UTP or in PGB Kerteh.

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APPENDICES

Table A1: Random Mean Time to Failure Data Based on Carazas et al. (2010) Journal

No.	Internal pressure (in MPa)	Mean tube radius (in mm)	Tube wall thickness (in mm)	Model uncertainty	Stress acting on tube (in MPa)	Larson-Miller parameter	Time to failure (in hours)
	p	R_{mean}	h	f_{model}	s_{mech}	P (LMP)	t_r
1	9.261375	20.33336	3.898958	1.012853	48.29876	44501.67	303,819.34
2	10.04499	20.33606	3.917888	1.025821	52.13917	44497.27	307,679.18
3	9.899113	20.09625	4.086182	1.000405	48.68483	44501.23	300,082.22
4	10.7251	20.85671	4.143254	1.019474	53.98904	44495.15	305,760.69
5	7.991973	20.66238	4.172111	1.017284	39.58024	44511.66	305,216.90
6	8.39805	20.59334	3.744907	0.99177	46.18109	44504.09	297,510.92
7	8.960822	20.51685	3.882254	1.054501	47.35596	44502.75	316,320.55
8	8.356828	19.77442	3.9806	0.985119	41.5142	44509.44	295,551.06
9	9.265799	19.85695	3.951916	1.018374	46.55729	44503.66	305,489.09
10	9.52211	20.16442	4.044316	1.03082	47.47596	44502.61	309,215.58
11	8.379797	20.51567	3.719147	1.031592	46.22488	44504.04	309,457.11
12	9.342965	20.57054	3.5495	1.026924	54.1456	44494.97	307,993.85
13	11.1906	20.00281	4.211175	1.011155	53.1546	44496.11	303,272.14
14	10.14194	20.75152	3.950564	1.017126	53.27359	44495.97	305,061.93
15	9.918685	20.24651	3.85529	0.966186	52.08916	44497.33	289,791.69
16	11.52771	20.29448	4.24118	0.979491	55.16125	44493.81	293,759.32
17	9.885679	20.34874	3.825695	0.987422	52.58159	44496.76	296,157.63
18	10.79056	20.30361	4.084807	0.990708	53.63467	44495.56	297,135.21
19	10.7897	20.51651	4.2686	1.003613	51.85943	44497.59	301,019.92
20	7.067659	19.67592	3.90362	0.992239	35.62404	44516.19	297,732.66
21	10.15084	20.06224	4.163429	0.996051	48.91366	44500.96	298,774.15
22	10.71407	19.81853	4.005947	1.012224	53.0055	44496.28	303,593.90
23	9.371323	20.37398	3.931962	1.016127	48.55875	44501.37	304,799.33
24	10.47641	20.44285	4.281852	1.003887	50.01754	44499.7	301,116.32
25	10.06654	20.28527	3.922268	1.008296	52.06235	44497.36	302,422.96
26	9.299022	20.488	3.781229	1.013204	50.38529	44499.28	303,908.36
27	11.85463	20.56334	3.89955	0.999638	62.51256	44485.38	299,745.43
28	7.753832	20.53775	3.755392	1.013734	42.40471	44508.42	304,129.87
29	9.254828	20.3329	3.745654	0.983319	50.23888	44499.45	294,944.94
30	8.714052	20.11494	4.18331	0.989969	41.90046	44509	297,003.35
31	9.611225	20.08738	4.103431	0.991865	47.0495	44503.1	297,532.94
32	9.609814	20.07471	4.341791	0.978382	44.43196	44506.1	293,507.76
33	9.686673	20.85364	4.044864	0.992195	49.94047	44499.79	297,609.57
34	8.242642	20.03615	3.740672	1.024475	44.15004	44506.42	307,338.58
35	9.205708	20.96221	4.011936	1.052293	48.09946	44501.9	315,652.31
36	10.81653	20.18782	4.318374	0.98894	50.56583	44499.07	296,628.62
37	10.08162	20.60173	3.699114	1.001623	56.14824	44492.68	300,389.82

38	9.106875	20.37979	4.041916	1.002489	45.91789	44504.4	300,728.67
39	10.19163	20.35653	3.973566	0.985933	52.21158	44497.19	295,714.02
40	7.81319	20.74125	4.08406	0.997676	39.67996	44511.54	299,332.94
41	10.25767	20.32081	4.094185	1.009051	50.91225	44498.67	302,658.42
42	10.72565	20.69662	4.092225	1.000925	54.24547	44494.86	300,195.18
43	11.33701	20.07613	3.76256	1.002339	60.49159	44487.7	300,570.97
44	10.64293	19.99918	3.817941	1.010017	55.74991	44493.13	302,910.39
45	10.52955	20.47003	4.102346	0.990343	52.5407	44496.81	297,034.31
46	11.14533	20.28584	3.905937	1.017441	57.88433	44490.69	305,120.25
47	9.622981	20.5694	3.869509	1.004085	51.15351	44498.4	301,166.77
48	11.51421	21.18794	4.102754	1.010705	59.46306	44488.88	303,087.91
49	9.745679	20.46396	4.096405	0.976359	48.68542	44501.23	292,868.78
50	9.733981	20.19384	3.593642	1.010444	54.69838	44494.34	303,046.56
51	10.65583	20.05572	3.900656	0.999252	54.78829	44494.23	299,689.18
52	9.694991	19.99504	3.933798	1.014239	49.2785	44500.55	304,227.43
53	9.760201	19.97075	3.89096	0.995263	50.09523	44499.61	298,528.76
54	8.910906	20.04221	4.152074	0.958772	43.01325	44507.72	287,634.94
55	12.50438	20.47662	4.130684	0.984647	61.98667	44485.99	295,253.79
56	9.630609	20.23139	4.140609	0.963676	47.05602	44503.09	289,076.25
57	9.966668	20.35163	4.114882	1.011834	49.29374	44500.53	303,505.90
58	11.62991	20.44663	4.043391	1.010246	58.81015	44489.63	302,955.32
59	10.15862	19.34925	4.05506	0.987153	48.47318	44501.47	296,108.50
60	10.03598	20.48312	4.272694	0.985428	48.11207	44501.88	295,593.73
61	10.18573	20.42053	4.101947	1.016665	50.70715	44498.91	304,943.91
62	10.16506	19.75698	3.854726	0.992176	52.09991	44497.31	297,587.27
63	10.35336	19.57175	3.882325	1.017061	52.19384	44497.21	305,051.06
64	11.29017	20.44268	3.941009	0.977689	58.56403	44489.91	293,193.13
65	10.03054	19.91548	3.976763	1.00791	50.23256	44499.45	302,321.51
66	10.22826	19.84313	3.472744	1.006405	58.44387	44490.05	301,806.10
67	10.83092	20.39887	3.726605	1.008173	59.28682	44489.08	302,329.74
68	9.644497	20.326	4.079791	1.005486	48.05001	44501.95	301,611.11
69	11.04047	20.53712	4.057855	1.033981	55.87668	44492.99	310,096.76
70	10.12318	20.09472	3.822824	0.991389	53.21259	44496.04	297,342.94
71	10.62243	20.9357	3.796344	1.000296	58.57953	44489.89	299,972.90
72	9.041064	20.61827	4.009811	0.989023	46.48875	44503.74	296,684.66
73	9.399412	20.94157	3.894889	0.992104	50.53762	44499.1	297,577.82
74	8.970105	20.77043	4.280248	1.017108	43.52854	44507.13	305,133.05
75	10.49346	20.36083	4.127317	1.017378	51.76619	44497.7	305,149.56
76	10.02846	20.4968	3.846669	0.995015	53.43621	44495.78	298,428.60
77	9.047401	20.29453	4.130269	1.012984	44.45539	44506.07	303,888.51
78	11.04467	19.81627	4.207037	1.017148	52.02337	44497.4	305,078.38
79	12.15389	19.75654	4.124042	0.990392	58.22413	44490.3	297,005.31
80	8.733428	20.60014	4.16889	0.993429	43.15533	44507.56	298,032.01
81	11.65625	19.40563	3.780202	0.975128	59.83723	44488.45	292,415.45
82	9.315496	20.33267	3.886098	1.011943	48.74012	44501.16	303,542.73

83	9.859591	20.09865	3.905503	1.027667	50.73982	44498.87	308,243.92
84	10.72867	19.63873	4.006119	1.01807	52.59389	44496.75	305,350.57
85	9.018472	19.90356	4.241767	1.004153	42.31721	44508.52	301,255.71
86	9.444365	20.79034	4.223033	0.997	46.49539	44503.73	299,077.43
87	8.351037	19.97198	4.131586	1.009594	40.3687	44510.75	302,903.50
88	8.348459	19.78084	4.244489	0.980009	38.9068	44512.43	294,037.83
89	9.305692	19.95838	4.418689	0.987842	42.03205	44508.85	296,364.24
90	9.322657	20.18294	3.839039	0.999298	49.01192	44500.85	299,747.50
91	10.62859	21.26469	3.803535	0.998867	59.422	44488.93	299,538.07
92	10.48112	20.39863	3.59676	1.004283	59.44255	44488.9	301,162.06
93	11.82495	20.14598	4.289244	1.006743	55.54016	44493.37	301,930.21
94	10.09883	20.63424	3.805301	0.97901	54.7609	44494.27	293,618.21
95	11.33497	20.01697	3.5153	0.999562	64.54405	44483.06	299,706.94
96	10.80661	20.30797	3.987031	0.992227	55.04354	44493.94	297,580.29
97	8.131387	20.4534	4.169213	1.007218	39.89111	44511.3	302,194.43
98	11.51775	20.09537	4.010732	0.99817	57.70852	44490.89	299,342.07
99	12.10921	20.12263	4.206302	1.026736	57.92957	44490.64	307,907.74
100	11.31847	20.07042	4.19007	1.007867	54.21541	44494.89	302,277.64

Table A2: Random Mean Time to Failure Data Based on Jaske and Shannon (2002) Case Study

