

# The Cost of Cycling Coal Fired Power Plants

By: Steven A Lefton, Phil Besuner APTECH Engineering Services



Steven A Lefton is a chemical engineer with extensive experience (30 years) in USA and European design power plant operations, start-up, costs, cost analysis, testing, life assessment, chemistry, maintenance and reliability.



Philip M. Besuner is a reliability engineer. He has a MS in mechanical engineering with special emphasis on fracture mechanics and probabilistic statistical modeling and analysis of power plant's and their components/failures/ remaining life and costs.

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.

## 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?

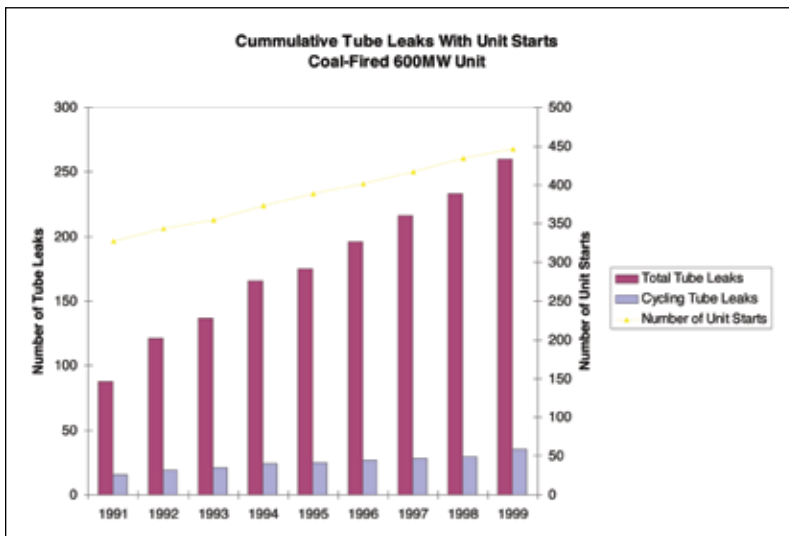
Passing the high cost to cycle power plants on to competitive utilities, by not cycling on/off or going to two-shift operation for specific units with low cycling costs, is an effective competitive strategy when cycling costs are analyzed.

## 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.

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



**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

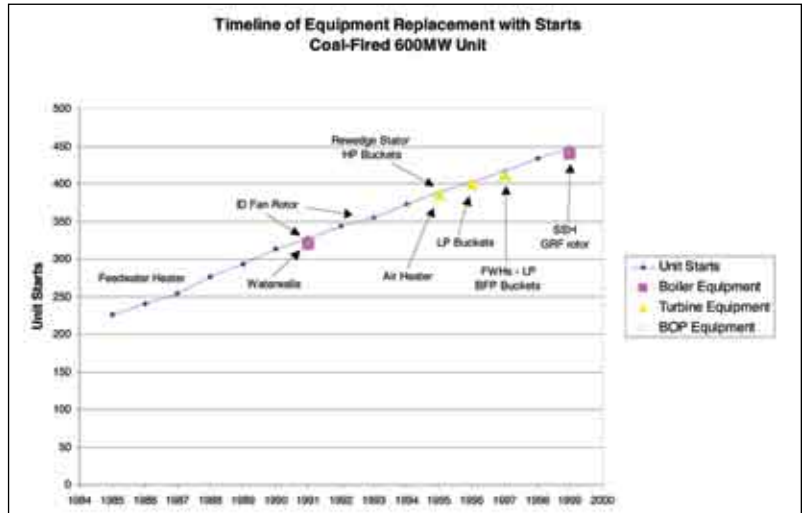


Figure 2: Equipment replacements versus starts for a 600 MW coal-fired unit

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 where 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.

CONTINUE TO NEXT PAGE

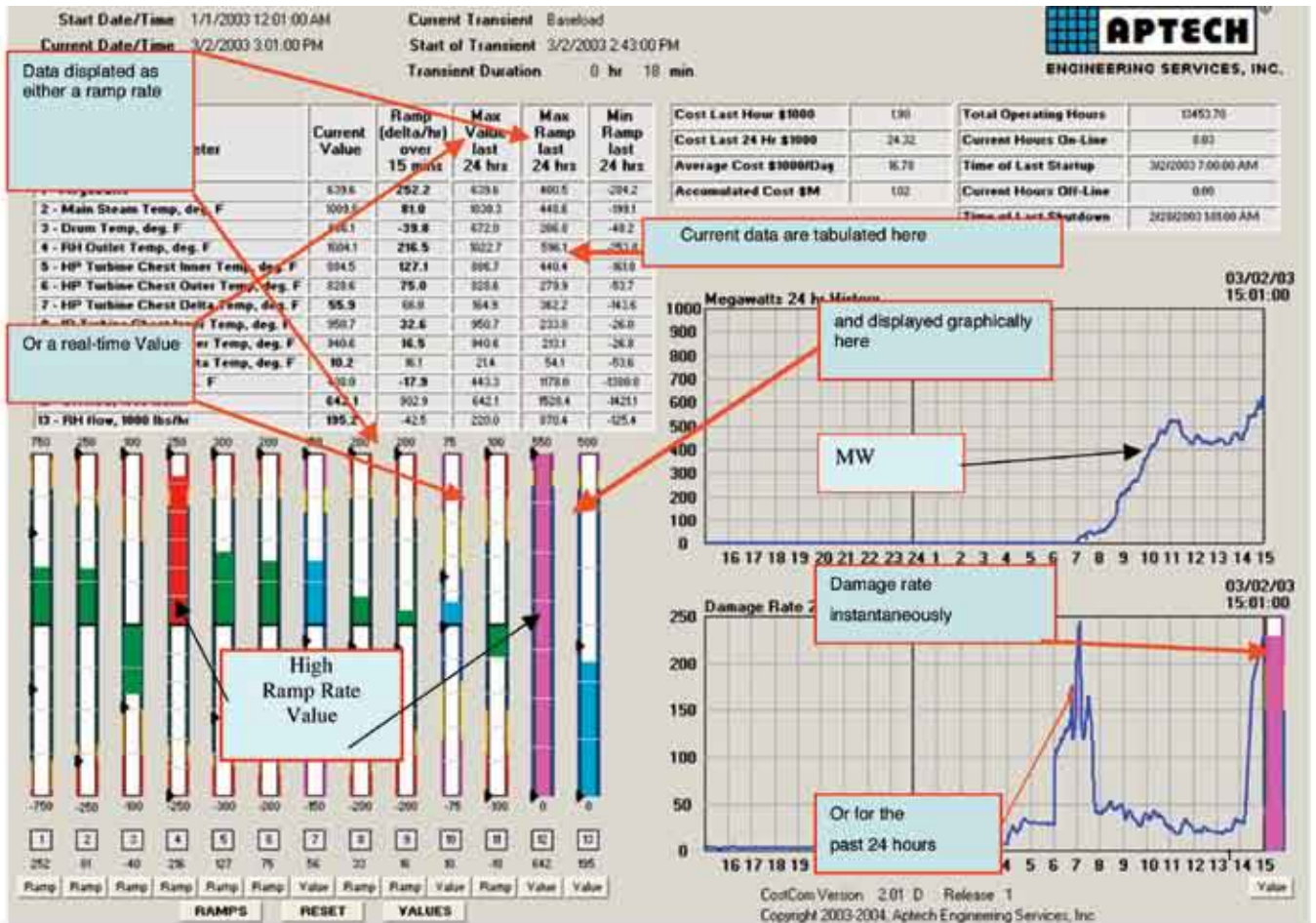


Figure 3: Real-time operating data

CONTINUED FROM PREVIOUS PAGE

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

CONTINUE TO NEXT PAGE

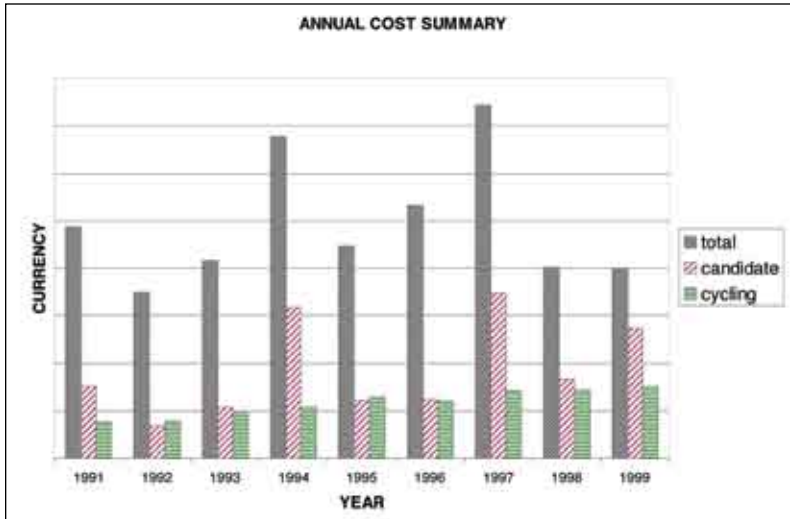


Figure 4: Annual cost summary

**CONTINUED FROM PREVIOUS PAGE**

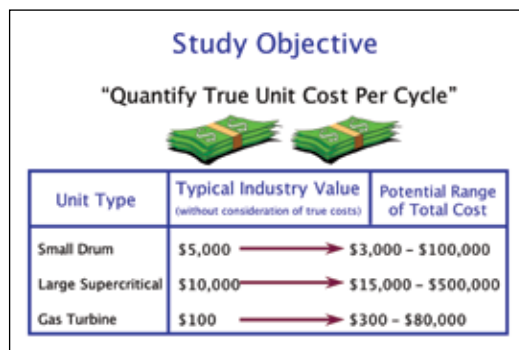
- Long-term generation capacity costs increase due to a shorter unit life.

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, worn 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

Figure 5: Quantifying true unit cost per cycle



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.

August 1, 2011

## Make Your Plant Ready for Cycling Operations

By Steven A. Lefton and Douglas Hilleman, PE, Intertek-Aptech

*Cycling your steam power plant is inevitable, so now is the time to learn how to minimize equipment damage and assess the true costs of cycling. Whether cycling is required by the grid operator because of renewable integration or other factors, you must be proactive about updating operating processes and upgrade equipment so the transition to cycling operation goes smoothly.*

Few conventional steam plants were designed to follow load, cycle from minimum to full load every day, or shut down and start up daily, as so many plants are called upon to do these days. The challenge for owners of plants required to operate in this way is to fully understand the effects on plant and component life expectancy, and the actual costs, of these new operating profiles. If the actual costs are unknown, making a profit becomes a matter of luck rather than good management.

In a competitive electricity market, not knowing your true generating costs could place your plant or your company in economic jeopardy. For example, if the actual cost of cycling a unit is not included in your bid price, and the plant must cycle, not only are you not being compensated for unknown damage to plant equipment, but you also are not being compensated for future maintenance and unplanned repair outages. Those costs often far exceed the short-term profits gained by submitting an artificially low market bid price.

Furthermore, the bill for the true cost of operation will arrive after the fact, often years later, in the form of lower capacity factors, less generation, and higher production costs. If, at that time you update production costs to reflect your new reality, your plant may no longer be competitive, resulting in even worse economics.

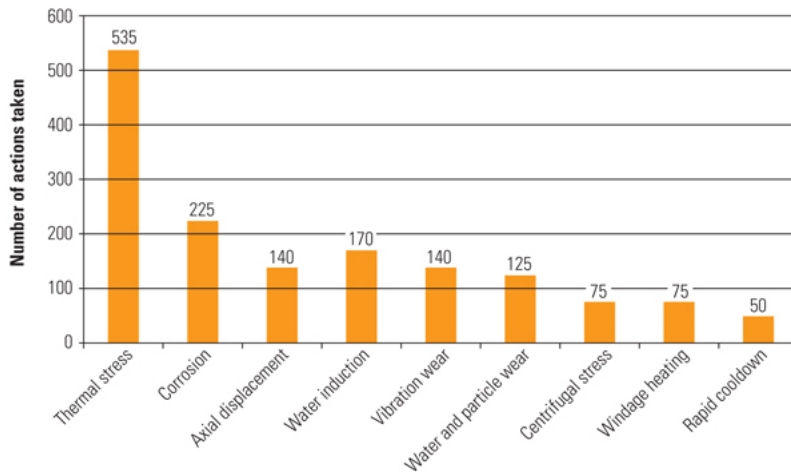
The same scenario applies in a regulated environment: Future higher-than-expected operating and maintenance costs have to be justified to the public utilities regulators and may not be recoverable.

The following discussion applies equally to solid fuel-fired steam plants and natural gas-fired combined cycle plants.

### Cycling for Dollars

Cycling your plant without understanding the costs or applying care and expert guidance when cycling often leads to significant damage, frequent forced outages, and loss of power generation. Bad long-term decisions may be driven by short-term or uninformed decisions, making your plant unreliable during high-profit periods. The fatigue damage added to an older baseload power plant causes creep fatigue interaction damage, rapid increase in boiler tube failures, and many other component failures, including turbine generator and balance-of-plant early creep fatigue failures. In effect, excessive cycling will either decrease the life expectancy of your equipment, or the costs to maintain the equipment will rise, sometimes significantly. Also remember that poorly written startup and shutdown operating instructions or a failure to follow standard processes can often contribute to increased cycling damage and resultant costs.

In our experience, about 60% to 80% of all power plant failures are related to cycling operations. If plant management understands the costs and has a process that provides actual operating costs, it is able to take proactive operational measures rather than deal with unexpected costs and poor performance years after damage to plant systems is done (Figure 1).



