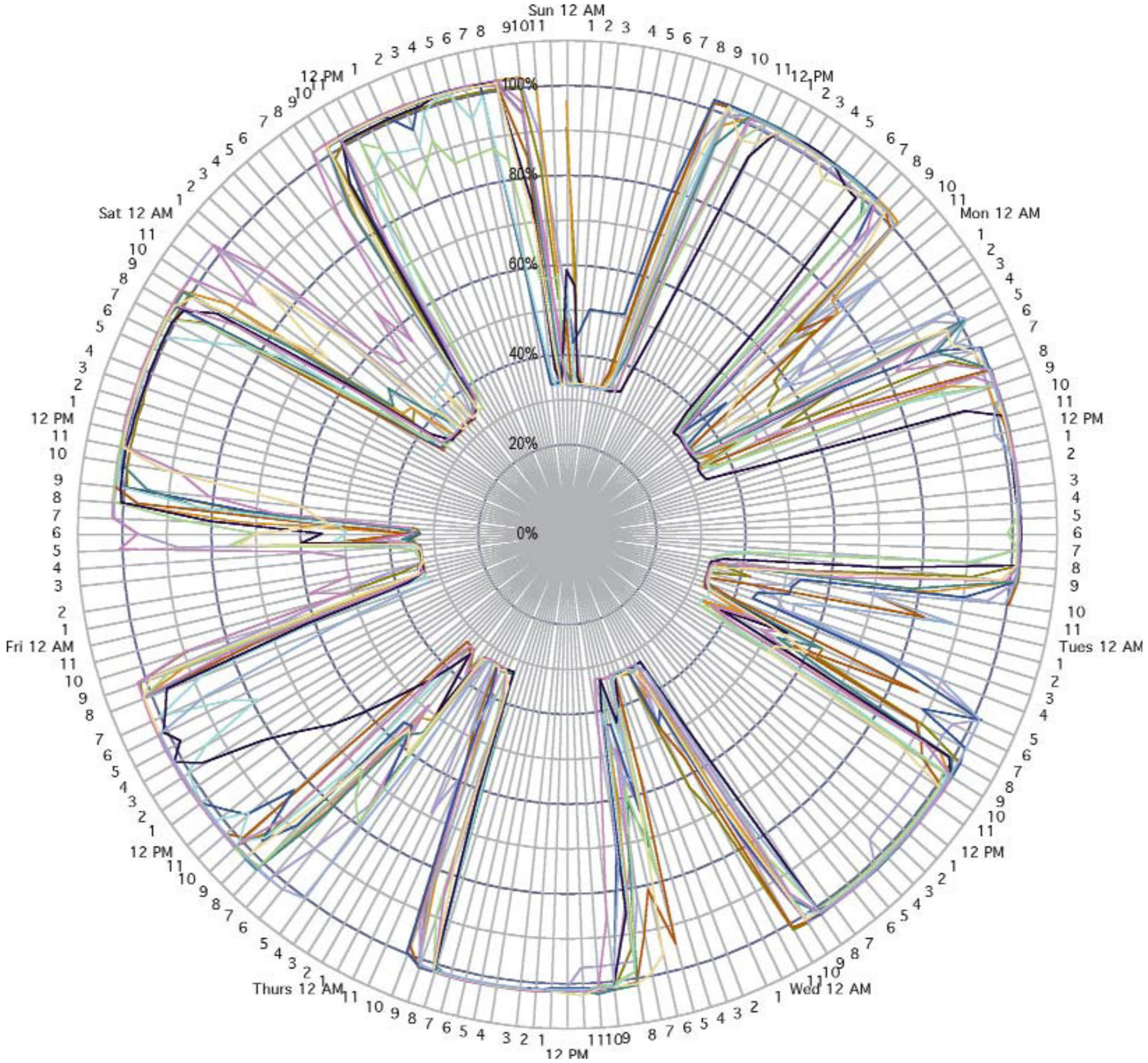
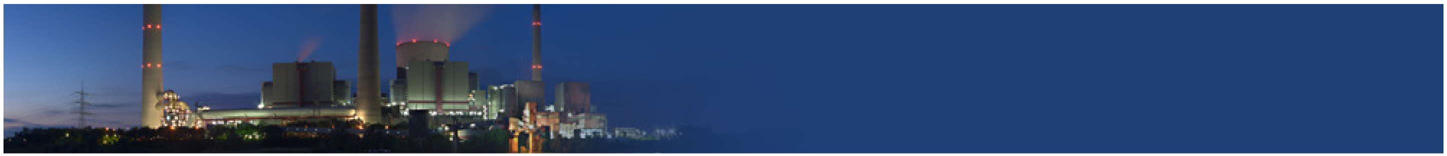
ELECTRIC POWER
RESEARCH INSTITUTE

Primer on Flexible Operations in Fossil Plants

September 2013





Introduction

This primer describes the significant changes that have occurred over the past decade in the duty cycles of fossil power plants and the implications for plant equipment and costs. These changes include the increasing shift in coal-fired and natural-gas-fired power plants from high-capacity-factor, baseloaded operation to various modes of flexible operation, including load-following and low-load operation.

The primer reviews the different types of duty cycles, the stresses that the changes in plant operation put on plant equipment, the potential damage to equipment due to cycling, other effects of cycling, and the mitigation strategies that plant operators are putting into place.

Historical Modes of Operation

Cycling and load following are not new but have long been part of the system of matching electricity generation to demand.

Historically, some U.S. power plants, because of their relative economics compared to other supply sources on the system, were among the first to be dispatched. They ran continuously year round at high load factors (roughly 95%) and had few shutdowns and startups. These plants operated as “baseload” capacity. Baseload units were designed and built to operate most efficiently at steady-state, high-load levels (Figure 1). They were designed to take full advantage of the energy available from high-temperature, high-pressure steam. These units were also normally designed for operation with constant pressure and temperature at the turbine throttle throughout most of the operating range.

Figure 1 – Baseload fossil plants were typically designed to run at steady-state, high-load levels.

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Other electric generating units, historically, were designed to operate in "cycling" modes. These modes mimicked cycles in electricity demand. That is, cycling units varied their hourly load depending upon demand levels. Some units smoothly "followed load" over the course of a day, while other units would be expected to vary load continuously, responding to requests for load increases/reductions as frequently as every four seconds as needed to balance load on a system. Some types of electric generating units, such as simple-cycle combustion turbines, which were built to start up and shut down quickly, were specifically designed to operate efficiently in cycling modes.

Rise in Flexible Operation

Over the past decade, these patterns in duty modes and plant dispatch have changed. What's new today are the increasing frequency and level of cycling and the types of plants required to run in cycling modes.

Several factors are contributing to changes in plant duty cycle. These factors vary from region to region and country to country.