No.	Internal pressure (in MPa)	Mean tube radius (in mm)	Tube wall thickness (in mm)	Model uncertainty	Stress acting on tube (in MPa)	Larson-Miller parameter	Time to failure (in hours)
	p	R_{mean}	h	f_{model}	s_{mech}	P (LMP)	t_r
1	3.755278	89.61669	17.53898	1.021511	19.18787	44535.02	210,627.30
2	3.341399	85.5726	17.64481	0.997815	16.20489	44538.44	205,756.78
3	3.307408	86.86877	17.6022	1.01187	16.32242	44538.3	208,654.77
4	2.863696	85.77735	17.11048	0.980292	14.35613	44540.55	202,152.59
5	3.955138	84.07715	17.35813	0.993936	19.1574	44535.05	204,941.26
6	3.340431	88.0533	17.10743	0.989032	17.19346	44537.3	203,940.23
7	3.491543	88.2034	17.04098	1.026891	18.07209	44536.3	211,742.79
8	3.310424	85.9953	18.16315	0.97054	15.67354	44539.04	200,134.72
9	3.274499	87.22738	16.88277	0.99402	16.91819	44537.62	204,970.44
10	3.570352	88.22421	16.69636	1.005599	18.86588	44535.39	207,347.78
11	3.029758	87.94684	17.75716	1.001628	15.00565	44539.81	206,549.58
12	3.818767	86.82317	16.74191	0.99285	19.80403	44534.31	204,713.85
13	3.685727	87.07482	16.75321	1.003175	19.15657	44535.05	206,846.53
14	3.158228	85.20804	17.33789	1.012226	15.52129	44539.22	208,732.34
15	2.61762	87.11921	16.6221	0.995361	13.71938	44541.28	205,263.74
16	4.369342	87.49537	17.02328	0.980072	22.45732	44531.27	202,065.20
17	2.840864	85.33989	17.8726	1.021243	13.56485	44541.46	210,602.57
18	3.584336	87.10623	18.18015	1.009956	17.17357	44537.33	208,255.42
19	3.732598	84.40192	16.31917	0.994585	19.30481	44534.88	205,074.26
20	3.726902	85.18774	16.14388	1.020232	19.66605	44534.47	210,361.15
21	3.017628	87.66947	17.62665	0.983308	15.00874	44539.81	202,771.37
22	3.381614	86.60847	16.62227	0.99149	17.61951	44536.81	204,445.06
23	3.420109	87.26916	16.27217	0.962107	18.34237	44535.99	198,381.98
24	3.300837	88.64927	18.12919	0.984342	16.14064	44538.51	202,978.54
25	3.222944	85.74589	16.75625	0.996199	16.4926	44538.11	205,422.00
26	3.188676	85.925	18.35348	1.013222	14.92834	44539.9	208,941.01
27	4.057647	84.8517	16.88165	0.979603	20.39482	44533.64	201,979.22
28	2.89258	85.50588	16.5428	0.992232	14.95107	44539.87	204,611.96
29	3.585786	86.1027	17.59956	0.989639	17.54282	44536.9	204,063.62
30	3.306026	88.18079	16.23376	0.978748	17.95813	44536.43	201,815.64
31	4.036351	88.19513	18.0097	0.994503	19.76637	44534.36	205,054.90
32	3.324563	86.2985	18.31329	1.000654	15.66648	44539.05	206,345.14
33	3.198193	86.64653	16.80537	0.96619	16.48951	44538.11	199,233.31
34	2.943287	86.91229	16.74427	1.000539	15.27733	44539.5	206,323.52
35	3.356392	89.72025	17.21642	1.007591	17.49122	44536.96	207,766.08
36	2.944933	89.12764	16.06629	0.958401	16.33699	44538.28	197,627.97
37	3.666977	85.28511	16.64515	1.026309	18.78856	44535.48	211,618.95

38	3.458678	89.07614	18.01469	1.018159	17.10192	44537.41	209,947.38
39	3.803543	86.41653	16.76157	1.007494	19.60967	44534.53	207,734.62
40	4.159523	88.16337	16.68053	0.983102	21.98476	44531.81	202,692.36
41	3.936991	88.98053	17.03136	1.015956	20.56886	44533.44	209,474.52
42	3.475778	89.23939	16.89407	1.016035	18.36007	44535.97	209,502.74
43	3.287922	89.28357	16.52825	1.013107	17.76095	44536.65	208,902.08
44	3.338417	86.23992	16.85987	0.99054	17.07633	44537.44	204,252.00
45	3.412569	84.85226	17.72642	1.015372	16.33518	44538.29	209,376.91
46	3.368269	87.98156	16.13739	1.002727	18.36391	44535.96	206,758.24
47	3.259429	87.59495	17.36863	1.008631	16.43823	44538.17	207,986.05
48	3.496362	89.12434	15.84205	1.006348	19.66986	44534.47	207,497.96
49	3.319854	87.80925	15.9365	1.008463	18.29221	44536.04	207,941.58
50	3.634241	87.74009	17.82961	0.969733	17.88421	44536.51	199,956.93
51	3.146465	88.00699	18.26987	1.059679	15.1567	44539.64	218,520.82
52	3.737351	87.54064	16.84763	0.986317	19.41936	44534.75	203,368.82
53	3.002744	85.78695	17.57087	0.995437	14.66042	44540.2	205,274.44
54	3.186398	86.19774	16.62379	0.994777	16.52213	44538.07	205,128.52
55	3.317755	84.63409	17.35312	1.016627	16.18125	44538.46	209,636.42
56	3.619721	86.51852	16.54748	0.995192	18.92571	44535.32	205,201.53
57	3.09417	88.36838	17.32102	0.964283	15.78584	44538.92	198,843.71
58	3.585136	85.89859	16.44448	0.993498	18.72714	44535.55	204,853.31
59	3.494062	83.03682	16.8221	0.995409	17.2473	44537.24	205,255.18
60	2.743126	87.69004	18.60805	1.009218	12.92692	44542.19	208,126.03
61	3.213663	86.66421	16.9725	0.984225	16.40946	44538.2	202,953.06
62	3.7014	85.84192	17.5034	1.001915	18.15278	44536.2	206,591.89
63	2.995247	88.39683	18.03391	0.999179	14.6818	44540.18	206,046.07
64	3.665821	90.42305	17.69188	0.994262	18.73598	44535.54	205,010.75
65	3.375316	86.6385	15.82918	0.990082	18.47425	44535.84	204,150.10
66	4.16912	87.30139	16.17268	0.968709	22.50524	44531.22	199,721.94
67	3.049673	84.4574	17.7246	1.015282	14.53164	44540.35	209,367.92
68	3.443234	88.07102	16.24171	0.999339	18.67101	44535.61	206,058.10
69	3.65753	87.38236	15.80361	0.983156	20.22346	44533.83	202,712.84
70	2.899486	86.5892	16.33852	0.990732	15.3664	44539.4	204,300.43
71	3.104812	85.3386	14.99959	0.992445	17.6645	44536.76	204,641.66
72	3.223189	86.42521	17.07136	1.010974	16.31767	44538.31	208,469.84
73	4.056302	89.85197	17.77469	0.997665	20.50482	44533.51	205,703.13
74	2.995733	88.62954	16.31018	1.012231	16.27881	44538.35	208,729.46
75	3.50172	88.28553	17.00137	1.013859	18.1839	44536.17	209,054.83
76	3.991377	86.36944	16.63271	1.020772	20.7262	44533.26	210,466.61
77	2.98531	86.33606	16.93305	1.0352	15.22111	44539.56	213,472.00
78	3.759297	86.52337	16.1248	0.988608	20.17185	44533.89	203,837.25
79	3.700465	89.70342	15.88448	1.030144	20.8974	44533.06	212,398.34
80	3.833916	84.12187	17.12871	1.010562	18.82898	44535.43	208,371.60
81	3.127988	87.53611	17.48625	0.964462	15.6587	44539.06	198,881.33
82	3.768324	82.91348	16.86425	1.029708	18.52706	44535.78	212,321.24

83	3.469935	87.27611	16.74147	0.989604	18.08936	44536.28	204,053.53
84	2.777619	88.7688	15.7178	0.993935	15.68705	44539.03	204,959.40
85	3.781116	88.58335	14.78552	0.997342	22.65351	44531.05	205,625.18
86	3.804126	86.82902	17.7229	1.005491	18.63738	44535.65	207,326.79
87	3.324882	88.28041	15.94389	1.0386	18.40968	44535.91	214,155.53
88	3.492739	85.86025	15.92762	1.044288	18.82814	44535.43	215,326.17
89	2.62501	87.89728	17.35858	1.012412	13.29206	44541.77	208,782.76
90	3.195627	85.69793	16.17657	1.009405	16.92934	44537.61	208,142.99
91	3.150664	87.0696	16.52207	0.987553	16.60367	44537.98	203,638.34
92	3.491501	88.55382	16.03243	1.000117	19.28502	44534.91	206,215.12
93	3.49166	85.36031	16.98512	0.986792	17.54767	44536.9	203,476.53
94	3.507111	86.26176	17.4681	0.990954	17.31898	44537.16	204,336.08
95	3.292528	87.44309	16.58648	0.975169	17.35804	44537.11	201,080.58
96	3.757947	87.38301	17.45327	1.016038	18.81485	44535.45	209,500.76
97	3.513335	85.31886	17.02642	1.016066	17.60522	44536.83	209,513.05
98	2.698792	86.19884	16.9413	0.999748	13.73169	44541.27	206,168.46
99	3.289263	86.77105	18.63145	1.004359	15.31887	44539.45	207,111.10
100	3.036799	89.68989	16.82002	0.999754	16.19321	44538.45	206,156.71

Table A3: Random Mean Time to Failure Data for 0.015 COV value.

No.	Internal pressure (in MPa)	Mean tube radius (in mm)	Tube wall thickness (in mm)	Model uncertainty	Stress acting on tube (in MPa)	Larson-Miller parameter	Time to failure (in hours)
	p	R_{mean}	h	f_{model}	s_{mech}	P (LMP)	t_r
1	3.183629	84.86107	18.9384	0.992103	14.26552	44540.66	204,588.99
2	3.24927	87.41387	16.96023	0.989587	16.7469	44537.81	204,057.01
3	3.530213	86.1882	16.73609	1.014181	18.18003	44536.17	209,121.19
4	3.233189	88.99536	17.10763	0.9863	16.81932	44537.73	203,378.91
5	3.553941	85.44709	15.8803	0.967578	19.12268	44535.09	199,506.21
6	3.017151	88.72368	17.35903	1.014297	15.42095	44539.33	209,160.08
7	3.272753	86.42814	17.89429	0.982983	15.80716	44538.89	202,700.07
8	3.588814	89.10744	16.61139	1.026938	19.25125	44534.95	211,746.11
9	2.95247	90.98568	16.78892	0.982406	16.00059	44538.67	202,580.13
10	3.290181	87.21772	18.28643	0.989458	15.69263	44539.02	204,036.02
11	2.855079	83.46209	16.64242	1.011234	14.31828	44540.6	208,534.30
12	3.738871	86.38798	16.41508	0.993023	19.67663	44534.46	204,750.30
13	2.731857	84.83285	16.28839	0.989185	14.228	44540.7	203,987.52
14	3.447667	89.61704	18.10081	1.001418	17.06938	44537.45	206,495.15
15	3.572345	87.12378	16.80278	1.008926	18.5229	44535.78	208,035.70
16	3.788311	88.62598	16.63079	1.017918	20.18802	44533.87	209,881.00
17	3.224628	88.95987	16.83336	0.993217	17.04131	44537.48	204,804.06
18	3.906441	87.20203	16.98964	1.018658	20.05043	44534.03	210,034.40
19	3.731064	88.5015	17.44921	0.989476	18.92376	44535.32	204,022.76
20	3.523793	88.1866	16.84312	1.000931	18.44974	44535.86	206,387.40
21	4.057323	89.5131	18.61741	1.003878	19.50774	44534.65	206,989.58
22	2.996121	88.30392	16.4811	1.013933	16.05288	44538.61	209,081.56
23	4.07652	90.14007	17.61257	1.004187	20.86338	44533.1	207,046.00
24	2.997738	88.79123	17.08019	1.001917	15.58372	44539.15	206,606.03
25	3.565325	84.70314	16.83781	0.991016	17.93547	44536.45	204,345.63
26	4.377605	87.45132	16.43158	1.01478	23.29827	44530.31	209,217.17
27	2.423276	88.9317	17.83996	0.98758	12.07996	44543.16	203,667.73
28	3.072298	86.80166	16.59227	0.992419	16.07258	44538.59	204,644.61
29	3.771584	84.86534	16.53403	1.015807	19.35867	44534.82	209,450.21
30	3.728568	87.82322	16.4436	1.01022	19.91382	44534.19	208,295.23
31	3.143113	86.8458	17.61518	0.978976	15.49608	44539.25	201,875.29
32	2.884949	88.92657	17.62723	1.009505	14.55411	44540.33	208,176.52
33	3.79674	85.45012	15.9598	0.99627	20.32807	44533.71	205,416.36
34	3.784485	87.34326	16.48916	0.994563	20.04646	44534.03	205,065.90
35	3.973995	88.49193	15.46443	1.004434	22.74034	44530.95	207,086.91
36	3.389914	85.05266	15.90732	0.986434	18.12506	44536.24	203,399.69
37	3.177639	85.23953	18.41653	1.027416	14.70746	44540.15	211,869.58
38	3.356716	87.741	17.30223	0.997731	17.02218	44537.5	205,735.09
39	3.280843	86.99846	17.47195	0.994499	16.33637	44538.28	205,072.24