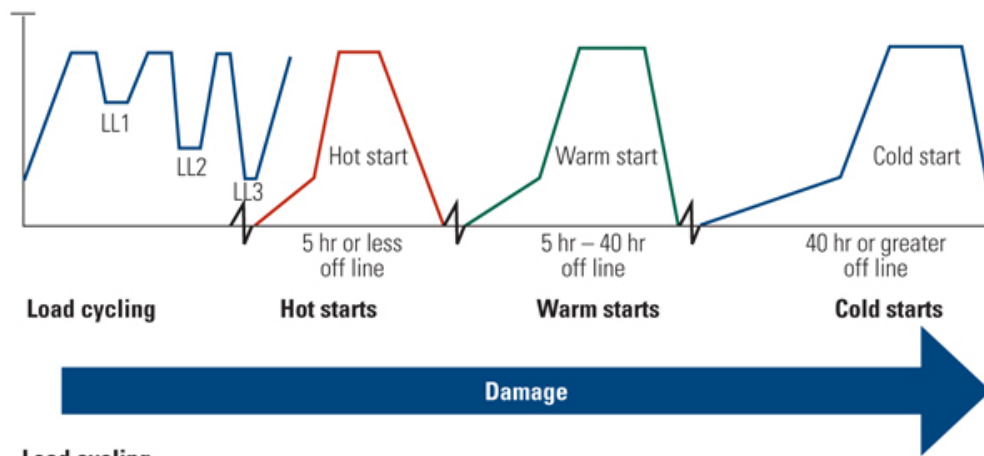
**1. Common problems in cycling plants.** A survey of 215 steam plants found many common equipment problems. *Source: Intertek-Aptech*

## Locating Failures

Failures in coal plant equipment caused by frequent cycling are not isolated events but often occur at unexpected times throughout a plant. Many of the failure modes and locations are not unexpected, but others may be surprising even to an experienced plant operator. Prevention of these failures or managing failure rates is key to success. One approach to reducing cycling damage is to modify the unit's low-load limit to prevent cycling damage. By reducing the low-load limit on a 750-MW supercritical gas-fired unit from 150 MW to 28 MW at night, it was possible to make the daily cycling load profitable, but it was no small task.

The following subsections are provided to give you a sense of the magnitude of systems and components within a typical coal-fired plant designed for baseload operation that are affected by cycling and load-following service. Although they are not listed separately, controls are also affected; some plants must upgrade old analog controls to digital controls in order to improve response to remotely supplied automatic generation controls before they are capable of cycling.

**Steam Turbine Generators.** The life of a steam turbine is directly related to thermal transients experienced over time. In fact, the typical steam turbine startup ramp rate is well-defined by the manufacturer, as there are limits to the heating rates of the rotating parts. Steam turbines require slow temperature changes to manage the thermal stress in their heavy metal components (Figure 2).



**Load cycling**

LL1—lowest load at which design SH/RH temperatures can be maintained  
 LL2—current “advertised” low load  
 LL3—lowest load at which the unit can remain online

**2. Relative damage caused by cycling steam plants.** *Courtesy: Intertek-Aptech*

An essential design element of a reliable cycling unit is a steam bypass system. When in operation, high-temperature steam is pressure-reduced and cooled by mixing condensate with the hot steam in a desuperheater and then bypassed around the steam turbine to the condenser. Additional steam bypass to the condenser often requires condenser modifications. In some steam turbine designs, the steam seals may need to be replaced to prevent steam flow from bypassing the rotor stages or sections. Finally, an electric heated turbine blanket system may be beneficial during hot restarts to reduce thermal stress and distortion, ensuring a quicker start.

**Boiler.** In the superheater section, damage to tubing is usually caused by overheating that results from low or no flow of cooling steam through the tubes during startup and/or poor combustion gas temperature management. Damage to superheater tubing is usually evident by severe bowing and thermal distortion due to overheating damage of tubes fully exposed in the gas path. Also, superheater tube damage can result from condensate, and stagnate or reverse steam flows during startup. Similar overheating damage often occurs in reheater tubing (Figures 3 and 4).



**3. Tube bending.** Thermal forces bowed and permanently bent this boiler superheater tubing, including the water-cooled support tube and clips. *Courtesy: Intertek-Aptech*



**4. Breaking bad.** Corrosion fatigue damage in the steam-cooled wall in the heat recovery area is evident in this photo. The steam-cooled sidewall has a damaged economizer header penetration. Cycling caused differential thermal growth, and the penetration is badly damaged. Note the numerous repair welds and the broken and missing refractory caused by thermal growth. *Courtesy: Intertek-Aptech*

The effects of cycling the steam generator usually materialize as stress cracking in the waterwall tubing at attachments like the windbox, corner tubes, and wall box openings. Stress cracking in the waterwall tubing at the buckstay attachments is usually caused by nonuniform thermal movement of the boiler and its support system (Figures 5 and 6).





**5. Wobbly walls.** Outside the boiler we see the thermal damage in supports. The photo shows thermal damage on the boiler support structure, specifically the sidewall buckstay at the windbox attachment. *Courtesy: Intertek-Aptech*



**6. Bending corners.** Boilers are typically rectangular boxes rather than round or spherical. This photo shows waterwall corrosion fatigue damage at the lower furnace seal and attachment of the front wall vee bottom to the sidewall, showing weld repairs. It is an example of cycling damage at a corner or a change in shape.

*Courtesy: Intertek-Aptech*

Although temperature levels are much lower in the economizer, thermal damage can still occur there. Economizer tube failures are usually caused by thermal shocking of the inlet header and tubing with relatively cold water, often during startup. Corrosion may also occur in areas of the economizer where cold water reduces the metal temperature (structure or tubing) below the acid dew point of the stack gas during low-load operation. When the stack gas is reduced below the acid dew point, the minute portions of sulfur that remain in the gas can combine with the condensed moisture and form dilute solutions of very corrosive sulfuric acid on tubes and structures.

In addition to boiler design- and operation-caused tube failures, poor boiler water chemistry control can be a contributing cause. In some plants, the entire water chemistry program must be reformulated to optimize remaining boiler tube life.

Often, the key to reducing waterwall tube wastage is simply using a nitrogen blanket over the internal tube wetted surfaces when the boiler is removed from service or draining it. Also consider a nitrogen blanket in the condensate storage tank to minimize the oxygen content in the condensate during starts.

In heat recovery steam generators (HRSGs), the typical cycling problems can be traced back to superheater and reheater drains that fail to clear accumulated condensate. Flow-accelerated corrosion (FAC) in the low-pressure

evaporator and failure of feedwater heaters from thermal shock and FAC also are often found (Figures 7 and 8).



**7. Inflexible headers.** Reheater outlet header and tube-to-header weld fatigue damage at the end of the header is shown. The high-stress location is the short run of tubing where the tube cracked, due to low tube flexibility. The stress is a result of thermal loading and deflection during startup cycles. *Courtesy: Intertek-Aptech*



**8. Leaky heaters.** This HRSG feedwater heater tube was one of many failures that resulted from cold-end corrosion during cycling. There were numerous leaks at the

tube-to-header connection caused by thermal cycling damage. *Courtesy: Intertek-Aptech*

**Fuel Systems.** Coal pulverizers are prone to fireside explosions, especially when using western coals. They require careful fuel purging and the addition of an inert gas blanket (inerting) when they are cycled off-line. Also, pulverizers are prone to much increased mechanical wear when they are cycled or operated at the low end of their design minimum flow rates. (For more information on proper operating and maintenance of coal pulverizers, see “ ‘Blueprint’ Your Pulverizer for Improved Performance,” March 2009 and “To Optimize Performance, Begin at the Pulverizers,” February 2007 in the *POWER* archives at <http://www.powermag.com>.)

Another unanticipated consequence of cycling a solid-fuel plant is the additional maintenance required on the coal silos. When burn rates are difficult to predict, the holding time of western coals in silos can extend beyond six or seven days, the maximum time considered safe. Longer storage of western coals often causes an increase in the frequency of hot spots and fires inside the coal silos. The same safety issues apply to coal pile management and inventory control, as burn rates constantly change due to plant load cycling or low-load following.

**Air and Gas Systems.** The forced and induced draft fans on coal-fired units can range from a few hundred to well over a thousand horsepower. Frequent starting and stopping of the fans—and, just as importantly, the motors that drive the fans—will increase failure rates, inspection intervals, and motor-fan maintenance. In some cases, fans have required retrofit of new drive systems for soft or low-stress starting. Additionally, air heaters and baghouses are subject to wet gas corrosion, plugging, and damage caused by operating below the wet gas dew point during low-load operations.

**Water Systems.** It may seem counterintuitive, but makeup water consumption greatly increases for a cycling unit because of the large amounts of water used during startup. In fact, it’s possible that the plant’s demineralized water supply and water storage may need to increase to support the increased boiler water usage.

The entire feedwater system is affected by thermally cycling plants. For example, feedwater heaters are subject to cooldown and rapid heating during a hot or warm startup cycle, and this often leads to early tube failures. Boiler feed pumps are normally designed for full-load operation and experience accelerated wear when operated at low loads. Also, boiler feed pumps may be required to stop and start several times for one startup cycle, thus causing many feedwater transients. In some plants, a smaller, low-load feedwater pump may be necessary for a cycling unit to limit damage to the main feedwater pumps. In others, boiler feedwater and condensate pumps may require added recirculation capability, and the economizer may require recirculation to keep exit water temperatures in check.

**Combustion Turbines.** Gas-fired combined cycles may be quick-acting in comparison with a coal-fired plant, but they are not immune to the same thermal stress–related equipment damage described above. Based on our experience with combined cycle plants, we have found that the largest line item on a plant’s operating and maintenance budget is costs related to cycling.

One reason cycling costs are proportionally higher in combined cycles is that turbine inspection and repair intervals are transitioned to being principally based on numbers of starts rather than operating hours. Therefore, the cost to maintain combined cycle availability is high on a per-unit-of-electricity-produced basis. The cost of replacement parts found damaged during overhauls, or “parts fallout” due to cycling, is often a factor of two or more over the plant life compared with baseload operation.

## Asset Management Principles

Managing power plants to operate at low cost and without excessive damage is the goal of every plant owner (see sidebar, p. 66). The cost of baseload operation is, for example, two-dimensional—the costs are based on operating hours at full load. However, cycling a unit poses a multi-dimensional problem that is difficult to comprehend or cost estimate. The challenge expands progressively because “cycling operation” is a broad concept that encompasses load-following, low load, hot starts, warm starts, and cold start of a plant with different lengths of time between operations; it is definitely not solely time-based.

Following are some useful suggestions for how to begin defining the true cost of cycling your plant. First, examine all the operating and maintenance cost categories that apply beyond fuel. We discussed a number of examples earlier. Equipment suppliers often provide life-reduction curves based on the time or number of instances that a steam turbine, for example, exceeds temperature and pressure design and ramp rate limits when started or load cycled. Other areas in your cycling operation cost accounting include:

- Increased equipment maintenance costs.
- Increased forced outages costs.
- Heat rate losses during startup through synchronization and loading to zero load.
- Heat rate losses during operation at loads lower than full load, including increased auxiliary power usage.
- Heat rate losses due to cycling, such as leaky seals and valves, and worn out or less-efficient heat transfer equipment during cycling.
- Additional startup fuel, chemicals, and staff required.
- Long-term loss of critical equipment life, such as the boiler/HRSG components (superheaters, reheaters, economizers, feedwater heaters, condenser, and other balance-of-plant equipment).

When these costs, defined for a range of operating scenarios, are determined, then you are ready to begin to prepare a pragmatic accounting of costs to meet a particular dispatch order or operating/shutdown order priority goal.

The financial model will also answer the question we are asked most frequently: Is it more financially prudent to shut down a particular unit at night to save fuel and incur the multitude of cycling costs or stay online at minimum load and burn fuel? The answer to that question is obviously unit/system-specific, but there are some trends based on client experience after the true cost of cycling has been determined. Many of our clients have reduced unit minimum loads to 5% to 20% of rated load on fossil boilers so that units can “simmer” overnight. This approach keeps the equipment hot and ready to quickly ramp up to full load (a big advantage in a competitive market), yet it uses minimum fuel at night.

## The Costs of Cycling Are Considerable

Now that the types of equipment affected by cycling have been generally defined and the need for a detailed financial model determined, let's examine more explicit data on the costs of cycling.

Our data generally indicate that cold starts are the most damaging, followed by warm starts and then hot starts, as illustrated in Figure 2. However, although load-following is much less damaging than hot starts, load-following can be very damaging when moving to lower loads that have lower temperatures and, thus, greater temperature changes. It is very important to recognize, count, and classify all these minor load-following operations and ensure that the sum of the load-following periods is properly accounted for in the cycling damage and the financial model.

Former baseloaded units that have been pressed into heavy load-following service often incur millions of dollars of additional damage as a result of operating mode changes. Intertek-Aptech has prepared a number of financial models to document the true cost of such cycling. In one case the model was used as part of a successful public utility commission case filing for a cost of operations recovery claim. Table 1 illustrates the general range of cycling costs

included in that specific claim and contrasts common rules of thumb with hard data. Table 2 summarizes the estimated cycling costs for a 500-MW conventional coal-fired plant developed as part of a recently completed cycling study. The estimates developed using the approach described in the following sections were several times larger than customers' estimates.

Unit type	Typical industry value <sup>a</sup>	Range of actual costs
Small drum boiler	\$5,000	\$3,000 to \$100,000
Large supercritical boiler	\$10,000	\$15,000 to \$500,000
Combustion turbine	\$100	\$300 to \$80,000

Note: a. Does not consider the true cost of cycling.