- *Natural Gas Prices.* In the United States, one key factor has been sustained low natural gas prices and higher coal prices. This trend has led to natural-gas combined-cycle plants being dispatched ahead of coal units in some regions, particularly older, less efficient subcritical coal units. While in Europe, gas prices are much higher, combined-cycle plants are in long-term lay-up, and coal units are providing the load-following duty.
- *Renewable Generation.* A second factor in some regions is the increasing deployment of different sources of intermittent renewable generation such as solar and wind, which are dispatched as "must-take" and force fossil plants to provide load-balancing services (Figure 2). The need for fast-ramping fossil plants is particularly acute when the renewable generation is not treated as dispatchable generation.
- *Economic Conditions.* A third factor is the economic recession, which reduced overall demand and, in many cases, industrial demand specifically. Industrial demand is typically flat throughout the year, while residential and commercial demand varies seasonally as well as throughout the day. The trend toward lower industrial demand and an increasing proportion of electricity consumption by the residential and commercial sectors has created more volatility in overall consumption.

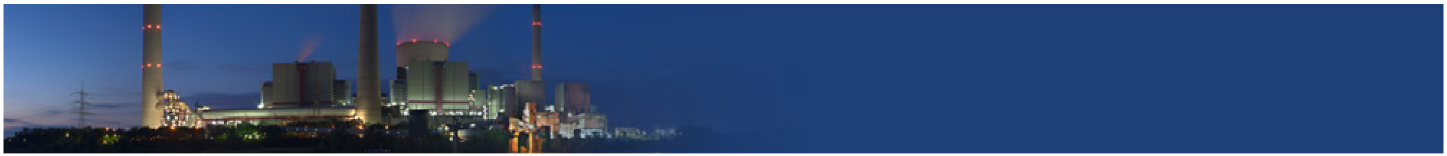
Figure 2 – Increasing use of renewable generation is one important factor contributing to changes in plant duty cycles.

- *Environmental Controls.* A fourth factor involves the high capital costs of installing mandated environmental controls, which is leading to rising bid prices, and therefore, declines in merit order, for some formerly baseloaded coal-fired plants, forcing them to operate more in a flexible operating mode.

Impacts on Plants

The consequences of these trends is that many fossil plants, especially coal-fired plants, which in the vast majority of cases, were designed for baseload operation, are being operated at other duty cycles. These cycles include load following and two-shifting, which involve more frequent startups and shutdowns, and low-load operation.

The changes in plant operation put new stresses on plant equipment and can potentially lead to equipment damage, higher heat rate,



shorter equipment life spans, and deceased reliability in the form of higher outage rates. These effects increase a unit's cost of generation over the short or long term.

To address these issues, mitigation strategies are available, as described in the section titled "Strategies to Mitigate the Effects of Cycling." These strategies include: (1) minor-cost items, such as additional instrumentation, modified or new procedures, and training; (2) moderate-cost items, such as modifications for motor soft start or adding by-pass systems; and (3) items requiring additional research, such as new thinner materials that can withstand the pressures and temperatures of a large thermal power plant, and are, therefore, less susceptible to the effects of thermal mechanical fatigue.

Duty Modes

The term "cycling" encompasses a wide range of plant operating modes. Today flexible operation is broadly defined as any mode of operation other than baseload. In general, these modes can apply to both coal and gas-fired units, although these asset types have different operational limitations relative to the various modes. Generating assets can be forced to operate in more than one mode or switch modes over time or season depending on changes in demand.

To better understand the issues of flexible operation, it's useful to define the specific types of duty modes:

- ***Two-shifting.*** Starting up and shutting down a plant each day to meet load demand during periods of high demand (Figure 3).
- ***Double Two-shifting.*** Starting up and shutting down a unit twice a day, regularly to match the early morning and evening peaks in load demand.
- ***Minimum Load/Reduced Load/Turndown.*** Steady-state power at which a plant can safely operate within its limits when demand is low.
- ***Weekend Shutdown.*** Schedule involving shutdown on weekends while providing load during the week. Many times, these plants turn down to some minimum load when demand is low and/or overnight.
- ***Load Following.*** Operating online for more than 48 hours, with varying load throughout the day as demand changes. Many times, these plants turn down to some minimum load when demand is low.
- ***On-load Cycling.*** Cycle requiring baseloading during the day and ramping down to minimum load overnight.
- ***Sporadic Operation.*** Typically, operating for more than two weeks and shut down for several days at a time. Many times, these plants turn down to some minimum load when demand is low and/or overnight.

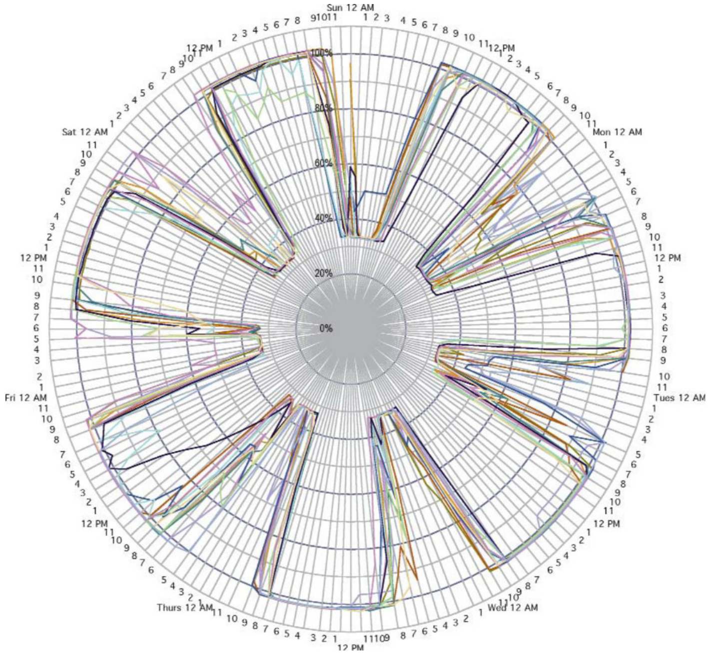


Figure 3 – Illustration of a load cycle. The circular shape represents a week. One rotation equals seven days. The cycle shown is two-shifting, maximum load daily, off at night (from EPRI report 1004412).

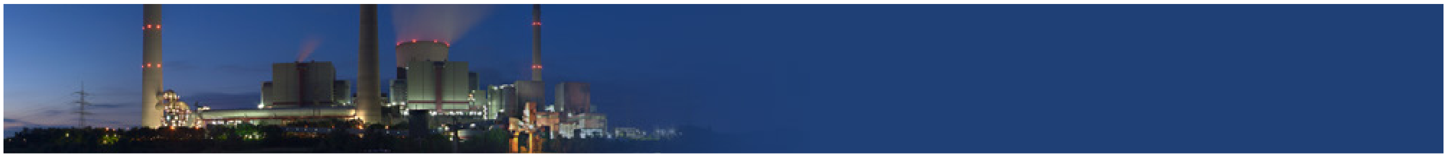
Operational Stressors

The changes in plant operation that are necessitated by variable duty cycles can stress plants in different ways.

