

SYSTEMATIC INVESTIGATION OF FAILURE ANALYSIS ON  
A STEAM TRAP BYPASS TUBE IN A  
COALFIRED POWER PLANT

MOHD ARIF ANUAR MOHD SALLEH

UNIVERSITI TUN HUSSEIN ONN MALAYSIA

PERPUSTAKAAN UTHM



\*3000002161879\*

02/01/2011

UNIVERSITI TUN HUSSEIN ONN MALAYSIA

**BORANG PENGESAHAN STATUS TESIS\***

JUDUL: SYSTEMATIC INVESTIGATION OF FAILURE ANALYSIS ON A STEAM TRAP BYPASS TUBE IN A COAL FIRED POWER PLANT

SESI PENGAJIAN: 2007/2008

Saya MOHD ARIF ANUAR BIN MOHD SALLEH  
(HURUF BESAR)

mengaku membenarkan tesis (PSM/Sarjana/Doktor Falsafah)\* ini disimpan di Perpustakaan Universiti Tun Hussein Onn Malaysia dengan syarat-syarat kegunaan seperti berikut:

1. Tesis adalah hakmilik Universiti Tun Hussein Onn Malaysia.
2. Perpustakaan dibenarkan membuat salinan untuk tujuan pengajian sahaja.
3. Perpustakaan dibenarkan membuat salinan tesis ini sebagai bahan pertukaran antara institusi pengajian tinggi.
4. \*\* Sila tandakan (✓)

SULIT

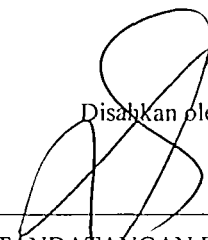
(Mengandungi maklumat yang berdarjah keselamatan atau kepentingan Malaysia seperti yang termaktub di dalam AKTA MALAYSIA RASMI 1972)

TERHAD

(Mengandungi maklumat TERHAD yang telah ditentukan oleh organisasi/badan di mana penyelidikan dijalankan)

TIDAK TERHAD

  
(TANDATANGAN PENULIS)

Disahkan oleh  
  
(TANDATANGAN PENYELIA)

Alamat Tetap:

698F, Batu 3, Jalan Jeniang,  
08300 Gurun, Kedah, Malaysia.

ASSOC. PROF. DR.-ING. DARWIN SEBAYANG  
(Nama Penyelia)

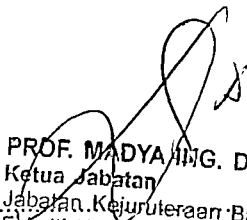
TARIKH: 30 NOVEMBER 2007

TARIKH: 30 May 2008

- CATATAN:
- \* Potong yang tidak berkenaan.
  - \*\* Jika tesis ini SULIT atau TERHAD, sila lampirkan surat daripada pihak berkuasa/organisasi berkenaan dengan menyatakan sekali sebab dan dikelaskan sebagai SULIT atau TERHAD.
  - ♦ Tesis dimaksudkan sebagai tesis bagi Ijazah Doktor Falsafah dan Sarjana secara penyelidikan, atau disertai bagi pengajian secara kerja kursus dan penyelidikan atau Laporan Projek Sarjana Muda (PSM).

“We hereby declare that we have read this thesis and we find that this thesis is sufficient in terms of scope and quality for the award of Masters Degree in Mechanical Engineering”

Signature


  
PROF. MADYA ING. DR. DARWIN SEBAYANG  
Ketua Jabatan  
Jabatan Kejuruteraan Bahan & Rekabentuk  
Fakulti Kejuruteraan Mekanikal & Pembuatan  
Universiti Tun Hussein Onn Malaysia  
: Associate Professor Dr-Ing Darwin Sebayang

Name of Supervisor I

Date

: 30 May 2008

Signature

  
:.....

Name of Supervisor II

Date

: Dr Syahril D.I.C  
: 30 May 2008

**SYSTEMATIC INVESTIGATION OF FAILURE ANALYSIS ON A STEAM  
TRAP BYPASS TUBE IN A COALFIRED POWER PLANT**

**MOHD ARIF ANUAR MOHD SALLEH**

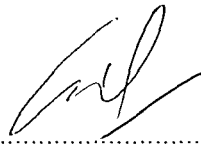
A project report submitted in partial fulfillment of the requirements for the award of  
Masters Degree in Mechanical Engineering

Faculty of Mechanical and Manufacturing  
Tun Hussein Onn University of Malaysia

NOVEMBER 2007

“I declare that this project report entitled Systematic Investigation of Failure Analysis on a Steam Trap Bypass Tube in a Coal Fired Power Plant is the result of my own research as cited in the references. The project report has not been accepted for any degree and is not concurrently submitted in candidate of any other degree”

Signature



: .....