**Table 1. Cost to cycle a unit, per operation.** The true cost of cycling a unit is often much larger than the estimates used by many plant operators. *Source: Intertek-Aptech*

Type of transient	Cost category	Cost estimates (1,000 \$)		
		Expected	Low	High
Hot start; 1 to 23 hours offline	Maintenance and capital	53.2	42.6	67.4
	Forced outage	25.1	20.1	31.7
	Startup fuel	8.5	5.9	12.7
	Auxiliary power	4.4	3.5	5.5
	Efficiency loss from low- and variable-load operation	2.1	1.7	3.4
	Water chemistry cost and support	0.6	0.5	0.7
	<b>Total cycling cost</b>	<b>93.9</b>	<b>74.3</b>	<b>121.4</b>
Warm start; 24 to 120 hours offline	Maintenance and capital	57.0	45.3	71.0
	Forced outage	26.9	21.3	33.4
	Startup fuel	17.8	12.5	23.7
	Auxiliary power	9.4	7.5	11.7
	Efficiency loss from low- and variable-load operation	2.3	1.9	3.8
	Water chemistry cost and support	2.3	1.8	2.9
	<b>Total cycling cost</b>	<b>115.7</b>	<b>90.3</b>	<b>146.5</b>
Cold start; more than 120 hours offline	Maintenance and capital	85.4	67.7	106.2
	Forced outage	40.2	31.9	50.0
	Startup fuel	26.8	18.8	10.2
	Auxiliary power	12.0	9.6	15.0
	Efficiency loss from low- and variable-load operation	2.6	2.1	4.1
	Water chemistry cost and support	6.9	5.5	8.6
	<b>Total cycling cost</b>	<b>173.9</b>	<b>135.6</b>	<b>194.1</b>
Load follow down to 180 MW	Maintenance and capital	8.2	4.8	12.9
	Forced outage	3.9	2.3	6.1
	Efficiency loss from low- and variable-load operation	0.5	0.4	0.8
	Mill cycle gas	0.7	0.6	1.1
	<b>Total cycling cost</b>	<b>13.3</b>	<b>8.1</b>	<b>20.9</b>

**Table 2. Typical cycling costs for a 500-MW coal-fired power plant.** Costs are shown in 2008 dollars. *Source: Intertek-Aptech*

## Cost-of-Cycling Estimates

The Intertek-Aptech staff has developed two approaches to developing cycling cost estimates, such as the one summarized in Table 2, so that results can be compared and validated: the top-down estimate and the bottom-up estimate. Unit- and plant-specific information and industry data on similar units are also used in these analyses.

**Top-Down Estimates.** Top-down estimates use historical unit operating data and historical cost data to determine the costs of cycling operations (hot, warm, and cold starts and shutdowns; load following; and ancillary services such as

regulation and ramping). Fundamentally, we take wear and tear costs and other cycling-related costs and statistically determine the costs of cycling using detailed multivariable regression techniques that examine cost versus total cycling damage.

The first step to determining operating costs is to examine the actual validated plant maintenance costs, primarily found in work orders. The costs we take into account include the operating, maintenance, and capitalized maintenance costs incurred by the unit, while those unrelated to equipment maintenance are eliminated. Other cycling-related costs—such as the cost of fuel and chemicals for water treatment used for startups, and costs related to the increased outages caused by cycling—are also accounted for. These costs are then analyzed, processed, and tallied to create annual “candidate” cycling costs for the unit. All of these costs are candidates for our analyses, which determine the relationship between costs and the unit’s total cycling operational damage.

The second step is to add cycling damage to the maintenance cost estimates. The damage the unit accumulates from cycling is determined by examining the plant’s operating records. Specifically, the hourly average power output of the unit’s generator is analyzed to count cycles (all types of cycling and load-following) and determine the historical damage that the unit has accumulated versus baseload operation. We calibrate the damage during load transients and starts to plant signature data obtained during typical transients and starts.

Finally, we take the accumulated damage and historical costs to calculate a statistical “best estimate” of the cycling costs and calculate the upper and lower bounds using statistical regression techniques. In sum, we develop probabilistic estimates of the effects of cold, warm, and hot starts; shutdowns; and load-following operating modes.

We prove these estimates are valid by backcasting historical costs as a function of cycling costs. We know past costs are the best predictors of future costs when unit cycling remains constant. However, a significant increase in cycling and ramp rates can significantly accelerate equipment damage and increase future costs.

**Bottom-Up Estimates.** The other cost-estimating process is the bottom-up analysis. It is referred to as a bottom-up because it starts with the detailed work order history and a review of failure events and analysis completed earlier. The bottom-up review includes seven to 10 years’ worth of plant work orders, when available. The review includes a detailed analysis of work orders by a subject matter expert (SME), often including the plant personnel, to classify the costs as either related to cycling or to normal plant (baseload operation) costs. Actual failure reports, overhaul records, and prior inspection reports are also checked to determine the root cause of previous failures so that the costs can be properly classified.

This analysis uses actual plant signature data from representative starts and shutdowns and gives consideration to known design and operations issues. Load-following and actual plant ramp rates are examined, including the absolute temperature change from carefully selected data points to validate the type of damages.

## Tips from the Cycling Experts

- Understanding the true cost of operating a plant under all potential operating scenarios is vital to a successful cycling plant.
- Both the equipment and operating procedures are key factors in managing the cost of cycling.
- Cycling at the lowest possible ramp rate that satisfies system needs or economics will often reduce the damage rates. Cycle at a fast rate only when really necessary, as it is costly.
- Operators of all cycling plants need to pay special attention to water chemistry and transients.
- Low-impact or cost cycling will require targeted equipment modifications for a plant originally designed to operate in baseload mode.

- Develop startup and shutdown procedures, and ensure that operators adhere to them, so that desired operating results are achieved and are repeatable.
- Perform a comprehensive cost-of-cycling study to develop a specific set of cost-justified modifications and target cycling countermeasures with a known payback.
- Many items identified in the cost-of-cycling study can be implemented immediately and at low cost, such as revised operating procedures or control system modifications.
- Employ a cost-monitoring system, such as Intertek-Aptech's COSTCOM (Cost Control of Operations and Maintenance or Cost COMMunication) real-time software, to alert operators when the plant is using a damaging ramp rate or operating mode, and then display real-time costs to operators.
- Keep offline time short and the equipment hot to reduce cold starts, especially with the boiler/heat recovery steam generator.

## Comparing Cost Estimates

The result of these cost analysis approaches are cost estimates for various plant systems and sub-systems that identify the actual (usually the minimum) cost of cycling (based on recent historical costs). Those estimates can be used to predict future cycling costs. These cost estimates may be adjusted by latent damages factors determined by the SMEs, based on failure rates, inspections, interviews, or signature data. The estimates identify high-risk failures without detailed condition assessment inspections of many components. The estimates may drive limited specific condition-based inspections to validate the risk of failure or time for replacement. The estimates also include specific countermeasures with a valid cost-benefit at several levels with a return on investment for budget planning.

When the two cost estimates are completed, the customer has a report of detailed operating costs with recommended design improvements, equipment upgrades/replacement, and operating process improvements. The plant owner has hard data that specifies the costs of cycling the plant and a plan for managing cycling costs in the future with hardware and operating plant improvements. These plant improvement costs are usually ranked by cost-benefit and implementation costs. Some operating process or procedure improvements can be realized at little or no cost. Usually, those plant modifications with the highest benefit-cost ratio are quickly put into the company's capital planning cycle.

The electricity market has appreciably changed over the past decade, especially with the introduction of large amounts of nondispatchable wind and solar power in some regional markets. Cycling a plant is not necessarily a bad practice. But the decision to do so should be made by an owner who has full knowledge of all the available options and estimates of the real costs that must be paid, today or in the future, as a result of that decision. Give plants the tools they need to manage cycling costs, and they will produce winning results.

— **Steven A. Lefton** ([steve.lefton@intertek.com](mailto:steve.lefton@intertek.com)) is director, power plant projects and **Douglas Hilleman, PE** ([douglas.hilleman@intertek.com](mailto:douglas.hilleman@intertek.com)) is senior project manager for Intertek-Aptech.

[Close Window](#)



August 1, 2011

# Mitigating the Effects of Flexible Operation on Coal-Fired Power Plants

By Steve Hesler, Electric Power Research Institute

*As coal-fired power plants increasingly operate in cycling modes, many plants are confronting the potential for higher levels of component damage and degraded performance of environmental control equipment. Generators and EPRI are working together to find ways to mitigate the effects of cycling operation and to manage the transition of formerly baseload plants to flexible operation.*

Coal-fired power generating units in the U.S. continue to switch from high-capacity-factor operation to various modes of flexible operation. Cycling and load following are not new. However, over the past decade, and in particular the past few years, a perfect storm of factors has gathered to require even baseload coal plants to prepare for increased flexible operation.

The first factor is reduced demand caused by the recent recession. From 2008 to 2009, overall electricity demand in the U.S. declined 4%, according to the Energy Information Administration (EIA). An Electric Power Research Institute (EPRI) study, "Unprecedented Generation Shifts" (funded by the Power Technology, Market Analysis, and Risk Program), found that in 2009, coal-fired generation declined 11.1%, or about 75 terawatt-hours (TWh). That was the greatest recorded one-year decline in coal generation.

The second factor is lower natural gas prices and increased coal-to-gas switching. In 2008–2009, gas prices declined significantly, making gas-fired generation a lower-cost option for economic dispatch than coal-fired plants. In the same two-year time period, the net capacity factor for gas-fired combined cycle plants increased by 5%.

The third factor, which will play a role in the next decade, even when the economy improves, is increased deployment of intermittent renewable generation (principally wind) in certain regions of the U.S. That increased variable generation is forcing coal and combined cycle plants to provide system load-balancing services. The EIA reports that the amount of nondispatchable generation in the U.S. increased by a factor of four from 2005 to 2009. Wind generation alone increased from 18 TWh to 71 TWh during this period. Contributing to the complications for coal-fired plants, renewable generation is typically dispatched as "must-take," and the trends in both seasonal and daily wind production are often out of phase with demand.

The overall impact of these trends for coal plants has been increases in various modes of flexible operation, with the following operational impacts: increased load-following operation, higher unit turndown during low demand, lower minimum load operating, two-shifting, frequent unit starts (hot, warm, and cold), increased load and thermal ramp rates, frequent reserve shutdown, and long-term plant layup.

For example, analysis of data from the North American Electric Reliability Corp.'s Generating Availability Data System, as reported by coal units in the 2005–2009 timeframe, indicates an increase in reserve shutdown hours in 2009. This increase is observed across a range of unit sizes, in both supercritical and subcritical designs. In turn, this trend has produced a reduction in reported net capacity factor, particularly for older subcritical units, which are experiencing high turndown.

## From Baseload to Flexible Operation

Few coal-fired units in the existing U.S. coal fleet are designed specifically for flexible operation. In 2009, more than 60% of the total North American subcritical coal-fired generation was produced by units commissioned prior to 1980. Those were primarily baseload units constructed during the 1960s and 1970s to meet expected trends in demand

growth. Since 1980, power producers have opted to build large-capacity, more-efficient units with supercritical steam conditions, which are also designed for baseload operation.

New duty cycles force baseload plants and equipment to operate closer to—or beyond—nominal design limits and through more thermal cycles than originally anticipated. The operational impacts of flexible operation cited earlier result in significantly increased occurrences of thermal transients in the material of critical high-temperature boiler and turbine components. These transients, and other operational factors associated with flexible operation, have the following effects on coal-fired generating assets:

- Increased rate of wear on high-temperature components.
- Increased wear-and-tear on balance-of-plant components.
- Decreased thermal efficiency at low load (high turndown).
- Increased fuel costs due to more frequent unit starts.
- Difficulties in maintaining optimum steam chemistry.
- Potential for catalyst fouling in NO<sub>x</sub> control equipment.
- Increased risk of human error in plant operations.

Additional wear on plant components requires increased spending on preventive and corrective maintenance. This requirement is often challenging to plants that are placed lower on the dispatch stack and that, therefore, receive less revenue and operating budget. Increased human error is due primarily to the increased amount of transient operation, which produces more opportunities for error. Major plant events caused by human error can result in costly equipment damage and related safety challenges.

## Damage Mechanisms

Load following involves rapid increases and decreases 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 of these changes can force the unit to operate away from the original design point.

A few important material damage mechanisms are responsible for the majority of the financial impacts caused by operating coal plants in flexible modes. The severity of the impact of these mechanisms can be mitigated to a certain extent through improved plant operation and process controls, but it is impossible to completely eliminate the reduction in major component life caused by flexible operation. Examples of these damage mechanisms follow.

**Thermal Fatigue.** This phenomenon can produce cracking in thick-walled components, especially castings such as turbine valves and casings. Also affected are boiler superheater and reheater headers, where ligament cracking is commonly seen between tube stubs. These headers are expensive, thick-walled vessels operating under high steam pressure, making this damage of particular concern to plant owners. Header cracking (Figure 1) is caused by frequent, large temperature swings associated with flexible operation and, in some cases, by thermal quenching produced either by condensate formed during idle standby or poorly controlled attemperator sprays (again associated with transient operation).



**1. Cracked header.** Cold feedwater introduced to a hot header caused the crack in this economizer header. The cold water created a large through-wall temperature gradient change in temperature during startup and during off-line top-off opportunities. *Courtesy: EPRI*

**Thermal Expansion.** Several systems in a coal plant consist of 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 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 superheaters and reheaters (Figure 2).



**2. Leaky tubes.** Tube-to-header cracking caused by thermal transients is shown in this photo. Variation in tube thermal expansion, caused by differences in tube length, increases stress in some tubes. *Courtesy: EPRI*

**Corrosion-Related Issues.** Two-shifting, or any other operation that challenges the ability of a 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 the increased need for makeup water and the interruption in operation of the condensate polishers and deaerators. Corrosion and fatigue can combine to accelerate damage to waterwalls (Figure 3).



**3. Waterwall cracks.** Waterwall damage caused by corrosion fatigue is often found in steam generators. *Courtesy: EPRI*

**Fireside Corrosion.** Load cycling and relatively quick ramp rates under staged conditions will have a negative impact on both fireside corrosion and circumferential cracking.