40	3.454539	84.23359	18.29515	0.992407	15.90522	44538.78	204,643.09
41	3.647687	87.83941	16.98053	1.001999	18.86929	44535.38	206,605.52
42	2.979785	86.69155	17.0088	1.007137	15.18756	44539.6	207,684.62
43	3.392385	88.11578	18.58083	1.001171	16.08769	44538.57	206,449.58
44	3.122539	90.18095	18.47645	1.012275	15.24068	44539.54	208,743.92
45	3.570878	90.31622	15.75317	1.003719	20.47259	44533.55	206,951.69
46	3.510227	86.53028	16.92598	1.006444	17.94525	44536.44	207,526.94
47	3.244105	85.86158	15.95457	1.00369	17.45858	44537	206,961.77
48	3.656253	90.05761	16.54079	0.986819	19.90676	44534.19	203,469.72
49	3.56453	83.34096	17.57555	0.99147	16.90253	44537.64	204,444.62
50	3.32805	87.33898	16.23332	1.002256	17.90567	44536.49	206,663.50
51	3.256624	84.83949	16.30165	1.002935	16.94861	44537.58	206,808.76
52	3.145571	84.25234	16.60418	0.983134	15.96114	44538.71	202,730.49
53	3.724486	84.64078	16.99839	1.002332	18.54549	44535.75	206,675.80
54	3.46167	87.83334	17.1303	0.981963	17.74925	44536.67	202,479.61
55	3.40839	86.62407	17.74936	0.969578	16.63433	44537.94	199,931.42
56	3.654157	87.79655	18.04197	1.017874	17.78201	44536.63	209,885.02
57	3.568469	85.83223	17.52502	1.02107	17.47728	44536.98	210,545.81
58	3.186941	86.66614	17.10637	0.997783	16.14603	44538.5	205,750.43
59	4.278579	86.8707	18.16476	1.017456	20.46177	44533.56	209,784.42
60	3.155055	84.62448	17.23727	1.025777	15.4894	44539.26	211,527.30
61	2.823839	86.8589	18.17542	1.00103	13.4949	44541.54	206,434.22
62	3.597912	86.84302	16.97831	1.017447	18.4031	44535.92	209,793.55
63	3.305349	87.68377	17.71566	0.992571	16.35984	44538.26	204,674.59
64	3.007979	87.93088	16.33729	1.009063	16.18961	44538.45	208,076.48
65	3.506936	87.91248	17.39372	0.999255	17.72498	44536.69	206,045.64
66	3.448958	90.71593	15.91003	1.018843	19.66529	44534.47	210,074.67
67	3.580464	86.00834	17.32342	0.999656	17.7765	44536.64	206,128.12
68	3.256999	86.44594	15.79377	0.980852	17.82692	44536.58	202,250.13
69	2.915422	86.01376	18.16717	0.979141	13.80327	44541.19	201,918.18
70	3.44359	89.09924	15.70258	0.984998	19.53954	44534.62	203,096.24
71	3.781294	87.34161	17.98634	0.981085	18.36195	44535.96	202,295.43
72	2.974118	86.95629	17.90583	0.988188	14.44324	44540.45	203,780.62
73	4.277944	86.97266	15.50373	0.99444	23.99837	44529.51	205,019.74
74	3.246105	85.64095	17.67843	0.9915	15.72535	44538.98	204,456.98
75	3.367193	89.44966	17.05894	1.026135	17.65609	44536.77	211,589.19
76	3.132959	88.76808	15.01215	0.98968	18.52544	44535.78	204,067.00
77	3.392377	83.61335	17.54155	0.986704	16.17006	44538.48	203,465.49
78	3.838726	85.09093	16.51127	0.962688	19.78291	44534.34	198,494.43
79	3.569492	88.91132	17.35469	1.026359	18.28717	44536.05	211,632.01
80	3.806322	88.30689	16.54829	1.001259	20.31174	44533.73	206,445.12
81	3.349387	88.92843	19.03338	0.996596	15.64912	44539.07	205,508.33
82	3.652765	84.75395	17.80673	1.026041	17.38592	44537.08	211,571.24
83	3.703092	86.29678	16.19373	0.994493	19.73387	44534.39	205,053.02
84	3.463978	86.95421	15.14198	1.000445	19.89221	44534.21	206,279.60

85	3.743624	90.17922	16.21893	1.00283	20.81501	44533.15	206,766.43
86	3.349469	87.18389	18.23164	0.978709	16.0172	44538.65	201,817.68
87	3.491477	82.82186	16.56595	0.996567	17.45572	44537	205,492.78
88	3.299405	88.27268	16.40076	0.978367	17.75816	44536.66	201,738.04
89	3.22765	88.58697	16.98004	0.987966	16.83905	44537.71	203,722.28
90	3.42474	85.86005	17.3067	0.995839	16.99044	44537.54	205,345.07
91	3.481934	86.39091	16.83369	0.998654	17.86937	44536.53	205,920.96
92	4.257549	87.15099	16.44687	0.97641	22.5605	44531.15	201,309.67
93	3.692198	89.28809	18.07612	0.995333	18.23784	44536.11	205,234.26
94	4.071427	88.79536	18.22869	0.99914	19.83268	44534.28	206,010.72
95	3.072706	84.78019	16.16431	0.982312	16.11603	44538.54	202,560.09
96	3.176643	89.43737	17.97289	0.98114	15.80773	44538.89	202,320.10
97	3.759317	88.96006	16.01617	1.000542	20.88071	44533.08	206,294.44
98	3.817505	86.63899	16.13315	0.974708	20.50094	44533.51	200,969.34
99	3.45224	84.92844	18.36637	0.992927	15.9636	44538.71	204,750.00
100	4.026104	88.41202	17.97952	1.021239	19.79786	44534.32	210,568.07

A4: Random Mean Time to Failure Data for 0.025 COV value.

No.	Internal pressure (in MPa)	Mean tube radius (in mm)	Tube wall thickness (in mm)	Model uncertainty	Stress acting on tube (in MPa)	Larson-Miller parameter	Time to failure (in hours)
	p	R_{mean}	h	f_{model}	s_{mech}	P (LMP)	t_r
1	3.983553	87.64621	17.32514	0.998705	20.1524	44533.91	205,919.44
2	3.247915	86.11152	14.89777	1.017851	18.77348	44535.49	209,874.91
3	3.347642	86.4173	17.21739	0.999764	16.80244	44537.75	206,155.64
4	3.482734	88.67483	16.66614	0.967374	18.53043	44535.77	199,467.15
5	3.63166	87.60668	17.45065	1.000222	18.23185	44536.11	206,242.33
6	3.335365	86.35346	16.6618	0.972036	17.28627	44537.2	200,434.81
7	3.057437	87.23322	16.29585	1.001821	16.36674	44538.25	206,582.12
8	2.985493	86.64454	16.66563	0.993439	15.52157	44539.22	204,858.02
9	3.128967	87.81821	16.82093	1.054583	16.33562	44538.29	217,463.15
10	3.878226	86.70183	16.5349	1.006827	20.33574	44533.7	207,593.16
11	3.47741	85.93087	18.58239	1.040508	16.08065	44538.58	214,561.94
12	2.613566	90.22753	16.92015	0.984669	13.93697	44541.03	203,057.66
13	3.559393	85.73401	17.67594	1.019686	17.26421	44537.22	210,261.42
14	3.496524	84.41938	16.47853	1.004514	17.91266	44536.48	207,129.26
15	3.512243	84.98902	17.7749	0.994788	16.79346	44537.76	205,129.36
16	3.645552	85.40681	16.69567	0.981355	18.64885	44535.64	202,349.54
17	3.72983	86.07119	17.77721	1.003692	18.05857	44536.31	206,958.87
18	3.271759	88.61735	17.48443	1.014321	16.58245	44538	209,158.75
19	3.454127	87.48531	16.68222	1.03123	18.11422	44536.25	212,637.49
20	3.705581	86.26636	16.34628	0.999992	19.55595	44534.6	206,188.05
21	3.568305	88.65712	17.27978	0.98543	18.30786	44536.03	203,191.63
22	3.432715	89.00114	17.38804	0.990919	17.57044	44536.87	204,327.43
23	3.274102	85.62246	17.36461	1.000945	16.14413	44538.51	206,402.67
24	3.310754	88.9738	16.1006	1.024576	18.29562	44536.04	211,264.21
25	3.638019	84.95664	17.82873	1.026635	17.33572	44537.14	211,694.07
26	4.223443	84.80021	16.72334	1.024795	21.41611	44532.47	211,292.45
27	3.32542	86.31217	15.49939	0.981397	18.51841	44535.79	202,358.86
28	3.050614	88.52163	17.35834	0.977791	15.55709	44539.18	201,630.69
29	3.010825	86.73945	17.31956	1.011043	15.07875	44539.73	208,490.81
30	4.174323	85.08762	17.98866	1.019583	19.74485	44534.38	210,226.72
31	3.175607	89.87552	16.15753	1.021849	17.66417	44536.76	210,705.40
32	3.732788	88.1513	16.78265	0.998855	19.60656	44534.54	205,953.26
33	3.749077	86.34997	17.49034	0.969426	18.50923	44535.8	199,890.34
34	2.929416	86.80142	16.74173	1.016651	15.18824	44539.6	209,646.68
35	3.929399	86.98516	17.12358	1.005512	19.96074	44534.13	207,324.11
36	3.731717	89.47514	16.15415	0.965429	20.66935	44533.32	199,055.14
37	3.082733	85.44043	16.98476	0.98316	15.50743	44539.23	202,738.21
38	3.604405	87.47486	15.81689	1.032858	19.93406	44534.16	212,963.12
39	3.352789	85.07473	17.4756	0.998383	16.32205	44538.3	205,873.27

