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Maintenance Strategy for a Heat Recovery Steam Generator

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Abstract: It is a legislative requirement to have a management system sufficient to ensure the continued integrity of pressure plant equipment, documented to an acceptable level.

The main purpose of this paper is to develop and formalise a maintenance strategy for a Heat Recovery Steam Generator (HRSG) with a case study in the Bulwer Island Cogeneration Station is provided.

This was to meet regulatory requirements and also to satisfy a number of other key drivers for the station. These included the safety of the people, plant, and environment, and the maximising of plant availability to ensure revenue and avoid contract penalties. In addition there is now a condition monitoring regime in place which targets the known failures associated with the operation of a HRSG. This historical data will be able to be used to trend and support a life assessment of the plant for continued operation in the future.

There were two primary methods employed to develop the maintenance strategy. The first was through the application of the various Australian Standards related to pressure plant and boilers. These set a number of requirements in terms of inspection of the plant. The second method involved the application of Reliability Designed Asset Management techniques for items of plant, including the rotating components.

1. Introduction

The trend in the power generation industry over the past 15-20 years has been towards the use of Combined Cycle Gas Turbine (CCGT) power stations, and more recently Combined Heat and Power plants (CHP), fired on either natural gas or light distillate fuel. CCGT and CHP plants are desirable due to higher efficiencies over traditional power plants. CCGT plants use gas turbine generators to generate electricity; the waste heat is used to make steam to generate additional electricity via a steam turbine. This last step enhances the efficiency of electricity generation; typical cycle efficiency for a CCGT plant is in the region of 50%.

CHP plants, also known as co-generation plants, involve the simultaneous generation of usable heat and power (usually electricity) in a single process. In its simplest form, it employs a gas turbine to drive an alternator, and the resulting electricity can be used either wholly or partially on-site. The heat produced during power generation is recovered and used to raise steam for a number of industrial processes. CHP plants can achieve overall efficiencies in excess of 70%.

These modern power stations present their own operational and maintenance problems. This technical paper records the assessment of the steam raising plant and the design of a robust inspection, maintenance and repair strategy which meets the requirements of the Workplace Health and Safety Legislation [1-2], which provides a self regulation approach to pressure plant inspections:

"The owner is responsible for ensuring that the extent and frequency of inspection is appropriate & adequate for the continued safe operation of the pressure equipment. This may require the seeking of expert advice"

The completion of this research delivered a management system sufficient to ensure continued integrity of the pressure equipment, and documented to an acceptable level. This level is still to be assessed by a competent inspection body, registered to provide certification in accordance with the current legislation. While it is the intent of Bulwer Island Energy Partnership (BIEP) to attain this sign off for the proposed management system, it was not part of this research to attain the same, but will be pursued within the Station's Business Strategy.

2. Plant Description

The Bulwer Island Cogeneration Station is situated at the BP refinery in Pinkenba, Queensland. The Station owned by BIEP generates over 90% of the total electrical energy demand, 75% of the high-pressure steam requirements and all of the demineralised water for Bulwer Island Refinery.

The station is sited within the refinery perimeter and operates as one of the processing units. The unit is managed on site by BIEP permanent staff, with BP operators and maintenance staff contracted to run the station and carryout maintenance activities as directed by BIEP.

Go To Contents Page Go To Next Article Go To Last Page

The Cogeneration Station is capable of generating 33 MW of electrical energy and 132 MW of thermal energy and consists of the following primary components:

- 2 x Siemens SGT-400 Gas Turbines (12.9MW each)
- 2 x Senior Thermal Heat Recovery Steam Generators (39.5MW(t) each)
- 1 x Peter Brotherhood Condensing Steam Turbine (7.3MW)
- 1 x Rolls Royce John Thompson Super-D Water Tube Boiler (52.6MW(t))

A Line Diagram for the Station depicting the interaction of the above equipment is shown Fig. 1.

The station, 10 years into commercial operation, is still in its infancy with regard to properly designed reliability maintenance process for some equipment.

