The Cost of Cycling Coal Fired Power Plants

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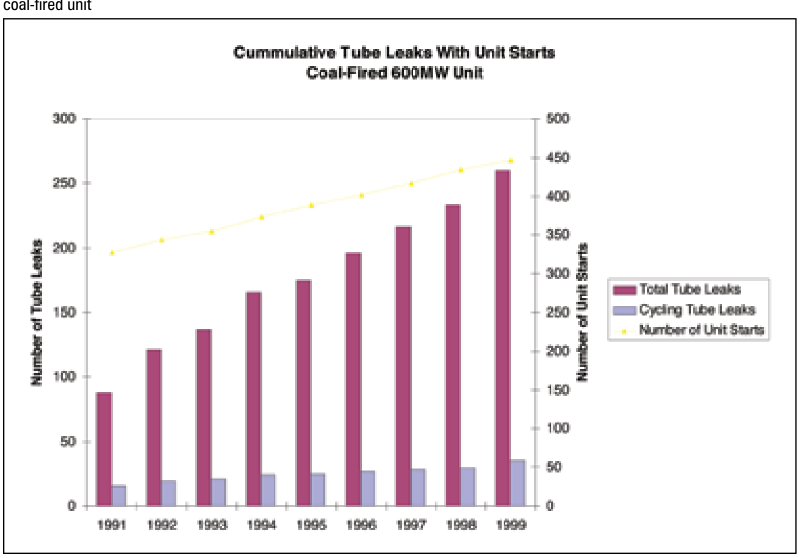
Cycling operations, that include on/off startup/shutdown operations, on-load cycling, and high frequency MW changes for automatic generation control (AGC), can be very damaging to power generation equipment.

This is especially true when the plants have not been designed for cycling operations. A comprehensive analysis conducted on more than 150 coal-fired units has shown that the financial costs associated with cycling operation are very high.

An analysis of selected older coal-fired plants has found them to be more rugged and cost effective to cycle than the newest combined cycle units. Low fuel prices are another advantage of coal. Making the decision to cycle coal-fired units should be carefully considered, as there are numerous long term effects, component damage and significant costs that need to be carefully calculated.

The true cost of on/off, load cycling and high load operations of 90-120 percent of rated capacity are often not known or not well understood by utility operators. Even when a unit is designed for cycling, there are external effects in the balance of plant design, water chemistry, pulverizer and coal/ash types. To optimize operations and determine the true cost of each operation, cycling of units should be subjected to a thorough analysis of their cycling operations. Utilizing this knowledge, a power plant is able to significantly reduce costs, have more operational flexibility, faster MW response and improved profitability.

Figure 1: Cumulative tube leaks versus unit starts for a 600 MW coal-fired unit



WHY ANALYZE CYCLING DAMAGE AND COSTS?

Knowledge of operating costs in real-time is critical to the competitive power business. During high profit times, operators should be able to respond faster to changes in load while at the same time operating at or above the unit's maximum rating. During low power price periods, an operator must decide to either shutdown and incur significant cycling damage or to operate at minimum load.

Other questions include: What, in terms of fuel costs and cycling costs, is the least expensive combination of units to meet system load? Can I reduce the cost/price of base-load power in a long-term power sales contract? How much savings is there if I reduce the number of unit cycling operations? Does one maintain plant equipment on the basis of operating time, or on the basis of number of accumulated cycles?

Passing the high cost to cycle power plants on to competitive utilities, by not cycling on/off or going to two-shift operation for specific units with low cycling costs, is an effective competitive strategy when cycling costs are analyzed.

ANALYSIS AND DAMAGE MODELING

APTECH has analyzed the cycling costs in more than 300 power-generating plants, including more than 250 American units, 20 Canadian units and 16 European Union units. The units have included 15 MW to 1300 MW coal, oil, and gas fired units with sub critical drum-type and supercritical once through Benson type boilers with varying turbine, boiler, and balance of plant manufacturers. All of the units had a range of designs and operational regimes. Some were designed for cycling with European style turbine bypass systems, plants designed for base-loaded operations and units subjected to heavy cyclic operations. Many of the units were being operated at or above the unit's maximum continuous rating operation (MCR).

