Paper on
COMBINED CYCLE POWER PLANT PERFORMANCE DEGRADATION

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Combined Cycle Power Plant Performance Degradation

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Abstract

This paper investigates the causes and the effect of performance degradation in a combined cycle power plant. Performance degradation ultimately affects the power output and heatrate which in turn reduces the revenue while increasing the expenditure of the power plant. Degradation issues should be carefully considered in the design and operation of the plant.

Degradation of equipment such as gas turbine generators, steam turbine generators, heat recovery steam generators and condensers are discussed.

Degradation due to the normal wear and tear of the equipment is predictable based on the operating experiences of the installed plants. Normal wear and tear refers to the situation when the plant is operated at its design conditions. Degradation can be aggravated by the use of improperly treated fuel and feedwater which is fed into gas turbine and HRSG make-up respectively. Severe ambient operating conditions such as the presence of fine sand and dust particles in the air which may pass through the air inlet filters can also cause the deterioration of the gas turbine compressor.

Industrial practice in ways of minimizing the effects of performance degradation is discussed. This includes the proper treatment of fuel and water, regular GTG compressor washing, condenser tube cleaning and others.

Degradation characteristics of a combined cycle plant on the whole is discussed. This includes prediction of degradation between periods of major overhaul.

A case study is discussed to demonstrate the effect of performance degradation on a typical 100 MW combined cycle power plant. The case study estimates the loss of revenue due to the following conditions:

- Inlet air filter clogging
- Gas turbine compressor and turbine fouling
- HRSG tube fouling and scaling
- Condenser tube fouling and scaling

The paper further presents the degradation parameters in relation to loss of revenue such that the plant operator can take positive steps to minimise degradation. The understanding of predominant degradation parameters would enable suitable monitoring system be built into the plant and formulation of degradation models (or plant performance evaluation models) to correlate the key parameters to the plant performance in both technical and financial terms.

Nomenclature

HRSG	*Heat Recovery Steam Generator*	k	*Thermal conductivity*
GTG	*Gas Turbine Generator*	L	*Length of scale*
STG	*Steam Turbine Generator*	T	*Temperature*
CCPP	*Combined Cycle Power Plant*	ΔT	*Temperature differential*
HP	*High Pressure*	f_w	*Water-side Fouling factor*
LP	*Low Pressure*	η	*Efficiency*
IP	*Intermediate Pressure*	P	*Power output*
HPB	*High Pressure Boiler*	m	*Mass flow of fluid*
RH	*Relative Humidity*	ρr	*Pressure ratio*
SPE	*Solid Particle Erosion*	U_f	*Fin tube heat transfer coefficient*
IPP	*Independent Power Producer*	U_b	*Bare tube heat transfer coefficient*
TIT	*Turbine Inlet Temperature*	↑	*Increasing*
C	*Constant*	↓	*Decreasing*
Q	*Heat energy transfer*		

Introduction

A new power plant which is designed, constructed and commissioned properly shall be able to operate at the plant's declared power and heatrate as guaranteed by the contractor. This is valid provided that the plant is operated within the equipment operating limits and when the plant is in a new condition. The power plant's overall performance would be gradually reduced over time due to the degradation of the plant's components. It is necessary for the plant owner/operator to monitor and minimise the plant's degradation to optimise the revenue.

Degradation

Degradation is the loss of machine performance (Gas turbine, Steam Turbine, HRSG, Condenser and other auxiliaries) over time due to the wear and tear during operation/startup/shutdown and the presence of contaminants in fuel, water and air which is ingressed into the system. Degradation can generally be divided into the following categories:

Type of Degradation	**Typical causes**
Recoverable Degradation	Clogging, scaling and build up of deposits on the working surfaces that are in constant contact with the working fluids.
Non-Recoverable Degradation	Wear and tear of machine components, aging, loss of working surface, corrosion/oxidation, erosion and other damages to the working parts. .

Typical contaminants

There are three paths in which contaminants can flow into the system and that is through the air, fuel and water. A typical power plant configuration would include the inlet air filtration system, fuel centrifuge/scrubber and water treatment system to reduce the level of contaminants to an acceptable level within the equipment specification limits.

Typical contaminants	**Description**
Air-borned contaminants	Microscopic particles from industrial emission and transportation, dust from vehicular and construction activity, and natural sources
Fuel contaminants	Traces of Sodium, Potassium, Calcium, Lead, Sulfur and other metals for liquid fuel only.
Water contaminants	Sodium, Potassium, Calcium, Silica, Carbonate, Sulphate, Chloride, Suspended Solids especially from river & sea water

Gas Turbine Generator Degradation

Degradation causes	**Description**
Erosion	Small abrasive particles entering into the Gas Turbine via air/fuel path and propelled by the compressor, combustion gas through the hot section turbine at high velocity can cause erosion. This results in damage to the compressor and turbine blade surfaces and its protective coating. It depends on the size of objects ingested into the GTG (i.e. objects with sufficient mass and hardness to physically damage GTG blades & components) and the period of exposure. This is a non-recoverable degradation.
Corrosion / Oxidation	The combustor and the hot section turbine blades are subjected to high velocity gas with traces of contaminants at high temperature. Furthermore microscopic pitting and damage to the protective coating of the blades shall further induce oxidation/corrosion process. The stage efficiency is reduced by alteration of blade surface finish. This is a non-recoverable degradation.
Deposition	Air borned and fuel borned contaminants such as water soluble constituents, insoluble dirt, etc. are deposited on the rough surfaces of the combustion chamber and turbine blades. Deposition on the blades would affect the blade surface roughness. This is a partially recoverable degradation and is dependent on the effectiveness of the blade and combustor cleaning process.

HRSG Degradation

Degradation causes	**Description**
Fouling	Fouling in the HRSG is almost entirely due to scaling and sludge buildup. Scale material in the form of dissolved solids is deposited on the water side tube surfaces when evaporation occurs. Scale material is a relatively hard and adherent deposit, while sludge is softer and can be easily dislodged. Scale buildup is associated with compounds whose solubility decrease with increasing temperatures. Conversely, sludge is precipitated directly from the boiler water when their solubility are exceeded.
Oxidation	Steam flowing through the superheater tubes, reacts with the alloy constituents of the tube material (Fe, Cr, etc.) as given by the following equation : $4H_2O + 3\ Fe \rightarrow Fe_3O_4 + 4H_2$ The magnetite scale thus formed normally adheres to the tube surface and limits the extent of further reaction. As such, the oxidation rate is asymptotic in nature. As the oxide becomes thicker, they become more brittle and when critical thickness is reached, the protective layer is lost and thus becoming susceptible to spalling which can cause tube blockage and solid particle erosion (SPE)
Heat Transfer in Scaled Tubes	Scale causes resistance to the heat transfer between the hot exhaust gases and the boiler water. Heat transfer through the scale can be represented by the following equation. $Q = k\Delta T/L = \Delta T/f_w$ (where $f_w = L/k$) The quantity of heat energy transferred is proportional to the thermal conductivity of the scale and inversely proportional to the scale thickness. The tube side fouling factor (f_w) affects duty and tube wall temperatures. This impact is more significant in a finned tube boiler as compared to a bare tube boiler. The thermal conductivity of several substances which are characteristic of boiler scale deposits are presented in the table below.