40	3.79504	85.96098	16.25165	1.004986	20.07337	44534	207,214.92
41	3.583247	90.58552	16.63956	1.016598	19.50714	44534.65	209,612.60
42	3.815837	84.54533	18.25966	1.001768	17.66797	44536.76	206,564.25
43	3.767954	88.20938	17.04193	1.031944	19.503	44534.66	212,777.08
44	3.061586	89.12655	17.8709	0.994042	15.26888	44539.51	204,983.70
45	3.361706	89.3618	18.08114	0.989914	16.61444	44537.97	204,125.22
46	3.282197	90.638	17.97427	1.020544	16.55098	44538.04	210,442.16
47	3.11841	88.67881	17.61443	1.006819	15.69946	44539.01	207,616.44
48	3.626588	86.78772	17.92688	0.985997	17.55706	44536.89	203,312.45
49	2.927137	87.52434	17.30451	0.992288	14.80515	44540.04	204,624.25
50	3.824548	88.41014	16.51494	1.011486	20.47412	44533.54	208,553.12
51	3.56385	86.21599	16.92967	1.050908	18.14926	44536.21	216,695.12
52	3.548527	88.08041	17.78667	0.98142	17.57247	44536.87	202,368.57
53	3.743095	84.91095	18.79355	0.988886	16.91164	44537.63	203,911.62
54	3.086012	87.99597	17.34264	1.021973	15.65832	44539.06	210,741.86
55	3.544576	86.65661	16.57294	1.00171	18.53389	44535.77	206,547.64
56	3.347512	86.77966	17.59876	1.034548	16.50662	44538.09	213,330.58
57	3.342366	92.18779	16.30143	1.025654	18.90174	44535.35	211,483.23
58	3.777565	85.12741	16.33993	1.016429	19.68028	44534.45	209,576.74
59	3.450471	86.43634	17.66435	1.045413	16.88407	44537.66	215,569.08
60	3.130076	90.4861	16.82276	1.013679	16.83603	44537.71	209,024.90
61	3.742916	85.91795	16.44351	0.972669	19.55687	44534.6	200,553.63
62	2.811875	88.14015	16.86655	0.948884	14.69412	44540.17	195,673.56
63	3.492248	85.38494	16.63458	1.013673	17.92564	44536.46	209,017.89
64	3.427593	87.57694	17.7003	1.018054	16.95893	44537.57	209,926.48
65	3.752154	86.36805	16.97649	0.980557	19.08911	44535.13	202,182.70
66	2.939515	85.23809	16.8919	0.993174	14.83307	44540.01	204,806.97
67	3.219429	88.19794	18.40872	1.010271	15.42459	44539.33	208,329.84
68	3.411574	86.07923	17.36406	0.990934	16.91227	44537.63	204,333.93
69	3.549441	86.50911	17.93338	1.006758	17.12221	44537.38	207,596.10
70	3.232751	88.70486	17.26881	0.992543	16.6057	44537.98	204,667.47
71	3.545055	89.6801	18.01331	0.995254	17.64922	44536.78	205,220.94
72	3.425079	82.77268	16.98454	0.998419	16.69182	44537.88	205,878.76
73	3.749486	86.5996	16.69391	0.971814	19.45044	44534.72	200,377.85
74	3.7961	87.79008	16.82736	0.98933	19.80465	44534.31	203,988.01
75	3.89803	86.66548	16.54701	1.025478	20.41606	44533.61	211,438.67
76	3.274746	88.0953	17.61948	1.027802	16.37334	44538.24	211,940.01
77	2.921878	87.09587	15.86925	1.010142	16.03626	44538.63	208,299.81
78	2.867856	86.66981	17.8318	1.000566	13.93895	44541.03	206,336.12
79	3.459773	88.00759	17.47544	0.996376	17.42367	44537.04	205,453.50
80	3.526703	89.36967	18.41217	0.947577	17.11804	44537.39	195,391.74
81	3.57723	85.49618	18.08967	0.983565	16.90686	44537.63	202,814.38
82	3.712572	85.89963	17.58533	1.031844	18.13492	44536.22	212,763.94
83	3.408078	87.95579	18.2473	0.968097	16.42765	44538.18	199,626.98
84	3.433193	84.94561	15.73768	1.014708	18.53098	44535.77	209,227.98

85	2.881838	87.87417	15.22397	1.034551	16.63423	44537.94	213,330.45
86	3.877683	88.30051	15.92755	0.965052	21.49743	44532.37	198,973.12
87	3.504619	84.02141	17.04954	1.014354	17.27103	44537.21	209,161.90
88	3.714417	87.14575	18.20747	0.99968	17.77817	44536.63	206,133.09
89	3.443296	84.95899	18.17451	1.030221	16.09611	44538.56	212,440.37
90	4.081871	86.40874	16.02453	1.001091	22.01059	44531.78	206,401.52
91	3.325676	88.47953	17.42796	1.015227	16.88403	44537.66	209,343.98
92	3.710323	84.56044	16.60677	0.945974	18.89268	44535.36	195,052.25
93	3.638303	87.19218	16.89185	1.026457	18.78015	44535.49	211,649.43
94	3.530466	88.99573	16.68598	1.035638	18.82997	44535.43	213,542.49
95	3.492972	83.53481	17.23268	0.972136	16.93206	44537.6	200,457.27
96	3.935125	86.23554	16.14434	1.022891	21.01961	44532.92	210,901.92
97	3.654939	88.55699	16.10248	1.019084	20.10065	44533.97	210,122.00
98	3.364204	87.78454	17.21376	1.014198	17.15634	44537.35	209,130.24
99	3.851447	85.68992	17.73019	1.011282	18.61402	44535.68	208,521.17
100	3.617913	85.18804	16.69746	0.999387	18.45807	44535.85	206,069.13

Table A5: Random Mean Time to Failure Data for 0.050 COV value.

No.	Internal pressure (in MPa)	Mean tube radius (in mm)	Tube wall thickness (in mm)	Model uncertainty	Stress acting on tube (in MPa)	Larson-Miller parameter	Time to failure (in hours)
	p	R_{mean}	h	f_{model}	s_{mech}	P (LMP)	t_r
1	3.108239	89.1474	16.97107	1.0760478	16.3273	44538.3	221,889.83
2	2.998308	87.4367	18.36207	0.9459742	14.2774	44540.64	195,075.47
3	3.871469	86.2655	17.88867	0.9882403	18.6696	44535.61	203,769.30
4	3.582785	88.791	16.50023	0.938136	19.2797	44534.91	193,434.04
5	3.594599	86.9478	16.49349	0.9481505	18.9494	44535.29	195,500.79
6	3.731008	87.8597	17.06932	0.9913882	19.2043	44535	204,415.63
7	3.625017	86.5528	17.62962	1.0036969	17.7971	44536.61	206,961.33
8	2.859637	87.0412	16.31063	1.1010184	15.2604	44539.52	227,045.68
9	3.097061	88.2722	16.58901	1.054648	16.4799	44538.12	217,475.77
10	2.70584	86.0576	17.74131	1.0501816	13.1252	44541.96	216,573.38
11	3.175307	86.0387	17.43484	1.0110853	15.6697	44539.05	208,496.35
12	3.899342	89.4549	16.46856	0.9642465	21.1807	44532.74	198,808.59
13	3.510345	88.6712	16.14155	1.0118787	19.2836	44534.91	208,640.57
14	3.02345	90.9051	16.87931	1.0881195	16.2831	44538.35	224,379.59
15	3.570595	85.8015	15.81769	1.0822225	19.3683	44534.81	223,145.76
16	2.779013	85.6345	17.53258	0.9577372	13.5736	44541.45	197,505.01
17	3.198239	86.4822	16.19793	0.9146101	17.0757	44537.44	188,593.44
18	3.543115	87.4007	16.40507	0.9941663	18.8765	44535.37	204,990.24
19	3.573415	88.9975	16.07687	1.0105953	19.7815	44534.34	208,373.26
20	3.047983	84.9133	16.79891	0.9875268	15.4066	44539.35	203,639.25
21	2.662944	85.887	16.83241	1.0287143	13.5876	44541.43	212,143.35
22	3.610872	87.6986	16.68414	1.0212118	18.9802	44535.26	210,566.82
23	3.766535	86.6382	16.62489	1.0297241	19.6287	44534.51	212,318.62
24	3.717416	87.2118	16.87532	0.9890717	19.2116	44534.99	203,937.90
25	3.080637	87.2351	16.715	0.8891112	16.0778	44538.58	183,339.68
26	2.948548	87.3566	16.04222	0.9929339	16.0561	44538.61	204,750.95
27	3.025051	88.956	17.59412	0.9049567	15.2947	44539.48	186,611.24
28	3.147634	87.148	17.9704	1.0126451	15.2645	44539.51	208,820.22
29	3.613663	87.7009	16.28888	1.020445	19.4563	44534.71	210,406.10
30	3.51745	83.6476	17.72432	1.03112	16.6001	44537.98	212,623.03
31	3.488715	86.1159	18.45319	1.0351507	16.2809	44538.35	213,456.01
32	3.13127	87.9285	16.95878	1.0584142	16.2351	44538.4	218,253.83
33	3.565829	90.6042	17.92399	0.9218991	18.025	44536.35	190,091.96
34	3.208646	85.2659	15.39114	0.9996995	17.7757	44536.64	206,137.09
35	3.870559	87.5574	17.18666	1.0447033	19.7185	44534.41	215,406.96
36	4.122738	86.6293	16.09112	1.0273434	22.1955	44531.57	211,813.71
37	4.300604	87.4338	17.3034	1.0178365	21.7309	44532.1	209,855.94
38	3.761721	86.0359	16.49694	1.0120655	19.6184	44534.52	208,677.30
39	3.780063	87.4289	16.92846	0.9739023	19.5226	44534.63	200,808.19
40	3.606103	88.6064	16.90398	0.9160421	18.9023	44535.35	188,879.86
41	3.135939	88.4317	16.67064	0.9976445	16.635	44537.94	205,719.34
42	3.269301	89.3658	17.70814	1.0146718	16.4988	44538.1	209,231.53
43	3.570799	86.0291	17.81171	1.0568128	17.2467	44537.24	217,917.91