Author

: Mohd Arif Anuar Mohd Salleh

Date

: 30 November 2007

## ACKNOWLEDGMENT

In the name of Allah, the most gracious, the most merciful

Firstly, with the highest praise to Allah that I managed to complete this project successfully. I would like to express my heartiest thankful to my supervisors, Associate Professor Dr-Ing Darwin Sebayang and Dr. Syahril D.I.C for their continuing guidance, valuable advices, ideas, support and encouragement in completing this project successfully.

Besides that, I would like to express my special thanks to the lecturers, technicians of mechanical laboratories and to those who involved and giving sincere cooperation during completing this project.

I would also like to express my special thanks to my dad Prof. Dato' Dr. Mohd Salleh Hj. Din, my mum Prof. Madya Datin Maziah Onn, and also to my siblings that inspired me and always supported me through this project. Besides that, I would also like to express my special thanks to my friends and Noor Farhani Mohd Alui.

## ABSTRACT

A steam trap bypass tube in a power plant was totally fractured. The aim of this study is to examine the evidence presented by the steam trap bypass tube failure, determining the failure mechanism, determining the root cause of the failure and to recommend appropriate corrective actions. The power plant is a coal fired power plant with its normal operation temperature of 540°C. This study consists of failure mode inventory collection of the steam trap bypass tube failure, collection of background information about the process, component function and operating conditions. Detailed investigation carried out by visual examination, nondestructive testing (NDT), metallurgical testing which consists of microstructure examination, chemical testing and mechanical testing. Optical Microscopy (OM), Scanning Electron Microscopy (SEM) combined with Energy Dispersive X-ray Spectroscopy (EDS), Glow Discharge Spectrometer (GDS) and Energy Dispersive X-ray Diffraction (XRD) experiments were used throughout the investigation on the sample obtained. From the evidence with considering the contribution factors such as temperature, pressure and environment, a fault analysis was made and it can be concluded that the cause of failure to the steam trap bypass is due to multi causes which consists of creep failure and hydrogen damage. The root cause of high temperature creep and hydrogen damage which occurred at the steam trap bypass tube is due to material properties that are inadequate for the actual operating conditions of a steam trap bypass tube which is not according to the specification. The material must be actually ASTM SA-335-P22 (2.25Cr-1Mo) with 490MPa minimum tensile strength and 320MPa minimum yield strength. However from the investigation found that the material used was ASTM SA-192 (low strength carbon steel) with 324MPa minimum tensile strength and 180MPa minimum yield strength.



## ABSTRAK

Sebatang paip perangkap stim pada sebuah stesen janakuasa didapati telah musnah sepenuhnya. Tujuan kajian ini adalah untuk mengkaji kesan yang diperlihatkan dari paip yang pecah, mengetahui mekanisma kegagalan, mengetahui punca utama kegagalan serta memberi cadangan kaedah supaya kegagalan tidak akan berulang pada masa hadapan. Stesen janakuasa tersebut adalah dari jenis stesen janakuasa yang menggunakan arang batu sebagai bahan bakar dan beroperasi pada suhu 540°C. Kajian ini terdiri daripada penemuan mode kegagalan, pengumpulan maklumat latar belakang proses, fungsi komponen serta keadaan beroperasi. Kajian dilakukan dengan melakukan pemerhatian secara visual, ujian tanpa musnah (NDT), ujian metalurgi yang terdiri daripada pemerhatian mikrostruktur, ujian kimia serta ujian mekanikal. Optical Microscopy (OM), Scanning Electron Microscopy (SEM) gabungan Energy Dispersive X-ray Spectroscopy (EDS), Glow Discharge Spectrometer (GDS) dan Energy Dispersive X-ray Diffraction (XRD) eksperimen telah digunakan sepanjang melakukan kajian pada sample yang diperolehi. Hasil dari penemuan dengan mengambil kira faktor-faktor seperti suhu, tekanan serta keadaan sekeliling, satu analisis punca kegagalan dilakukan dimana punca kegagalan adalah disebabkan dwi punca yang terdiri daripada rayapan bersuhu tinggi serta kemusnahan hydrogen. Punca utama kegagalan pada pipe perangkap stim ini adalah disebabkan sifat bahan yang digunakan adalah tidak bersesuaian dengan keadaan operasi dimana bahan pipe yang digunakan tidak mengikut spesifikasi. Bahan yang digunakan pada pipe perangkap stim yang musnah haruslah ASTM SA-335-P22 (2.25Cr-1Mo) dengan 490MPa kekuatan tegangan minimum dan 320MPa kekuatan alah minimum. Namun demikian setelah penyelidikan, bahan pada pipe perangkap stim yang digunakan adalah ASTM SA-192 (keluli karbon rendah) dengan 324MPa kekuatan tegangan minimum dan 180MPa kekuatan alah minimum.