Although various methods are used at the station, including visual for corrosion and leaks, borescope during major plant outages, magnetic particle inspection and ultrasonic thickness checks, there was no set or defined inspection regime, especially for the two Heat Recovery Steam Generators.

In general terms, an HRSG is an unfired boiler which extracts heat from a process stream. It is commonly connected to a gas turbine exhaust and converts the waste heat into steam.

The steam may be used to drive a steam turbine generator or, as at the BP Refinery, for process requirements. Recovery of this waste heat is key to increased cycle efficiency.

The design of the Bulwer Island HRSG's is of a vertical gas path construction, with supplementary duct firing capability. It is operated in accordance with AS 2593 [6] by BP's contracted operators.

3. Components of a HRSG

This research considered the components and the core equipment and developed a specific equipment strategy for each. The major equipment is listed below:

- Steam Drum
- Piping
- Structure
- Pumps
- Relief and Control Valves
- Combined Cycle Duct work
- Steam Headers
- Piping Supports
- Instrumentation
- Burners (duct firing)

Hot exhaust gas exiting the gas turbines (580-600°C) flows through the diverter valve and enters the ductwork passing the steam superheater coil and auxiliary duct burners in a horizontal flow, before redirection through a 90 degree bend rising vertically upwards and entering the steam generating and boiler feed water economiser area. The HRSG is able to produce 20 tonnes per hour (tph) of High Pressure (HP) steam (at 3,100 kPa and 375°C) from exhaust gas waste heat.

Three equally spaced supplementary burners are housed in the ducting and are aligned horizontally across the exhaust gas flow. Each burner run is fitted with a semi curved diffuser plate and 20 gas burner tips firing on natural gas to allow the necessary additional heat input required to increase HP steam output to full Maximum Continuous Rating (MCR) of 45 tph. A simplified Combined Cycle Gas Turbine system is shown in Fig. 2.

The primary function of the steam drum is to provide steam/water separation. It has a number of additional functions including: mixing feedwater with saturated liquid, addition and mixing of chemical additives, purifying steam through removal of impurities and residual moisture, blowdown for boiler water chemistry