Startup

Cycling involves more frequent startups as plants go online to match demand patterns. Fossil plants that once experienced startups every few months may now be cycling far more frequently, in many cases once a day.

Startups involve changes in temperature and pressure throughout a plant. Starting up a plant requires a sequence of operations to be performed to bring the plant into service and to warm the boiler along a profile that matches thermal constraints of construction



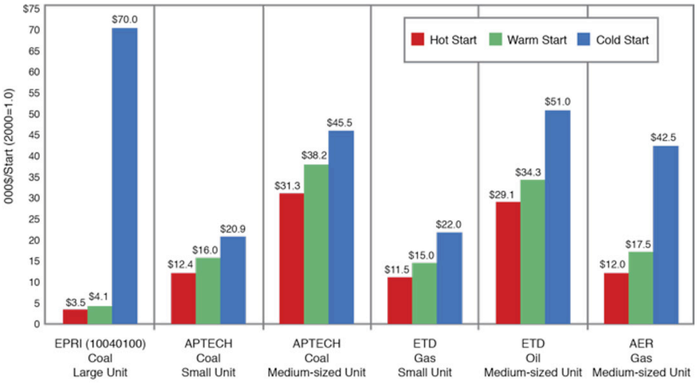


Figure 4 – Potential equipment damage increases with greater frequency of cold starts (from EPRI report 1004412).

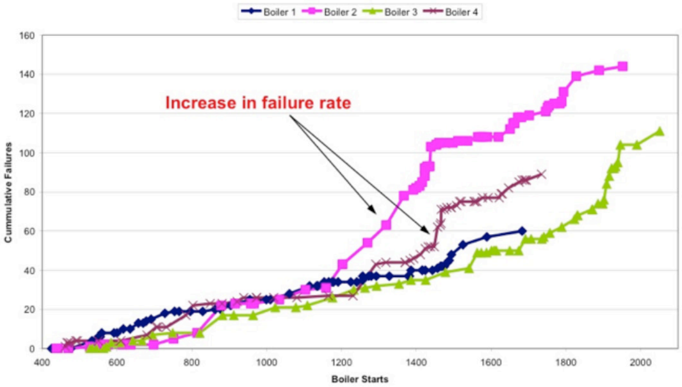


Figure 5 – Rates of boiler failures increase with increasing boiler starts (courtesy E.ON).

materials. Optimizing the process requires a careful balance between minimizing the startup energy cost and limiting the plant damage.

Starts are defined differently by each utility and unit, but are typically categorized as follows:

- ***Hot starts*** are less than 8 hours of shutdown, with turbine metal temperatures above 400°C.
- ***Warm starts*** are 8-48 hours of shutdown, with turbine metal temperatures greater than 200°C.
- ***Cold starts*** are more than 48 hours, with turbine metal temperatures less than 200°C.

Starts that involve greater temperature and pressure changes (cold starts) have more potential for equipment damage than starts with less temperature and pressure change (hot starts). Figure 4 shows the results of cost studies conducted in 2001 to 2002 by EPRI, APTECH, ETD, and AER. The figure shows the estimated non-fuel cost per type of start for different kinds of plants. A general rule is warm starts are three times more stressful than a hot start, and cold starts are five times more stressful than a hot start.

During startup, potential problems may arise in boilers when flow through the boiler may not have been established or may be at low rates, which can cause localized overheating (Figure 5). For turbines at startup, temperature differences between the turbine and the surrounding steam being admitted to the turbine can create temperature gradients that lead to cracking damage.

Ramping

Ramping is the process of increasing plant load. It occurs more often under load-following as plants increase or decrease load. As with start-up, it involves changes in temperature and pressure. If the changes occur too rapidly, equipment can be damaged. The ramp rate is the amount of load that can be added to a turbine per unit of time. This rate is usually a manufacturer's specification to control how much load can be added to unit systems without overstressing them.

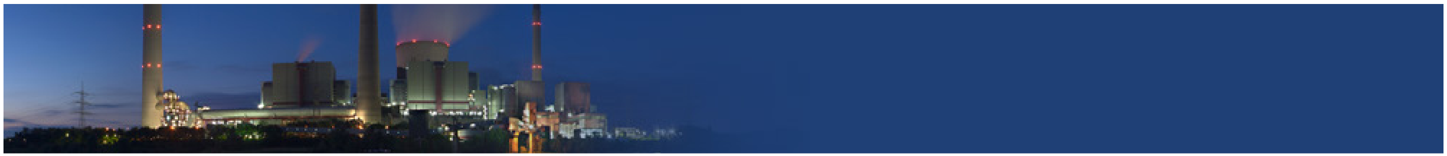
Low Load

Low-load operation typically involves operating plants below design flow rates, temperatures, and pressures. Fossil plants may be forced to operate at low load when other resources, such as renewable generation or lower-cost units, are dispatched. This operational mode can create challenges for some plant processes, which may not operate properly below design parameters.

For example, one type of environmental control technology, known as selective catalytic reduction (SCR), is significant in the cycling debate because it is one of the prime limiting factors in a unit's low-load operation.

SCR systems, which are currently deployed in 260 U.S. coal-fired units, reduce nitrogen oxide (NOx) emissions by injecting ammonia into the flue gas stream as the gases pass through a catalyst chamber.

For SCR systems to perform correctly, flue gas temperatures must be at or above a minimum operating temperature, defined by the catalyst vendor, to achieve required levels of NOx reduction and avoid ammonia passing through unreacted. The temperature limit is designed to avoid deposition of ammonium bisulfate, a sticky corrosive liquid that forms at lower flue gas temperatures and can deactivate the catalyst by filling the catalyst pores.



Shutdown or Layup

Shutdown or ***layup*** involves the powering down of a plant for economic dispatch, forced outage, or scheduled maintenance outage. During shutdown, plants are required to maintain cycle chemistry regimes in order to preserve protective oxide surfaces on all components throughout the steam and water circuits. Failure to maintain these regimes can cause corrosion.

Damage to plant equipment from improper layup procedures continues to be a problem for U.S. fossil plants. Improper layup practices are a major contributor to boiler tube failures and to steam turbine pitting and cracking.

Layup of idle equipment may be conducted in one of two ways: wet or dry.

- ***Wet layup*** permits chemically treated and deaerated water to remain in the boiler, deaerator, condenser, and all associated piping. The focus is to ensure the proper chemical treatment and prevent air entering any wet area in the cycle, which can initiate pitting and promote corrosion.
- ***Dry layup*** is an alternative for protecting closed-in equipment, such as pressure vessels and piping. It is an especially effective method when equipment must be opened and inspected periodically. Two options can be used for dry layup: nitrogen gas blanketing and dry air.