**Rotor Bore Cracking.** When subjected to transients 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. This 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.

## Impacts on 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, the impact of fuel oil residues on linings, and their 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 (ABS), a sticky liquid that can fill catalyst pores, thus diminishing catalyst surface area and reducing reactivity.

## Strategies for Mitigating Flexible Operation Damage

A range of strategies will be needed to mitigate damage to coal units caused by flexible operation. These strategies should be generally assessed in terms of benefit-to-cost ratio when selecting action plans for specific units. Significant capital investment in improved-design boiler components may be warranted for new, efficient units with control technology installed.

In older plants, the most cost-effective strategy from a life-cycle cost perspective may be to focus on improved operator performance and selected plant controls upgrades. This approach could also include installation of additional process sensors (typically temperature), strategically located to guide operators through transients to reduce damaging over-temperature events. Increased attention to the location, operation, and capacity of drains is another cost-effective operation and maintenance strategy.

EPRI has undertaken a number of research efforts to better understand possible mitigation strategies.

**Efficiency Improvements.** One option for mitigating the effects of flexible operation is for plants to implement system modifications that recover plant efficiency lost to continuous cycling operation. However, many plants today do not have sufficient capital available to undertake major system modifications. To address this challenge, a recent EPRI study identified modification measures that have the potential to achieve the most impact for a reasonable investment. The options involve modifications to equipment and operating procedures that will be cost-effective for reducing heat rate under cycling operating conditions.

For each option, preliminary assessments were made of the potential benefits (in terms of electrical output and heat rate recovery) and possible reliability risks. Examples include sliding pressure operation, variable-speed drives for main cycle and auxiliary equipment, and boiler draft control schemes and operating philosophy.

**Cycle Chemistry Guidelines for Transient Operations.** An area of particular concern for plants under cycling duty is following appropriate cycle chemistry guideline limits during plant startup, shutdown, and layup. Proper protection of the entire steam circuit (boiler, piping, feedwater, and turbine) is critical during these modes of flexible operation.

With this in mind, EPRI worked with the 40 members of the EPRI Cycle Chemistry Technical Advisors Group to develop cycle chemistry guidelines for all transient operations and shutdowns. The guidelines include specific procedures and advice for cycling, shutdown, startup, and layup for each boiler and feedwater treatment; they also cover all major water- and steam-touched surfaces. Correct layup procedures, combined with appropriate chemical treatment during shutdown and startup, will significantly reduce corrosion and deposits in the steam cycle equipment, including the boiler, steam-touched tubing, and the turbine.

**Two-Shift Operating Practice.** Changes in operational practices can be an effective strategy for mitigating cycling damage. Several years ago, EPRI studied worldwide experience with two-shift operation (usually weekday starts with overnight shutdowns) and found that economic two-shifting can be achieved with due care and application of sound engineering and operational practice.

Among the findings:

- Many utilities have performed trials on two-shift operation to reduce startup and shutdown time. Generally, startup times can be nearly halved from original base-load 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. A target time to full load on a 500-MW machine is approximately 60 minutes.
- 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. In the United Kingdom, natural-circulation drum boilers have been fitted with off-load circulating systems to pump water slowly around the evaporative section to balance temperature variations. The aim is to eliminate flow stagnation and tube-to-tube temperature differences. In addition, interstage drains or vents have also been fitted to promote flow through the superheater stages and avoid quenching problems that may arise when cold condensate from platen elements is otherwise pushed into the relatively hot final superheater stages.
- A primary constraint on ramping operation is matching steam and turbine metal temperatures. Sliding pressure offers advantages over throttle control during startup by establishing a flow to the turbine earlier in the sequence, with lower overall heat input and by retaining high temperatures on shutdown.

**Mitigating SCR Issues at Low Load.** To avoid problems with SCR units during low-load operation, conventional design practice calls for a flue gas or water-side economizer bypass to elevate the flue gas temperature at low load to a level high enough to allow reagent injection. However, many units are not equipped with economizer bypass capabilities. In these cases, operators have a number of options to comply with the minimum operating temperature:

- Evaluate actual SCR inlet operating conditions ( $\text{NH}_3$  and  $\text{SO}_3$  concentrations, and temperature distribution), and compare them with the SCR design conditions.
- Modify current operational practices (such as fuel sulfur content and  $\text{NO}_x$  reduction levels at low load).
- Improve the SCR inlet temperature distribution by installing a static mixer.

Independent verification is needed to show that catalyst activity will recover during higher-temperature operation after ABS formation at low load. To address this and related issues, EPRI is conducting a laboratory-scale test program to study ABS formation and evaporation in SCR catalyst. EPRI is also assessing the impacts of an economizer bypass and potential alternatives, determining the impacts of low load on catalyst deactivation for specific application, and developing guidelines to minimize the impacts on SCR operation and performance.

## E.ON's Strategies for Managing Cycling—A Toolbox Approach

The Germany-based utility holding company E.ON has taken a toolbox approach to improving the cycling performance of its coal and combined cycle plants, using the following tools.

**Flexible Operation Studies.** These studies reduce component damage through procedure optimization and design modification. Included in the studies are an initial appraisal of plant-specific risk areas, installation of additional instrumentation, flexible operation trials, assessment of thermal transients, modifications to operating procedures and design to address issues identified, repeat trials to confirm success, and detailed stress analysis to inform strategy going forward.

Examples of steps taken include optimization of overfire air to prevent excessive platen superheater temperatures, use of progressive drainage to minimize thermal transients, and optimization of attemperator spray usage to avoid quenching. Studies conducted in the mid-1990s achieved substantial reductions in thermal transients, reduced hot start times from 90 to 60 minutes, and produced typical savings of £800 (\$1,292) per start in fuel, auxiliary power, and water costs.

**Operator Coaching.** Simplified damage algorithms for creep and fatigue are also developed for operator coaching. Plant data for critical components is screened to identify and understand the most damaging operational conditions. Operators can then seek to minimize the extent of such conditions during future unit starts.

**Inspections and Component Assessment.** Targeted inspections based on component risk, defect history, and operating regime are conducted during outages. Defect assessments are made as appropriate. For high-cost strategic components and/or those whose failure has severe consequences—such as headers, pipework, steam chests, and rotors—detailed safety cases based on finite element modeling are sometimes required. For severe defects, these safety cases may stipulate an allowable number of starts before component re-inspection is required. Structures and support systems, which are also affected by flexible operation, are also examined and managed proactively.

**Maintenance Strategies.** Maintenance strategies are developed about every three to four years to allow future budgeting and phasing of component replacement (as informed by inspection and experience). These strategies are forward-looking to anticipate requirements of expected operating regimes in terms of hours and starts, and are sometimes scenario-based. They include a detailed review of site-specific defect/failure histories to date.

**Design Modifications.** Modifications are proposed to the design of replacement components to “design out” damage mechanisms, if possible (for example, selective use of P91 metal in place of 2¼ Cr for thick-sectioned high-temperature headers, and increased flexibility of header antler arrangements).

**Damage Estimation.** Estimates can be made of damage costs per start to inform the plant's trading position based on increased routine maintenance costs, damage to major components, and estimated cost of consumables per start.

**New-Build Design.** Lessons learned are incorporated into specifications for new-build plants.

*Adapted from material provided by Dan Blood, team leader within the Plant Integrity Department of E.ON New Build & Technology.*

## Future Research

Two new EPRI research projects are planned to get under way this year.

One project will coordinate plant field studies to demonstrate operational strategies for reducing the impact of two-shifting, ramping, and turndown on plant equipment. Multiple host units will allow the research to be conducted across a range of generating asset types and systems. The strategies will seek to reduce thermal transients experienced by components in the steam generating and turbine systems of coal-fired plants, and to manage impacts on environmental control equipment. The project will first apply cycle transient analyses to develop options and then run operational trials to refine processes. This strategy has been successfully demonstrated by power producers outside the U.S.

A second project will develop guideline documents to help power companies successfully transition their fleets to flexible operation. The project will utilize existing EPRI research results on component-level cycling impacts and mitigation and will compile lessons learned and strategies used by organizations worldwide. Resources to be developed will include a *Flexible Operation Readiness Guide*, which will address the need to first assess equipment condition and organizational readiness for flexible operation duty; a *Guidelines for Managing Flexible Operations*; and a *Primer on Fossil Plant Cycling for Power Marketing and System Operators*.

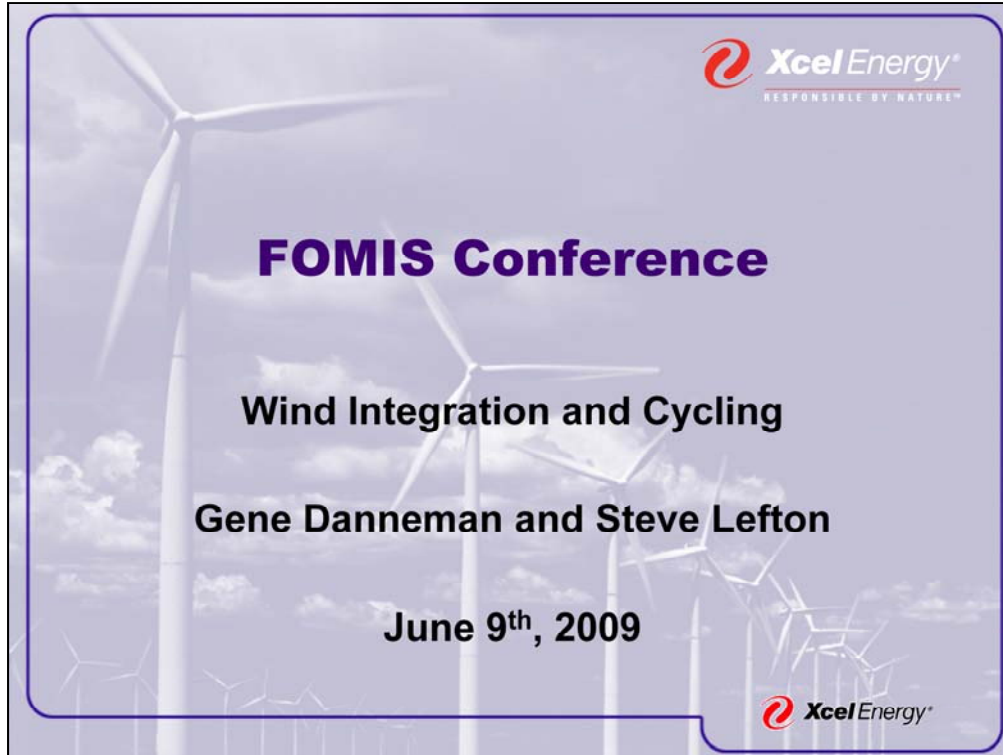
In addition to research aimed at existing coal units, EPRI will explore initiatives to define the design characteristics of the future coal-cycling unit. Some new European power plants have already been designed for flexible operation. Design changes for cyclic operation include installation of a turbine bypass, installation of more thermocouples and other monitoring equipment, modifications to standard boiler tube supports, upgrading the fan prime mover, use of variable-frequency drives on motors, and inclusion of bypass systems for use during startups.

In the U.S., information on design characteristics for cycling units could be used in future procurement specifications in situations where the prime requirement is operating flexibility. Starting with a clean sheet of paper would be expected to yield significant improvements in unit flexibility. This research effort should start soon in order to be available for potential new-builds in the next decade. ■

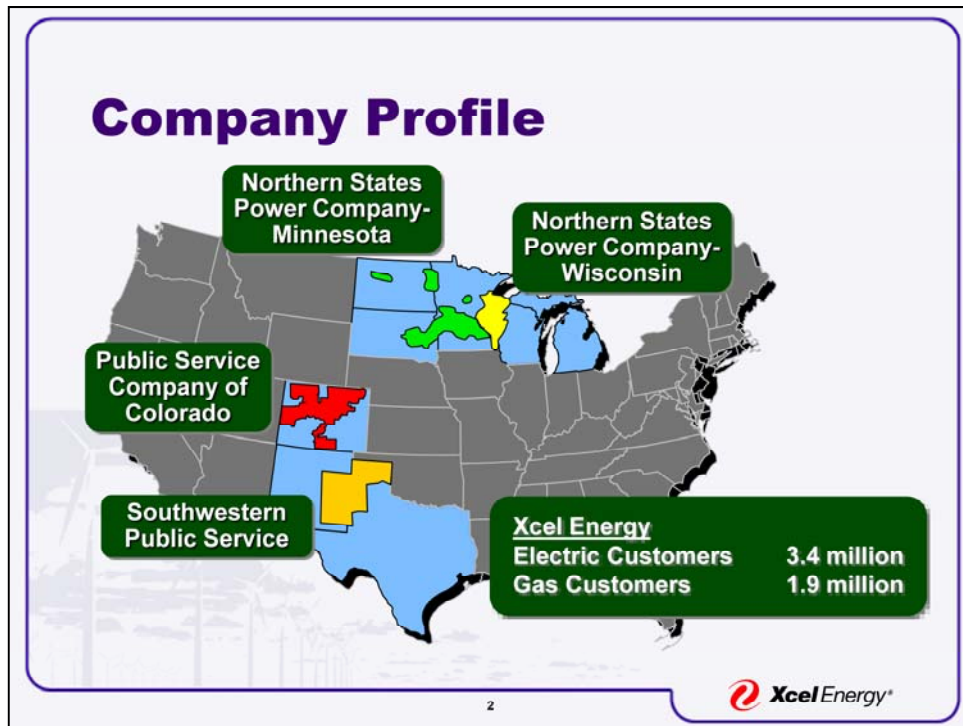
— **Steve Hesler** ([shesler@epri.com](mailto:shesler@epri.com)) is program manager for EPRI Generation Fossil O&M.