Fig. 1 Line Diagram for the Bulwer Island Cogeneration Station

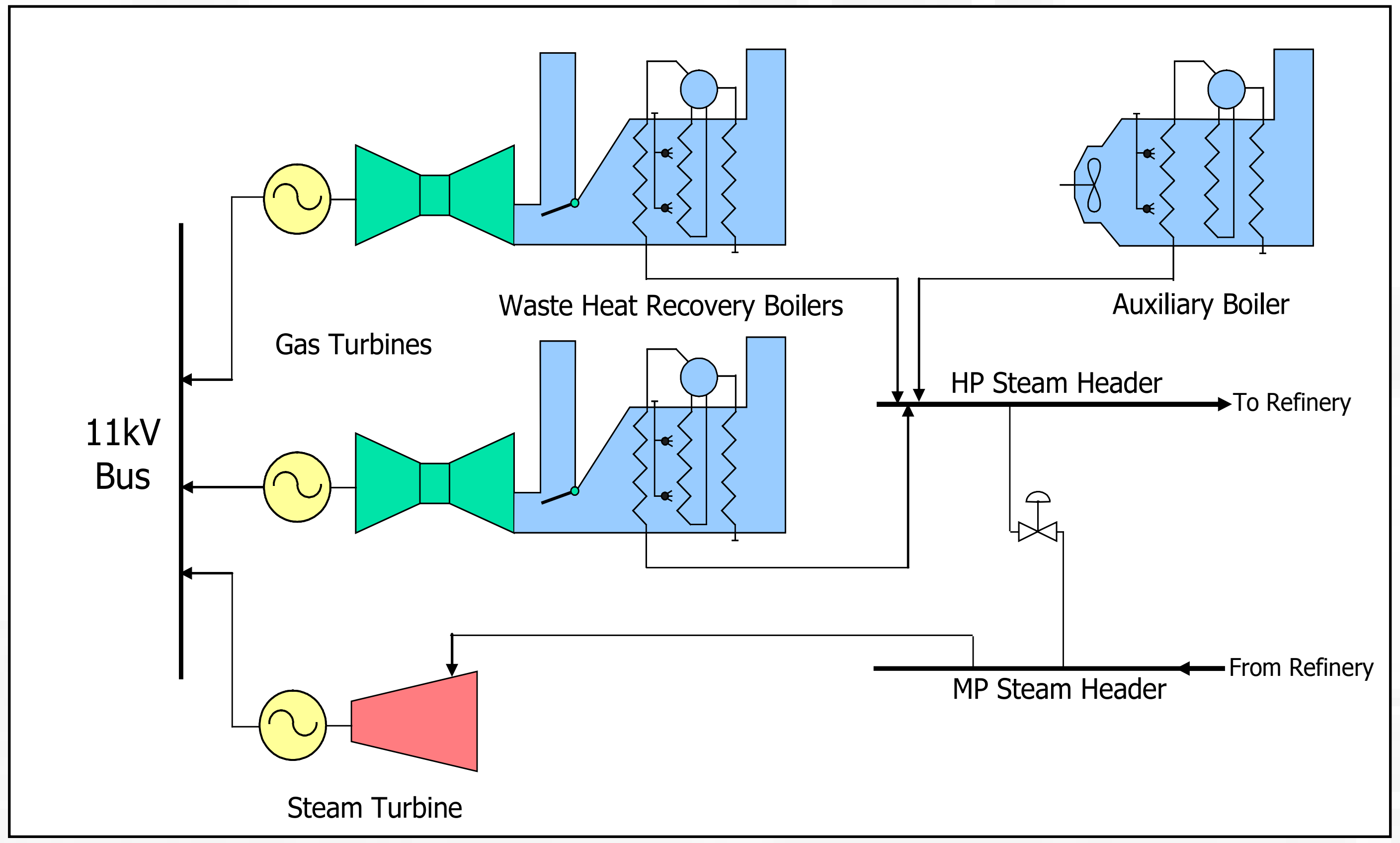
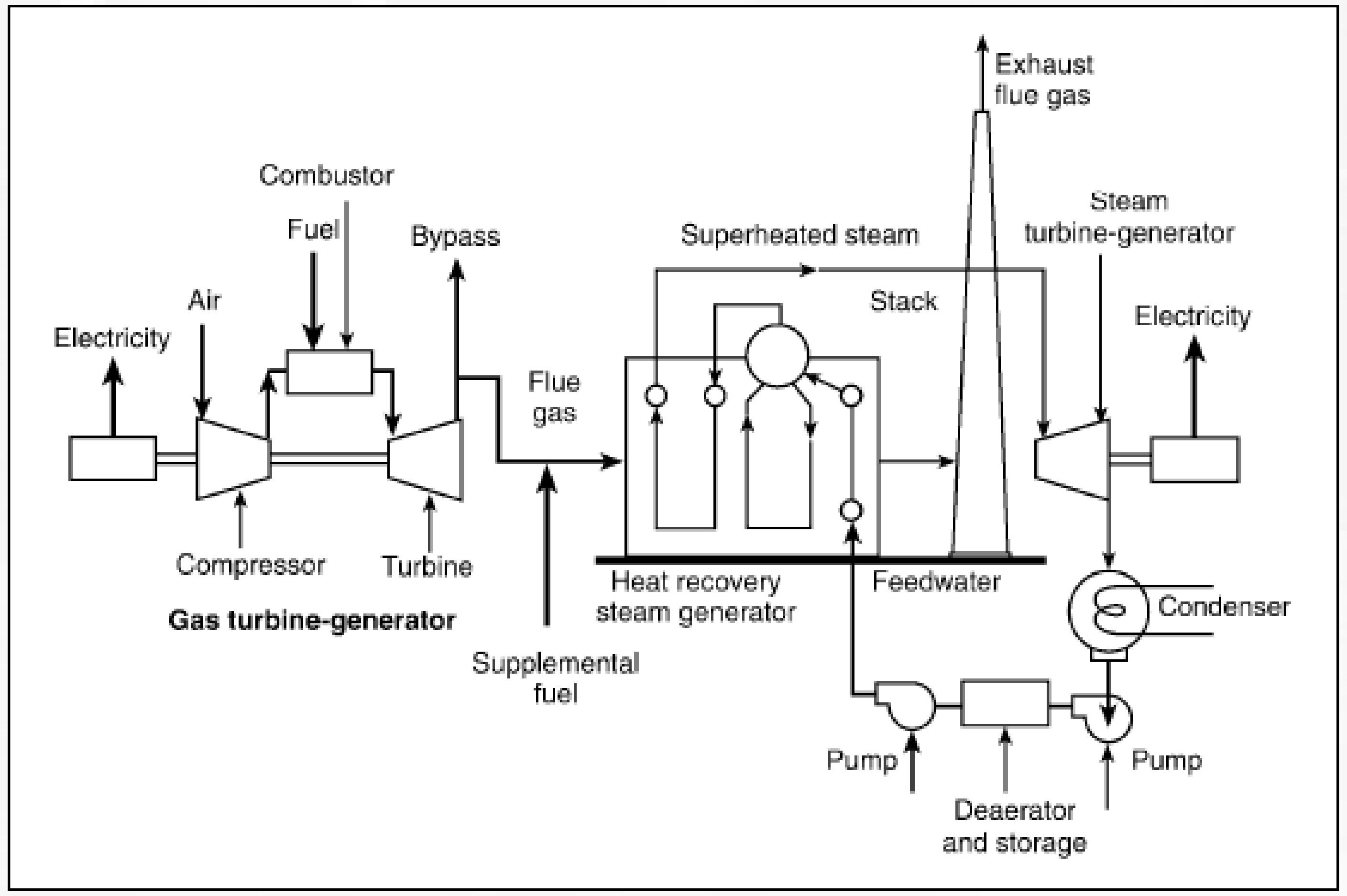