The decision on which layup method to use can be made for each piece of equipment; for example, the boiler can be drained and kept dry for repairs, while the deaerator contains water and a nitrogen blanket for a quick restart.

Shutdowns vary by duration.

- A ***short-term shutdown*** involves periods extending overnight or through a weekend. It is typical of cycling operation and utilizes a wet layup or hot standby approach.
- An ***intermediate shutdown*** consists of periods extending more than a weekend and up to one week. This duration could typify a shutdown for equipment repair of a modest nature. Either wet or dry approaches can apply.
- A ***long-term shutdown*** involves periods extending for a few weeks to six months. This duration could include major equipment repair, planned outage, or a long-term layup due to system load requirements, and could include mothballing. Both wet and dry approaches can apply, but if return-to-service is not an issue, totally dry layup is preferred for extended outages.

However, at the beginning of an outage, the duration of the required layup is not always clear; short-term outages can quickly become long-term outages, with different layup requirements or preservation techniques.

Many older, formerly baseloaded plants that are now being operated as cycling and peaking units face special challenges. For these plants, layup practices may not have been a significant concern in the past, but now are critical for reliably performing in a new operating mode requiring many starts per year or extended downtimes between periods of operation. These same units, however, may not be equipped for nitrogen blanketing or have adequate drainage systems to accommodate layup practices and may need modifications.

Power Plant Damage Due to Cycling

Operating a power plant in any mode triggers damage mechanisms, and damage to material and equipment accumulates over time. Steady-state load operation, associated with baseload operation, can lead to stresses from operating constantly at high temperatures and pressures.

Cycling load is associated with stresses from varying temperatures and pressures, which trigger fatigue and fatigue-related damage mechanisms. Damage accumulates with each cycle, and severity of damage is a function of type of load cycle.

Load-following involves rapid increases and reductions in process temperatures, which create significant thermal stress on pressure boundaries. When plant loads change, the consequences are numerous: pulverizers or mills go off and on, furnace temperatures and heat profiles are altered, pollution control requirements change, and steam and flue gas velocities vary. All these changes can affect the design basis of the equipment.

Chief Types of Cycling-Related Damage

The following are the predominant types of cycling-related damage.

- Thermal Fatigue. The most common problem resulting from cycling is thermal fatigue damage, which manifests itself in the form of material deformation or cracking of an individual component or in the mechanical failure of structures. Cracking of a component is caused by large temperature swings associated with flexible operation and, in some cases, by thermal

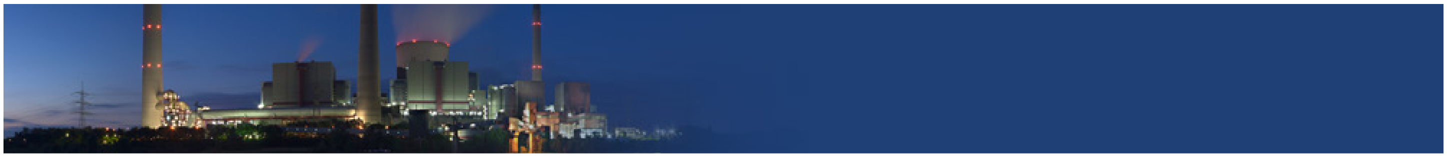


Figure 6 – Cold feedwater introduced to a hot header caused thermal fatigue cracking in this economizer header (courtesy of EPRI).

Figure 7 – Waterwall damage caused by corrosion fatigue is often found in steam generators (courtesy of EPRI).

quenching produced by inadequate condensate draining. These temperature swings are related to excessive steam-to-metal and through-wall temperature differences associated with rapid rates of steam temperature change during startup, shutdown, fast ramping, and load following. Difference in temperatures across the wall of a drum or pipe creates stress due to the differences in expansion and contraction between the inside and outside surfaces of the component wall.

The principal components at risk typically comprise any thick-walled sections such as boiler superheat headers, steam pipework, valves, high-pressure (HP) and intermediate-pressure (IP) steam chests, and turbine inlets. Boiler superheater and reheater headers are expensive, thick-walled vessels operating under high steam pressure, making this damage of particular concern to plant owners (Figure 6).

Thermal mechanical fatigue, which occurs in turbine blades, vanes, and other hot-section components, is caused by large temperature changes, resulting in significant thermal expansion and contraction, which is reinforced or countered by mechanical strains associated with centrifugal loads as engine speed changes.

- *Thermal Expansion.* Several systems in a coal plant have components that undergo high thermal growth relative to surrounding components. The most important example of this phenomenon is the large movement of boiler structures relative to the relatively cooler support framework. This part of a plant includes waterwall sections, gas ductwork, and the ties used to support superheat and reheat tubing. These support ties are designed to accommodate growth, but are subject to accelerated life consumption if the frequency of thermal cycling increases. Differential expansion also contributes to tube-to-header cracking in superheater and reheaters.
- *Corrosion.* Two-shifting, or any other operation that challenges the ability of the plant to maintain water chemistry, can lead to increased corrosion and accelerated component failure. Increased levels of dissolved oxygen in feedwater can be the result of condenser leaks, aggravated by more frequent shutdowns. Other factors affecting chemistry include increased need for make-up water and the interruption in operation of the condensate polishers and deaerators. Corrosion and fatigue can combine to accelerate damage to waterwalls (Figure 7).
- *Fireside Corrosion.* Load cycling and relatively quick ramp rates under staged conditions can contribute to both fireside corrosion and circumferential cracking in plant boilers.
- *Rotor Bore Cracking.* When subjected to changes in the temperature of the admitted steam, the high-pressure and intermediate-pressure steam turbine rotors can suffer thermo-mechanical stress excursions, resulting in low-cycle fatigue damage. The damage can result either from introducing hot steam to a relatively cold rotor exterior, or the opposite. In both scenarios, the problem arises from the massive rotor forging and the resulting time required for the metal temperature difference between the rotor exterior surface and the inner (bore) region to equilibrate.
- *Impaired Performance of Environmental Control Equipment.* Load-following and other modes of flexible operation can affect