The table on the next page shows the Thermal conductivity of boiler scale deposits

Thermal conductivity of boiler scale deposits

Material	Thermal Conductivity W/(mK)	Material	Thermal Conductivity W/(mK)
Analcite	1.269	Magnetic Iron Oxide	2.884
Calcium Phosphate	3.605	Silicate scale	0.0865
Calcium Sulfate	2.307	Fire brick	1.010
Magnesium Phosphate	2.163	Insulating brick	0.1010

STG Degradation

Degradation causes	Description
Performance Loss Due to Leakages	Rubbing of rotating stationary parts will result in increased clearance and hence increased steam leakage occurring in the stage, diaphragm and end seals.
Solid Particle Erosion	Solid particle erosion occurs when iron oxide particles (magnetite) in the form of scale (produced in the inner surface of the HRSGs superheater tubes) are entrained in the steam flow. This erodes the steam path. The damage is usually most severe on the first HP, first IP, first reheat stages and nozzles as well as the control valves.
Moisture Erosion (Water Drop Erosion)	Moisture erosion in the STG is caused by water droplets that form as the steam crosses the saturation line. Larger water drops lag behind the steam flow and attack (cause erosion) the tip region of the last stage blades where the circular velocity is the highest.
Steam Path Chemical Deposition	Chemical deposition is caused by the presence of impurities in the steam attributed to the following factors :- • Evaporation from boiler water • Entrainment (carryover) of boiler water droplets into superheater tubes and subsequently into the STG. • Impurities present in feedwater for desuperheating sprays.
Foreign Object Damage	This is caused by the inadvertent admission of foreign material into the turbine steam path. Typical foreign materials include , weld bead and slag that may have come loose from upstream piping and components which may not have been flushed clean before startup.

Condenser (Once through) Performance Degradation

Degradation causes	**Description**
Condenser Scaling/Fouling	As the temperature and concentration of the cooling water increases, several types of ions which are initially soluble, are precipitated on the surfaces of the condenser tubes. River water usually contains significant quantities of Calcium Carbonate. Scaling occurs under higher water temperatures and aerated conditions. The following reversible equation applies. $Ca(HCO_3)_2 \leftrightarrow Ca\,CO_3 + CO_2 + H_2O$ CO_2 loss tends to shift the equation to the right and thus increasing the scale formation.
Biological Fouling	Micro-organisms present in cooling (river/sea) water tend to form slime films on the heat transfer surfaces thus increasing the water side fouling factor.

Degradation of Other CCPP Components

Diverter Dampers -. A tight gas seal after a period of time cannot be expected as damper blade edges and seals deteriorate in service. Dampers can and do remain in one position for months at a time while the HRSG is operating and thus sometimes fail to operate to their design requirements.

Case Study of the Effect of CCPP Component Degradation on CCPP Performance

Method of Conducting Case Study

GTPro is used to calculate the plant configuration design performance. GTMaster is used to calculate the off-design plant performance based on the various fouling and deration factors which include :-

1. Inlet Filter Pressure drop
2. GTG turbine and compressor efficiency
3. Fouling factor at the HRSG
4. Fouling factor at the condenser
5. Diverter damper leakages

For analysis of degradation of individual CCPP components, it is assumed that all other components are operating at design conditions.

A case study for a typical 100 MW CCPP is conducted to analyse the effects of degradation of the various CCPP components. The plant is simulated based on an ambient temperature of 32 ° C/ 80%RH. The plant is made up of the following equipment.

Item	**Description**
1.	GE 6551 B GTG
2.	Dual pressure HRSG
3.	Once through cooling for condenser
4.	Condensing STG

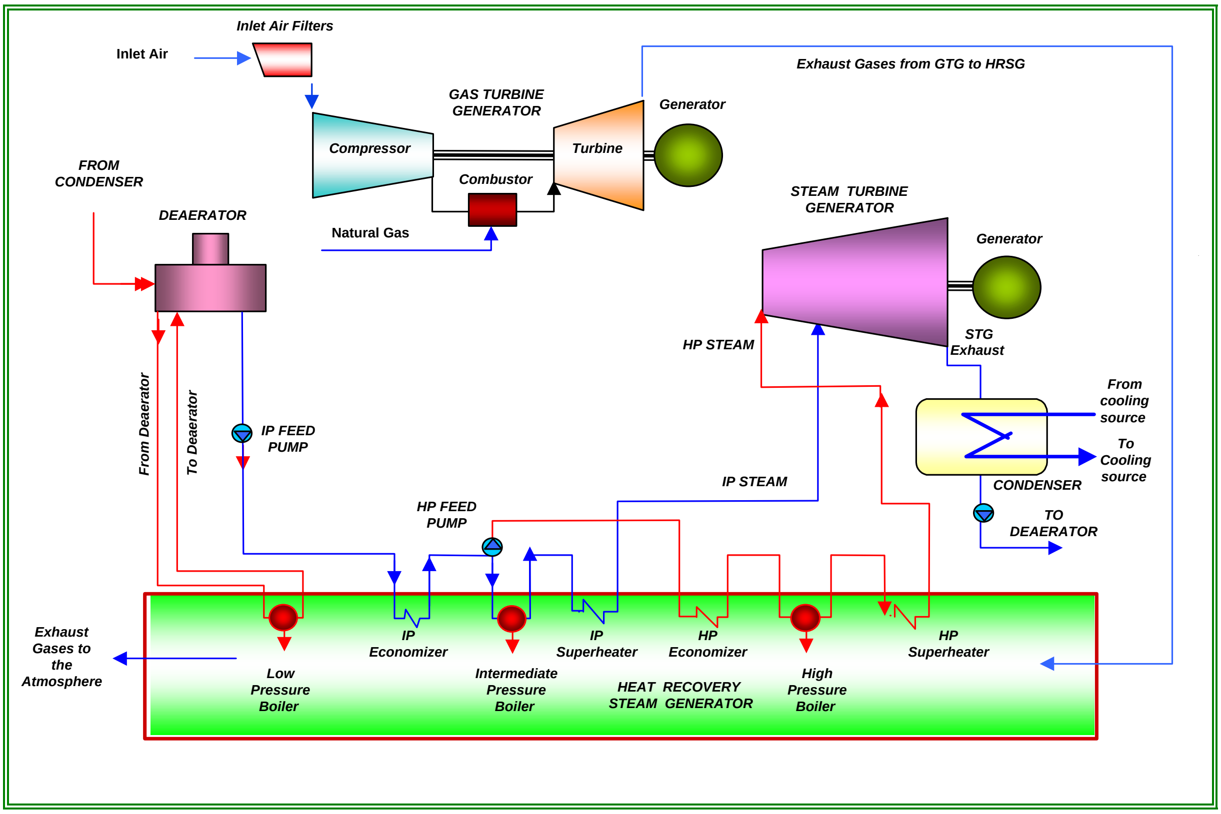

Figure 1 : Schematic of a Typical CCPP

It is assumed for the case study that only a single component undergoes degradation at any one time. This is to gauge the magnitude of the effect of these individual degradations on the CCPP.

GTG Inlet Air Filter Clogging

The effect of GTG inlet air filter pressure drop is shown below.