[Close Window](#)





- Good Morning
- I'm Gene Danneman, Operations Support Manager for Xcel Energy Supply and my co-speaker is Steve Lefton VP – Power Division (Intertak – Aptech Engineering Services).
- Xcel Energy, one of the nation's largest utilities, owns a fleet of coal, gas, nuclear, hydro, and wind plants that we must operate reliably, economically and dispatch efficiently to meet system load requirements.
- I will be sharing some of the results of our Aptech Engineering Total Cost of cycling Analysis



- Map illustrates the 8 states where we serve (in blue).
- Xcel Energy was created in 2000 by the merger of Northern States Power Company and Public Service Company of Colorado.
- Xcel Energy comprises four operating companies:
  - NSP-MN (green)
  - NSP-WI (yellow)
  - Public Service Company of Colorado (red)
  - Southwestern Public Service (gold)
- The company serves 3.4 million electric customers and 1.5 million gas customers.

## Corporate Strategy

- ▶ Deliver safe, reliable, affordable energy to our customers
- ▶ Transform our business through environmental leadership
  - ▶ Advanced technology
  - ▶ Energy efficiency
  - ▶ Business innovation
- ▶ Our tagline: *Responsible by Nature*



3

- The company's strategy involves delivering safe, reliable, affordable energy to its customers;
- And transforming the business through environmental leadership in 3 major ways:
  - Advanced technology
  - Energy efficiency
  - Business innovation
- Last year, Xcel Energy began using a new tagline: RESPONSIBLE BY NATURE.
- It captures the approach for everything the company does: the responsibility to serve its customers, and to do so in an environmentally responsible way.

## Leader in Renewable Energy

### No. 1 provider of wind energy

- ▶ 3,000 megawatts in 2008
- ▶ 7,400 megawatts by 2020

### No. 5 in solar power capacity

- ▶ 2,000 new solar systems
- ▶ Central solar photovoltaic power plants
- ▶ 600 megawatts of concentrating solar power, with storage

### Biomass and hydroelectricity



4

- Xcel Energy is focused on its environmental responsibility, and that means building a clean energy future for its customers and the communities it serves.
- Through its environmental leadership, it is implementing business strategies that grow its position as one of the countries leading utilities for clean energy.
- **Biomass:** Xcel is retrofitting its coal-fired Bay Front generation station in Wisconsin to be the largest biomass power plant in the Midwest.
- Energybiz Leadership conference held March 10
- We are witnessing an exciting transition in the energy industry as we apply new technology to make major differences in the economy and the environment. Challenges include developing transmission for wind; carbon legislation and renewable portfolio standards.
- The Edison electric Institute CEO stated: The country faces something like a perfect storm. No excess capacity left from the 70's and 80's over build; a deep economic recession and the need to address climate change.

## Problem Statement

- Generation units originally designed for baseload operations are now running in cycling modes (load following and on/off) – these cycling costs were not quantified.
- Current system decisions are likely sub-optimized in terms of minimizing long-term costs.
- Ever increasing amounts of variable wind are planned that will aggravate these issues.

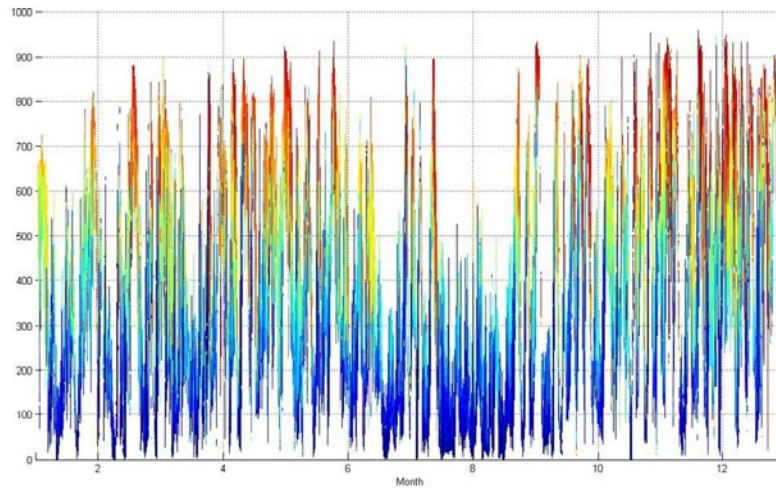
5



According to the DOE report *20% Wind Energy by 2030*, factors that facilitate the integration of wind power into the electric system and further improve overall reliability and cost-effectiveness include the following:

- Wind forecasting enhances system operation.
- Flexible, dispatchable generators, such as natural gas plants, facilitate wind integration.
- Aggregation and geographical spread of wind projects reduces variability; the more wind farms, the smoother the overall output can be.
- Large balancing areas reduce impacts, for wind and for all technologies.
- Changing load patterns, such as those enabled by a smart grid and plug-in electric vehicles, can complement wind power generation.
- So what is the problem? – While we are scrambling to deal with climate change, we need to keep our current fleet economical and our staff safe from process hazards. It's a hidden problem that must be addressed and quickly.

## MN Wind 2008 - Monthly

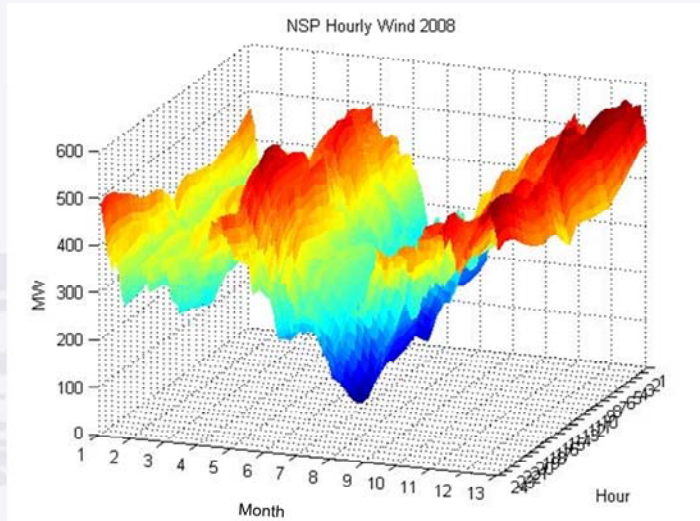


6



- This graphic shows partially smoothed composite hourly Megawatt production for the Minnesota wind farms. The intent of this slide is to show the variability of wind production as we see it today.

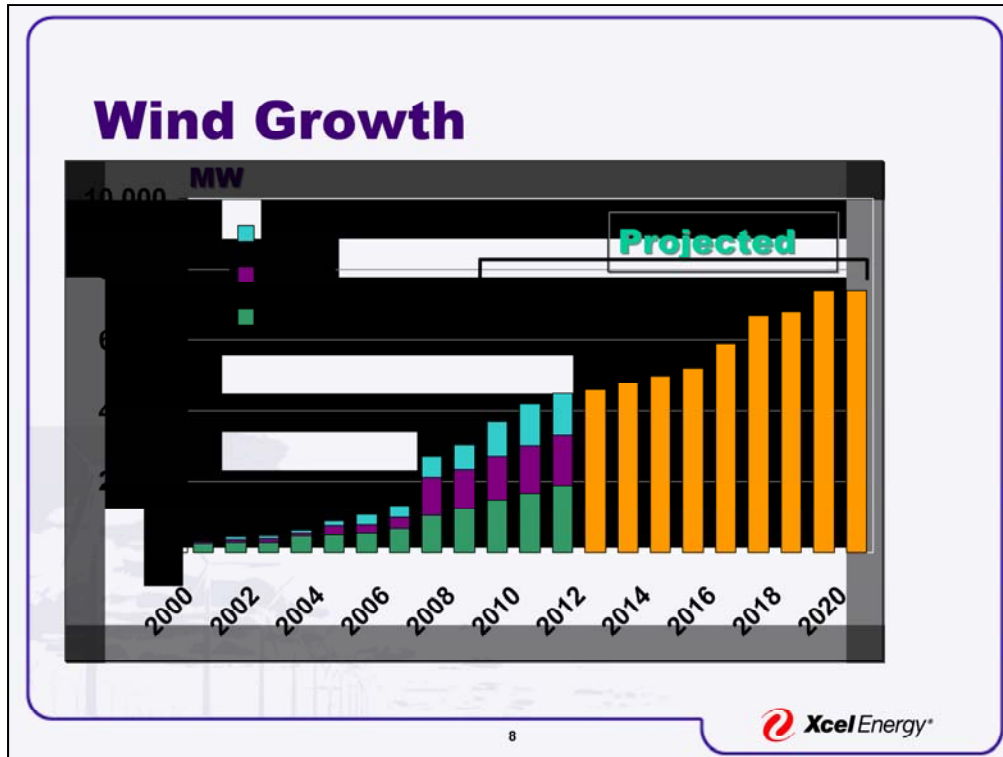
## MN Wind 2008 (smoothed)



7

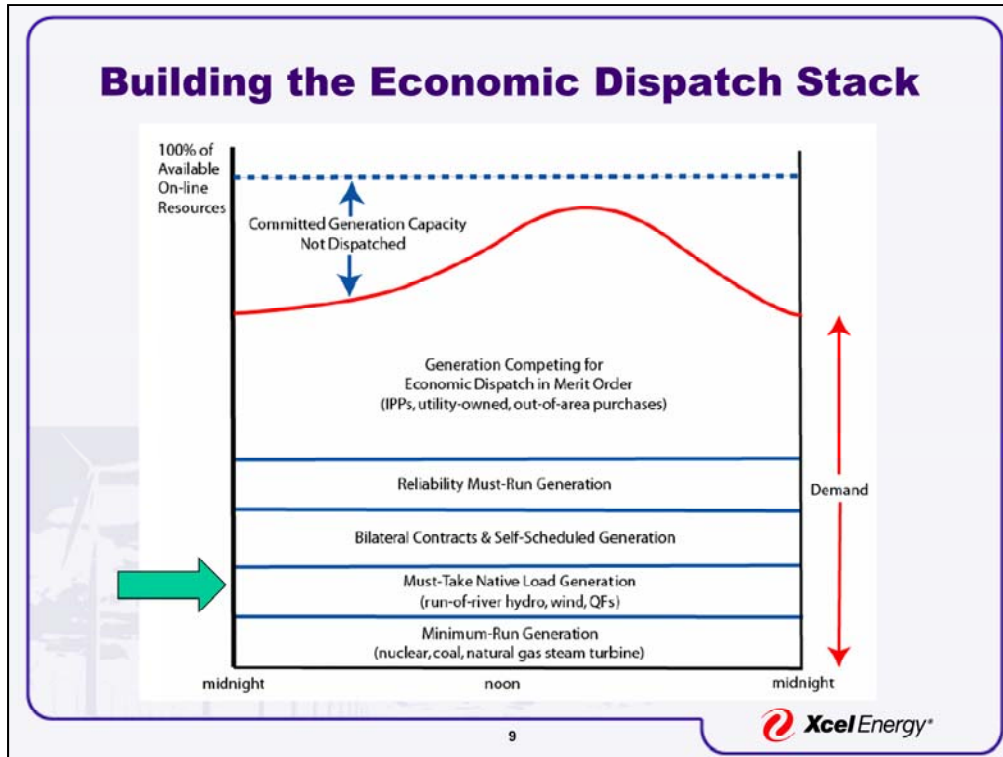


- This three dimensional graph illustrates the hourly wind generation in megawatts for Minnesota plotted against the month and time of day. The highly variable generation data used to create this graph was smoothed 15 days forward and back to produce this graphic.
- Notice the high production in April, May, December and January (red).
- Notice the low production in Late July and Early August which is a summer peak period (dark blue) for native load.
- This smoothed graph shows what the current production would be from wind with some energy storage.



- Xcel plans to bring 7583 MW of wind resources online by 2020.
  - PSCo: 2,859 MWs
    - ✓ **20% Renewable by 2020**
  - NSP: 3,969 MWs
    - ✓ **30% Renewable by 2020**
  - SPS: 755 MWs
    - ✓ **20% Renewable by 2020**
- By 2013 (4 years) when wind “capacity penetration” exceeds about 15%-20%, we predict that the additional Megawatts generated by wind and introduced in our portfolio will dramatically change the way power must be dispatched and will increase cycling of existing base load plants. The ancillary services required to support the regulation and load following of variable wind energy are referred to as Base-Load Unit dispatch flexibility and spinning reserve.
- Xcel is convinced that such increased cycling will lead to greater wear and tear on the plants from load follows and startup-shutdown cycles and will lead to more forced outages.





- The daily dispatch stack of generation resources required to meet demand is shown generically in this graphic with wind generation considered a must-take resource second to bottom in the stack.
- Source - <http://www.oe.energy.gov/DocumentsandMedia/value.pdf>

**THE VALUE OF ECONOMIC DISPATCH - A REPORT TO CONGRESS - PURSUANT TO SECTION 1234 OF THE ENERGY POLICY ACT OF 2005**

**This information was provided to congress supporting the renewable energy policies. There is a major flaw in this graph. It fails to recognize high wind, low native loads when baseload units are affected.**

## Energy Imbalance Options

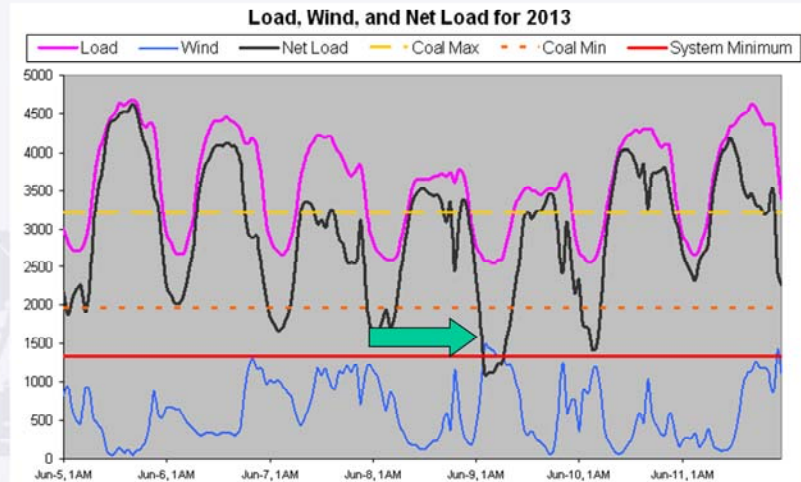
- ◆ Energy Storage
- ◆ Regional Market Dispatch –interconnection imbalance
- ◆ Transmission Upgrades
- ◆ Consumer Load Flexibility
- ◆ Wind Production curtailment
- ◆ **Increased flexibility from traditional generators**
  - ◆ **Reduced Minimums**
  - ◆ **On/Off cycling time reduction**
  - ◆ **Up/Down Load Ramp increase**

10



- This list of options was given to congress. Many of them have been considered too expensive or troublesome to implement.
- There are many approaches to keeping energy production balanced with energy demand.
  