44	3.565906	89.5597	16.80845	1.1138523	19.0001	44535.23	229,670.33
45	3.330109	87.4423	17.15495	1.0660403	16.9742	44537.55	219,822.36
46	3.248442	85.1213	17.05408	1.0061645	16.2138	44538.43	207,478.63
47	3.321219	85.6074	16.97233	0.9751846	16.752	44537.81	201,086.95
48	2.908192	84.9831	16.86229	0.9178689	14.6568	44540.21	189,277.25
49	2.967484	88.4919	16.53431	1.0510018	15.882	44538.81	216,727.16
50	3.564845	84.7361	17.62721	1.0230756	17.1366	44537.37	210,961.15
51	3.811125	85.5051	16.83184	1.0413997	19.3604	44534.82	214,727.71
52	3.478374	89.2703	17.43156	0.9124538	17.8134	44536.59	188,145.18
53	3.645187	87.2872	16.58384	1.0213709	19.186	44535.02	210,598.51
54	4.498354	88.4911	18.55767	0.921345	21.4501	44532.43	189,960.93
55	3.682442	87.289	17.13316	0.9814913	18.7611	44535.51	202,377.09
56	3.427653	85.5506	17.64587	0.92052	16.6179	44537.96	189,814.42
57	3.556671	85.8973	16.48464	1.0144458	18.5329	44535.77	209,173.98
58	3.550438	89.219	16.82704	1.0259264	18.8249	44535.43	211,539.88
59	3.192972	86.6173	16.44653	1.020268	16.8161	44537.74	210,383.91
60	3.193342	89.3671	16.64809	1.0485541	17.1419	44537.36	216,215.36
61	3.536233	85.9364	15.42028	1.0862798	19.7072	44534.42	223,980.47
62	3.889296	83.4584	17.46258	1.0486585	18.588	44535.71	216,228.84
63	2.989363	87.1142	16.43124	0.9558326	15.8488	44538.84	197,100.67
64	2.807393	84.9872	16.84821	1.0125868	14.1613	44540.78	208,814.11
65	3.171316	85.7266	16.30219	0.9773249	16.6767	44537.89	201,528.72
66	2.540277	90.6061	15.72301	0.9813135	14.6387	44540.23	202,361.88
67	3.475471	86.3857	16.90902	0.9714202	17.7557	44536.66	200,305.47
68	3.472899	87.5101	16.83934	1.0062632	18.0478	44536.32	207,489.20
69	3.496824	85.7919	17.91103	0.9692413	16.7494	44537.81	199,861.32
70	3.28731	88.6888	17.60585	0.9797939	16.5597	44538.03	202,038.49
71	2.975706	88.8273	17.1257	0.9757397	15.4343	44539.32	201,208.24
72	3.860102	85.4341	15.69263	1.0011987	21.0152	44532.92	206,429.06
73	3.240965	89.693	16.49255	0.9541525	17.6256	44536.81	196,745.19
74	3.3517	85.1825	17.84072	1.1116695	16.0031	44538.67	229,237.90
75	3.497878	89.1478	17.00364	0.9758771	18.3389	44535.99	201,221.56
76	3.179882	87.5103	17.51797	1.0244007	15.885	44538.8	211,241.22
77	3.773933	86.6676	16.53129	1.0188531	19.7854	44534.33	210,076.07
78	3.402819	86.1819	17.51595	1.0720242	16.7425	44537.82	221,057.69
79	3.012839	87.2824	16.82759	1.0058445	15.6272	44539.1	207,415.76
80	3.371303	89.6968	17.07357	1.0453307	17.7113	44536.71	215,547.48
81	3.708124	87.4679	19.09643	1.0473008	16.9844	44537.54	215,957.78
82	3.385629	88.561	16.45088	1.0497301	18.2261	44536.12	216,451.84
83	3.278384	87.6577	16.77096	0.9575259	17.1353	44537.37	197,443.35
84	3.376606	87.1261	17.59872	1.0340822	16.7166	44537.85	213,233.28
85	3.639015	89.7119	16.91647	0.9850404	19.2985	44534.89	203,106.15
86	3.282032	86.9189	13.93991	1.0258989	20.4643	44533.56	211,525.28
87	3.57689	89.6323	16.9142	1.0007818	18.9548	44535.29	206,354.03
88	3.535888	84.2405	16.41916	1.0322219	18.1413	44536.22	212,841.84
89	3.840266	89.8278	15.97672	1.018394	21.5916	44532.26	209,971.64
90	3.958893	87.0949	16.79172	1.0584691	20.5339	44533.48	218,241.01
91	3.611818	84.0412	16.47655	1.0561915	18.4226	44535.89	217,783.19
92	3.229274	84.595	16.50903	1.0611156	16.5473	44538.04	218,809.19
93	3.372807	85.1186	16.0636	1.0234476	17.872	44536.53	211,033.89

94	3.116997	88.995	18.71903	0.9254586	14.819	44540.02	190,841.71
95	3.122163	89.4849	17.94777	0.9655936	15.5666	44539.17	199,115.12
96	3.253272	85.6019	17.72679	0.9733953	15.7099	44539	200,723.33
97	3.737109	87.5605	18.76765	0.9827544	17.4355	44537.03	202,644.46
98	3.261752	88.4012	17.61686	0.9419771	16.3674	44538.25	194,240.67
99	3.097949	85.6458	16.06961	0.9941072	16.5111	44538.08	204,990.51
100	3.223536	87.3897	18.06522	0.9707533	15.5937	44539.14	200,179.07

Table A6: Random Mean Time to Failure Data at 850^{o}C.

No.	Internal pressure (in MPa)	Mean tube radius (in mm)	Tube wall thickness (in mm)	Model uncertainty	Stress acting on tube (in MPa)	Larson-Miller parameter	Time to failure (in hours)
	p	R_{mean}	h	f_{model}	s_{mech}	P (LMP)	t_r
1	4.16991	86.2891	18.94407	1.0215297	18.9937	44535.24	225,012.14
2	3.182465	85.2146	16.73155	1.0195167	16.2085	44538.43	224,584.77
3	3.497679	88.0665	16.78341	0.9842664	18.3531	44535.97	216,807.00
4	3.708552	84.5424	17.08392	1.0172324	18.3523	44535.98	224,069.17
5	3.216536	86.3736	17.90717	1.0076578	15.5147	44539.23	221,976.18
6	3.480109	87.62	16.97506	0.9997559	17.9633	44536.42	220,221.44
7	3.109538	86.3407	17.29383	1.0015701	15.5246	44539.21	220,634.93
8	3.443045	87.0751	15.56086	0.9667418	19.2665	44534.93	212,941.45
9	3.19588	90.0937	17.39033	0.9761519	16.5568	44538.03	215,029.38
10	3.182773	89.4023	17.15528	0.9867758	16.5866	44538	217,369.67
11	3.796981	84.1764	17.86576	0.9931	17.8899	44536.51	218,755.58
12	3.007893	87.8764	16.83905	0.9956243	15.697	44539.02	219,324.04
13	3.361012	88.2544	17.93836	1.0013275	16.5357	44538.06	220,575.74
14	4.037866	86.6112	16.32722	0.9896611	21.4197	44532.46	217,978.21
15	3.661313	87.0376	16.76936	1.006976	19.0032	44535.23	221,806.05
16	3.645636	87.5614	16.68712	1.0012044	19.1296	44535.08	220,533.92
17	2.936504	84.7777	16.62099	0.9997315	14.978	44539.84	220,232.98
18	3.582959	87.6924	17.49932	1.0146509	17.9549	44536.43	223,502.79
19	3.585681	87.0372	17.48932	1.0295308	17.8445	44536.56	226,781.40
20	3.405678	87.2715	17.22045	1.0001513	17.2596	44537.23	220,312.53
21	3.466693	90.4063	17.1169	1.0171551	18.31	44536.02	224,052.39
22	3.471041	87.671	16.05482	0.9914995	18.9544	44535.29	218,397.02
23	3.535888	86.9904	16.92324	0.9736791	18.1755	44536.18	214,475.68
24	3.741865	89.0981	16.95917	0.9946768	19.6586	44534.48	219,092.98
25	3.789656	87.4269	16.4346	1.042537	20.1598	44533.9	229,632.92
26	3.281112	91.0126	16.34907	0.9833201	18.2654	44536.07	216,599.02
27	4.241337	88.2688	16.92516	0.9972749	22.1196	44531.66	219,651.39
28	3.461438	85.1889	17.34405	1.0143767	17.0016	44537.52	223,447.86
29	3.568946	87.7469	16.07119	0.9941884	19.4861	44534.68	218,986.36
30	4.013718	87.2513	17.46247	1.0024964	20.0545	44534.03	220,813.28
31	2.983926	90.2773	18.03298	0.9960783	14.9382	44539.89	219,428.34
32	3.35831	87.5932	17.21186	1.0111174	17.0908	44537.42	222,729.32
33	2.962751	87.9698	16.30633	0.9615784	15.9835	44538.69	211,821.91
34	3.504629	89.7829	15.27821	0.9916719	20.5951	44533.41	218,425.79
35	3.703621	84.5876	16.83228	0.9905322	18.6119	44535.68	218,185.87
36	3.379291	86.8501	16.46074	0.9907394	17.8298	44536.57	218,235.90
37	3.764991	85.5671	17.05363	1.0345568	18.8909	44535.36	227,882.46
38	3.833282	87.0205	17.76336	1.0105759	18.7788	44535.49	222,600.37
39	3.915403	89.0472	16.81604	0.9769554	20.7335	44533.25	215,183.26
40	3.504962	87.5852	15.91067	1.0083021	19.2941	44534.9	222,096.51
41	3.55648	86.3611	17.69544	1.0445841	17.3571	44537.12	230,100.46
42	4.044655	87.016	15.33573	0.9773432	22.9496	44530.71	215,256.41