## TABLE OF CONTENTS

CHAPTER	TOPIC	PAGE
	TITLE	i
	DECLARATION	ii
	ACKNOWLEDGEMENT	iii
	ABSTRACT	iv
	ABSTRAK	v
	TABLE OF CONTENTS	vi
	LIST OF TABLES	ix
	LIST OF FIGURES	x
	LIST OF SYMBOLS	xiv
	LIST OF ABBREVIATIONS	xv
	LIST OF APPENDIX	xvi
1	<b>INTRODUCTION</b>	1
	1.1 Statement of Problem	2
	1.2 Objective of Study	3
	1.3 Scope of Study	3
11	<b>LITERATURE REVIEW</b>	5
	2.1 Steam Trap Function and Operation	9
	2.1.1 Steam Trap Bypass	11
	2.1.2 Condensate Formation in Steam Trap Bypass Tube	13
	2.2 Material Damage and Mechanisms	13
	2.2.1 Alloy Steel	18

2.3	Failure Mode Inventory	21
2.3.1	Hydrogen Damage Failures	21
2.3.1.1	Classification of Hydrogen Processes	22
2.3.1.2	Hydrogen Damage Theories	25
2.3.1.3	Hydrogen Damage Characterization	30
2.3.2	Corrosion Failures	36
2.3.2.1	Uniform Corrosion	37
2.3.2.2	Pitting Corrosion	37
2.3.2.3	Crevice Corrosion	38
2.3.2.4	Galvanic Corrosion	39
2.3.2.5	Stress Corrosion Cracking	39
2.3.3	Erosion Failures	41
2.3.4	Liquid Metal Embrittlement Failures	42
2.3.5	Creep Failures	43
2.4	Characterization Summary of Failure Modes	52
<b>III</b>	<b>METHODOLOGY</b>	<b>54</b>
3.1	Collection of Background Information	58
3.2	Visual Examination	59
3.3	Nondestructive Testing	59
3.4	Cutting the Samples	60
3.5	Mounting specimen	61
3.6	Grinding	62
3.7	Polishing	63
3.8	Etching	64
3.8.1	Micro Etching	65
3.8.2	Macro Etching	65
3.9	Optical Microscopy (OM) Examinations	66
3.10	Scanning Electron Microscopy (SEM) Examinations	67
3.11	Energy Dispersive X-ray Diffraction (XRD)	68
3.12	Chemical analysis	69
<b>IV</b>	<b>RESULTS AND DISCUSSION</b>	<b>71</b>
4.1	Visual Examination	72

4.2	Nondestructive Testing	74
4.3	Metallurgical Testing	75
4.3.1	Microstructure Examination	76
4.3.2	Chemical Testing	86
4.3.3	Mechanical Testing	99
4.4	Fault Analysis	104
<b>V</b>	<b>CONCLUSION AND RECOMMENDATIONS</b>	<b>107</b>
	<b>REFERENCES</b>	<b>110</b>
	<b>APPENDIX A</b>	<b>114</b>
	<b>APPENDIX B</b>	<b>122</b>

## LIST OF TABLES

NO	TITLE	PAGE
2.1	ASTM specifications for steels commonly used in refinery and petrochemical equipments	15
2.2	Materials used in boiler construction	16
2.3	Maximum tube-metal temperature permitted by ASME code and boiler manufacturers	17
2.4	Initial Creep Temperature	51
2.5	Summary of Steam Trap Bypass Tube Failure Modes	53
3.1	ASTM Standards Used in Metallurgical Testing	57
4.1	Mechanical and operating data of tube	72
4.2	Result of bulk chemical composition test	86
4.3	Chemical specification (%) for ASTM SA-335-P22 and ASTM SA-192 compared to bulk chemical composition result of the failed tube	87
4.4	Hardness test results done at cross section of tube	100
4.5	Ultimate tensile strength ( $\sigma_{UTS}$ ) and yield strength ( $\sigma_y$ ) of tube converted from the hardness value obtained	103
4.6	Fault analysis of a steam trap bypass tube failure	106