- This presentation will focus of the consequences of those items noted in red.
- Reducing the minimum load that our base load units will operate at under routine or emergency conditions.
- Reducing the amount of time off-line during on-off cycling
- Increasing the load following ramp rates of our base load units to chase the wind variability

## Load, Wind and Net Load: January 2013



11

XcelEnergy®

- This is a simulated slide showing PSCO native load/ wind production and net load during a system bottoming event - high wind/ low load.
  - The top dashed yellow line represents all base load coal units running at maximum capacity.
  - The dashed orange line represents all base load units running at design minimum capacity.
  - The solid orange line represents all base load units running at emergency minimum
- In this example, on June 9<sup>th</sup> at 1 AM, the net load has dropped below the coal emergency minimum. All other sources of power are off-line and the base load coal plants are backed down to emergency minimum status.
- Wind production will be curtailed or we risk a system reliability event due to over-excitation and a potential blackout .

## **Xcel Energy Cost of Cycling team**

- ▶ **Aptech Engineering Services**
- ▶ **Generation Asset Analysis and Reporting**
- ▶ **Pawnee Staff**
- ▶ **Harrington Staff**
- ▶ **SherCo Staff**
- ▶ **Other Company Resources**
  - Accounting; Generation Model Services;**
  - Resource Planning & Bidding; Energy Supply**
  - Finance; Engineering and Construction;**
  - Production Resources; Testing Engineering;**
  - Commercial Operations; Transmission**

12



- In July 2008, a Xcel Energy Supply Operations team was chartered to determine the total cost of cycling three of our largest coal fired units as a sub-team to the Wind Integration Team
- On September 15<sup>th</sup>, 2008; Aptech Engineering Services was awarded the contract to complete 9 reports which would document the as-is cost of cycling; analyze the impact of a future load pattern scenario for the year 2013 and provide an engineering assessment of what actions could be taken to mitigate cycling costs. Aptech has completed many of these types of studies and provides credibility to the study.
  
- Pawnee Unit 1 (PSCO) 505 MWnet unit Max Dependable Capacity was the first analyzed (330 MWnet AGC minimum)
- Harrington Unit 3 (SPS) 347 MWnet unit Max Dependable Capacity was the second analyzed (163 MWnet AGC minimum)
- SherCo Unit 2 (NSP) 685 MWnet Max Dependable Capacity was the third analyzed (250 MWnet AGC minimum)

## Who is Aptech Engineering ?

- ▶ Now Intertek-APTECH is a full-service US-based engineering consulting company specializing in life management of facilities.
- ▶ Unit and System-wide Cycling and Cycling-Related Projects
- ▶ Analysis of the costs to cycle over 350 Utility and IPP clients in USA and Europe
- ▶ Over 125 projects for EPRI

13



- Headquarters at Sunnyvale, CA (San Francisco)
- The company's services help clients globally to identify and prevent the failure of equipment, improve reliability, predict life-span, and to analyze the risks and costs associated with the operation and maintenance of equipment and infrastructure assets.
- Partial list of clients include: Duke, Cinergy, AEP, NRG, Salt River, Texas Utility, FP&L
- Aptech has been supporting the oil and power industry since inception in 1979
  
- More than 90 APTECH employees based across two US locations in San Francisco and Houston

## Challenges of Wind Integration

- ▶ More Net Load Ramp Up & Down situations on all units
- ▶ More Turn-down on baseload units
  - ▶ Lower unit minimums
  - ▶ Faster ramps up and down
- ▶ Greater Cumulative System Variability (Net Load = Load - Wind)
- ▶ Increased Starts/Stops on Gas-fired units
- ▶ Gas pipeline balancing & coal supply issues

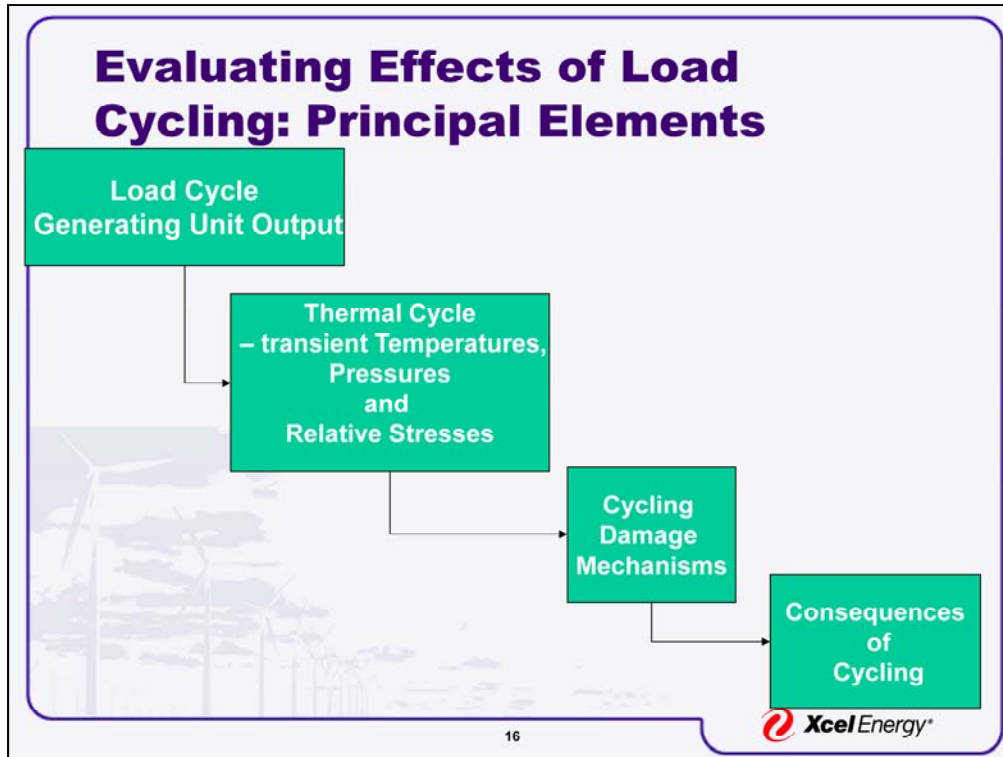
14



- This is a list of the challenges of integrating large quantities of wind energy to our regions.
- Focus of this briefing is on the first two lines

## **What is Cycling Damage?**

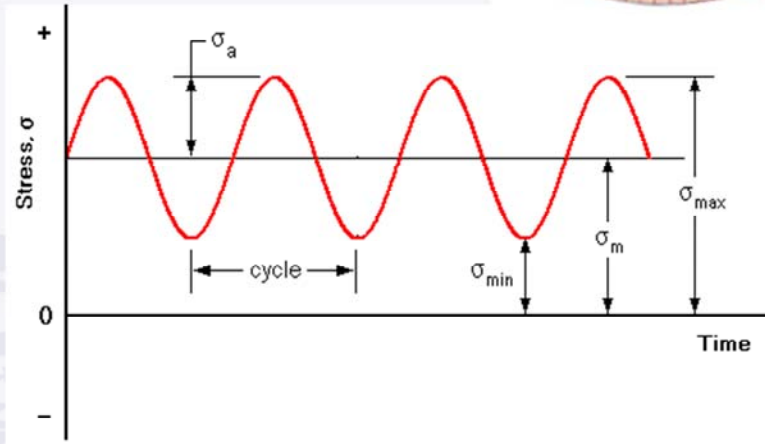
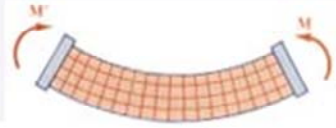
**Every time a conventional steam power plant is cycled (load ramping or on/off service) – the boiler, steam lines, steam turbine, and auxiliary components go through unavoidably large thermal and pressure stresses, which cause long-term, irreparable structural damage.**



- This flow diagram shows the basic analysis used to determine wear and tear for thermal cycles. Also evaluated are mechanical cycling and chemical (corrosion fatigue) cycling.
- Unit ramp testing was required to identify weaknesses in equipment design and current procedures.



## Stress Life Cycle

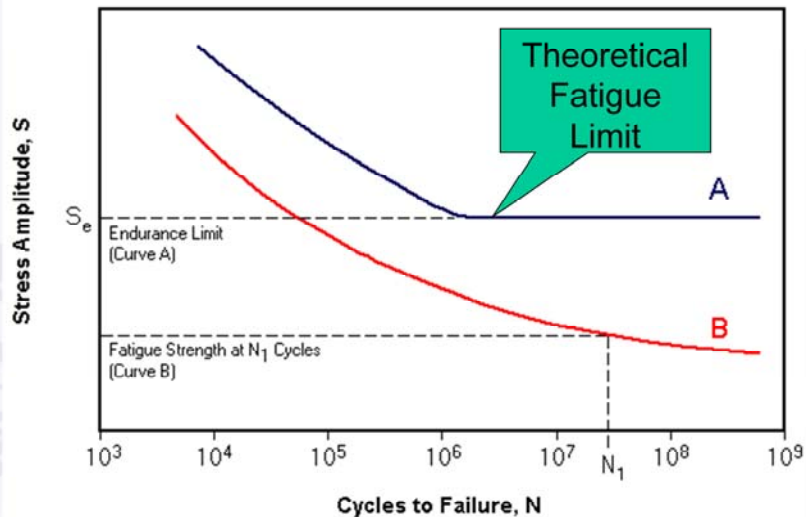


17

 Xcel Energy®

- This graphic shows a generic stress life cycle of stress versus time. By definition, a stress cycle goes from minimum to maximum back to minimum stress over a period of time to complete the cycle.

## Stress vs. Cycle: S-N curve



18

In materials science, **fatigue** is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. The maximum stress values are less than the ultimate tensile stress limit, and may be below the yield stress limit of the material

- The greater the applied stress range or amplitude per cycle, the shorter the life.
- Damage is cumulative. Materials do not recover when rested.
- Fatigue life is influenced by a variety of factors, such as temperature, surface finish, presence of oxidizing or inert chemicals, residual stresses, contact (fretting), etc.
- There are two general types of fatigue tests conducted. One test focuses on the nominal stress required to cause a fatigue failure in some number of cycles. This test results in data presented as a plot of stress ( $S$ ) against the number of cycles to failure ( $N$ ), which is known as an S-N curve
- For metal that has been welded, seen corrosion or creep damage; the curve becomes a shotgun pattern with far less predictability of fatigue life.
- There is no theoretical lower limit for corrosion fatigue. This damage mechanism is the dominant mode of failure for units in on/off cycling per Aptech.

## Thermal Cycling: low-cycle fatigue – inverse power law

$$N = \frac{C}{(\Delta T)^\gamma}$$

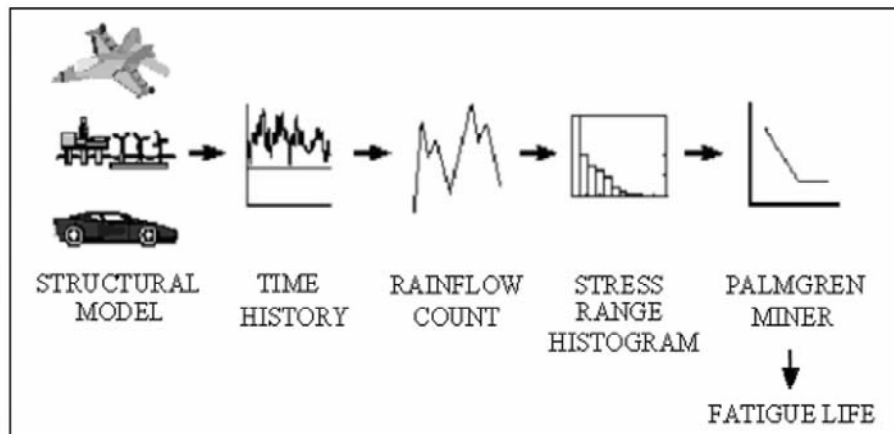
- **N** is the number of cycles to failure.
- **C** is a constant, characteristic of the metal.
- **γ** is another constant, also characteristic of the metal.
- **T** is the range of the thermal cycle

19



- A snoozer!
- Thermal cycling is commonly treated as a low-cycle fatigue problem, using the inverse power law relationship. Coffin and Manson suggested that the number of cycles-to-failure of a metal subjected to thermal cycling is given by **this formula**
- where:
- **N** is the number of cycles to failure.
- **C** is a constant, characteristic of the metal.
- **γ** is another constant, also characteristic of the metal.
- **T** is the range of the thermal cycle.

## Time Domain Fatigue Life Prediction



20

 Xcel Energy®

- Planes, trains, windmills and cars all have cyclic life expectancies. Over time each sees stress cycles of varying stress levels. Those stress cycles are counted and the magnitude of each stress cycle calculated. The analysis determines which of those cycles causes damage and which do not. From this analysis, the remaining cyclic life or fatigue life can be estimated.