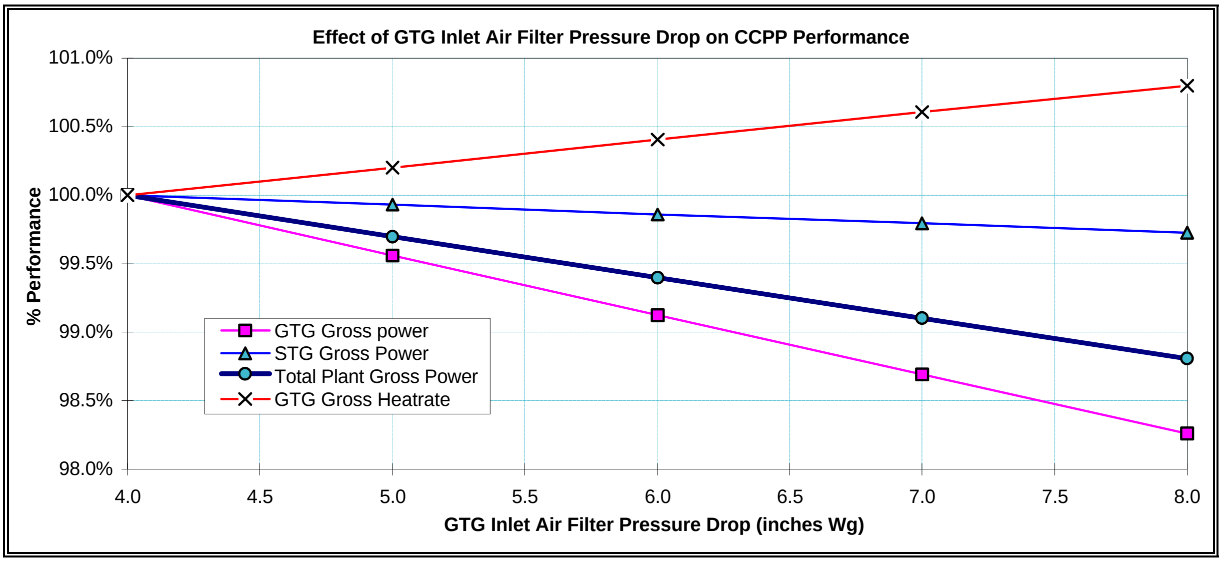

Figure 2 : Effect of GTG Inlet Air Filter Pressure Drop on CCPP Performance

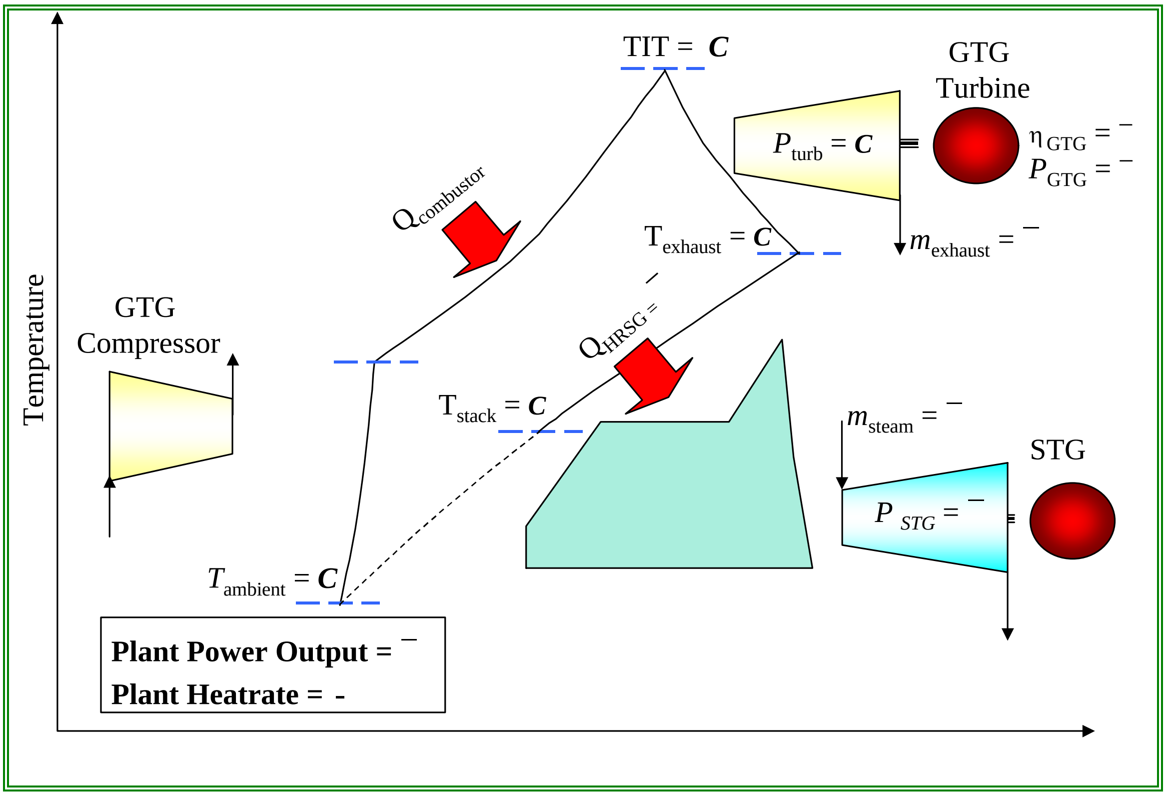

Figure 3 : Schematic of the effect of GTG inlet air filter pressure drop on CCPP performance

Effect of GTG inlet air pressure drop on revenues		
GTG inlet air pressure drop	*6” H2O*	*8” H2O*
% loss of revenue	*0.8%*	*1.6%*