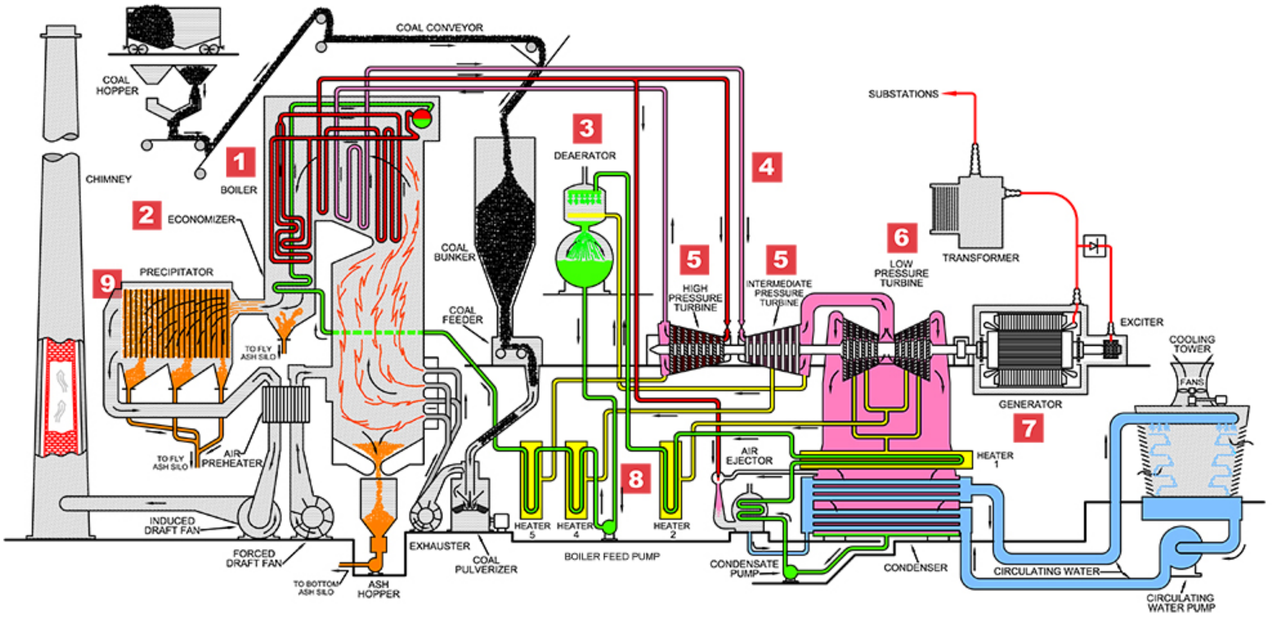
the performance and reliability of flue gas desulfurization (FGD) equipment and selective catalytic reduction (SCR) systems. The chemical processes involved in these systems require precise control of the reaction conditions, which are influenced by reagent flow, water flow, and flue gas temperature.

Startups of FGD systems should be minimized because of the need to purge systems to avoid slurry solidification, impact of fuel oil residues on linings, and the lengthy warm-up time. Low-load operation of FGD systems may be difficult to optimally control if the reagent flow is at a fixed rate.

Operation of large coal-fired plants at low load can force units with SCR systems to operate with lower flue gas temperatures. Low temperatures create operational problems for SCRs because of the formation of ammonium bisulfate, a sticky liquid that can fill catalyst pores, thus diminishing catalyst surface area and reducing reactivity.

Damage in Different Plant Components

Figures 8 and 9 illustrate potential cycling damage in different parts of a coal-fired and a natural-gas-fired combined-cycle plant.



1 BOILER
- Thermal fatigue cracking in thick-walled sections and valves of drum boilers.
- Increased boiler tube failures due to differential expansion.
- Fireside circumferential cracking in waterwalls.
- Thermal fatigue cracking in superheater and reheater ligaments.
- Corrosion and fatigue can combine to accelerate damage to waterwalls.

2 ECONOMIZER
- Thermal fatigue and corrosion in economizer inlets.

3 DEAERATOR
- Stress corrosion cracking in weldments.

4 PIPING
- Creep-fatigue in main steam and reheat piping.
- Flow-accelerated corrosion in steam piping.

5 HIGH-PRESSURE AND INTERMEDIATE PRESSURE TURBINE
- Thermal fatigue cracking in thick-section rotors, casings and valve bodies.
- Erosion of valve components.

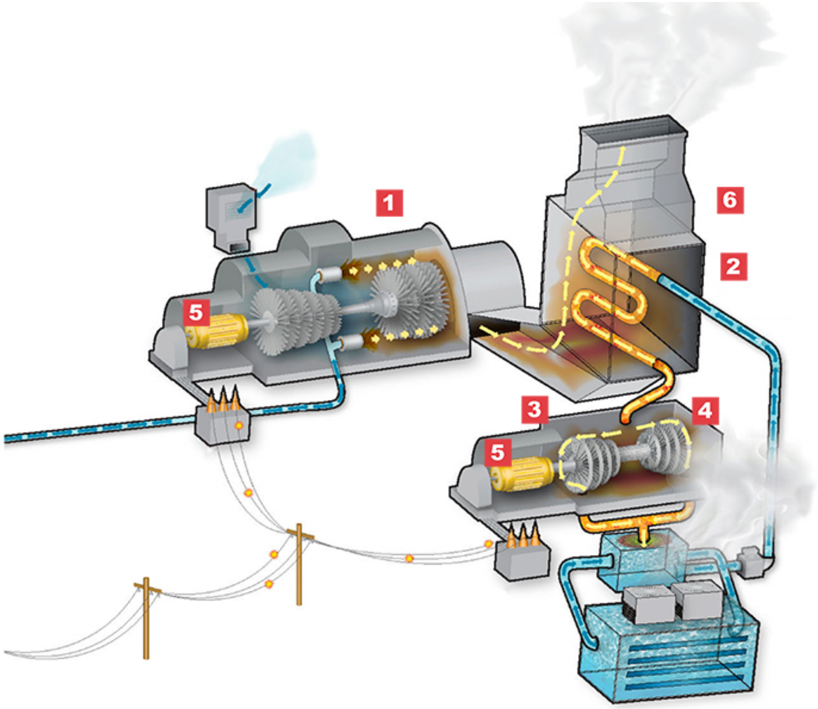
6 LOW-PRESSURE TURBINE
- Moisture erosion of blading.

7 GENERATOR
- Wear of copper insulation due to differential expansion.
- Loosening of stator windings.

8 FEEDWATER HEATERS
- Thermal fatigue of thick sections of the tube plates and end covers
- Low cycle fatigue of bolting

9 PRECIPITATOR/SELECTIVE CATALYTIC REDUCTION (SCR)
- Impairment of emissions control at low load.

Figure 8 – Potential cycling damage in coal-fired power plant (courtesy Grand Island Electric Utility).



1 GAS TURBINE
- Thermal fatigue cracking in compressor and turbine rotor components.
- High cycle fatigue cracking in combustor due to pressure dynamics at off-design.
- Thermal fatigue cracking in turbine blades and vanes.
- Thermal fatigue cracking in turbine exhaust casings.

2 HEAT RECOVERY STEAM GENERATOR
- Flow-accelerated corrosion.
- Quenching damage from condensation in drains and attemperator sprays.
- Thermal fatigue cracking in thick-walled components.
- Increased boiler tube failures specifically at tube to header welds.
- High transient stress locations within high energy piping systems, manifolds, or nozzles.
- Water-side corrosion due to constantly changing water chemistry.
- Valve hard surface delamination and seat cracking.

3 HIGH-PRESSURE AND INTERMEDIATE PRESSURE TURBINE
- Thermal fatigue cracking in thick-section rotors, casings and valve bodies.
- Erosion of valve components.