Fig. 2 Simplified Combined Cycle Gas Turbine System



control, and provides limited water storage to accommodate changes in boiler load.

The economiser receives boiler feedwater from the deaerator and increases boiler water temperature to the approach temperature for the evaporator section. The economiser is subject to 'steaming' during start up which leads to internal corrosion and fatigue. Thermal expansion also varies significantly over gas path. The economiser has critical feedwater chemistry issues related to possible high oxygen and low pH making it susceptible to flow accelerated corrosion.

The evaporator, which is the main steam generator, receives saturated water from steam drum downcomer. Its main function is to generate steam at specified pressure as evaporation occurs at constant temperature (i.e. isothermal process). The steam production rate depends on heat transfer area, heat transfer coefficient, and 'pinch point'.

The Bulwer Island HRSG is a forced circulation type requiring a circulation pump to ensure flow through the tube bank and headers.

The superheater receives steam from the steam drum outlet and increases the temperature of the saturated steam for use in the refinery processes. Additional enthalpy (energy) is added as the temperature increases. Superheaters see the highest metal temperatures in the HRSG and therefore have low metal-gas heat transfer coefficients. Hence effectiveness of heat transfer is significantly less than the evaporator or economiser. Superheaters also see the largest thermal expansion of all the HRSG components.

Circulation through the evaporator is driven by pumps that draw water at close to saturation temperature from the steam drum and circulate it through the evaporator. A phase change occurs and a saturated steam and water mix is returned to the drum.

Supplementary firing is achieved by duct burners installed to provide additional heat input to HRSG. This process requires in excess of 12% oxygen being present in gas turbine exhaust gas to enable the burners to fire. This process allows increased steam production from the HRSG.

4. Cycle Chemistry

The cycle chemistry in combined cycle plants influences about 70% of the heat recovery steam generator failure mechanisms [EPRI] [4].

EPRI has developed guidelines to assist operators and site chemists to develop effective overall cycle chemistry programs to prevent HRSG Tube Failures (HTF) [5].

These guidelines provide information on four different chemistries: all-volatile treatment (AVT), phosphate continuum (PC), caustic treatment (CT), and oxygenated treatment (OT). The Bulwer Island HRSG's utilise an AVT chemistry cycle.