GTG Compressor Degradation

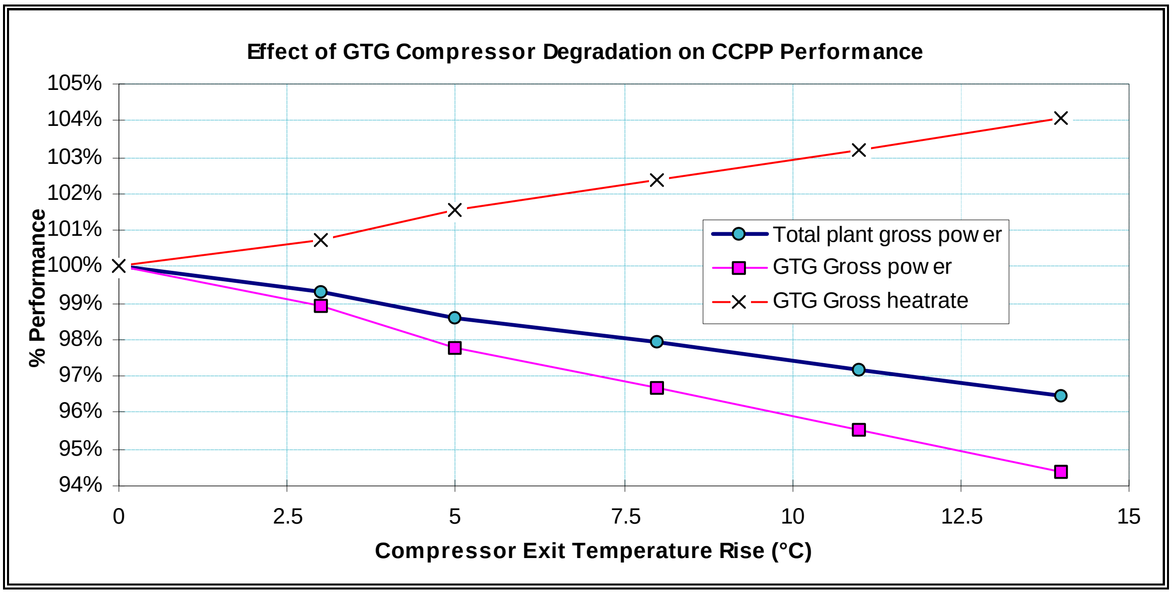

Figure 4 : Effect of GTG compressor degradation on CCPP Performance

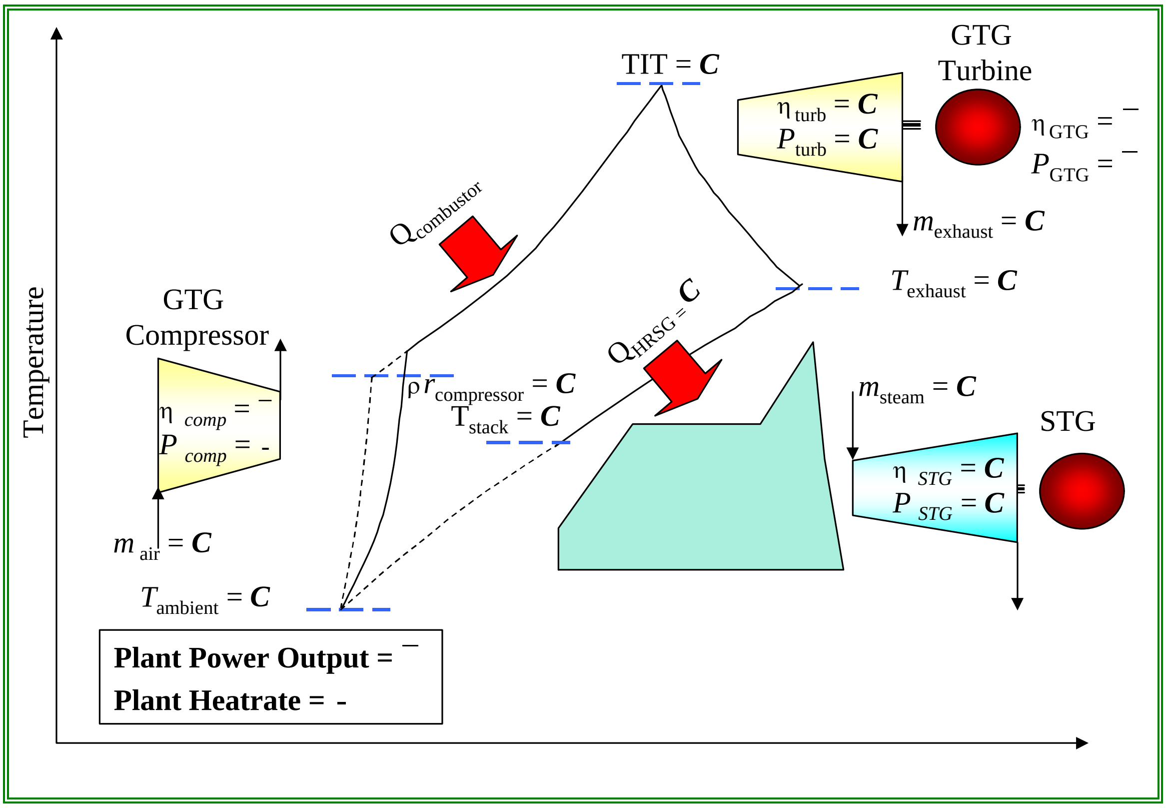

Figure 5 :Schematic of the effect of GTG compressor degradation on CCPP performance

Effect of GTG compressor degradation on revenues			
Compressor exit temperature rise	*3 °C*	*8 °C*	*14 °C*
% loss of revenue	*0.8 %*	*2.6%*	*4.4%*