4 LOW-PRESSURE TURBINE
- Moisture erosion of blading.

5 GENERATOR
- Wear of copper insulation due to differential expansion.
- Loosening of stator windings.

6 SELECTIVE CATALYTIC REDUCTION (SCR)
- Impairment of emissions control at low load.

Figure 9 – Potential cycling damage in combined-cycle natural-gas-fired power plant.

Some components, although themselves small and not costly to repair or replace, may nonetheless involve high costs because they are difficult to access. Accessibility issues may involve the need to cut through and replace other components and can thus lead to increased unplanned down time.

Long-Term Damage Effects

Several of the damage mechanisms, such as thermal fatigue, may not appear immediately after a plant switches to cycling modes. Instead the life of equipment may be consumed before damage is evident or failure occurs. The damage may thus manifest itself three to five years after cycling commences, when a component fails, leading to an unplanned outage (Figure 10).

Outages

Increased cycling leads to more operating problems and a greater failure rate for key items of equipment and control systems. The forced outage rate (FOR) will, therefore, increase.

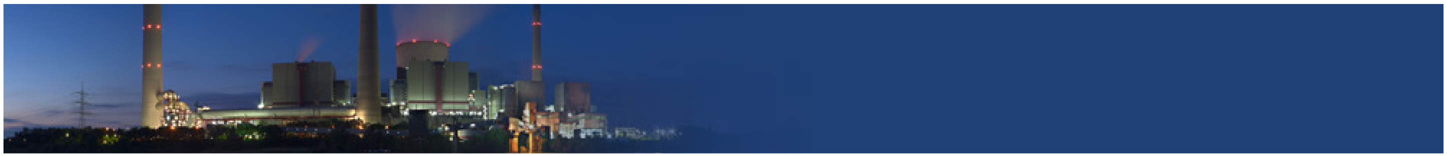


Table 1 – Estimated Forced Outage Rates for Turbine and Generator Systems: Baseload vs. Cycling (From EPRI report 1008351)

		Baseload (1984–1993)	**Cycling (1984–1993)**	**Baseload (1994–2003)**	**Cycling (1994–2003)**
EFOR	Steam Turbine	1.27	1.22	0.47	1.40
	Generator	0.29	1.54	0.43	1.06
	Combined	1.55	2.73	0.90	2.44
EUOR	Steam Turbine	1.59	2.35	0.65	2.26
	Generator	0.39	2.25	0.53	1.88
	Combined	1.97	4.50	1.17	4.05
$EFOR_d$	Steam Turbine	1.25	0.94	0.47	0.93
	Generator	0.29	1.02	0.43	0.66
	Combined	1.53	1.99	0.89	1.58

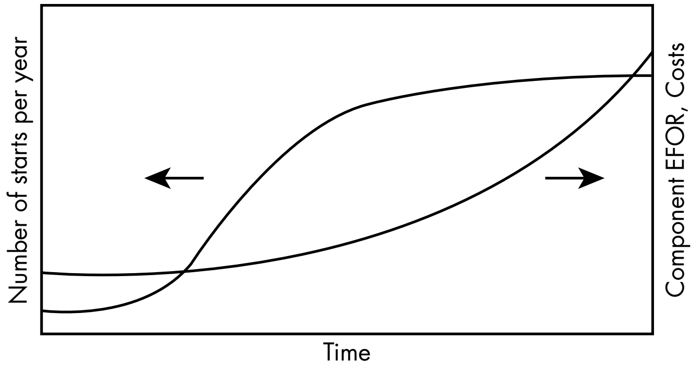


Figure 10 – Lag time may exist before damage due to cycling reveals itself (courtesy of EPRI).

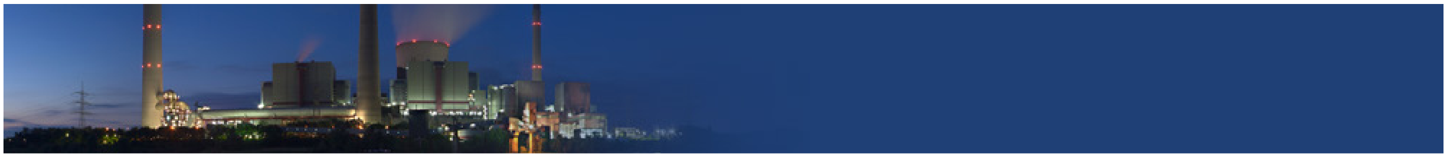
Unplanned outages involve several costs for the unit and the utility. The most obvious and immediate cost is the cost of the equipment or process repair. The unit will also experience lost revenue, because it is not generating and selling power during the outage. In addition, during the outage, the utility will need to purchase replacement power, which may be costly if the timing coincides with high power prices.

Research indicates that a relationship exists between an increased number of starts and, after some delay, an increase in the equivalent forced outage rate (EFOR). The initial delay is about seven years between the peak in starts and the peak in EFOR. Thus, although a substantial increase in the number of starts results in more failures, these failures will not occur until a significant period of additional service has accumulated. The extent of EFOR depends on several factors, including the quality of maintenance and the age and design of the plant.

To better understand how cycling may affect outages, an EPRI study assembled and analyzed reliability data over a 20-year period (1984–2003) specifically for turbine and generator components. The units consisted of fossil steam turbines only (not combustion turbines or combined-cycle units). The 20-year period was divided into two 10-year periods (1984–1993 and 1994–2003) to allow comparison of trends over two significant time blocks.

Table 1, which is reproduced from the EPRI study, shows three different forced outage rate formulations for turbine and generator systems in baseload and cycling plants. The formulations include EFOR (equivalent forced outage rate), EUOR (equivalent unplanned outage rate), and EFORd (equivalent forced outage rate—demand).

In nearly all cases, the forced outage rates were greater for cycling units than for baseload units. In the case of EFORd, the outage rates for cycling units are 63% higher than baseload units.



Other Effects of Increased Cycling

Increasing Heat Rate

A power plant's ***heat rate*** is the amount of heat energy needed to generate one kilowatt-hour (kWh) of electricity. Improving heat rate has long been a goal for electric utilities seeking to lower the operating costs of their generating plants. Reducing the heat rate, which equally lowers fuel consumption, emission rates and costs, directly benefits the power producer's bottom line. For example, a 1% heat rate reduction at a typical 500-MW coal-fired plant operating at 90% capacity factor and firing bituminous coal will achieve over $700,000 in annual fuel savings (assuming a fuel cost of $2/million Btu).

EPRI research has found that more frequent periods of cycling can have significant impacts on overall average heat rate. In the long term, load cycling results in a net increase from the steady-load heat rate. Units with the most extreme cycling operations (e.g., two-shifting) show extreme degradation of heat rates when operating at low-load factors.