Most combined cycle plants and HRSGs start life with non-optimum chemistries which often result in HTF early in life. If the chemistry is not optimized during the commissioning phase, then the chemical influenced failures will occur with time. It is necessary to apply a comprehensive approach to cycle chemistry to maximise availability and performance and to reduce the incidence of HTF.

The majority of the materials used in the construction of HRSGs are carbon steel. It is used for tubing, drums, casings, and ducts. Temperature limitations are influenced by the carbon content. Low carbon steels are limited to about 427°C and high carbon steels to about 538°C due to potential oxidation.

Carbon steel is usually applied in the economiser and evaporator sections with 1 to 2.5% chromium steels in the low temperature superheater. Most HRSG designs use finned tubes to increase heat transfer, which makes the circuits more compact and difficult to access [EPRI][6].

4.1 HRSG Tube Failures (HTF)

EPRI has conducted a number of HRSG Tube Failure surveys [4]. Results indicate that the evaporator and superheater are the primary locations of failure followed by the economiser circuits. Cycle chemistry is vitally important as nearly all the failure mechanisms are influenced by the cycle chemistry.

- FAC in evaporators
- Thermal fatigue in economisers/superheaters
- Creep-fatigue in superheater
- Corrosion fatigue in evaporators and economisers
- Under-deposit corrosion in evaporators
- Hydrogen damage
- Caustic gouging
- Acid phosphate corrosion
- Pitting

4.2 Flow-Accelerated Corrosion (FAC)

Flow-Accelerated Corrosion (FAC) is the most important HTF. Failures typically occur in evaporators and economisers.

FAC occurs across the temperature range 70° to around 300°C with a maximum near 150°C. The following sites were identified as the high risk areas of concern in the HRSG:

- Economiser tubes at inlet headers
- Vertical evaporator tubes (near to headers and at bends)
- Superheater outlet elbow

5. Maintenance Strategy

The main purpose of developing and formalising a maintenance strategy for the HRSG was brainstormed against the Stations Business Plan and the following key objectives were developed:

- Safety of People
- Safety of Plant
- Protection of the Environment
- Statutory Regulations
- Maximum Availability (Revenue return)
- Condition Monitoring
- Trending data to allow life assessment

5.1 Research Project Components

The project set out to formally identify the various equipment components and to review both historical failures on site and from industry experiences. These steps allowed for a comprehensive breakdown of the equipment which can then be reviewed to optimise the preventive maintenance strategies and to assess these routines against past and future failures.

5.2 Identify Statutory Requirements & Standards

A key requirement of the project was to ensure that the required statutory compliance would be able to be met at the conclusion.

This was originally assumed to be mostly based on the Australian Standard AS 3788 - Pressure Equipment In-Service Inspection [7]. However as the project progressed it became apparent that there are a large number of additional standards related to the various equipment components that needed to be reviewed. These included boiler, relief valve, safety systems, inspection qualifications and control systems. A complete list of these standards is contained in the references. The project included a review of Condition Monitoring Techniques and current Preventative Maintenance routines which could be applied to various items of the equipment. The main maintenance strategy was to focus on the External and Internal Inspections required under the various standards, specifically that of AS 3788.

Several of plant items including pumps, gearboxes, relief valves, required a reliability risk review which is not covered in AS 3788. For these, Reliability Driven Asset Management techniques were used.

5.3 Inspection Techniques evaluated

There are a number of inspection techniques available to assess the condition of a boiler such as the HRSG of this research. These included ultrasonic thickness checks, magnetic particle inspection, dye penetrant, replication sampling, borescope inspections, and thermography. These were reviewed and assessed against the various equipment items, potential failure mechanisms, and known equipment failures.

This research developed a written specific inspection schedule appropriate for the equipment items of the HRSG. This was utilised during the July annual outage in the 2011 maintenance plan.

5.4 Non-Destructive Testing (NDT)

Non destructive testing is the method used for the examination of materials and components to examine their condition without destroying their usefulness.