GTG Turbine Degradation

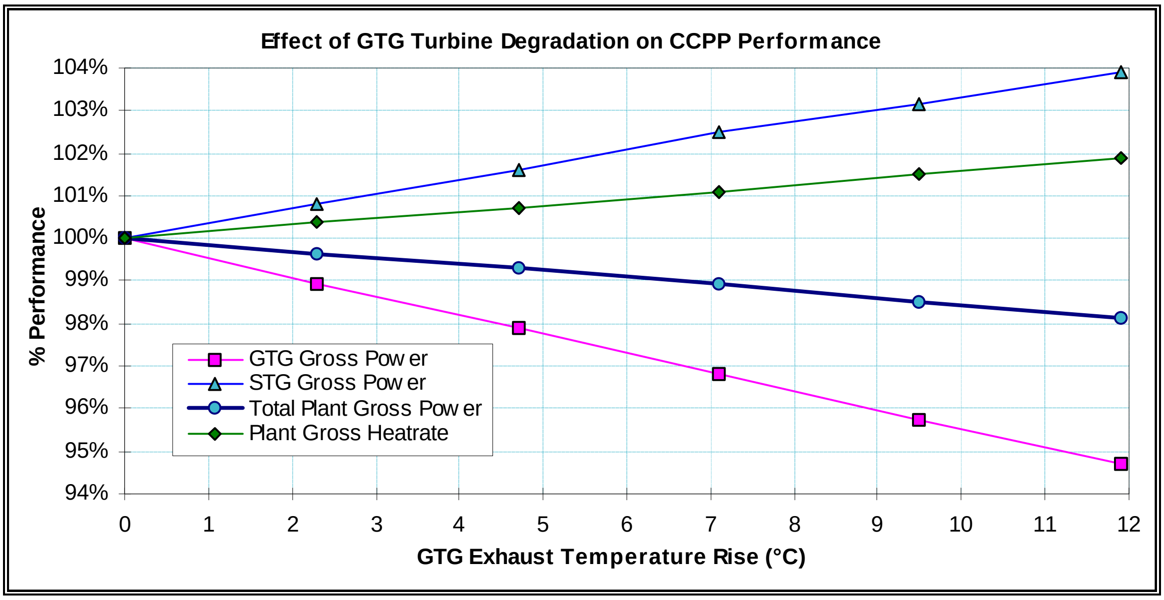

Figure 6 : Effect of GTG turbine degradation on CCPP Performance

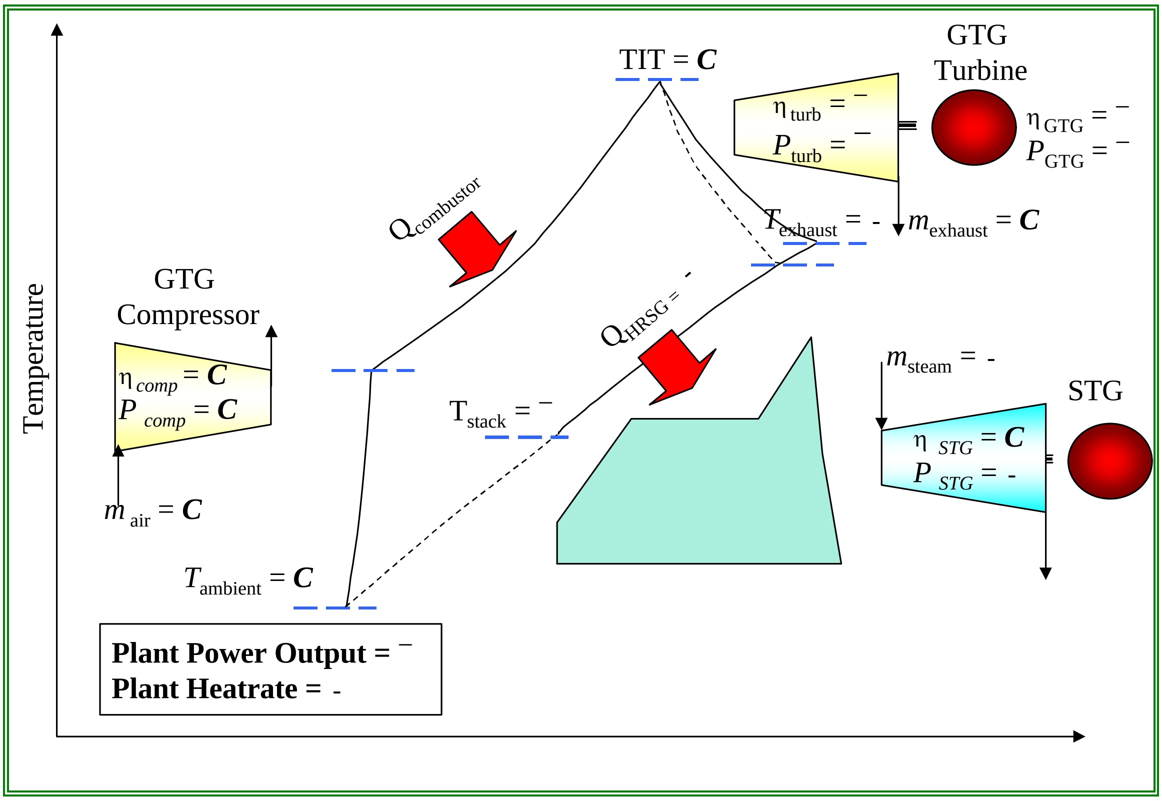

Figure 7 : Schematic representation of the effect of GTG turbine degradation on CCPP performance

Effect of GTG turbine degradation on revenues			
GTG Exhaust Temperature Rise	*2.3 °C*	*7.1 °C*	*11.9 °C*
% loss of revenue	*0.4%*	*1.1%*	*1.9%*

Heat Recovery Steam Generator Degradation

A brief investigation is carried out on the effect of degradation on the HP boiler of the HRSG on the CCPP. Two conditions are considered where one case considers a Bare tube evaporator while another case considers Finned tube evaporator

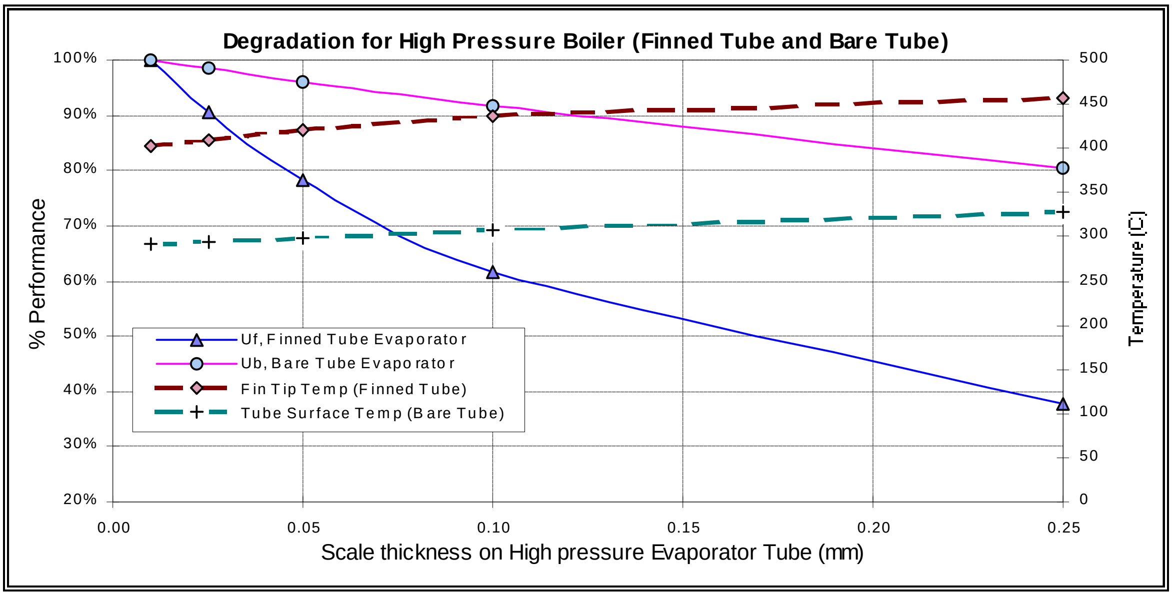

Figure 8: Effect of HRSG fouling on High Pressure Boiler Performance

Increase in the water-steam side fouling factor (f_w) due to the formation of thick layer of scale results in reduced duty and higher tube wall temperatures. The larger the fin surface area (obtained by using high fin density) the higher the temperature of the tube wall and tip. In cases of extreme degradation the tubes can be overheated and even result in tube failure. The next investigation looks at how the HRSG degradation would affect the performance of the entire combined cycle plant. Refer to *Figure 9* .