Decreasing Revenue

Units operating in cycling modes, especially those accustomed to baseload operation, will generate decreasing levels of revenue, due to more frequent periods of low-load operation and shutdown. The units do not operate as efficiently at low loads as at higher loads. More startups will lead to higher operating costs (and lower revenue) than steady-state operation, because when the unit is started, depending on the length of the outage, a significant amount of fuel needs to be added to obtain desired operating temperatures and pressures before the unit can produce power. Some units, such as small subcritical coal units, with relatively lower efficiency and higher heat rates, are also likely to experience less favorable dispatch orders, which will further depress revenue.

In addition, the reason for cycling is to increase gross margin. For example, a unit is cycling to a lower load in off-peak hours because the unit cost exceeds the market price during that time period. In some markets, this kind of flexibility may be subject to ancillary services revenue.

Higher Emissions per kWh

Higher emission rates of pollutants, such as nitrogen oxide and sulfur oxide, occur during certain parts of the operational cycle, such as startup, ramping, and shutdown, which are characteristic of, and more frequent during, cycling duty. Thus plants under flexible operation will have higher emission profiles over time than baseloaded-operated plants.

In addition, emission control technologies, such as selective catalytic reduction systems for control of nitrogen oxides and flue gas desulfurization systems for sulfur dioxide, were designed for consistent temperature ranges under baseload operation. The emission control levels of these technologies may decline under cycling.

Staff Scheduling/Training

Increased cycling is likely to require scheduling of additional operating staff and increased training.

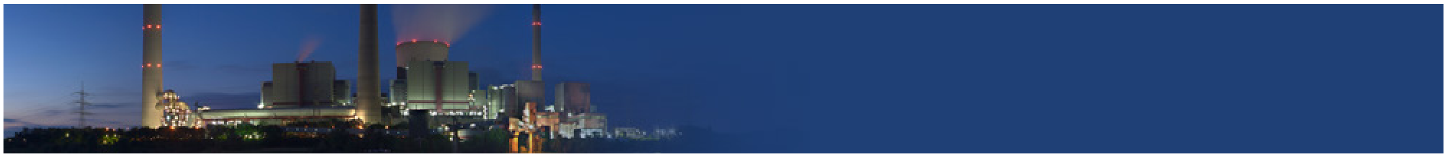
Under traditional baseload operation of a high-merit plant, plant personnel often gain comparatively little experience of unit startup and shutdown. Typically, these plants might undergo fewer than ten starts per year, and some personnel might participate in fewer than two starts per year. The operator's role is more that of a monitor, making fine adjustments and dealing with occasional emergencies. The time factors associated with infrequent startup enable the operator to approach the task over a relatively lengthy period of several hours.

Under cycling conditions, plant operators are required to carry out startup and shutdown regularly—and to do it quickly and efficiently. The requirements to understand and operate a plant under the highly dynamic conditions of cycling place a high degree of responsibility on plant operators. The opportunities for error and to cause damage to the plant are greatly increased. The operating staff also needs to be aware of the functional requirements of cycling, the commercial aspects of plant running costs and efficiency, and the long-term effects of operation on the life expectancy of the plant.

Although the requirements of operators can be somewhat lessened by the adoption of automation and improved data display, a need still exists for a higher level of knowledge and understanding than is necessary under baseload operation.

For maintenance staff, new preventive maintenance and predictive maintenance strategies may need to be adopted due to:

- changes in the availability of the unit
- additional stressors that might change the preventative maintenance frequencies
- additional stressors that might require additional preventative maintenance
- additional training to acquire the needed skills



Fuel Procurement

Due to the uncertainty of future load under operational flexibility, plants may be unable to predict future fuel requirements and purchase fuels under long-term contracts, which offer more favorable terms than shorter-term contracts. Reduced efficiency and non-optimal heat rate, which may occur in cycling modes, will lead to increased fuel costs per megawatt, because the heat rate increase and supplemental fuel use will increase with the increased startups. Future dispatch scheduling uncertainty may also result in more incidences of coal bunkers being left filled for long periods of time. Stock piling can lead to concerns over fire hazards, especially for fuels with high volatility.

Reliability

Plants that operate with increased cycling, particularly those not designed for it, will experience decreasing levels of reliability. This trend is due to the greater potential for damage and failure of equipment operated outside its design limits, as noted earlier in this primer. Such incidents will result in the increasing frequency of unplanned outages to repair or replace equipment. The consequences will involve higher capital costs to replace equipment failing before its design life, higher operating costs to repair and maintain equipment, and accompanying declines in net unit revenue.

Cost Impacts of Cycling

The cost impacts of cycling on power plants are difficult to evaluate, because they consist of more than the tangible cost elements such as startup fuel, increased heat rate (reduced efficiency), and plant staff hours. Many of the major costs of cycling are "hidden," and consist of costs for replacement energy, reliability (equivalent forced outages), higher fuel costs, delayed start times, lost profit, and higher emission rates.

Other intangible, or latent costs, are involved as well, including the incremental wear-and-tear on plant components due to damage. The intangible costs are realized in future years at which time the component requires extensive repair or capital replacement. Collectively, they can reduce the life of the plant, thus affecting the depreciation rates.

A major challenge of cost assessment for flexible operation, therefore, is to quantify the cost impact today due to damage associated with a unit start or fast ramp. This incremental life consumption results in the eventual need for future resources to repair or replace the component.

One strategy for estimating these latent costs is to analyze historical plant spending on operations and maintenance as well as capital projects. The spending data is then correlated against the amount of flexible operation which that asset experienced. This analysis should take into account the time difference between the onset of flexible operation duty and the resulting cost impacts realized, often five to seven years later. Another challenge to this approach is the need to categorize those plant costs that are due to "normal" wear-and-tear, and those that are due to increased flexible operation. This categorization requires judgment.

In 2013, EPRI conducted a cost analysis to determine the annualized non-fuel O&M cost (see EPRI report 3002000817). Cost data are combined with each unit's historic operational data (online hours and unit starts) to develop a top-down statistical model of the O&M costs for a typical plant over its service life. The analysis provides a model that can be used to estimate unit lifetime maintenance costs in a range of plant-cycling scenarios.

In the study, cost assessments were conducted for combined-cycle gas turbines (CCGTs) with capacities of 110-492 MW and conventional coal-, gas-, or oil-fired plants with capacities of 185-280 MW. Cost-correction factors were applied for capacity. Equivalent Hot Starts (EHS) were calculated for all units in the database to determine the relationship between O&M costs and EHS to understand the cycling impact. The study assumes a hot start equals 1 EHS, a warm start equals 3 EHS, and a cold start equals 5 EHS. For CCGT units, the study results showed that the strongest indicator of annual O&M costs is the number of EHS that a unit has performed. For conventional units, the study did not have sufficient data to draw a conclusion.

Strategies to Mitigate the Effects of Cycling

A range of strategies are being investigated to mitigate damage to fossil units caused by flexible operation.