The materials and welds of boiler plant can be examined using NDT and either accepted, rejected, or repaired. Ongoing use of NDT techniques can then be used to monitor the integrity of the boiler throughout its design life.

5.5 Visual Inspection

Visual inspection is used extensively to evaluate the condition or the quality of a weld or component. It is easily carried out and is most effective for the inspection of welds.

It requires good lighting and the knowledge of what to look for. Its use can be extended through the use of a boroscope for internal inspection of tubes and headers.

5.6 Dye Penetrant Inspection

Dye penetrant inspection relies on the ability of a liquid to be drawn into a surface-breaking flaw by capillary action and is revealed by bleed out of a coloured or fluorescent dye from the flaw.

Coloured penetrant requires good white light while fluorescent penetrant needs to be used in darkened conditions with an ultraviolet “black light”.

5.7 Magnetic Particle Inspection

Magnetic particle inspection is a method to find surface flaws in ferromagnetic materials such as steel and iron.

This technique utilises a magnetic source to reveal distortion caused by the presence of a flaw. The flaw (a crack) is located from the “flux leakage”, following the application of fine iron particles, to the area under examination.

Go To Contents Page
Go To Last Page

5.8 Ultrasonic Inspection

Ultrasonic inspection utilises sound waves of short wavelength and high frequency to detect flaws or measure material thickness. Defects anywhere through the specimen thickness reflect the sound, back to the transducer. Flaw size, distance, and reflectivity can be interpreted.

5.9 Metallographic Replication

Metallographic Replication is used as a tool for evaluating microstructures and other surface features in the field. Portable polishing equipment is used to produce a replica through abrasive preparation of the selected area. The resultant grain structure is copied or photographed and the metallurgical replica is then assessed in the laboratory.

Features such as grain size and orientation, carbides and cracks are easily identifiable. This can be used as a tool to verify microstructures of component and to make informed decisions regarding extended or continued service or characterization of the flaws that are detected.

In completing any of the NDT inspections it is essential that qualified and certified personnel are employed to carryout and evaluate the equipment components. This is also a requirement of AS 3788.

6. Discussion

AS 3788 was used to determine the inspection period and the scope to meet the regulatory requirements of the Queensland Workplace Health and Safety Acts and regulations. Section 4 sets the general requirements for pressure equipment inspection with an external and internal inspection interval of 1 year for "All other boilers". The internal inspection is able to be extended to up to 4 years if the boiler has adequate water treatment facilities, demonstrated reliability, and has not been subjected to a fuel change outside of the original design parameters.

Table 1 is a summary extract from AS 3788

The Bulwer Island HRSG's currently have a set inspection regime of 1 year external and 2 year internal inspections. With adequate documentation now being collected it is expected that the internal inspection will be able to be extended in the future.

Pressure relief devices are required to be inspected in accordance with AS 1271 and to an interval no greater than that of the equipment it is designed to protect [8].

A regime has been implemented to Trevi test the safety devices inline with an external inspection and to inspect any that do not pass and to remove and inspect and maintain all pressure relief valves in line with the internal inspection period.

A formal inspection scope was compiled for the various component items of the HRSG on an external and internal inspection interval. The NDT techniques described above were used to undertake assessment of the various components.

The information from EPRI on the most likely places for HTF to originate was used to determine the appropriate locations to conduct ultrasonic thickness checks. These locations were tabulated and marked on the tube bank drawings and constituted part of the inspection document issued to the inspection contractor. An example of the Thickness Measurement Location (TML) table is shown in Table 2.