43	3.916061	86.3983	17.0546	0.9811791	19.8387	44534.27	216,118.62
44	3.422719	86.0535	17.37258	1.0129151	16.9541	44537.58	223,126.13
45	3.341369	85.0726	16.24922	1.0152089	17.4937	44536.96	223,628.36
46	3.110069	86.9268	16.72499	0.9563822	16.1643	44538.48	210,676.17
47	3.905031	89.5783	16.75177	0.9808709	20.8817	44533.08	216,044.93
48	3.28387	85.0742	16.22078	0.9692333	17.2231	44537.27	213,501.52
49	2.67246	91.2878	17.29744	0.9972171	14.104	44540.84	219,683.95
50	3.032132	86.7977	17.20923	0.9859396	15.2931	44539.48	217,192.68
51	3.74375	86.3768	15.70156	1.0065179	20.595	44533.41	221,696.06
52	3.192279	84.8389	17.39524	0.9345115	15.5692	44539.16	205,861.08
53	3.592201	86.9922	17.5612	1.0137055	17.7945	44536.61	223,295.43
54	3.026879	88.4207	17.59787	1.0069517	15.2086	44539.58	221,822.35
55	3.609287	91.3137	16.51376	1.0182204	19.9577	44534.14	224,277.57
56	3.787207	86.9761	17.12116	0.9904192	19.2392	44534.96	218,157.44
57	3.713685	87.1208	16.37375	1.0107029	19.7596	44534.36	222,622.71
58	3.352196	87.0906	17.04896	1.0470717	17.1239	44537.38	230,649.86
59	3.314627	88.268	16.34793	1.0077965	17.8968	44536.5	221,993.11
60	3.030234	89.2246	16.55864	0.9997145	16.3281	44538.29	220,221.57
61	3.442992	86.0998	16.4048	0.9771452	18.0704	44536.3	215,239.80
62	3.388286	91.6416	17.23756	0.989994	18.0135	44536.36	218,070.66
63	3.392014	87.6954	18.10513	0.9991285	16.4298	44538.18	220,091.90
64	2.927005	87.5139	16.19233	0.9846726	15.8194	44538.88	216,910.61
65	3.476827	87.4203	16.96452	0.9793159	17.9165	44536.47	215,718.87
66	3.00641	89.963	16.50367	1.0234091	16.3882	44538.23	225,441.25
67	3.524487	88.7846	16.67357	1.0091065	18.7674	44535.5	222,276.73
68	3.886398	85.176	17.7552	1.0352949	18.644	44535.64	228,046.51
69	3.452709	87.6361	16.85624	0.9982504	17.9507	44536.44	219,889.84
70	3.257398	91.082	17.10264	1.0272263	17.3476	44537.13	226,276.62
71	3.301442	86.2403	16.77388	1.0025924	16.9738	44537.55	220,851.93
72	3.134604	83.0145	17.34795	0.9684685	14.9999	44539.82	213,345.22
73	4.167195	91.6002	17.35723	0.9845353	21.9918	44531.81	216,845.93
74	3.411062	85.5145	15.30879	0.987357	19.0541	44535.17	217,483.92
75	4.000307	85.8066	16.85623	0.9792931	20.3636	44533.67	215,700.25
76	3.119909	87.1527	17.59929	0.9954195	15.45	44539.3	219,280.32
77	2.601712	91.5759	17.95403	1.0019118	13.2702	44541.8	220,723.00
78	3.906508	88.5565	17.78108	1.0379588	19.4559	44534.71	228,628.56
79	4.042161	87.3798	16.39677	0.9891784	21.541	44532.32	217,871.20
80	3.805017	84.6481	17.29908	0.9921756	18.6188	44535.67	218,547.85
81	3.58086	90.3204	17.08273	1.0048013	18.9329	44535.31	221,327.39
82	3.717611	85.856	16.42521	0.9482787	19.4323	44534.74	208,873.35
83	3.469779	85.3707	18.04392	1.0035131	16.4165	44538.19	221,057.91
84	3.663694	85.1866	16.97544	0.9979028	18.3852	44535.94	219,810.82
85	4.119498	87.1832	16.31099	0.9832714	22.019	44531.77	216,567.37
86	2.863373	86.7835	16.81186	1.0084335	14.7808	44540.07	222,151.26
87	2.969229	87.8214	17.45403	1.0210034	14.9399	44539.88	224,919.64
88	3.734465	87.1901	15.82768	0.9922975	20.5721	44533.43	218,563.72
89	3.740496	89.6575	17.31983	1.0059489	19.363	44534.82	221,577.74
90	2.641857	86.5263	16.98273	0.993899	13.4602	44541.58	218,956.54
91	3.742422	84.2722	16.39715	0.9795749	19.234	44534.97	215,768.60
92	3.721002	86.9171	15.27036	1.028047	21.1795	44532.74	226,435.08

93	4.244039	86.7749	16.85544	0.9691367	21.8491	44531.97	213,454.84
94	3.790299	87.8718	18.15587	0.9763918	18.3445	44535.98	215,072.32
95	3.260815	87.7592	17.28715	1.0143414	16.5537	44538.04	223,442.64
96	3.305994	84.4568	17.83412	1.006218	15.6561	44539.06	221,658.15
97	3.340302	87.2512	16.20754	1.0039957	17.9821	44536.4	221,155.33
98	3.292326	89.3421	16.72368	1.006553	17.5884	44536.85	221,720.94
99	3.896708	86.7987	17.20247	1.0526245	19.6617	44534.48	231,858.00
100	3.631253	89.8987	17.10263	0.9770625	19.0874	44535.13	215,215.96

Table A7: Random Mean Time to Failure Data at 1000°C.

No.	Internal pressure (in MPa)	Mean tube radius (in mm)	Tube wall thickness (in mm)	Model uncertainty	Stress acting on tube (in MPa)	Larson-Miller parameter	Time to failure (in hours)
	p	R_{mean}	h	f_{model}	s_{mech}	P (LMP)	t_r
1	3.82955	88.7251	18.3873	0.9817616	18.4789	44535.83	190,773.48
2	3.519549	84.6156	16.00435	1.0083097	18.608	44535.68	195,932.12
3	2.968514	88.1009	17.19854	0.9563707	15.2064	44539.58	185,854.70
4	3.108535	87.7347	16.58374	0.983742	16.4454	44538.16	191,168.34
5	3.404253	88.0006	16.99903	1.0038345	17.6231	44536.81	195,067.37
6	3.60755	86.8271	15.89817	0.9888285	19.7025	44534.43	192,140.79
7	3.84965	87.528	16.12166	0.9813689	20.9006	44533.06	190,685.28
8	4.306037	90.7555	16.59378	1.0110104	23.5508	44530.02	196,431.99
9	2.476534	88.2643	16.07089	0.9703804	13.6016	44541.42	188,585.34
10	3.402337	86.3464	18.03027	1.0206819	16.2937	44538.33	198,348.32
11	2.937714	86.7732	16.41184	1.0053379	15.5324	44539.21	195,370.05
12	3.612574	89.7583	17.1516	0.9731835	18.9054	44535.34	189,104.34
13	3.703714	87.3529	17.30344	1.0060605	18.6975	44535.58	195,494.57
14	3.819015	87.0451	16.93994	0.9822651	19.6238	44534.52	190,865.71
15	3.044816	87.4682	17.15282	1.0199945	15.5266	44539.21	198,218.63
16	3.857399	84.7272	17.48373	1.0138581	18.6932	44535.58	197,009.95
17	3.893374	89.3055	17.03423	1.0043097	20.4118	44533.62	195,145.72
18	3.28874	86.7819	16.91538	0.9720364	16.8724	44537.67	188,891.31
19	3.780983	86.4605	16.41672	1.0253029	19.913	44534.19	199,227.86
20	3.327164	87.4749	16.12126	0.9888691	18.0534	44536.32	192,156.84
21	3.91402	86.7366	16.95704	0.9789559	20.0205	44534.06	190,220.68
22	3.467151	87.3653	19.34264	0.982893	15.6602	44539.06	191,007.19
23	3.221257	87.2937	16.48575	0.9994613	17.0569	44537.46	194,220.30
24	3.36142	89.1867	18.48913	0.9956448	16.2146	44538.42	193,482.77
25	3.508056	85.9278	16.97478	1.017907	17.7581	44536.66	197,801.56
26	2.717953	82.8966	17.66744	0.9746923	12.7528	44542.39	189,427.54
27	3.110266	88.6681	16.73378	1.0299878	16.4805	44538.12	200,155.94
28	3.243341	87.4345	16.59534	0.9938085	17.0879	44537.42	193,121.55
29	3.644754	85.3826	17.75902	1.0245606	17.5234	44536.92	199,095.84
30	3.481722	88.9118	17.23111	0.9836713	17.9655	44536.42	191,147.13
31	3.877866	86.2701	16.44227	0.9685302	20.3466	44533.69	188,193.07
32	3.890227	85.5518	15.70846	0.9878297	21.187	44532.73	191,939.36
33	3.044583	85.3786	16.32036	0.9818351	15.9275	44538.75	190,800.28
34	3.262662	87.0774	19.509	1.0188394	14.5627	44540.32	197,999.03
35	3.556369	87.9756	15.67344	1.0051346	19.962	44534.13	195,308.28
36	3.587455	85.7123	18.10282	0.9738736	16.9857	44537.54	189,247.80
37	3.476067	88.8005	17.30593	0.982032	17.8365	44536.57	190,829.17
38	2.722224	87.8092	16.49047	1.0051417	14.4954	44540.39	195,337.13
39	3.476832	87.2162	17.44783	1.0140701	17.3796	44537.09	197,057.82
40	3.298094	85.5488	16.58628	1.0057109	17.0109	44537.51	195,435.11
41	3.668661	89.4582	16.3832	0.9762434	20.0322	44534.05	189,693.50
42	3.433677	87.5202	17.11305	0.9956909	17.5606	44536.88	193,485.04

43	2.700099	86.7621	17.40105	0.9962467	13.4628	44541.58	193,613.46
44	3.791948	86.5266	16.81323	0.9876181	19.5147	44534.64	191,906.50
45	3.645973	84.5069	17.29355	1.0298129	17.8165	44536.59	200,115.07
46	3.105502	89.3845	16.18341	1.0297462	17.1524	44537.35	200,105.53
47	3.182617	89.8995	15.03442	0.9983142	19.0307	44535.2	193,987.51
48	3.225642	85.1629	17.14898	0.9861607	16.0187	44538.65	191,640.52
49	3.399939	86.0007	17.76689	1.0070193	16.4574	44538.15	195,692.18
50	3.581444	88.1243	17.83816	1.0337986	17.6931	44536.73	200,890.29
51	3.699285	86.0909	16.42172	0.9788639	19.3935	44534.78	190,205.86
52	3.133424	90.8401	17.18748	1.0108973	16.5609	44538.03	196,445.33
53	3.558499	84.58	17.70221	1.0055633	17.0023	44537.52	195,406.48
54	3.849071	86.3941	15.72851	0.9821674	21.1423	44532.78	190,839.26
55	3.223571	83.886	15.80799	1.0048494	17.1061	44537.4	195,267.20
56	3.864328	87.182	16.76073	0.996593	20.1005	44533.97	193,647.69
57	3.249023	88.8384	16.44852	1.0132441	17.548	44536.9	196,896.43
58	3.35033	88.7737	17.63087	1.0179646	16.8693	44537.67	197,817.28
59	3.425115	87.2771	16.26953	1.0545369	18.3739	44535.95	204,917.03
60	3.47701	89.1844	17.7739	1.0017428	17.4466	44537.01	194,661.75
61	3.126383	88.171	17.15739	0.9871367	16.0663	44538.59	191,829.97
62	3.160032	86.6601	16.49727	0.9874272	16.5996	44537.98	191,883.80
63	3.619831	84.6516	16.40374	1.0305275	18.6802	44535.6	200,249.50
64	3.323402	85.6095	17.23484	0.9892595	16.5081	44538.09	192,240.34
65	3.232813	88.5869	16.80539	0.9988316	17.0413	44537.48	194,098.00
66	3.67431	86.5763	16.66411	1.0435253	19.0894	44535.13	202,773.32
67	3.034479	84.4057	15.81951	0.9525975	16.1906	44538.45	185,116.68
68	3.603155	86.727	17.1517	1.0298805	18.2192	44536.13	200,126.14
69	3.03093	88.063	15.65427	1.0050277	17.0505	44537.47	195,302.14
70	3.780079	88.4903	16.77869	0.9917977	19.936	44534.16	192,716.64
71	3.686459	86.33	17.34946	1.0504011	18.3436	44535.99	204,113.44
72	3.686012	87.1031	17.1886	1.0029862	18.6788	44535.6	194,897.21
73	3.450972	87.9459	16.79523	1.0047464	18.0705	44536.3	195,242.35
74	3.186442	84.8715	19.20715	1.0039285	14.0801	44540.87	195,103.41
75	3.413299	89.3772	15.90515	1.0180808	19.1807	44535.03	197,828.11
76	3.32868	90.8213	17.73302	0.9875142	17.0481	44537.47	191,898.49
77	3.730605	87.9413	15.5767	1.0008974	21.0619	44532.87	194,479.37
78	3.454526	87.762	16.7901	1.0033345	18.0568	44536.31	194,968.02
79	3.184515	88.4342	16.14618	0.9839684	17.4419	44537.02	191,207.43
80	3.418407	88.8094	17.5362	1.0210349	17.312	44537.17	198,411.72
81	3.539878	87.6513	16.30534	1.0493879	19.029	44535.2	203,912.94
82	3.852598	87.986	17.55608	1.0145581	19.3081	44534.88	197,142.88
83	3.375734	86.4077	17.13494	0.995704	17.0231	44537.5	193,490.26
84	3.679937	90.7942	17.97417	0.9911502	18.5887	44535.7	192,597.49
85	3.953041	88.1473	17.38955	1.026376	20.0379	44534.04	199,435.75
86	3.998064	85.4544	17.05932	0.9615341	20.0273	44534.06	186,835.07
87	3.284716	86.388	16.95189	1.0010404	16.7391	44537.82	194,528.78
88	2.980284	86.3932	17.72629	1.0045875	14.5251	44540.36	195,229.27
89	3.120197	85.6853	18.73054	1.0041707	14.2737	44540.65	195,149.51
90	3.574256	85.3442	16.37739	1.009146	18.6258	44535.66	196,094.55
91	3.555506	90.5513	17.53954	0.9905873	18.356	44535.97	192,489.26
92	3.522784	87.6722	16.98173	1.0035932	18.1872	44536.16	195,017.64