# Fatigue-Creep Interaction

Failure Mechanisms and Implications for Key Components

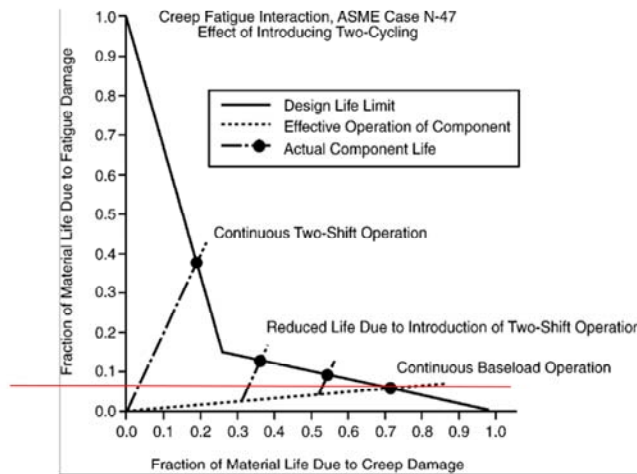
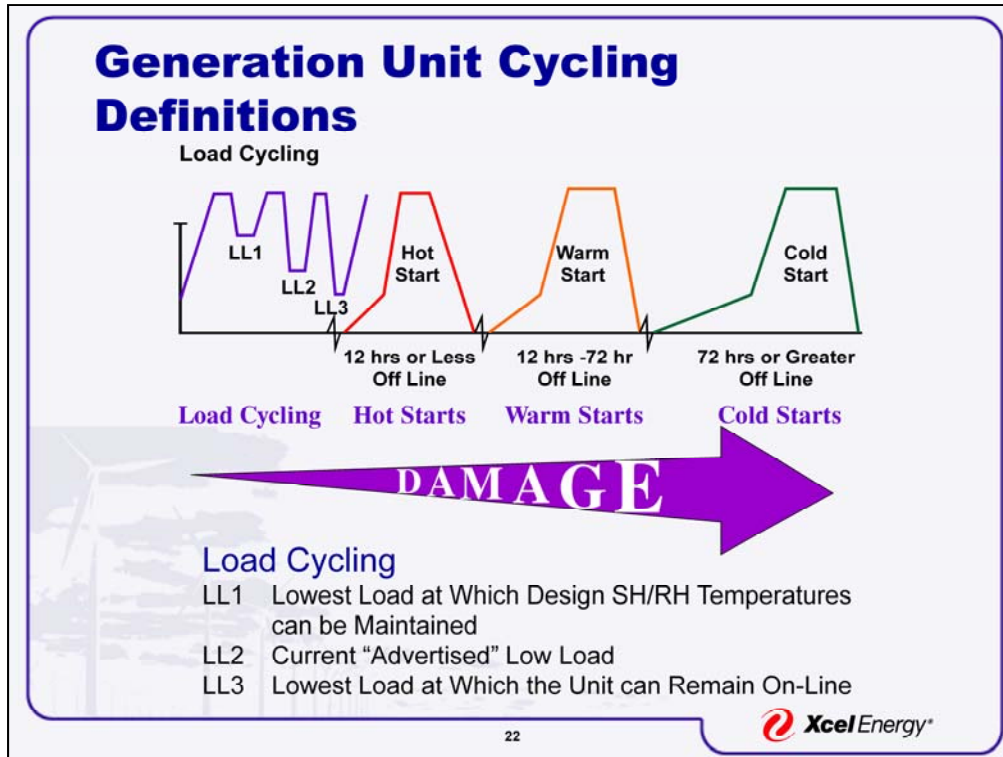


Figure 3-1  
Interaction and Consequences of Creep and Fatigue  
(Based on ASME N-47) for a Typical Power Plant Steel (2.25Cr1Mo)

21

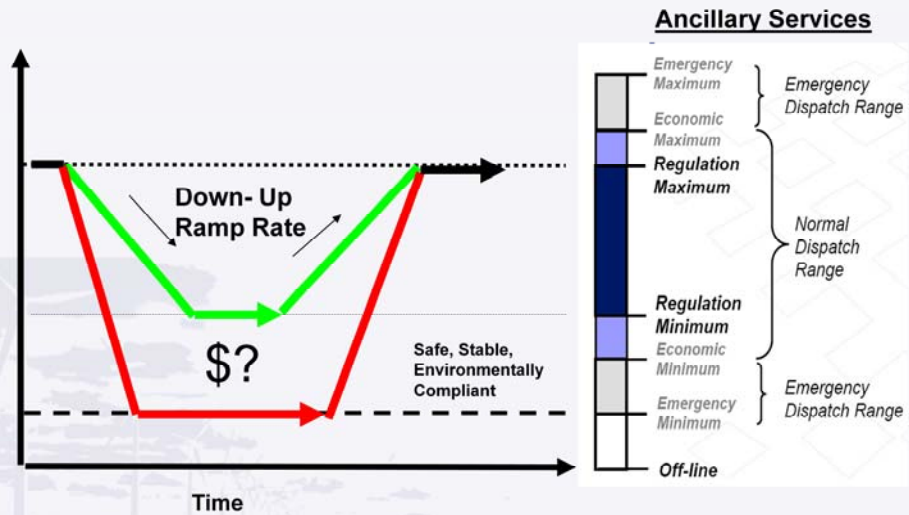
XcelEnergy®

- For metals that operate at temperatures above their creep damage point, we must also consider the deteriorated fatigue life caused by creep damage. Components that have incurred a high degree of creep damage will have fewer fatigue cycles prior to failure than a new component. The degree of steel alloying has a dramatic effect on this phenomena. This curve shows the characteristics of P-22/ T-22 chrome-moly steel in four different services.
- Source - *Damage to Power Plants Due to Cycling*, EPRI, Palo Alto, CA: 2001. 1001507.



- This graph from Aptech Engineering Services shows the different types of load cycles (megawatts versus time) that a unit could be exposed to and the relative damage that occurs each cycle.
- Three different low load cycling points LL1, LL2 and LL3 are defined on this slide. Each point affects the degree of thermal cycle transient experienced during a load following event because the metal incurs larger temperature changes.
- Three on/off cycles are defined based on hours off-line (hot, warm and cold starts) with the worst damage occurring during a cold start cycle.
- Definition of Equivalent Hot Start – Standardized in a 1985 EPRI study of Haynes Unit 5 (Supercritical 350 MW unit)
- Load follows each have relatively low damage costs but because there are so many of them, the cumulative impact of many load follows leads to the damage of an equivalent hot start.

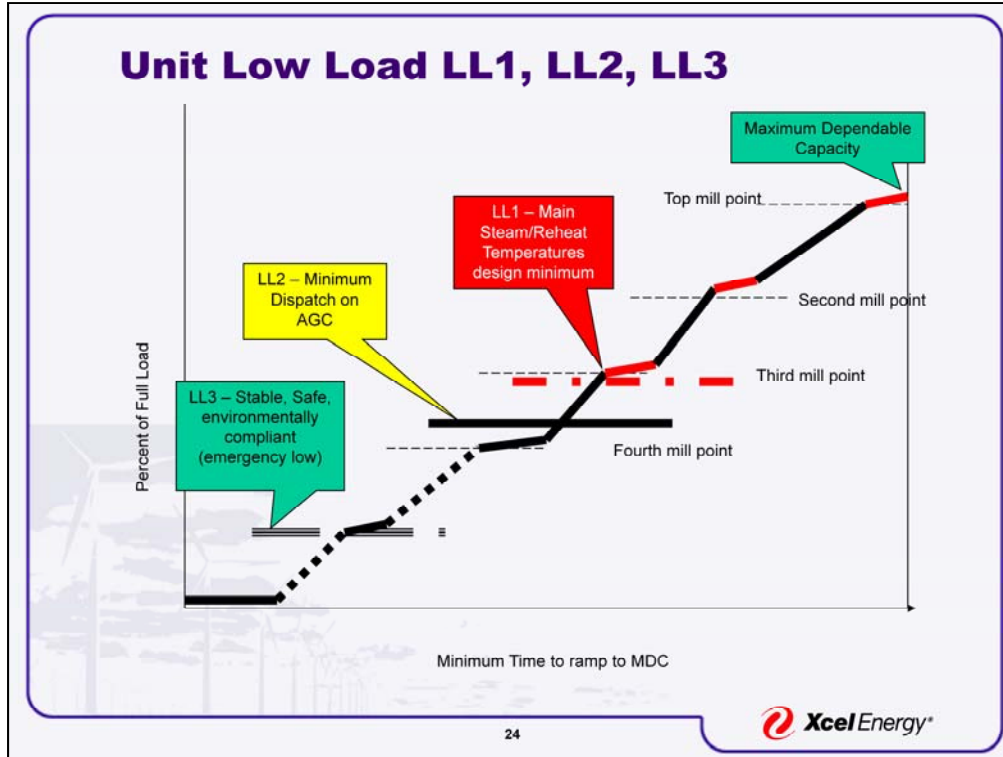
## Deep Load Following Scenario



23



- Our studies focused on the wear and tear from LL1 (control point) to the emergency minimum.



- This graph shows the load ramp for a typical coal fired unit which has six coal mills requiring two mills in service to maintain stable furnace combustion and minimum load and 6 mills in service at full load.
- Each break point on this graph affects the degree of thermal cycle transient experienced during a load following event.



## Top-Down Method

### Industry Parameters

- ⌚ EFOR
- ⌚ Maintenance costs
- ⌚ Capital costs
- ⌚ Capacity replacement costs
- ⌚ Design, size, etc.
- ⌚ Pressure / temperature
- ⌚ Costs vs. equivalent hot starts
- ⌚ Statistical analysis

### Expert opinions

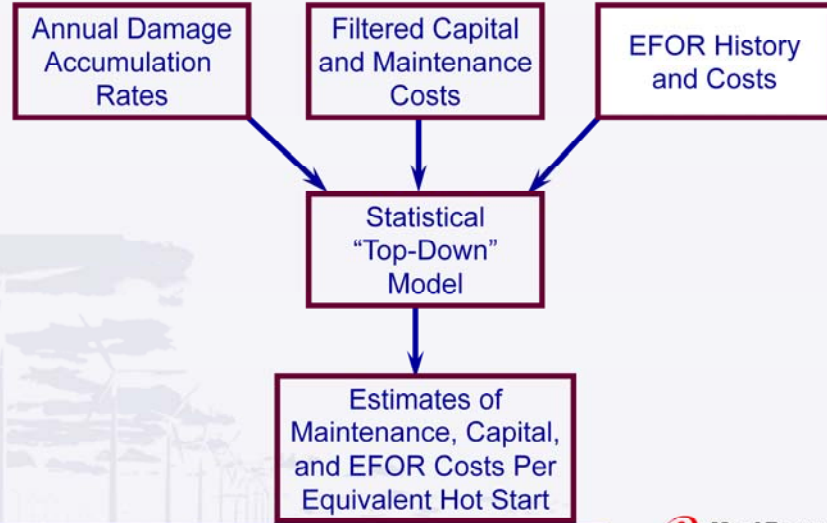
- ⌚ Plant operator surveys
- ⌚ Expert analysis



 Xcel Energy®

- There are many methodologies to estimate cycling costs. We contracted with Aptech Engineering Services to perform 3 unit analysis for Xcel Energy documenting baseline prior to wind addition and forecasting a future cost.
- Introduce Steve Lefton – Aptech Engineering Services

## Top-Down Analysis Procedure

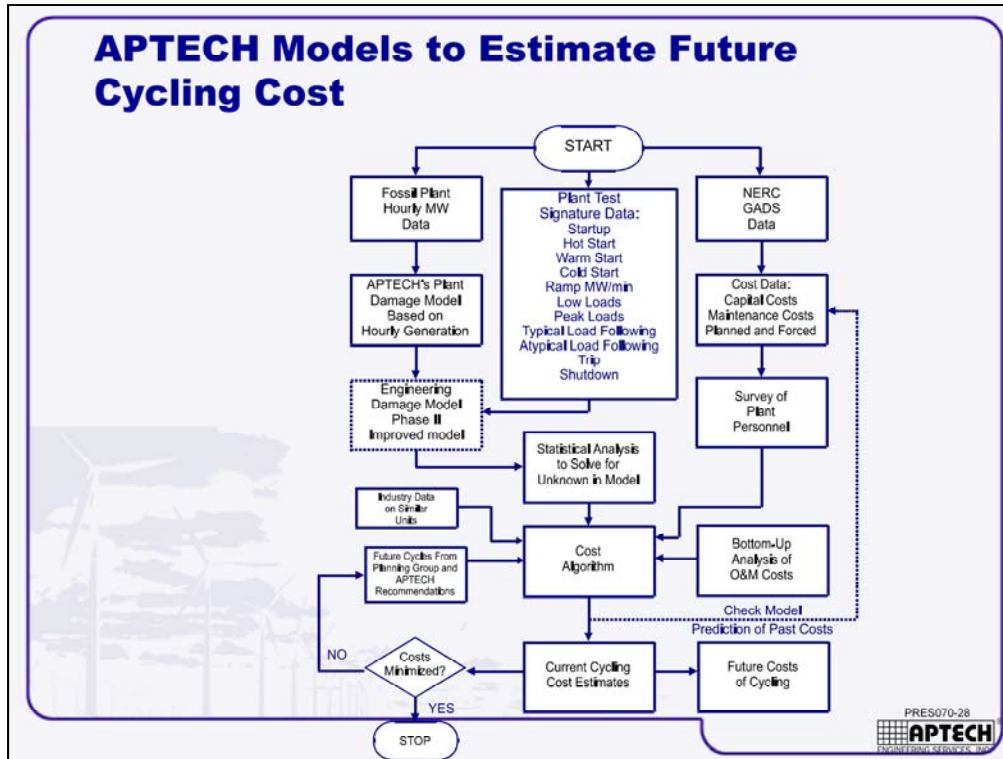


- Describe estimation methodology

## **Bottom-Up Methodology**

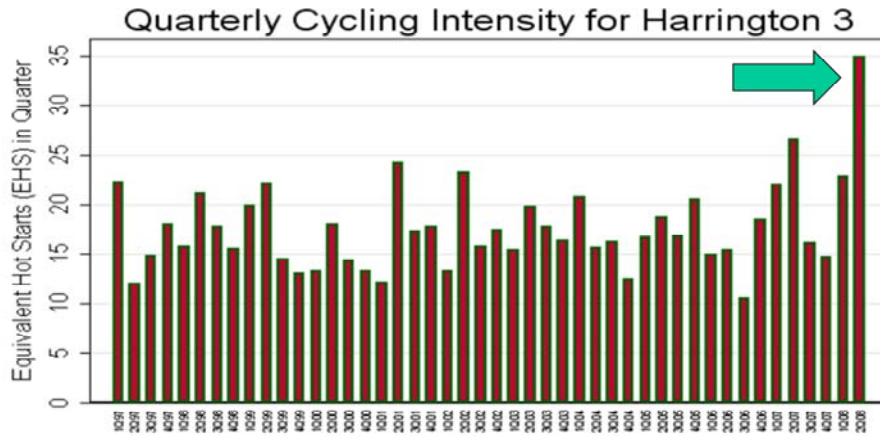
- ▶ Detailed audit of maintenance and capital costs
- ▶ In-plant investigations
- ▶ Detailed review of tube failures
- ▶ Analysis of cycling-related costs