From the research carried out it was determined that the main HP steam outlet pipe work is the most susceptible to FAC and also thermal stress and fatigue from the elevated temperatures present on the low carbon steel used at this location. The use of metallographic

Table1 Inpection Intervals

1		2	3	4	5	6
Pressure equipment		Commissioning inspection required? (see Clause 4.2)	First yearly inspection required? (see Clause 4.4.3)	Inspection interval, years		
				External inspection (see Notes 2 and 3 and Clause 4.4.4.1)	Internal inspection	
					Nominal interval (see Clause 4.4.4.1)	Extended interval (see Clause 4.4.4.1)
1	BOILERS (see Note 12)					
1.1	Electric boilers	Y	N	2	4	8
1.2	Coil-type forced circulation boilers	Y	N	2	(see Note 15)	
1.3	All other boilers	Y	Y	1	1	4 (see Note 4)
2	STEAM PRESSURE VESSELS					

Table 2 Thickness Measurement Locations

HRSG1 TMLs					
Number	Location	TML type	Line No	Description	Drawing reference
1	HRSG top level, South	Pipe before vertical elbow	HS-50506-150 (DBS)	Saturated steam inlet to HRSG superheater outlet pipework from TV50106	5000G0123
2	HRSG top level, South	Vertical elbow	HS-50506-150 (DBS)	Saturated steam inlet to HRSG superheater outlet pipework from TV50106	5000G0123
3	HRSG top level, South	Tee	HS-50507-250 (DCA)	Superheated steam outlet line, at base of saturated steam from TV50106 tie in point (tee) to superheated steam line	5000G0123
4	HRSG top level, South	Straight pipe	HS-50507-250 (DCA)	Superheated steam outlet line,approximately 5m downstream of attemperator TV50107	5000G0123
5	HRSG evaporator/economiser level	Horizontal elbow	BFW-50509-100 (DBS)	Economiser outlet pipework to HRSG level control valves; first bend after header	5000G0123
6	HRSG evaporator/economiser	Vertical elbow	BFW-50509-80 (DBS)	Economiser outlet pipework to HRSG level control valves; first bend after tie in point to spill back line (to TV50101 and its bypass line)	5000G0123

replication was used to assess the material condition. This NDT technique was new to BIEP staff and had never been conducted on the site's HRSG before.

The reported findings of the inspecting contractor were interesting in this regard as it was found that the microstructure in the superheater elbow appeared to have degraded, with many carbides at the grain boundaries.

The pearlite was fully speroidised, but the carbides were still grouped in the pearlite grains away from the weld. This has enabled a bench mark to be established after ten years of operation of the plant, and is in line with the 25 year life expectancy. This information will be used as a baseline on future internal inspections to assess further degradation of the grain boundaries. Fig. 3 shows both the replication site and the grain structure.

A Reliability Driven Asset Management assessment was conducted on the ancillary equipment of the HRSG. This included the pumps, gearboxes, valving, and external ductwork. The results were tabulated in a comprehensive database, including failure mechanisms and recommended course of action and interval to conduct various preventative or condition monitoring maintenance activities

The more obvious example is the use of vibration monitoring on the HRSG circulation pumps. However this had been in place for the life of the plant, although it had never been formally captured.

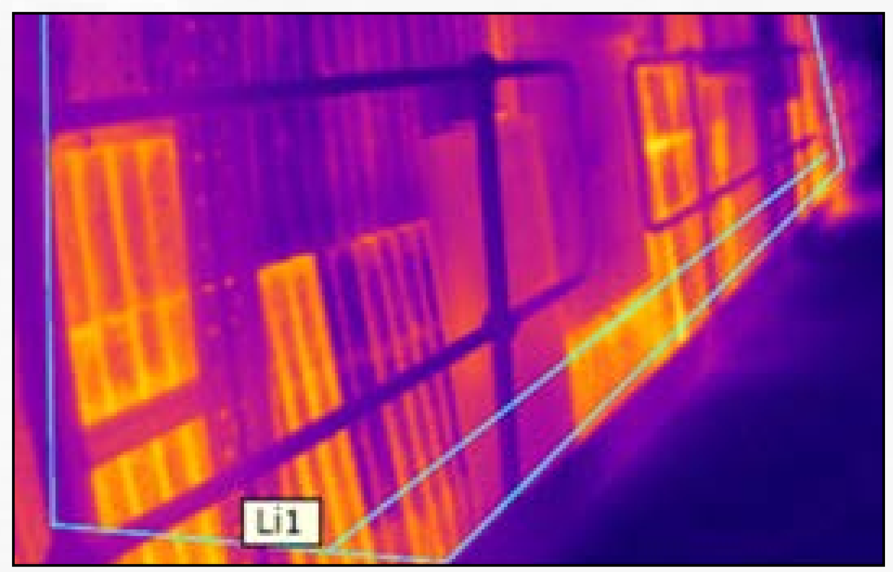
The assessment of the HRSG duct work for methods to determine the state of the fabric expansion joints, hatch covers, and general insulation, resulted in the proposal to conduct thermography to identify hot spots. Thermography is already utilised on site to assess the electrical switchgear condition so was a natural extension to the HRSG duct work.

