Thermal Fatigue of Power Plant Components

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Abstract

Recently Verve Energy have been required to operate their baseload Cockburn power station in a two-shifting (cyclic) manner. The detrimental financial and mechanical consequences of two-shifting are well known; the project objectives deal with quantifying these consequences. Mechanical damage was evaluated using a software package capable of assessing creep and fatigue and estimating remaining lifetimes. Of the components examined, analysis indicated that the majority have useful remaining lifetimes exceeding the operational requirement. Two components were identified as critical, needing further investigation; recently attached thermocouples will verify the temperature conditions experienced by one. Financial analysis required fuel usage and power production to be monitored during start-ups. The data was used to calculate the short-term differential cost of two-shifting compared to baseload operation. As an alternative to two-shifting, Verve Energy is considering operating overnight at low-load; this option has been found to be more expensive.

1. Introduction

On April 1st 2006 Verve Energy was formed as a result of the disaggregation of Western Power into four state owned entities. To encourage private investment, certain restrictions were applied to Verve Energy. These restrictions and changes in the electricity market have, in recent years, required Verve to change the operating regime of their Cockburn Combined-Cycle Gas Turbine (CCGT). Since commissioning in 2003, Cockburn has been utilised primarily as a baseload operator performing a relatively small number of starts coupled with extended operating hours. The present trend for Cockburn operation is increasingly more starts and fewer operating hours. In other words, Cockburn is currently being utilised in a cyclic (two-shifting) fashion despite being designed to operate at baseload.

1.1 Consequences of two-shifting

Two-shifting implies that the station will not only perform additional cycles, but also be required to rapidly respond to load changes, thereby exposing components to larger than conventional ramp rates (Bendeich, Payten & Snowden 2010). The consequences of subjecting components to these harsher conditions are both mechanical and financial.

1.1.1 Mechanical Consequences

The most common mechanical problem experienced as a result of two-shifting is thermal-fatigue damage, which manifests in the mechanical failure of structures or cracking of individual components (EPRI 2001). In high temperature, high pressure cycling power plant it is likely that some components experience both fatigue and creep, which can act synergistically to cause premature failure (EPRI 2001). The American Society of Mechanical Engineers has recognized creep-fatigue interactions and provides guidance concerning the reduced life expectancies of materials. The solid line in Figure 1 represents the design life limit expressed as a fraction of material creep life and fatigue life for 2.25Cr1Mo (P22), a commonly used steel. The limit line conservatively demonstrates the effect of combining creep and fatigue mechanisms that were previously considered independent by design criteria (EPRI 2001). The dotted line indicates the effective operation of the component; actual component life is given by its intersection with the broken line.