93	3.319002	86.7733	18.01549	1.0036005	15.9863	44538.69	195,030.10
94	4.140164	85.5501	16.89859	1.0282404	20.9598	44532.99	199,793.31
95	4.082526	84.3806	16.90605	0.9982089	20.3765	44533.66	193,960.33
96	3.483721	87.9244	15.56739	0.9981307	19.676	44534.46	193,948.63
97	3.775	83.8976	16.75342	1.0111157	18.9044	44535.34	196,475.94
98	3.677661	90.2844	16.503	0.9852193	20.1197	44533.95	191,437.35
99	4.034954	86.5876	18.13044	0.9686471	19.2702	44534.92	188,221.00
100	3.376464	85.4247	16.82634	0.9877498	17.1418	44537.36	191,943.82

Table A8: Random Mean Time to Failure Data at 1.0 MPa.

No.	Internal pressure (in MPa)	Mean tube radius (in mm)	Tube wall thickness (in mm)	Model uncertainty	Stress acting on tube (in MPa)	Larson-Miller parameter	Time to failure (in hours)
	p	R_{mean}	h	f_{model}	s_{mech}	P (LMP)	t_r
1	0.887898	87.1138	17.13398	1.0039135	4.51432	44551.83	207,076.72
2	0.988756	85.6236	17.09507	1.0278344	4.95235	44551.33	212,008.96
3	0.992533	89.8104	17.40728	1.0231434	5.12084	44551.13	211,040.36
4	1.126438	85.7913	18.1916	0.978583	5.31226	44550.91	201,847.17
5	0.943675	90.8003	18.05153	0.9732895	4.74674	44551.56	200,758.11
6	0.97913	86.0509	17.44399	1.0362845	4.83003	44551.47	213,752.78
7	1.186948	86.5123	16.36286	1.0277171	6.27553	44549.81	211,977.56
8	0.952974	84.8669	17.88086	1.0137756	4.52304	44551.82	209,111.12
9	0.991129	84.8752	16.86751	0.9868015	4.98724	44551.29	203,544.23
10	0.949513	87.2226	17.19764	1.0168536	4.81572	44551.48	209,744.51
11	1.07193	88.8426	15.92809	1.0182795	5.97894	44550.15	210,032.36
12	1.183938	88.4538	18.94058	0.9825513	5.52907	44550.67	202,664.63
13	1.20831	85.9168	15.44227	0.9932233	6.72273	44549.3	204,859.82
14	0.854372	87.3659	17.56902	0.9750713	4.24856	44552.13	201,128.25
15	0.987431	85.9185	18.47666	1.0025739	4.59166	44551.74	206,799.96
16	1.065145	87.3344	15.69875	1.0127747	5.92556	44550.21	208,897.12
17	0.972591	85.2476	15.08462	0.9826938	5.4964	44550.7	202,694.20
18	0.889911	88.2253	17.61388	0.9524708	4.45743	44551.89	196,464.93
19	0.80849	86.6539	16.70344	1.0011437	4.19428	44552.19	206,507.04
20	0.825547	87.664	17.20213	0.9826278	4.20708	44552.18	202,687.30
21	1.146986	87.8311	17.40701	1.0250004	5.78738	44550.37	211,419.80
22	1.088956	87.2806	18.24042	1.0256384	5.21067	44551.03	211,554.56
23	1.004237	88.7607	17.31035	1.0240421	5.14934	44551.1	211,225.58
24	0.896288	86.0667	18.03076	0.9860899	4.27828	44552.1	203,401.13
25	0.881944	85.234	16.06556	1.0046757	4.67905	44551.64	207,233.08
26	1.063081	86.1599	18.0155	0.9964867	5.08423	44551.18	205,541.64
27	1.062351	88.229	18.43037	0.9797523	5.08563	44551.17	202,089.55
28	1.143039	85.3753	17.20654	0.993589	5.67152	44550.5	204,940.79
29	0.969227	88.0988	18.47773	0.9964718	4.62112	44551.71	205,541.01
30	1.008977	87.9841	17.67391	0.9938284	5.02288	44551.25	204,993.58
31	0.871687	87.06	18.20269	1.0035943	4.16912	44552.22	207,012.72
32	0.913723	84.3066	17.21527	1.0128796	4.47468	44551.87	208,926.55
33	0.932752	86.0102	17.13806	0.9535139	4.68117	44551.64	196,678.97
34	1.120257	85.63	17.29176	1.042865	5.54759	44550.64	215,106.28
35	0.964887	85.8884	17.80574	1.0213697	4.65426	44551.67	210,676.98
36	1.044627	84.404	17.40538	1.0326666	5.06572	44551.2	213,005.15
37	1.08716	85.831	18.50388	1.0224844	5.04283	44551.22	210,904.84
38	0.952509	87.3293	17.70811	1.0286136	4.69739	44551.62	212,171.08
39	1.079239	86.7282	17.00556	0.9843618	5.50411	44550.69	203,038.25
40	1.008996	88.8103	17.98549	0.9847445	4.98231	44551.29	203,119.91
41	1.077201	89.6287	17.084	0.9647057	5.65137	44550.53	198,982.75
42	1.138263	85.1945	17.21236	1.0105197	5.63396	44550.55	208,433.52

43	1.054192	87.1228	18.84906	0.9515584	4.87261	44551.42	196,274.62
44	0.857934	87.6015	16.39587	0.9988196	4.58385	44551.75	206,025.54
45	0.830813	86.4139	15.37993	0.9450209	4.66802	44551.65	194,927.03
46	1.006078	87.0712	17.04896	1.0129264	5.13817	44551.11	208,932.63
47	0.917906	90.3856	15.2605	1.0229695	5.43662	44550.77	211,002.77
48	1.041151	85.8917	16.74076	1.012965	5.34183	44550.88	208,939.49
49	1.01008	87.5249	15.78786	1.0171223	5.59969	44550.58	209,795.71
50	1.163893	87.6778	16.41549	1.0044034	6.21654	44549.88	207,168.72
51	1.151186	87.573	17.07214	1.010031	5.90511	44550.24	208,331.25
52	0.848744	88.269	17.00815	1.0246891	4.40482	44551.95	211,363.11
53	0.967001	83.4222	17.42192	0.9842852	4.63034	44551.7	203,027.00
54	0.91934	83.2585	16.763	1.0185954	4.56618	44551.77	210,105.17
55	1.158745	87.1132	16.64402	0.9804088	6.06476	44550.05	202,219.90
56	1.069868	87.2041	17.63208	0.9778387	5.29131	44550.94	201,693.74
57	0.984751	86.6978	15.75395	0.9975473	5.41932	44550.79	205,758.65
58	1.212582	87.4256	17.35176	1.0033237	6.10951	44550	206,946.57
59	0.950659	88.5287	18.03517	0.979803	4.66647	44551.65	202,102.19
60	1.123105	88.2116	14.5323	0.9838021	6.81729	44549.19	202,915.93
61	0.991562	87.836	17.09297	1.0207022	5.09536	44551.16	210,536.90
62	0.773562	89.7818	16.77018	0.9914789	4.14139	44552.26	204,513.55
63	1.116363	88.8235	16.31155	0.9699484	6.07909	44550.04	200,062.02
64	1.209022	85.4521	17.15819	0.9914329	6.02124	44550.1	204,494.17
65	0.986391	86.5381	17.263	0.990021	4.94471	44551.34	204,208.58
66	0.99496	85.7751	17.31356	0.9708069	4.92925	44551.35	200,245.05
67	0.940702	90.2771	18.51262	0.978701	4.58735	44551.74	201,875.28
68	0.9093	86.9935	18.21459	1.0123113	4.34285	44552.02	208,810.02
69	0.928846	85.749	15.72305	1.0122678	5.06566	44551.2	208,797.17
70	0.826377	91.4768	18.14654	1.0038987	4.16577	44552.23	207,075.52
71	0.941178	89.3963	18.84944	1.0194168	4.46368	44551.89	210,275.15
72	0.928988	85.1036	16.58237	0.958596	4.76772	44551.54	197,726.92
73	0.982126	85.4977	16.50622	0.9857244	5.08714	44551.17	203,321.51
74	0.990556	87.1468	18.42957	0.9769065	4.68398	44551.63	201,504.59
75	1.074763	86.4989	16.00468	1.021549	5.80867	44550.35	210,707.73
76	1.004899	84.4419	17.66256	0.9629782	4.80426	44551.5	198,630.72
77	0.797521	88.6188	16.675	0.9836158	4.2384	44552.14	202,890.96
78	0.966364	83.7063	16.10273	0.9948225	5.02342	44551.25	205,198.67
79	1.083542	88.3725	16.5086	0.9828868	5.80033	44550.36	202,732.44
80	1.242195	87.6969	17.47674	1.0123169	6.23324	44549.86	208,801.02
81	1.055161	88.8044	17.58366	0.9729738	5.32898	44550.9	200,689.98
82	1.070394	85.3517	16.35872	0.9855468	5.58479	44550.6	203,282.28
83	1.096847	83.3495	18.0735	1.0176581	5.05833	44551.21	209,909.16
84	0.889145	84.0614	18.15413	1.0279645	4.11713	44552.28	212,040.35
85	0.928609	90.2324	18.01384	1.002045	4.65145	44551.67	206,690.53
86	1.048215	90.9295	17.41945	1.0016455	5.47168	44550.73	206,603.76
87	0.995141	88.3069	15.73171	1.0019118	5.58603	44550.6	206,658.10
88	1.274029	86.1921	17.09635	1.0087509	6.42308	44549.64	208,064.40
89	1.026872	87.0958	16.60167	1.0291253	5.38719	44550.83	212,272.88
90	0.778388	88.7892	15.61903	0.9817608	4.42489	44551.93	202,507.31
91	0.892983	88.0432	17.5911	0.9938738	4.46937	44551.88	205,005.88
92	0.834697	87.0783	17.22478	1.00193	4.21973	44552.17	206,669.12

93	1.14148	87.6491	18.33746	0.9952683	5.45603	44550.75	205,288.33
94	1.160229	88.3646	17.43657	0.9935666	5.87978	44550.26	204,935.07
95	1.073474	85.2937	15.80079	0.9710307	5.79469	44550.36	200,286.76
96	0.974213	84.5498	18.63936	0.9962734	4.41912	44551.94	205,501.16
97	0.851894	88.4177	17.28776	0.9929698	4.35698	44552.01	204,819.98
98	1.056163	86.4753	15.5398	0.9588845	5.8773	44550.27	197,780.78
99	0.894451	87.5834	19.12587	1.0112288	4.09597	44552.31	208,588.03
100	1.021834	86.7954	16.37056	0.9715575	5.41768	44550.79	200,397.36

Table A9: Random Mean Time to Failure Data at 6.0 MPa.