Although running a plant above MCR may be costly, it can save a rapid costly start up on another unit in the fleet. Regardless of type, each unit in the fleet should have its cost analyzed so that the utility can dispatch a unit with similar cost.

DAMAGE MECHANISMS OF CYCLING

Definitions of cycling have varied from on/off starts, (normally defined as hot, warm, and cold starts) and two-shifting to load cycling and high frequency load variations. Inclusion of all cyclic operations is critical to proper analysis. Many units have only a few starts, but provide a large amount of intra hour load following and AGC services. However, this can significantly add to a unit's cyclic damage. Hot starts are typically defined to have very high, 700F to 900F, boiler/turbine temperatures and less than 8 to 12 hours off-line.

Warm starts have boiler/turbine temperatures of 250F - 700F and are off-line for 12 to 48 hours. Cold starts are ambient temperature starts, with boiler turbine temperatures below FATT fracture appearance transition temperatures, 250F or less, and have 48 to 120 hours off-line. These definitions may vary due to unit size, manufacturer and dispatcher/Independent System Operator (ISO) definitions.

Damage manifests itself in terms of known past and future maintenance and capital replacements, forced outages and deratings from cycling. It can also result from high load operation. Often the damage mechanism is fatigue and corrosion of the boiler tubes. Boiler tube damage, from cycling operations on a constantly fired cyclone fired boiler, is shown in Figure 1. Replacement of major plant components versus cycles and operating time are shown in Figure 2. The time to failure from cycling operation in a new plant can be from 5 to 7 years and in older plants nine-months to two-years after start of significant cycling.

> To optimize operations and determine the true cost of each operation, cycling of units should be subjected to a thorough analysis of their cycling operations.

METHODOLOGY: CALIBRATING DAMAGE TO COSTS

The vast number, of unit types, equipment manufacturers, balance of plant types, and operational regimes makes the cycling costs difficult to categorize. However, damage models have been developed that include creep and fatigue and their interaction for each unit type, pressure range and temperatures. These models account for cyclic operation, base-loaded operation, and operation above MCR. The models are calibrated with plant signature data (temperatures and pressures) for key unit components

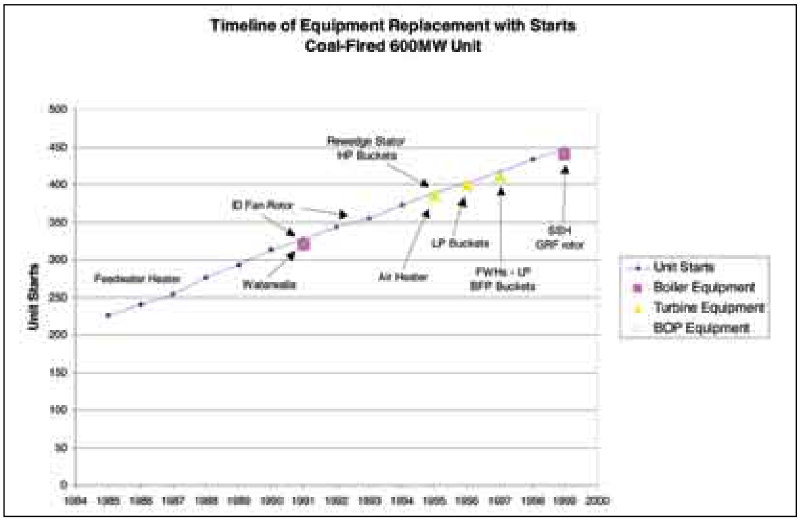


Figure 2: Equipment replacements versus starts for a 600 MW coal-fired unit

operating during typical load transients. Damage model validation process includes the assessment of key components with finite element analysis and creep/fatigue analysis methods.

By utilizing these models, it is possible to determine the remaining useful component life. Life cycle analyses of key high cycling cost components are statistically calibrated to the failure history of the components. All of the damage is calibrated to actual plant costs. Traditionally, un-calibrated engineering fatigue and creep analyses are rarely useful, and are often misleading in predicting cycling costs.