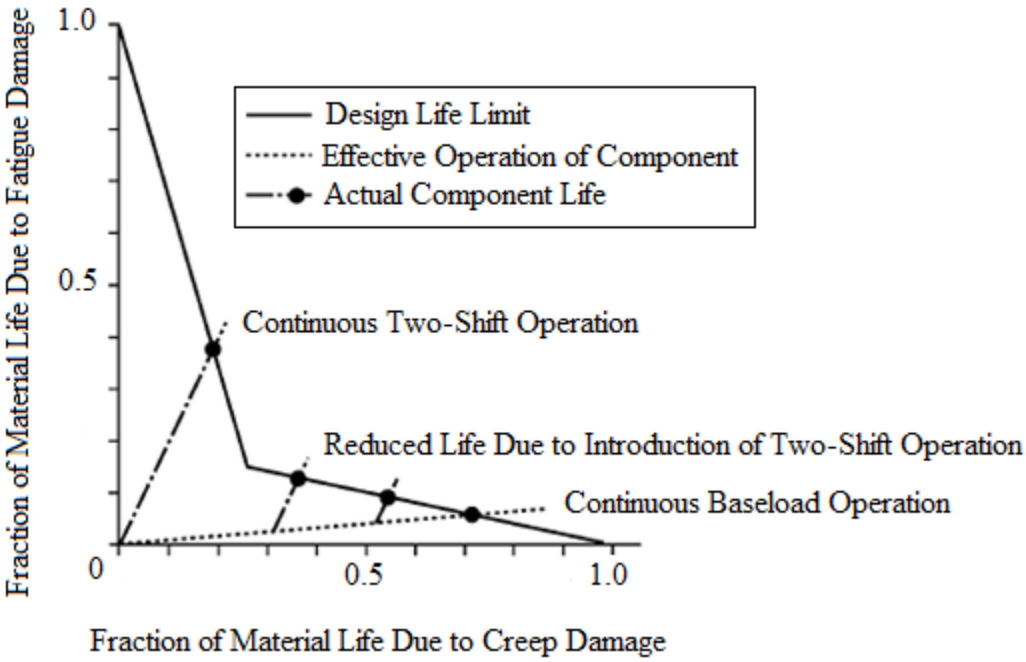

Figure 1 **The effect of introducing two-shifting on creep and fatigue interactions (EPRI 2001)**

Where two-shifting is adopted by a former baseload unit (as is the case at Cockburn), the residual life can be reduced to between 40% and 60% of the original design life (EPRI 2001). The key implication is that units designed for baseload operation and initially used in this capacity are susceptible to component failure when forced to operate in a cyclic regime. Cockburn is yet to experience the well-documented time-lag between commencing two-shifting and experiencing the resultant costs; lag times can be as long as three years (EPRI 2001).

1.1.2 Financial Consequences

The financial consequences of two-shifting arise primarily as a result of incurred mechanical damage. Below is a list of consequences associated with two-shifting, each of which has a financial penalty.

- More frequent scheduled outages
  - Each Gas Turbine (GT) start incurs a penalty of 20 additional operating hours for the GT and 50 hours for the Steam Turbine (ST). Maintenance based on Equivalent Operating Hours (EOH) has to be performed more frequently as the number of starts increases.
- More frequent forced outages

    - Transient conditions during start-ups and shutdowns make it difficult for automated controls to regulate plant conditions.
    - Notably thermal transients lead to thermal-fatigue thereby increasing the frequency of component failure.
- Reduction in availability
    - Increase in forced outages reduces plant availability. A portion of the money received by Verve is based on availability, regardless of whether the plant is utilised; the rest is obtained as compensation for the power generated. Availability reduction thus directly decreases Verve income and prevents generation opportunities.
- Increased operation and maintenance (O&M) costs
    - Two-shifting combined-cycle units is a relatively new practice worldwide; an active approach is adopted for monitoring and maintenance thus increasing those costs.
    - Increased capital spent on component replacement.
    - Wear and tear of components as a result of additional overhauls and maintenance.
    - Overall reduction in plant efficiency occurs as a smaller portion of plant operating time is spent at optimal load (baseload). The consequence is increased fuel usage when compared to baseload operation.
    - Potential for reduced plant life or increased capital required to extend plant life.
- Unforeseen costs as a result of the need for greater personnel training and more sophisticated evaluation and inspection techniques.

2. Damage Modelling and Results

A Cockburn-specific study is required to quantify the current mechanical integrity of the plant, identify critical components and assess the likely damage should two-shifting continue. However, performing an in-depth mechanical analysis of all CCGT components is impractical; it is therefore necessary to select a portion of the plant for further investigation. Literature identifies the HRSG (Heat Recovery Steam Generator) as a sub-section particularly vulnerable to the effects of two-shifting. Historically the global fleet of combined cycle units have exhibited a poor record of reliability and availability in terms of fatigue related, thermal transient driven, HRSG tube failures (EPRI 2006). It is still rare for HRSG design procurement specifications to define a set number of stop/start cycles, that the designed plant must be capable of performing (EPRI 2006). As a result many HRSGs have been designed to ASME Section I guidelines, which have no fatigue design requirements. HRSGs are not maintained on the basis of equivalent operating hours and are difficult to monitor and inspect due to limited space and access points. The future integrity and longevity of HRSG components is therefore uncertain and requires investigation.

HiTRLCAP (High Temperature Remaining Life Cost Assessment Program) is a software package capable of evaluating creep and fatigue damage and approximating component lifetimes. Modelling of plant conditions during start-ups and shutdowns was required to determine the necessary software inputs.