When actions are being selected for specific units, mitigation strategies are generally assessed in terms of a benefit-to-cost ratio. Significant capital investment in improved-design boiler components may be warranted for new, efficient units. In older plants, the most cost-effective strategy from a life-cycle cost perspective is typically to focus on improved operator performance and selected upgrading of plant controls.

Mitigation strategies broadly include three categories: minor-cost items, moderate-cost items, and items requiring additional research.

Minor-Cost Items

Sensors

Sensors might be added to plant equipment to monitor performance and prevent damage. These sensors could include monitors for cooling water and dissolved oxygen, flame scanners, high-temperature thermocouples, and tools for identifying the presence of condensate in the superheater and reheater before startup.

Other sensors might be used to identify and quantify the impact of cycling operation on components and systems; examples include thermal stress monitoring in heat recovery steam generators, deformation of waterwalls near penetrations, and boiler cyclic thermal forces.

Instrumentation and Controls

Instrumentation and control (I&C) systems in fossil plants are typically designed and tuned for operation at full load. As a result, many control strategies and tuning methods are non-optimal for current flexible operations. New I&C configurations are needed to better control thermal, mechanical, and fatigue stresses and allow plants to operate outside their historical operating envelope without equipment damage.

For example, upgraded combustion control systems are necessary to improve flame stability and monitor primary and secondary air flow. Boilers will need upgraded control systems to avoid oscillation of steam pressure and temperature, and to maintain drum level. Turbines will need to add automatic speed and load controls to reduce thermal stresses.

The ideal control system for two-shifting is one where the control system can be adjusted to suit a range of operating scenarios necessary to reach full load or any other loading scenario.

Modifications to Operating Procedures

Changes in operational practices can help to mitigate cycling damage. For example, research has found that economic two-shifting can be achieved with due care and application of sound engineering and operational practice. Many utilities have performed trials on two-shift operation to reduce startup and shutdown time. Generally, startup times can be nearly halved from original baseload procedures, so that large machines can be synchronized within 35 to 50 minutes of inserting the first burners—depending on unit size and configuration—and full load can be achieved in similar times.

Thermal transients—both in the form of quenching and high rates of temperature rise—can be avoided by carefully managing the unit when off-load and by adding engineered systems to alleviate the potential problems. For example, natural-circulation drum boilers may be fitted with off-load circulating systems to pump water slowly around the evaporative section to balance temperature variations.

A primary constraint on ramping operation is matching steam and turbine metal temperatures. ***Sliding pressure***, which is accomplished by reducing the throttle steam pressure, offers advantages over throttle control. Sliding pressure involves keeping the control valve position at a more efficient point with less throttling losses and improved hot reheat temperature. In addition, the reduced throttle pressure results in a decrease in boiler feed pump auxiliary power required. Not all boiler designs may accommodate sliding pressure operation; therefore, a thorough analysis is needed before this strategy is attempted. A recent EPRI study found that sliding pressure diminishes throttling losses and is a potential method to reduce the heat rate penalties associated with increased load following. One drawback to sliding pressure is that it slows down the response rate so the unit will have slower ramp rates while in sliding pressure operation.

Staff Training

Retraining plant engineering and maintenance staff for new operating procedures and protocols can also mitigate cycling damage.

For example, plant data for critical components can be screened to identify and understand the most damaging conditions. Operators can then seek to minimize the extent of such conditions during future unit starts.

Maintenance staff can be trained to conduct targeted inspections during outages and regular walkdowns, and to recognize damage such as boiler tube distortion, flow-accelerated corrosion, and support system damage.

Moderate-Cost Items

Installation of New Equipment or Modifications to Existing Equipment

New equipment or retrofits to existing equipment may be employed to mitigate cycling damage. Examples include the following:

- *Boilers.* Welding overlays can reinforce joints and vulnerable areas. Modifications to standard boiler tube supports can allow movement during temperature transients and reduce stress due

to thermal expansion. New boiler throttle valves can improve variable pressure operation. Damper systems may be needed to "bottle-up" the heat to minimize thermal differences and expedite unit start-up.

- ***Furnaces.*** Combustion systems can add low-load burners, supplementary fuel capability, and wide-range coal nozzles.
- ***Turbines.*** Water sprays can be added to turbines to reduce backend heating, and water seals can be replaced to avoid water induction and corrosion.
- ***Balance-of-Plant.*** Retrofits might include upgrades to pump valves and orifices, inclusion of bypass systems for use during startups, upgrading the design of the reheater due to fast temperature changes experienced during startups, and adding variable-speed pump motors.
- ***Drains.*** During two-shift operation, plants can progressively warm the boiler, steam legs, and turbine in a well-controlled manner by using drains to promote flow. Upgrading the drain system to increase its capacity and operability is a relatively simple and low-cost modification that can greatly improve a unit's two-shift capability. High-pressure feedwater heater drains may also need to be rerouted if they cannot adequately drain to the next lower pressure heater without flashing.
- ***Insulation.*** Capabilities for maintaining high temperatures can be improved by ensuring the integrity of the thermal insulation. Furthermore, good thermal insulation can assist in startup sequences and reduce startup times. Target areas for improved insulation include headers within top and bottom dead spaces, steam pipework and boiler stop valves, turbine control valves, and turbine casings.

Items Requiring Additional Research

Continued research, development, and technology demonstration are needed to mitigate a number of the effects of cycling. Several key areas of ongoing research include:

- Development of stronger ferritic materials for thick-walled components of high-temperature headers to reduce the thickness and, therefore, reduce the temperature gradients across the wall.
- Improvements in the properties of creep-strength-enhanced ferritic steel to improve resistance to cycling-related damage.
- Approval of advanced nickel alloys such as Inconel 740 for use in supercritical boiler and turbine designs, which would allow reduced wall thickness and improved thermal transient response.
- Reliable high-temperature strain gages that can be inexpensively integrated into the Plant Information (PI) systems.
- Identification of gaps in current control systems that result in temperature excursions in boiler components.

Conclusion

Over the past decade, the patterns in duty modes and plant dispatch have changed. Fossil-fuel-fired plants, including formerly baseloaded plants, are increasingly required to operate in cycling modes. These modes include two-shifting and load following, and involve increased startups, shutdowns, ramping, and low-load operation.

The changes in plant operation that are necessitated by variable duty cycles can expose plant equipment to new stresses. These stresses, which are associated with varying temperatures and pressures, have the potential to trigger thermal fatigue, thermal expansion, and corrosion damage. Other effects of greater levels of cycling duty include higher heat rate, declining revenue, higher emission rates, and deceased reliability in the form of higher outage rates.

To address these issues, mitigation strategies are available. These strategies involve (1) minor-cost items, such as additional instrumentation; (2) moderate-cost items, such as system modifications; and (3) items requiring additional research.

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3002000045 September 2013

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