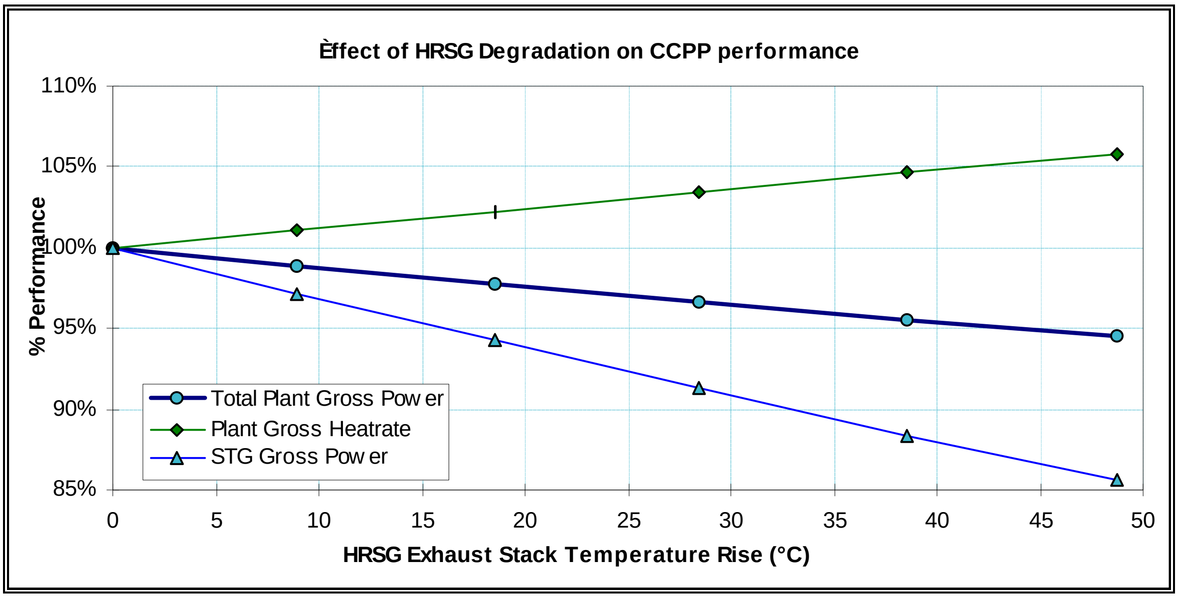

Figure 9 : Effect of HRSG degradation on CCPP Performance

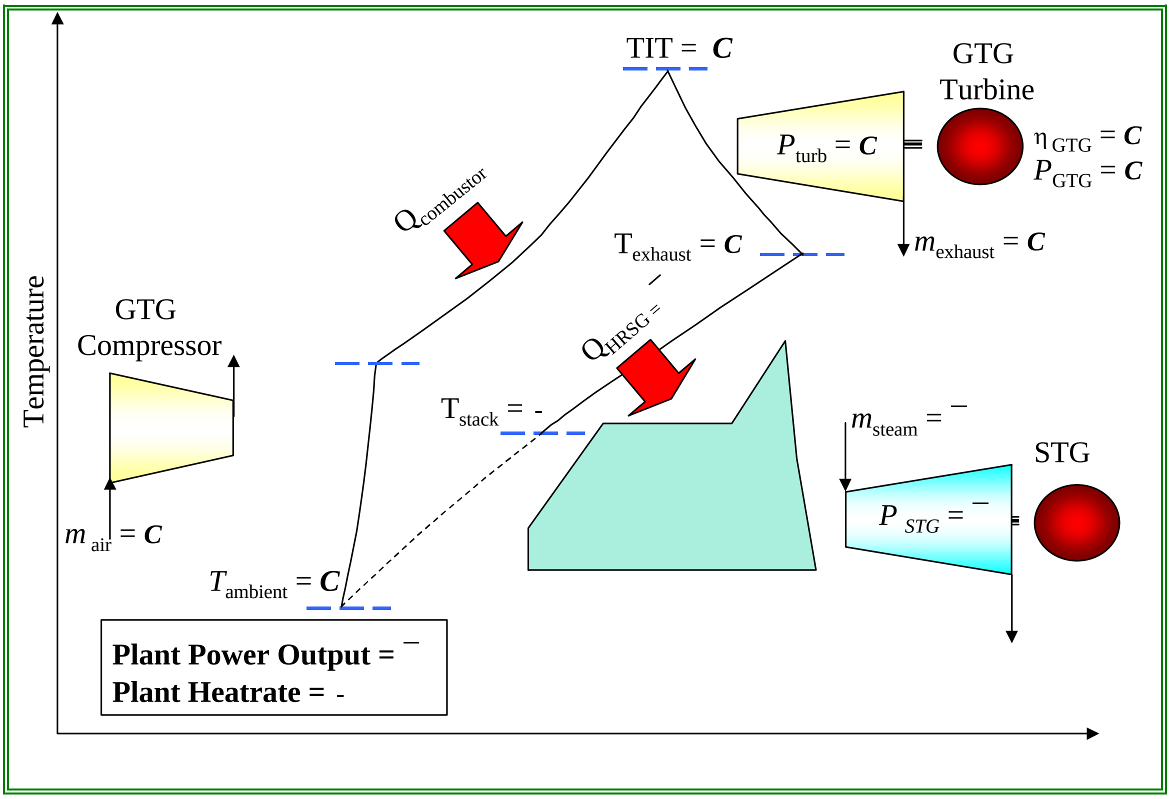

Figure 10 :Schematic representation of the effect of HRSG degradation on CCPP performance

Effect of HRSG degradation on revenues			
HRSG Exhaust Stack Temperature Rise	*8.9 °C*	*28.4 °C*	*48.7 °C*
% loss of revenue	*1.1%*	*3.4%*	*5.6%*

Condenser Degradation

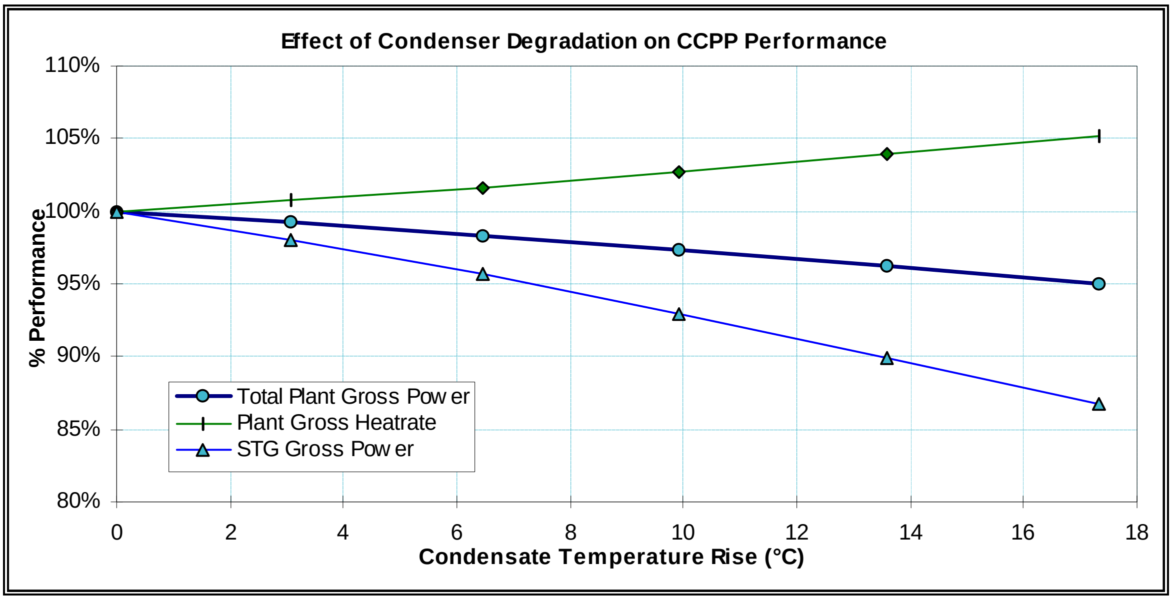

Figure 11 : Effect of condenser degradation on CCPP Performance

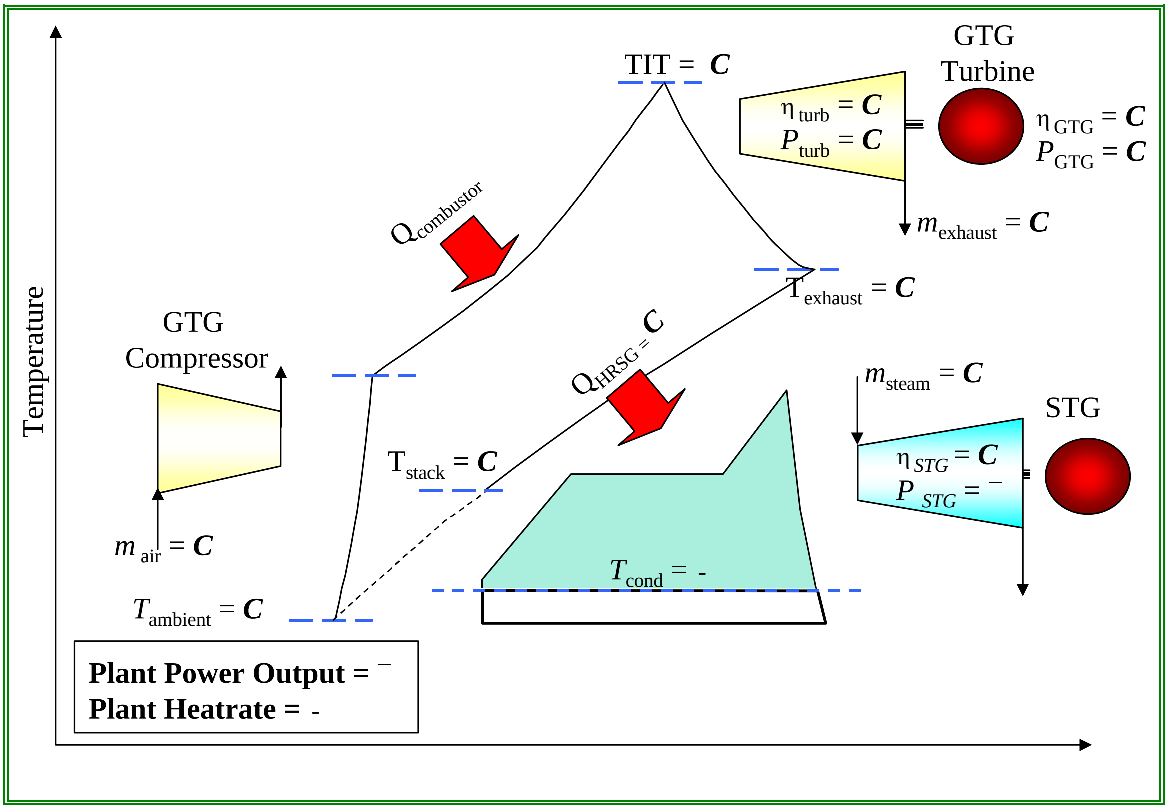

Figure 12 :Schematic representation of the effect of condenser degradation on CCPP performance