## LIST OF FIGURES

NO	TITLE	PAGE
1.1	Insulated steam trap bypass tube in actual process	2
1.2	Fractured steam trap bypass tube	3
2.1	(a) Inter-granular cracks and presence of numerous creep cavities at grain boundary (b) Inter-granular nature of propagation with many small parallel cracks	6
2.2	(a) Progressive nature of fracture (b) Crack is associated with carburizing more at outer surface	7
2.3	(a) Effect of general corrosion and flow pattern (b) Uniform dissolution at ID	8
2.4	Typical Power Plant Layout	10
2.5	Inverted bucket trap with a parallel air vent	12
2.6	Mechanism of hydrogen embrittlement	25
2.7	Solubility of Hydrogen in Iron as a function of temperature and of pressure	26
2.8	Effect of Hydrogen Pressure, on the U.T.S of 3% Cr-Mo Steel: (1) 41.5, (2) 53, (3) 67, and (4) 98 tons/sq.in.	27
2.9	Schematic of possible reaction steps involved in the embrittlement of a structural alloy by external molecular hydrogen environment	29
2.10	Schematic view of destinations for hydrogen in a metal microstructure: (a) solid solution; (b) solute-hydrogen pair; (c) dislocation atmosphere; (d) grain boundary accumulation; (e) particle-matrix interface accumulation; (f) void containing recombined hydrogen	29
2.11	Microcracking in hydrogen-charged specimens of X60 steel	30

2.12	Transition between brittle and ductile fracture	31
2.13	(a) Fracture surface observed in a specimen that fractured by brittle mode. (b) Large longitudinally oriented cracks	32
2.14	Fracture Surfaces of Corrosion-induced Hydrogen Embrittlement in Aluminium Alloy 2024	32
2.15	Fish eyes on the fracture surface	33
2.16	Cleavage fracture of the aureole of a fish eye region	34
2.17	Opened bubble on a galvanized steel surface	34
2.18	Partially intercrystalline fracture with ductile marks on the grain faces	35
2.19	Decarburized 1060 steel heated at 1205°C at 100X magnification	36
2.20	Typical undermining form of pitting in the microstructure of an aluminium alloy wrought product (100X)	38
2.21	Cross section of stress corrosion crack in stainless steel (500X)	40
2.22	Impingement failure of elbow in steam condensate line	41
2.23	Erosion corrosion of slide valve at 900°C in petroleum refinery	42
2.24	Schematic creep curve	44
2.25	Microstructural and fractographic features of creep fracture mechanism	46
2.26	Fractography showing extensive plastic deformation due to fracture at high temperature	46
2.27	Schematic illustration of formation of (a) wedge and (b) creep cavities	47
2.28	Microstructures from creep specimens showing creep cavities and wedge cracks (a) Cracks initiated at triple boundaries (b) Beadlike cracks along grain boundaries	47
2.29	Fracture mechanism map for pure iron	48
2.30	Fracture mechanism map for a 2.25 Cr1Mo steel containing 0.13wt%C	49
3.1	Sequence of failure investigation	55
3.2	Sequence of metallography investigation	56
3.3	The position of samples	58
3.4	Illustration of sample taken	60
3.5	Picture of wire cut Electrodischarge Machining (EDM)	61
3.6	(a) Picture of standard mounting machine (b) Close up picture of sample placement for mounting procedure	62