No.	Internal pressure (in MPa)	Mean tube radius (in mm)	Tube wall thickness (in mm)	Model uncertainty	Stress acting on tube (in MPa)	Larson-Miller parameter	Time to failure (in hours)
	p	R_{mean}	h	f_{model}	s_{mech}	P (LMP)	t_r
1	5.465208	86.8742	17.67116	0.97354	26.8678	44526.22	200,695.56
2	5.697305	89.131	16.08739	1.026546	31.5655	44520.84	211,598.26
3	5.314954	81.8743	15.77325	0.9927484	27.5883	44525.39	204,651.97
4	5.477461	84.2419	18.88532	0.9892057	24.4334	44529.01	203,938.13
5	6.616785	85.1338	15.21502	0.9765833	37.0234	44514.59	201,270.37
6	5.427264	85.856	16.52351	1.0058438	28.2	44524.69	207,348.54
7	4.902272	85.5298	16.72464	1.0012446	25.0702	44528.28	206,416.98
8	6.085753	82.2028	17.40284	0.9933825	28.7462	44524.07	204,776.59
9	6.595844	87.981	18.40712	1.010352	31.5263	44520.88	208,260.15
10	5.294083	85.6947	16.57572	0.9923349	27.3699	44525.64	204,567.88
11	6.093509	88.5535	17.31381	0.9964154	31.166	44521.3	205,389.07
12	6.520346	83.5863	16.07435	1.0354307	33.9057	44518.16	213,416.96
13	5.981339	85.0572	16.45758	0.9515157	30.9132	44521.59	196,134.37
14	5.830846	87.3622	16.07875	1.0419731	31.6813	44520.71	214,777.85
15	5.166946	84.4851	16.44312	0.9598484	26.5479	44526.59	197,874.38
16	5.970169	86.0509	16.59456	0.9787516	30.9582	44521.53	201,748.79
17	5.969764	88.265	18.60564	1.0088	28.3205	44524.56	207,957.36
18	5.979507	88.6159	16.31496	1.0184755	32.4781	44519.79	209,929.62
19	6.379491	85.5502	17.16474	1.0210826	31.7958	44520.57	210,470.75
20	5.69949	90.4672	16.50998	0.9972929	31.2306	44521.22	205,569.62
21	5.534363	88.8719	17.00713	0.9688768	28.9202	44523.87	199,723.58
22	5.862385	87.757	17.02739	0.9836669	30.214	44522.39	202,765.96
23	6.304264	84.3003	17.94257	1.0113193	29.6196	44523.07	208,469.79
24	6.886163	85.923	17.78739	1.0106033	33.264	44518.89	208,302.64
25	5.460442	85.1308	17.46939	0.9971743	26.6095	44526.52	205,569.62
26	5.086972	86.6792	17.69313	0.9738292	24.9212	44528.45	200,765.24
27	5.829951	86.4092	15.57949	1.005597	32.3349	44519.96	207,275.61
28	5.593107	88.009	17.3448	0.9704415	28.3799	44524.49	200,048.95
29	5.827871	85.3471	17.31072	0.9967063	28.7332	44524.08	205,461.90
30	5.625004	86.3714	16.56128	1.006228	29.3358	44523.39	207,421.68
31	6.177894	85.9579	15.65057	0.9928158	33.9309	44518.13	204,632.47
32	5.389507	89.4524	17.37988	1.0012134	27.7392	44525.22	206,396.36
33	6.566642	85.1393	16.57815	0.9812081	33.7239	44518.37	202,240.80
34	6.017241	85.2914	17.73969	0.9926378	28.9306	44523.86	204,622.11
35	5.344684	86.5796	16.68601	1.0156064	27.7323	44525.23	209,363.77
36	5.795535	86.6233	17.46534	1.010857	28.7443	44524.07	208,379.17
37	6.482855	87.1906	17.29037	1.0016296	32.6913	44519.55	206,455.87
38	5.559013	84.679	16.13472	1.0068165	29.1751	44523.58	207,543.88
39	6.288958	87.0339	16.95643	1.0135818	32.2799	44520.02	208,921.91
40	5.502296	85.2717	15.59433	0.9786615	30.0872	44522.53	201,734.75
41	5.776953	86.205	18.46932	1.0073114	26.9637	44526.11	207,657.73
42	5.366205	87.4062	16.88888	1.0070847	27.7721	44525.18	207,606.66

43	6.564697	84.8731	16.85392	1.0407584	33.0585	44519.13	214,519.85
44	6.031249	86.6872	18.01062	0.9958678	29.0291	44523.74	205,287.47
45	5.648275	86.8426	18.00968	1.0117256	27.236	44525.8	208,566.34
46	5.293028	88.4897	16.95808	0.989165	27.6198	44525.36	203,913.03
47	5.120338	85.4728	18.17483	1.0050277	24.08	44529.41	207,202.26
48	6.185119	88.7019	16.54228	1.0123141	33.1654	44519.01	208,655.83
49	6.06149	84.5758	17.62657	0.9944455	29.0842	44523.68	204,993.96
50	5.839826	86.1306	17.50046	0.9815157	28.7414	44524.07	202,330.16
51	5.365838	88.3313	17.81049	0.9964545	26.6119	44526.51	205,421.21
52	5.29353	88.3274	16.77028	0.9964652	27.8805	44525.06	205,416.72
53	6.622907	86.1214	17.61142	1.001108	32.3866	44519.9	206,349.96
54	5.611331	83.543	17.89443	0.9981152	26.1974	44526.99	205,765.79
55	6.689913	90.3955	18.99351	0.9546726	31.8392	44520.52	196,780.47
56	5.905288	87.0872	16.76511	1.010841	30.6753	44521.86	208,365.52
57	6.356798	88.4635	15.50724	0.9912141	36.2634	44515.46	204,290.03
58	5.956505	86.0727	17.77934	0.9977552	28.8364	44523.96	205,677.60
59	6.475931	86.1645	17.89333	1.0131138	31.1846	44521.27	208,831.32
60	6.340644	87.4041	16.85753	0.9799604	32.8754	44519.34	201,988.02
61	5.218192	86.9231	17.13777	1.0032208	26.4668	44526.68	206,817.01
62	6.596258	86.618	16.56019	0.9785972	34.5017	44517.47	201,698.58
63	6.353835	88.2087	17.14638	0.9879516	32.687	44519.55	203,636.30
64	5.917712	86.9276	14.90553	1.0068749	34.5115	44517.46	207,527.40
65	4.843309	91.6761	15.89118	1.014482	27.941	44524.99	209,130.82
66	6.910045	88.2649	16.38136	0.9810064	37.2322	44514.35	202,180.98
67	5.767974	84.0407	16.13598	1.0356493	30.0412	44522.58	213,483.24
68	5.247458	86.9091	16.41446	1.0072271	27.7835	44525.17	207,635.96
69	6.869025	85.5237	16.01372	1.0208366	36.6851	44514.97	210,393.58
70	5.828632	84.8458	17.18863	0.9935552	28.7711	44524.04	204,812.08
71	5.975891	86.4908	16.75242	0.996173	30.8528	44521.65	205,340.75
72	6.835983	84.9633	16.88543	0.9686802	34.397	44517.59	199,654.91
73	5.758563	86.1032	16.5915	1.0107163	29.8846	44522.76	208,344.05
74	5.714098	86.7814	15.00394	1.0021672	33.0498	44519.14	206,564.78
75	6.031194	85.4094	18.64569	1.0249932	27.6268	44525.35	211,299.58
76	6.323798	85.9036	17.19748	1.0154372	31.5882	44520.81	209,308.11
77	5.619656	86.4609	16.90338	0.9965817	28.7446	44524.07	205,436.17
78	6.525526	83.6999	16.57884	1.0114841	32.9448	44519.26	208,485.91
79	6.131322	87.4225	16.47893	1.0070563	32.5273	44519.74	207,575.41
80	6.641879	87.9025	17.92569	1.0178151	32.5699	44519.69	209,793.00
81	4.821645	88.1723	17.85235	1.0005122	23.814	44529.72	206,272.64
82	4.928884	86.36	16.43115	0.9949658	25.9056	44527.32	205,118.00
83	6.629103	87.3664	16.53739	1.0200548	35.0213	44516.88	210,241.44
84	6.664043	84.8956	15.9851	0.9703141	35.3922	44516.45	199,986.59
85	5.530201	89.6242	15.85286	0.9944846	31.265	44521.18	204,990.53
86	5.739948	84.4192	16.11595	0.97186	30.0672	44522.55	200,332.69
87	5.894399	85.8973	18.79595	1.0121864	26.9374	44526.14	208,662.94
88	5.858691	90.0736	16.84166	1.003231	31.3338	44521.1	206,793.20
89	6.787767	87.1213	15.91897	0.9966062	37.1481	44514.44	205,396.77
90	4.21401	87.1003	17.78481	0.9577759	20.6379	44533.36	197,477.10
91	5.369636	88.9921	16.13117	1.0030077	29.6231	44523.06	206,756.27
92	6.491793	90.1057	16.87274	1.0283563	34.6682	44517.28	211,954.53

93	5.790385	85.4582	17.63138	0.9889791	28.0656	44524.85	203,872.35
94	6.06671	85.8958	14.67584	1.0211795	35.5077	44516.32	210,470.63
95	6.237641	88.1328	17.43236	0.9816164	31.5356	44520.87	202,336.36
96	4.695431	82.3087	16.38532	0.986194	23.5867	44529.98	203,321.60
97	5.104727	84.3778	16.97455	1.0130932	25.3748	44527.93	208,858.29
98	5.71647	87.7223	17.07539	0.9937783	29.3675	44523.36	204,854.92
99	5.407273	88.0036	14.8137	0.9623109	32.1229	44520.2	198,353.61
100	5.109214	86.6593	17.74134	0.9897323	24.9564	44528.41	204,043.97