Effect of condenser degradation on revenues			
Condensate temperature rise	*3 °C*	*9 °C*	*13.6 °C*
% loss of revenue	*0.7 %*	*2.7%*	*3.9%*

Diverter Damper Leakage

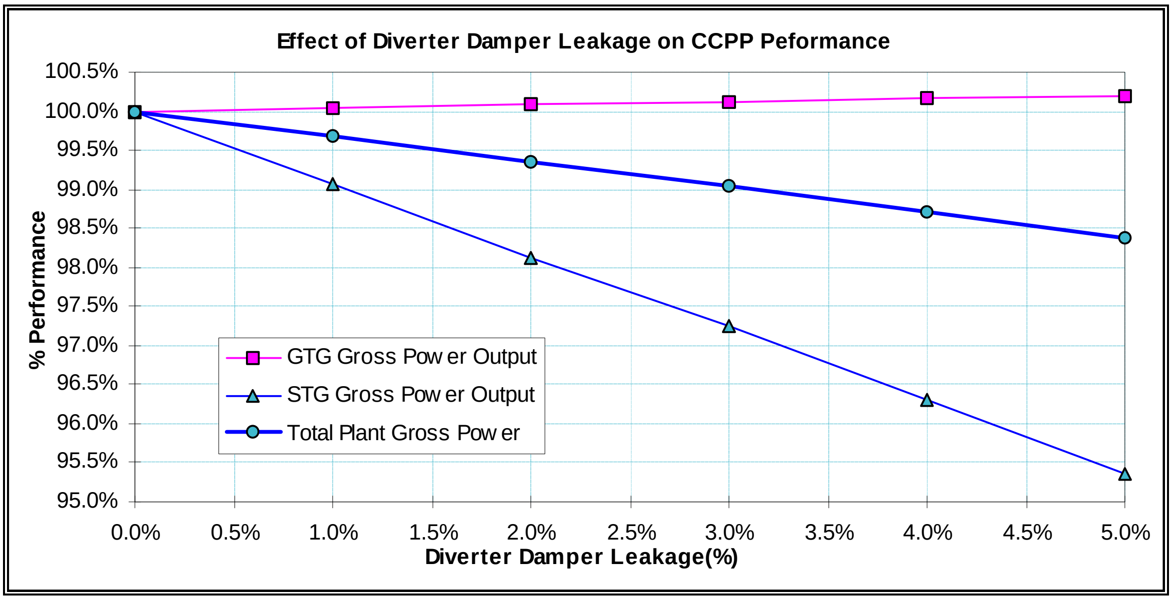

Figure 13 : Effect of diverter damper leakage on CCPP Performance

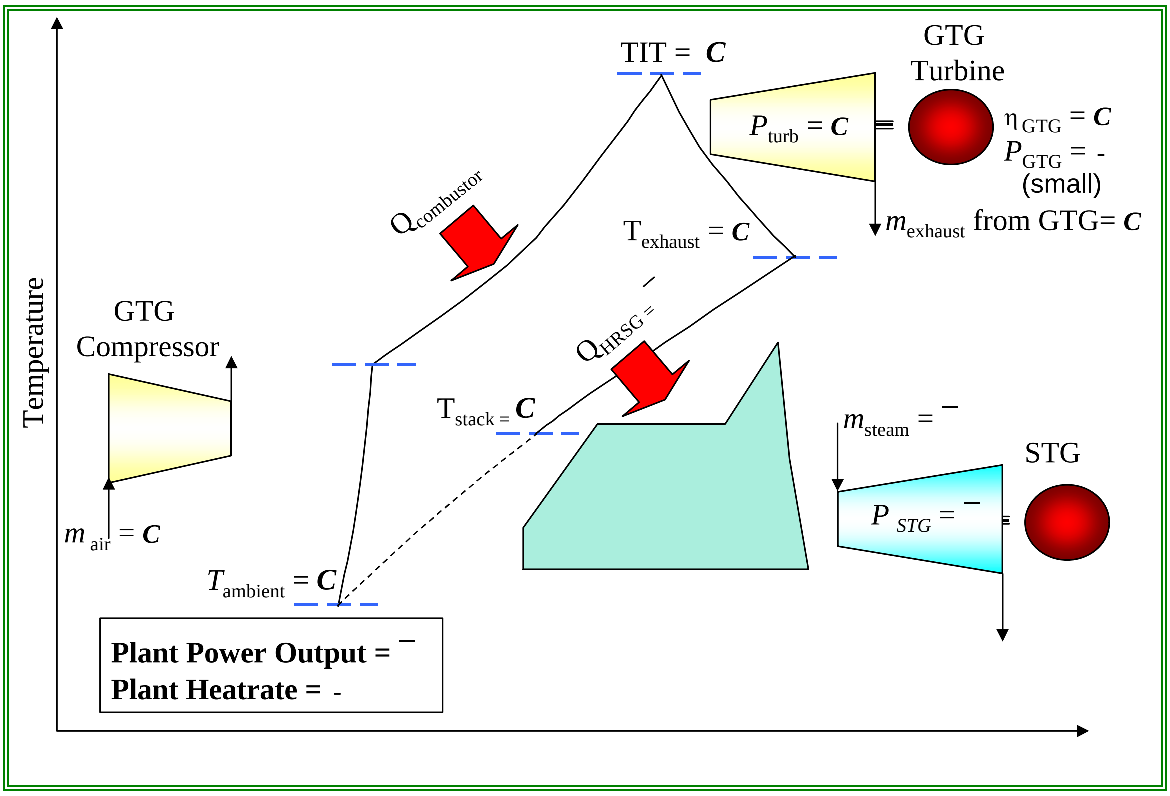

Figure 14 :Schematic representation of the effect of diverter damper leakage on CCPP performance

Effect of diverter damper leakage on revenues			
Exhaust gas leakage (% of total GTG exhaust gas)	*1%*	*3%*	*5%*
% loss of revenue	*0.3 %*	*0.9%*	*1.6%*

Minimizing Performance Degradation

From the above, it can be seen that degradation on various plant components have a significant impact on the plant performance and thus there is a need to minimize them.