3.7	Picture of mounted sample	62
3.8	Picture of standard grinding machine	63
3.9	Picture of standard polisher machine	64
3.10	Sample macro etched in hot 10% nital for 20 minutes	66
3.11	Picture of Optical Microscope (OM)	67
3.12	Picture of Scanning Electron Microscope (SEM)	68
3.13	Picture of Energy Dispersive X-ray Diffraction (XRD)	69
4.1	Sample at fracture surface showed brittle appearance	72
4.2	Fishmouth appearance that fractured apart due to high pressure	73
4.3	Longitudinal cracks in inside tube surface with the presence of oxide scale	73
4.4	Longitudinal cracks grow and initiate the tube fracture	74
4.5	Red dye penetration examination at (a) outside tube surface and (b) inside tube surface showing cracks	75
4.6	Inside tube surface shows similar crack distance (0.9 mm) between the longitudinal cracks (5X)	77
4.7	OM micrograph of cross section inside tube edge shows 0.35 mm thickness of oxide scale in inside tube surface (20X)	78
4.8	(a) Cross section of sample macro-etched with hot 10% nital shows light area at inside tube. (b) Failure mode inventory: Decarburized 1060 steel heated at 1205°C at 100X magnification	79
4.9	Microstructure examination with 20X magnification using optical microscope, (a) cross section of inside tube edge (b) cross section of outside tube edge (c) inside tube surface (d) outside tube surface.	80
4.10	OM micrograph at cross section of inside tube showing the grain size differences between the grains near and far from the inside tube edge.	81
4.11	Illustration of how a refinement in grain size improves resistance to hydrogen failure as measured by the time to failure of two strengths of AISI 4340 steels	83
4.12	SEM micrograph at the cross section of inside tube edge and outside tube edge shows graphitized microstructure, microvoids, pores and intergranular cracks	84
4.13	OM micrograph at cross section of inside tube edge shows voids and grooves (small cusps) in v-shaped	84



4.14	SEM micrograph of fracture surface with 20X magnification	85
4.15	SEM micrograph with higher magnification (500X) shows dimples, brittle facets, cleavage fracture and hair line cracks	85
4.16	EDS analysis to reveal decarburization at the (a) cross section of inside tube edge sample in the circle area (250X), (b) along the grain boundaries (2200X)	88
4.17	Graph of chemical composition along the grain boundaries at point 001	88
4.18	Graph of chemical composition along the grain boundaries at point 002	89
4.19	Graph of chemical composition along the grain boundaries at point 003	89
4.20	EDS analysis to reveal decarburization done linearly at different grains at cross section of inside tube edge sample (2200X)	89
4.21	Graph of chemical composition linearly at different grains at point 001	90
4.22	Graph of chemical composition linearly at different grains at point 002	90
4.23	Graph of chemical composition linearly at different grains at point 003	90
4.24	Graph of chemical composition linearly at different grains at point 004	91
4.25	Graphs of element percentage at points along the grain boundaries of cross section inside tube edge sample	91
4.26	Graphs of element percentage at points linearly at different grains of cross section inside tube edge sample	92
4.27	Mapping image at cross section of inside tube edge	94
4.28	Mapping image at cross section of outside tube edge	95
4.29	Pattern diffraction of the internal tube	97
4.30	Pattern diffraction of the outer tube	98
4.31	Hardness test points carried out at cross section of tube	99
4.32	Long cylindrical tube with an external radial edge crack extending from the boundary subjected to a uniform internal pressure. $K_I$ is for the edge crack	102
4.33	Mechanical properties graph of failed sample	104
4.34	Types of failures that tend to be the cause of steam trap bypass tube failure	105

**LIST OF SYMBOLS**

$^{\circ}\text{C}$	-	Degrees Celcius
$^{\circ}\text{F}$	-	Degrees Farenheit
%	-	Percentage
$N_c$	-	Grains cut by the circumference
$N_i$	-	Grains in area
M	-	Magnification
$N_A$	-	Number of grains per unit area
$N_V$	-	Number of grains contained in unit volume
HV	-	Vickers Hardness
$\sigma_y$	-	Yield strength
c	-	Constant
$\sigma_{\text{UTS}}$	-	Ultimate Tensile Strength
e	-	Elongation
$\sigma$	-	Stress

**LIST OF ABBREVIATIONS**

SEM	-	Scanning Electron Microscopy
OM	-	Optical Microscope
EDS	-	Energy Dispersive X-ray Spectroscopy
GDS	-	Glow Discharge Spectrometer
XRD	-	Energy Dispersive X-ray Diffraction
EDM	-	Electrodischarge Machining
NDT	-	Non Destructive Testing
OD	-	Outside Diameter
ID	-	Inside Diameter
ASTM	-	American Society for Testing Materials
UTS	-	Ultimate Tensile Strength

**LIST OF APPENDIX**

<b>APPENDIX</b>	<b>TITLE</b>	<b>PAGE</b>
A	Microstructure Examination Pictures	114
B	Chemical Analysis Data Result	122

## CHAPTER I

### INTRODUCTION

In a power plant industry, failures usually occur on tubes and pipelines. Establishing the causes of failures provides information of improvements in design, operating procedures and the use of components. Failure analysis is an engineering approach to determine how and why an equipment or component has failed. Failure occurs when it does not meet its requirements. Failure analysis can also be defined as an investigation to determine the underlying reasons for the nonconformance to system requirements and is performed to identify nonconformance root causes and to recommend appropriate corrective actions [1].