This worked very well, clearly showing the condition of the various joints through photographic representation of heat signatures. Fig. 4 shows an infra red image of the duct work and cladding on one of the HRSG's.

The Boiler Management System (BMS) is a vital component of the safe operation of the HRSG and a requirement exists to ensure that all trip

Fig. 3 Replication site and grain structure

Fig. 4 Infra Red image of HRSG cladding



related functions are tested in accordance with AS 61508 [9]. A comprehensive and documented BMS testing schedule was compiled for undertaking and recording of this information, along with any defects rectification actions.

An important requirement of any maintenance strategy system is to define how equipment repairs are made on the discovery of failed or worn components. For a Boiler system this is particular important if the plant is to maintain it's certified and registrable state to be able to stay or be returned to service.

For boilers and pressure vessels to hazard level B as defined in AS 4343 [10], it is a requirement to repair to the relevant design and fabrication standard, in this case to AS 1228 [11]. This standard requires the formulation of repair procedures, qualified welding procedures and appropriate visual inspection and NDT before returning the plant to service.

7. Conclusions

It is the requirement of the owner of registrable plant to ensure that sufficient documentation exists to record the current and past status of the boiler and pressure plant and to show due diligence is being met in its operation and maintenance.This research sets out to outline the minimum documentation, records, and inspection criteria to be reported.

To do this a systematic and documented review was carried out of the relevant Australian Legislation and Standards. These were applied during the development of the maintenance strategy for the Bulwer Island HRSG's.

In analysing the component failures of HRSG's it was discovered that the cycle chemistry is of vital importance in preventing tube failures which are the predominant failure type of this type of plant. As a consequence of the impact of this finding a review of the current cycle chemistry has been included in the 2012 Business Plan for the Station.

A number of maintenance techniques were reviewed in carrying out this project; several were new to the author and site staff. An understanding of these techniques was gained through research of the EPRI documentation and also the Inspection Contractors, ALS Global. Training on the basics of these techniques is been included in the 2012 Business Plan for the Station also.

The application of various NDT techniques to identified failure points and mechanisms has provided a much better understanding of the HRSG and its life assessment. An opportunity exists in the future which may allow the extension of the internal inspection interval. This will result in reduce shutdowns and lower maintenance costs.

A comprehensive and documented management system sufficient to ensure continued integrity of the pressure equipment was documented. This management system is still to be assessed by a competent inspection body. It is the intention for BIEP to attain this sign off, but this was not part of this project, and it will be pursued within the Station's Business Plan.

8. References

[1] Workplace Health and Safety Act 1995
[2] Workplace Health and Safety Regulation 2008
[3] Australian Standard™ 2593 - Boilers - Safety management and supervision systems
[4] Electric Power Research Institute (2002) Heat Recovery Steam Generator Tube Failure Manual, EPRI, Palo Alto, CA. 1004503
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[6] Electric Power Research Institute (2003) Delivering High Reliability Heat Recovery Steam Generators, EPRI, Palo Alto, CA. 1004240
[7] Australian/New Zealand Standard™ 3788 - Pressure equipment-In-service inspection
[8] Australian Standard™ 1271 - Safety valves, other valves, liquid level gauges, and other fittings for boilers and unfired pressure vessels
[9] Australian Standard™ 61508 - Functional safety of electrical/electronic/programmable electronic safety related systems
[10] Australian Standard™ 4343 - Pressure equipment - Hazard levels
[11] Australian Standard™ 1228 - Pressure equipment - Boilers