2.1 Component Condition Modelling

A large number of HRSG components were identified for analysis including tube bundles, 18 ‘porcupine’ headers, 58 upper branch headers, 58 lower branch headers and 2 drums; therefore a simple method for modelling component conditions was required. PGIM, a Verve

Energy data recording system, provides some relevant temperature, pressure and flow information at several locations in the HRSG. Only bulk properties of steam, gas and liquid are monitored; ideally component metal temperatures would be measured.

Table 1 contains typical HRSG heat transfer coefficients; due to the comparatively low heat transfer coefficient of the flue gas, it follows that metal temperatures run reasonably closely to water/steam temperatures (Starr 2003). This is particularly true for components such as drums, branch headers and 'porcupine' headers which are seperated from the exhaust gas path by a floor/roof plate. Component wall temperatures are therefore approximated as water/steam temperatures.

	Flue Gas	Economiser Water	Evaporator Water	Steam
Heat Transfer Coefficient ($Wm^{-2}K^{-1}$)	50	500	2500-10000	1000

Table 1 Typical HRSG heat transfer coefficients (Starr 2003)

As only specific locations are monitored, a means of relating measured data to nearby components is required. When located close to thermocouples, component conditions are taken as the measured values. For components further away, between two measured points, the estimated temperature is based on heat transfer. The heat transfer equation for convection indicates that a proportional relationship exists between the heat transfer surface area and heat transfer rate. Heat is transferred from the flue gas to the water/steam running inside tubes within the gas path; therefore the relative surface area of tube bundles is used to calculate the temperature of components between two thermocouples. The resulting data forms the basis of the inputs required by the HiTRLCAP software.

2.2 Component Damage Modelling

HiTRLCAP calculates component damage on the basis of the fit-for-purpose assessment procedure R5, developed by British Energy, BNFL Magnox Generation and Serco. The following modes of failure are considered; excessive plastic deformation due to a single application of a loading regime, incremental collapse due to a loading regime, excessive creep deformation or stress rupture, and initiation of cracks in initially defect-free materials by creep and creep-fatigue mechanisms. R5 does not apply the safety factors inherent in standard design codes such as ASME III, which tend to be exceedingly conservative.

HiTRLCAP uses simple thick-walled cylinder models to establish temperature and stress profiles through-wall (Bendeich, Payten & Snowden 2010). To account for stress variations with geometry, calculated stresses are modified by stress concentration factors or the superposition of polynomials based on closed form solutions. Closed form solutions detail the critical stresses in specific geometries and are based on comprehensive 3D finite element analysis.

2.3 Damage Modelling Results

All components demonstrated sufficient margins against plastic collapse. The majority of components satisfied the criteria for insignificant cyclic loading meaning failure will eventually be dominated by creep rupture rather than creep-crack initiation and growth. Critical ramp rates define the ramp at which components would be adversely affected by cyclic damage; in general critical ramp rates were in excess of 100°C/min whilst the maximum calculated ramp rate of all components was 38°C/min. Critical ramp rates provide an indication of a components sensitivity to thermal transients based on design and material.

Two components were identified due to the minimal difference between calculated and critical ramp rates (Table 2). For both components creep-fatigue lifetimes were greater than the required 25 years, however further investigation is necessary to determine whether actual ramp rates exceed critical values. Twelve thermocouples were recently installed on 'porcupine' Header M17 to verify calculated ramp rates.

Component	Calculated Maximum Ramp Rate (Deg/min)	Critical Ramp Rate (Deg/min)
HP Drum	6.39	>10
M17 Header	18.98	>19

Table 2 Critical components identified by HiTRLCAP

3. Cost Modelling and Results

All costs are provided in Monetary Units (MU), related to the cost of fuel.