A failure investigation and subsequence analysis should determine the primary cause of a failure, and based on the determination, corrective action should be initiated that will prevent similar failures. Although the sequence is subject to variation, depending upon the nature of a specific failure, the principal stages that comprise the investigation and analysis of failure is firstly the collection of background data and selection of samples [2]. Preliminary examination of the failed part which includes visual examination and record keeping will be the next stage of investigation. Nondestructive testing and mechanical testing that includes hardness test can also be done as part of the investigation. The next stage is the selection, identification, preservation or cleaning of all specimens. Macroscopic examination and analysis is the next stage where fracture surface, secondary cracks and other surface phenomena will be identified. After the macroscopic examination, microscopic examination and analysis is the next stage. Selection and

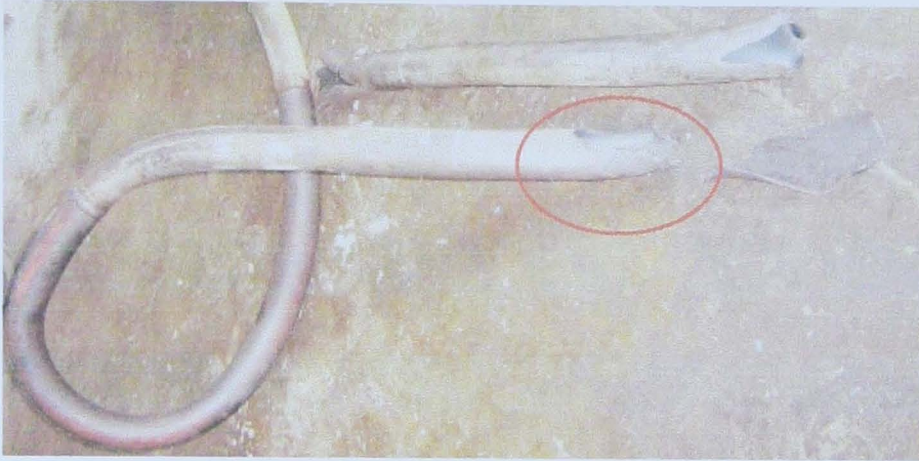
preparation of metallographic sections will need to be done thus the examination and analysis of metallographic sections. From the examinations, failure mechanism will be determined. For further investigation, chemical analysis which includes determining the bulk, local, surface corrosion products, deposit or coatings will be done. From the results, analysis of fracture mechanics will then be determined. Testing under simulated service conditions can be done for further analysis. The final stage is the analysis of all the evidence, formulation of conclusion and writing the report [2].

### 1.1 Statement of Problem

Cut-off a failed steam trap bypass tube of a coal-fired power plant was received. The tube is said to be made of a TU10CD9-10 (tube specification) which corresponds to ASTM SA335 P22. The outside diameter (OD) of the tube is 63.5 mm and the inside tube diameter (ID) is 53.34 mm. The received steam trap bypass tube was completely fractured and this study is to identify the root causes and to recommend appropriate corrective actions due to the failure. Figure 1.1 shows the insulated steam trap bypass tube in actual process and figure 1.2 shows the pieces of fractured steam trap bypass tube.



**Figure 1.1:** Insulated steam trap bypass tube in actual process.



**Figure 1.2:** Fractured steam trap bypass tube (in circle indicates picture of sample received).

## 1.2 Objective of Study

There are three primary objectives in this study, the first objective is to examine the evidence presented by the steam trap bypass tube failure and determining the failure mechanism. The second objective is to determine the root cause of the failure. The third objective is to recommend appropriate corrective actions to overcome the problem.

## 1.3 Scope of Study

The study involves collection of failure mode inventory of the steam trap bypass tube failure. This study also involves collection of background information about the process, component function, operating conditions and failure event sequence. Detailed investigation carried out by Non Destructive Testing (NDT), microstructure examination using Optical Microscopy (OM), Scanning Electron Microscopy (SEM) combined with Energy Dispersive X-ray Spectroscopy (EDS), Glow Discharge Spectrometer (GDS) and

Energy Dispersive X-ray Diffraction (XRD) testing on the sample will be done. From these results, analysis of the result will be done to determine the root cause of the steam trap bypass tube failure.