Critical components wher detailed plant signature data is analyzed include:

- Steam drum
- Water wall /evaporator tubing
- First/second pass water wall tubing
- Superheater and reheater tubing and headers
- Economizer inlet
- Start up system components

In addition, analysis is carried out for the turbine/generator-related components: Valves, cases, generator windings and steam chests.

The maximum temperature ramp rate and the overall range of temperature change experienced by a component during the transient are key indicators of cycling-related creep and fatigue damage. All of the parameters are used to quantify the severity of each unit's load, start up, and shut down transients. Signature data is also used in evaluating and troubleshooting a unit's cycling operations.

Using this information, the operators are able to determine the recommended temperature for the ramp rate limits for the superheater and economizer during all types of start up, and shut down and cooling. With this information the operators are able to minimize damage, maximize the asset's life and reliability while reducing maintenance costs.

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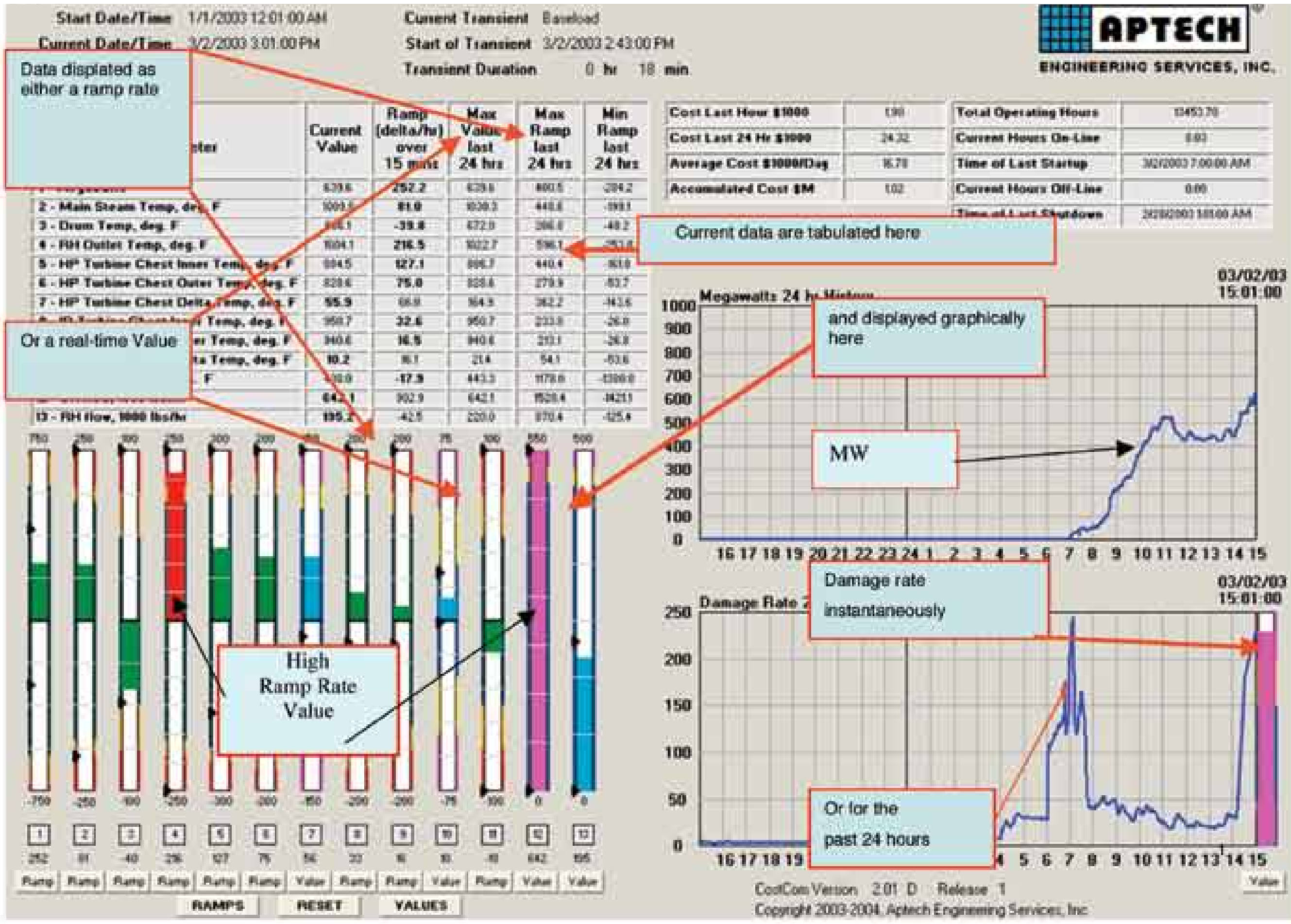