Minimizing GTG Performance Degradation

Control / Remedial	**Description**
Fuel Quality Control	• Treatment/scrubbing of liquid and gas fuel at site as some contamination may have occurred during transport • Constantly monitoring of fuel quality to meet the equipment specification limits.
Compressor / Turbine Wash	Compressor/Turbine wash can remove the fouling deposits and oil traces on the blades. The wash method include • On-line liquid cleaning • Off-line liquid cleaning • Solid compound cleaning
Strict Adherence to Manufacturer's Maintenance Program	The manufacturer's maintenance program includes :- • Scheduled servicing and parts replacement • Continuous trending and monitoring of compressor and turbine operational parameters • Scheduled Borescope inspection
Blade Coating System	There are options for blade coating which includes providing a thin layer or protective coating (very hard and corrosion resistant layer) or a sacrificial coating (coating which is sacrificed as it reacts with corrosive elements).

Minimizing HRSG Performance Degradation

The most effective means of controlling performance degradation in HRSGs is by utilizing good water treatment practices. Water chemistry is of the utmost importance to HRSG operation as all fouling and operational problems originate from here. Poor feed water quality is also detrimental to the operation of the STG.

An effective method for detecting fouling and performance degradation involves the trending of the HRSG performance data such as steam flowrate and pressure. This data is then compared against the base-line data to detect deterioration in performance.

Minimizing STG Performance Degradation

Control / Remedial	**Description**
Leakages	Improve tip leakage controls
Solid Particle Erosion	Application of diffusion coating to the first stage and reheat stage nozzles.
Moisture Erosion	Blades operating in the wet region are protected at the tips (either by hardening or with a protective coating). The equipment design should include moisture separation feature within the wet regions of the steam path to prevent erosion in the Steam Turbine.
Steam Path Deposits	Water used for attemperating sprays and exhaust hood sprays could also be a potential source of steam contaminants and thus mitigation measures must be taken accordingly.

Minimizing Condenser Performance Degradation

Control / Remedial	**Description**
Continuous Mechanical Cleaning of Condensers	This is a physical method of continuously cleaning condenser tubes by circulation of sponge rubber balls in the cooling water system. The frequent use of this system would reduce the quantity of chlorination required.
Continuous Acid Dosing -	Low cooling water pH almost reduces scales completely but an acidic environment can cause corrosion problems in virtually all components (i.e. steel and concrete) that make up the cooling water system. As such, a great deal of care and very tight control should be exercised when using this method
Chemical Additives	Chemical additives modify the crystal structure of compounds precipitating from supersaturated solutions such that scaling is minimized. These chemicals are expensive and are used in low dosage rates. Injection of these chemicals do not require very strict monitoring as over-dosing is very unlikely to cause attacks on concrete or metals.

Economics of CCPP Degradation

Case Study for Simultaneous Degradation

The examples discussed earlier consider the effect of degradation one component on the CCPP while in real life, all components undergo simultaneous but varying degradation. The case study below simulates this condition.

Design Conditions

The case study takes a simplified approach to show the effect of performance degradation on the CCPP. The "*New and Clean*" condition is what would be expected when the power plant has operated for less than 100 hours. Case 1 considers predominant GTG degradation while Case 2 considers predominant HRSG and condenser degradation. Case 3 is a composite of GTG, HRSG and condenser degradation.

Description	**Units**	***New & Clean***	***Case 1***	***Case 2***	***Case 3***
Inlet air pressure drop	in H_2O	4	6	4	6
GTG compressor temperature rise	°C	0	5	0	5
GTG turbine exhaust temperature rise	°C	0	5.6	0	5.6
HRSG stack temperature rise	°C	0	-1.2	5.7	5.1
Condensate temperature rise	°C	0	0	6.18	6.34
Exhaust gas leakage at diverter damper	%	0	1	1	1

Note : Temperature rise is defined as the change with reference to the Design Temperatures.

Results

Description	**Units**	***New & Clean***	***Case 1***	***Case 2***	***Case 3***
Net plant power output	MW	106.3	103.0	103.8	100.8
Net plant output	kJ/kWh	7,620	7,768	7,802	7,937
Loss of revenue per day	%	NA	3.6 %	2.3%	5.6%

Considering Case 1, the IPP stands to lose 3.6% of revenue per day while in Case 2, there would be a loss of 2.3 % a day. For the conditions of Case 3, there would be a loss of 5.6% revenue per day.

Some of the steps that an IPP owner can take to minimize the effects of degradation apart from those that have already been discussed include:

- Strictly follow maintenance procedures

- Ensure that degradation of the CCPP due its location has been considered at the design stage. (i.e. use of marinized GTG blades for CCPP located in sea environment or use of titanium tubes for once through condensers with sea water cooling)
- On-line monitoring of key parameters for early detection of plant equipment degradation.

Prediction of CCPP Degradation

Most manufacturers only provide typical degradation percentages for GTGs and CCPP from existing plants operation experience. These data do not reveal the detailed aspects of Combined Cycle Power Plant configuration and thus making the degradation estimates for a proposed plant difficult. It is also not possible to depend only on the tenderer's estimates or manufacturer's publication due to the lack of detailed information.

Since the characteristic of the Gas Turbine, HRSGs and STGs are well defined, it is possible to model a specific CCPP configuration to analyse the impact of degradation and to design the plant with the necessary mitigation measures to suit the specific conditions.

For example, it may be necessary to design and install suitable inlet air filtration system with on line pulse cleaning facilities for a power plant located near a clinker plant whereby the air pollutants are high. The loss of revenue due to pressure drop may be significant enough to justify the initial investment in suitable mitigation measures against degradation losses.

In other cases, it may be necessary to design and install suitable heat exchanger system, on line monitoring system, condenser cleaning system to cope with cooling (river/sea) water with high Total Dissolved Solids and Total Suspended Solids with significant traces of heavy metals. The impact of degradation on the revenue and Internal Rate of Return against capital investments shall be used to determine the selection of power plant configuration and mitigation infrastructure.

Conclusion

The largest contribution to CCPP performance deterioration is by GTG degradation. The combined effect of compressor /turbine degradation and inlet air filter clogging can reduce the performance of the CCPP rapidly. As such plant operators should ensure that the plant degradation is minimized. Possible performance degradation should be analyzed at the design stage such that proper counter-measures can be taken to reduce it.

From the above investigation, it could be seen that it is possible to;

- Provide useful real time data for plant performance diagnostics via trending and correlation of key measurable parameters to the plant component actual degradation physical effects.
- To develop on-line plant performance evaluation models to maximise the efficiency and reliability. A set of parameters of the new plant (design) conditions will be used as the baseline or benchmark and the calculated results from the real-time data, would be presented in the form not only to highlight the problems and probable causes but also the associated financial impact of the plant.
- Establish optimal plant performance inspection and overhaul schedules based on performance

- Acquisition of data for plant engineering appraisals to improve reliability.

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Biographical Information

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Yong Voon Yee received his degree in Electrical & Electronic Engineering from University of Melbourne, Australia. He joined Foxboro in 1990 as a control system engineer and was involved in the system & software design of Distributed Control System for offshore oil & gas production platforms. In 1995, he joined Vy Consult to pursue a career in Electrical and Power Generation. He was the site engineer for supervision of fast track installation, testing and commissioning of 20MW Gas Turbine Power Plant. He has been involved in the technical and economic feasibility study of a 100MW Combined Power Plant in the East Malaysia for an IPP company. Vy Consult is taking the lead in promoting cogeneration feasibility studies and applications in Malaysia.

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Paramjit obtained a degree in Mechanical Engineering from University of Malaya in 1996. He joined Vy Consult and has been involved in the development of power generation and cogeneration projects. He has been involved in the technical and economic feasibility study of a 100MW Combined Power Plant in the East Malaysia for an IPP company. Vy Consult is taking the lead in promoting cogeneration feasibility studies and applications in Malaysia.