3.1 Short-Term Cost Analysis

Short-term costing provides an indication of the immediate costs of two-shifting such as additional fuel usage (compared to baseload operation). Monitoring fuel flow, Gas Turbine (GT) power and Steam Turbine (ST) power over the period of a start-up, provides a measure of efficiency, by relating the amount of fuel used to the amount of energy produced. The fuel required at baseload to produce the same amount of energy can be readily calculated, and the difference in fuel consumption is clearly an additional cost of two-shifting. Each start-up/shutdown cycle adds 20 hours to the Equivalent Operating Hours (EOH) of the GT regardless of the type of start; thereby bringing maintenance forward without generating power. It is fitting to include the cost of 'additional' EOH using the frequency of outages and their historic costs. A/B outages (4 days long) are performed after 6000 GT EOH whilst a C outage (6 weeks long) is performed after 24,000 EOH. Table 3 shows the total differential cost of each type of start; the classification of starts is based on the ST rotor temperature when fuel flow begins. Actual costs will vary with changes in fuel price and the time spent loading from zero to baseload; the ratio of costs is generally more useful than the MU figures.

Start Type	Energy Produced (MWhr)	Fuel Used (TJ)	Baseload Fuel Required (TJ)	Fuel Difference (TJ)	Fuel Cost (MU)	Relation to A/B Outage (MU)	Relation to C Outage (MU)	Total Cost (MU)	Total Cost Ratio
COLD 1	687.0	7.8	5.4	2.4	11	0.8	17.5	29.3	1.00
COLD 2	755.3	7.7	5.9	1.8	8	0.8	17.5	26.3	0.90
WARM 1	1360.1	12.2	11.1	1.1	5	0.8	17.5	23.3	0.80
WARM 2	452.9	4.2	3.6	0.7	3	0.8	17.5	21.3	0.73
HOT	151.3	1.7	1.2	0.6	3	0.8	17.5	21.3	0.73

Table 3 Short-term differential cost of each type of start.

3.2 Low-Load vs. Two-Shifting Analysis

Cockburn engineers have recently approved operation at low loads, typically for overnight use, as an alternative to full shutdown. As a result, a comparison of the costs of two-shifting and low-load operation is warranted. The fuel used and power produced at low overnight load can be compared with the fuel used for starts, the power produced and the EOH penalty. Table 5 and 6 reveal that two-shifting i.e. overnight shutdown, is generally more economical than operating at low-load for the normal shut-off period of 8hrs. However, overnight operation may have other benefits such as reducing the severity of thermal transients thereby increasing component lifetimes.

Partial Load (MW)	Energy Produced (MWh) in 8 hrs	Fuel Used (TJ) in 8 hrs	Energy Produced (MWh) from part to full load.	Fuel Used (TJ) from part to full load	Total Energy Produced (MWh)	Total Fuel Used (TJ)	Total Fuel Cost (MU)	Total Revenue (MU)	Total Profit (MU)
50	400	7.59	137	1.22	537	8.81	41	19	-22
65	520	8.54	257	2.33	777	10.87	50	27	-23
80	640	7.21	216	1.89	856	9.1	42	30	-12

Table 5 Summary of low-load data

Operation Type	Energy Produced (MWhr)	Fuel Used (TJ)	Total Fuel Cost (MU)	Total Revenue (MU)	Profit (MU)	Relation to A/B Outage (MU)	Relation to C outage (MU)	Total Profit (MU)
COLD 1	687.0	7.8	36	24	-12	0.5	10.5	-23
COLD 2	755.3	7.7	36	26	-10	0.5	10.5	-21
WARM 1	1360.1	12.2	56	48	-8	0.5	10.5	-19
WARM 2	452.9	4.2	19	16	-3	0.5	10.5	-14
HOT	151.3	1.7	8	5	-3	0.5	10.5	-14

Table 6 Summary of revised start data

4. Conclusions and Future Work

The screening process carried out by HiTRLCAP indicates that the majority of components have a useful remaining lifetime that exceeds the operational requirement of the station. Two components of interest were identified; Header M17 and the HP Drum. Installed thermocouples will provide information concerning the conditions experienced by M17 including ramp rates and any tube-to-tube temperature differences. Future work may involve more comprehensive finite element modelling of both components and thermocoupling of the drum. Also HiTRLCAP may be used for preliminary damage assessments of other components such as turbines, turbine casings, valves and steam chests.

Short-term costing indicates that two-shifting is significantly more costly than baseload operation. Secondly, depending on the load, it is likely that low-load overnight operation is more costly than two-shifting.

5. References

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