Figure 3: Real-time operating data

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Signature data is utilized by APTECH to calibrate its cost control of operations and maintenance program. This real-time code displays temperature ramp rates in key components and alerts the operators of excessive ramp rates. Ramp rates that should not be exceeded are displayed in green (OK), yellow (caution) and red (high damage do not exceed). It also calculates the wear and tear/cycling costs of the startup, load change, or steady state plant operation Figure 3.

Damage modeling is combined with historical capital maintenance spending and unit loading over time, to derive cost per unit-specific typical load cycle. Typically, annual capital and maintenance spending information for a minimum of seven years, is evaluated. Costs not related to unit operation are not used. An example of total (raw) screened (candidate) and smoothed cycling costs for a large power plant is shown in Figure 4.

Hourly MW data is evaluated, for the same period, and based on correlation of MW output to historical capacity factors, starts and total annual generation, is generally extrapolated back in time to the unit's startup date. One-minute MW data is analyzed for several typical months of operations when the unit provides automatic generation control, MVAR, and voltage support. Outage data and availability, plus outage cause code data, is evaluated for the entire operational period since unit startup.

CYCLING COSTS

The overall range of cycling costs, compared with commonly assumed costs is shown in Figure 5. This includes all cycle types of hot, warm, and cold starts for the three types of small drum and large supercritical boilers. The unit's specific analysis results depend on the regression analysis of the costs versus cycles and the unit signature data during cyclic operations at all load changes. The increased incremental costs attributed to cycling fall into the following categories:

- Increases in maintenance and overhaul capital expenditures
- Forced outage effects, including forced outage time, replacement energy, and capacity
- Cost of increased unit heat rate, long-term efficiency and efficiency at low/variable loads
- Cost of startup fuels, auxiliary power, chemicals and additional manpower required for unit startup

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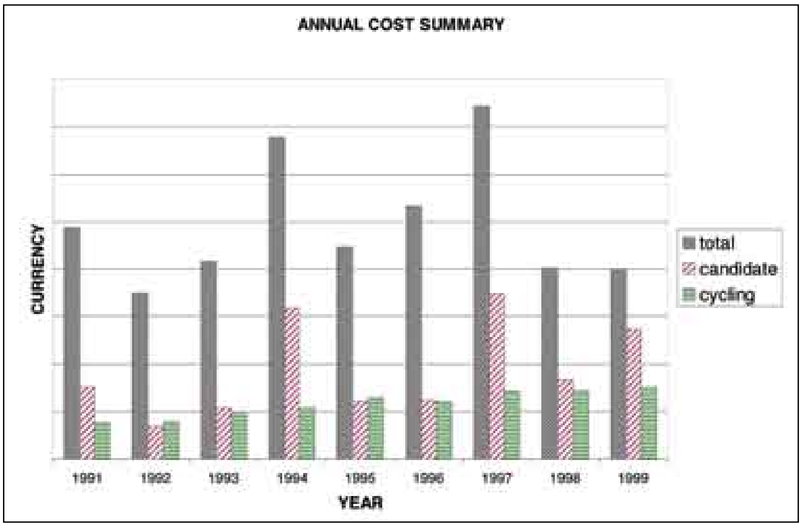

Figure 4: Annual cost summary

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- Long-term generation capacity costs increase due to a shorter unit life.

Measurement of unit heat rate cycling, while at steady state indicates there is significant degradation in unit heat rate when power plants cycle extensively. Poor efficiency is due to low load operation, load following, unit startups and unit shutdowns. The cumulative long term effects of cycling can increase the unit heat rate due to fouled heat exchangers, warn seals and wear/tear on valves and controls. The resulting cost increase for a base-loaded plant is significant.

REDUCING CYCLING COSTS

As a result of the analysis of the signature data during cycling operations, recommendations are made for operational changes, chemistry improvements and hardware additions and/or modifications. Operational changes consist of modifying temperature ramp rates of key components. To increase unit response and minimize damage and costs, it is recommended that the on-line ramp rates be increased by a factor of 2 to 10. This is accomplished by decreasing the ramp rate during cold and warm startup/shutdown operations. Startups and rapid shutdowns are generally the most damaging in units not specifically designed for cycling.

However, plant chemistry during startup, shutdown and unit lay-up can have a major impact on component damage and cost. Hardware modifications include short-term additions of thermocouples and additional monitoring of equipment. Thermocouples are used to monitor the temperature of the boiler down-comers to water wall temperatures and to monitor steam line temperatures/quenching during critical shutdowns. Longer-term, modifications to the boiler tube supports, gas fan turning gear, pump valve/orifices, pulverizer monitors and startup bypass systems, may be considered.

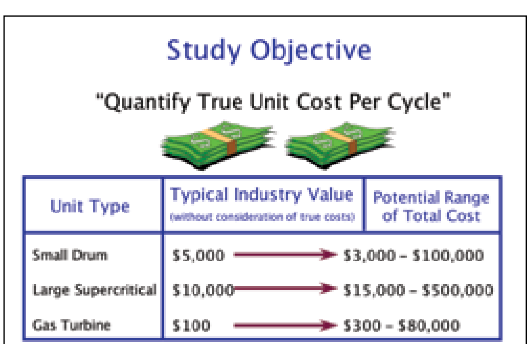
High MW ramp rates on plants not designed for cycling, and some that have startup bypasses, can lead to high temperature/pressure rates of change. When this occurs, it can produce component damage and increase maintenance costs. A recent analysis of two identical 550 MW units, at two different utilities, resulted in nearly identical basic cost per cycle when costs and historic cycles were analyzed.

On the other hand, when signature data was taken and validated by analysis of historic trends, one unit had cycling costs for typical starts that were half of the other unit's cost. The reason for this was due to gentler MW and temperature/pressure ramp rates. In an analysis of a European unit, designed for cycling with a turbine bypass, the majority of tube failures, and significant costs resulting from rapid starts, could be attributed to one component alone-the reheater. This was due to excessive fast temperature changes during startups. Calculations showed that by correcting this operational problem would result in a cost reduction of at least 20 percent per start and a similar, or greater, forced outage reduction.

It is important for utilities to examine the highest fuel/production cost units in their system and determine the cycling costs. Minimizing unit and system costs can be achieved by using real time cost data. Besides financial data and MW data, plant signature data is required to properly analyze and determine cycling costs. The assessment of actual plant temperatures, pressures, and unit chemistry during cycling operations is critical to correctly analyzing cycling costs. In addition, not including the high frequency intra-hour MW variations could lead to serious errors when calculating cycling costs. All of the data is used to assess damage per cycle, calibrate damage models, diagnose problems and make cost saving recommendations.

It is essential that in today's competition in the electric marketplace that coal-fired power plant, those cycled and base-loaded, be profitable. This is effectively done with a detailed cyclic cost analysis and optimizing the operations and maintenance of the plant.

Figure 5: Quantifying true unit cost per cycle



Unit Type	Typical Industry Value (without consideration of true costs)	Potential Range of Total Cost
Small Drum	$5,000	$3,000 – $100,000
Large Supercritical	$10,000	$15,000 – $500,000
Gas Turbine	$100	$300 – $80,000