- Aptech approach

## Harrington 3 EHS history



29



**Recent Quarterly Cycling Intensity for Harrington 3** - Note increased level of cycling in 2008.

The second quarter of 2008 – EHS = 34.9 (highest on record for the full duration of the study which went back to First Quarter of 1997)

## **Consequences of Cycling Damage - \$\$\$**

- ▶ **Increased O&M costs**
- ▶ **Reduction in the life of key plant components and overall unit life**
- ▶ **Decrease in overall unit reliability**
- ▶ **Increase fuel cost**

30



- O&M costs for overtime, repair and inspection increase
- Key components -
  - Superheater/ reheater tubing and connecting pipes
  - Turbine blading and shells
  - Generator windings
  - Transformers
- Fuel cost increases – forced outage replacement energy, heat rate degradation, startup fuel following an outage such as a maintenance outage

## Superheater Pendant Platen Damage

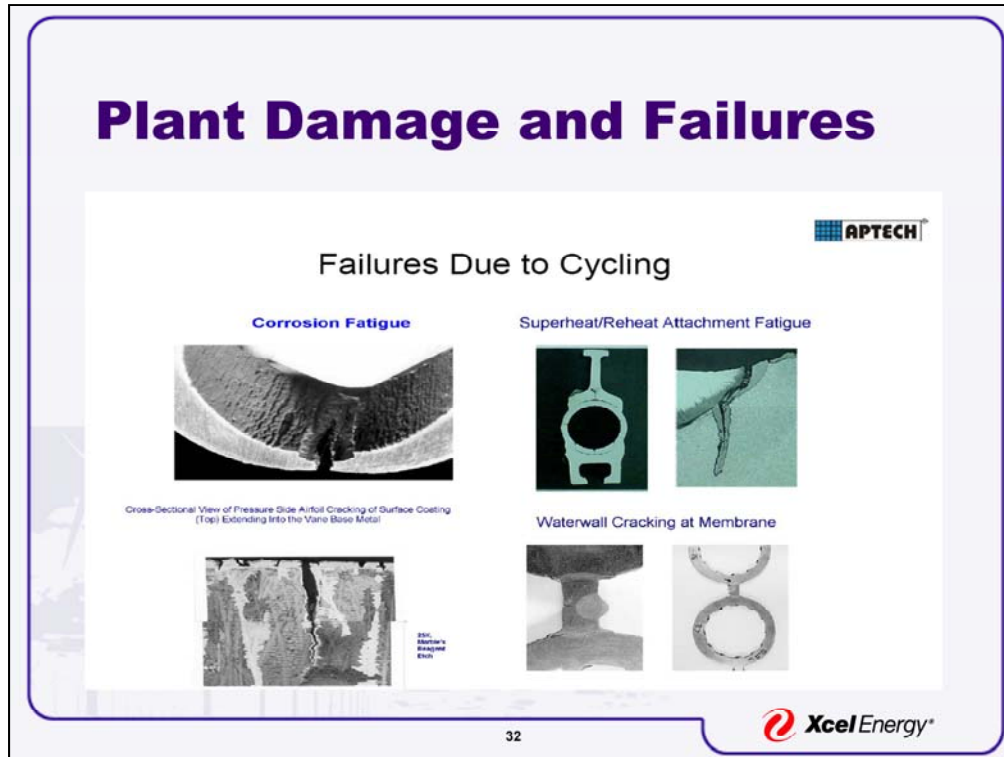


31

 Xcel Energy®

- Our managers want to see examples of cycling damage already occurring – Show me the money!
- Superheater pendant platen lead tube and water cooled space tube buckling due to cycling damage. What's the root cause of this damage? Operator error? Maintenance error? Engineering error? (all of the above could cause this).

# Plant Damage and Failures



## PLANT DAMAGE AND FAILURES

Common cycling-dominated power plant failures are shown in this figure, including boiler tube corrosion fatigue, superheater/reheater, tube attachment fatigue, turbine blade coating cracking that proceeds into the base metal, and water wall tube membrane cracking that proceeds into the tube wall.

These type of failures require the unit be removed from service, often immediately due to process safety hazards to plant staff.

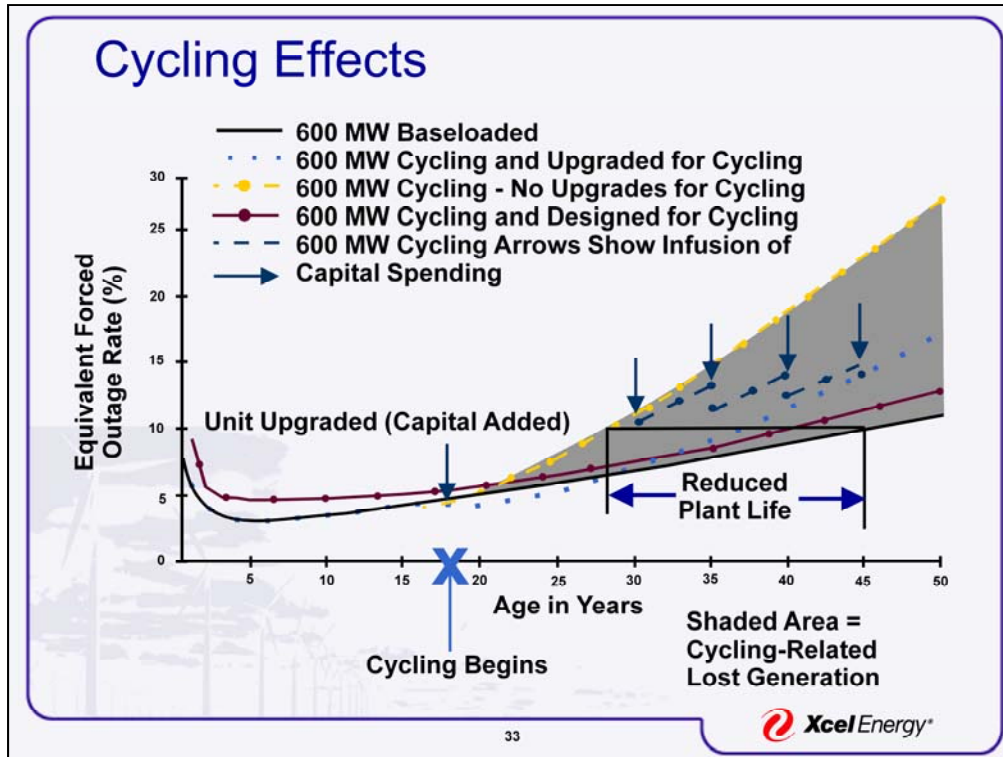
The repairs require that the entire unit be cooled to room temperature to allow access to the broken component resulting in an outage for several days.

The consequences of forced outages are expensive.

Think New Source Review > forced outages > lower emissions > replace component > NSR review > NOX box, etc. (these costs are not baked into capital maintenance).

Think Risk/ Property Insurance intervention (process safety and property insurance issues)





- Aptech chart of typical 600 MW unit and consequences of cycling effects on EFOR based on different capital decisions
- Maroon line - If the mission of a new plant is to cycle rather than be base loaded, a higher grade alloy is used for critical components such as the superheater, reheater and power piping.
- yellow line – Do Nothing - No upgrades - Baseloaded plants that are placed in cycling mode after being in base load operation will incur forced outages due to many wear out mechanisms. One of those wear out mechanisms is Fatigue Creep Interaction which is non-linear with time.
- Dark Blue staggered line – Upgraded major components optimize EFOR from reactive intervention
- Discuss New Source Review issues related to changes in EFOR and emissions.

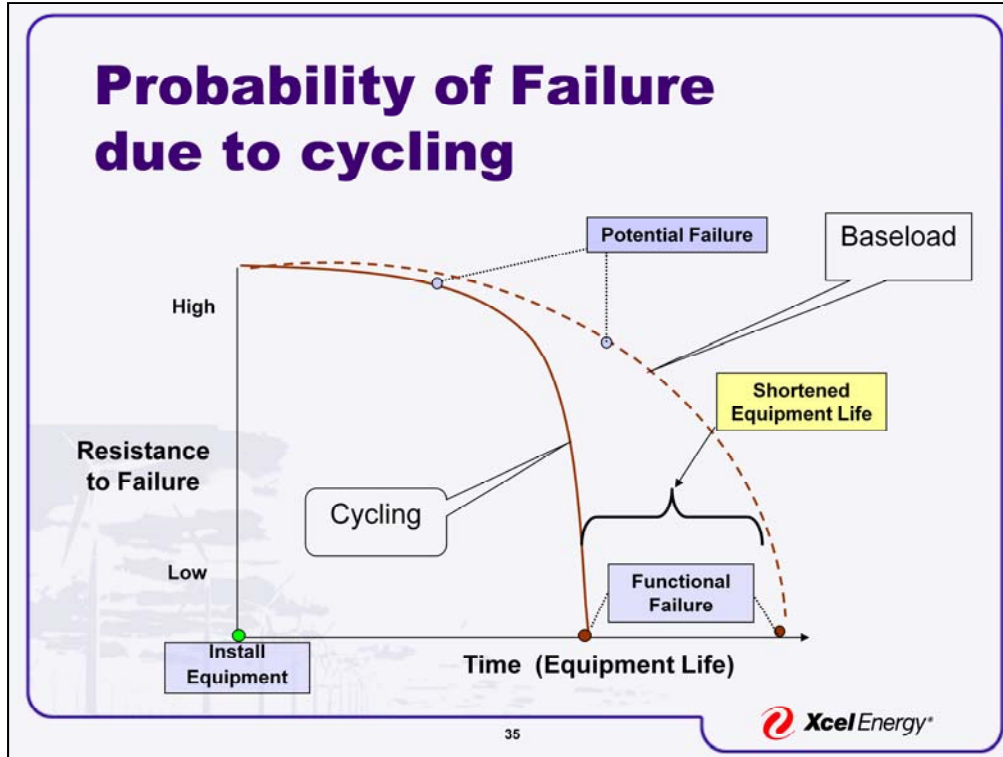
## Deep Load Following Impacts to Xcel Energy Wear and Tear \$

Plant Studied Lower minimum and faster ramp rates	Annual Cycling Impact (Maintenance, Capital, OT, EFOR- replacement energy, Fuel, Chemicals) (2000 ⇒ 2013)
Pawnee Unit 1 ~ 325 MW swing	Annual cycling cost ⇒ 5X 50% O&M; 10% Capital; 40% Fuel
Harrington Unit 3 ~ 200 MW swing	Annual cycling cost ⇒ 3X
SherCo Unit 2 ~425 MW swing	Annual cycling cost ⇒ 2X

34



- Cycling harder (not smarter) figures assume status quo with extensive maintenance to stay ahead of EFOR caused by cycling damage
- For our **simulated** changes in # of Equivalent Hot Starts, Pawnee Unit 1 estimated impact went up by a factor of 5, Harrington by a factor of 3, SherCo by a factor of 2. SherCo was designed for some cycling, the increase is not as great.
- These three units will not provide enough swing capacity to handle all the wind (and solar) load variability being planned. More units will need to cycle.
- The amount of megawatt swing will depend on many factors (is wind power in harmony with native load cycle or out of synch?)



- We now understand the failure mechanisms, consequences and costs due to increased cycling. Xcel is preparing mitigation strategies to optimize cycling costs.

## **Methods to Reduce Cycling Costs**

- ▶ **Operating procedures**
- ▶ **Maintenance procedures**
- ▶ **Equipment upgrades**
- ▶ **Wind curtailment**
- ▶ **Energy storage**

36



- The methods used to reduce the costs of cycling cover at least 5 board categories. The first three I have listed require extensive knowledge of the component history and most probable failure mechanisms. Operating and Maintenance procedures can have a dramatic and positive impact on the cost of cycling a unit and are relatively inexpensive to implement.
- Equipment upgrades cover a broad spectrum of options based on initial design, current age and unit operating mode.
- Wind curtailment is a tricky option
- Energy Storage helps reduce the rate of load change and variability over time.

## **Budget Considerations**

- ▶ **Fuel**
- ▶ **Power purchase**
- ▶ **Variable O&M, fixed O&M**
- ▶ **Emissions (\$/ton)**
- ▶ **Capital**
- ▶ **Resource planning**
- ▶ **Transmission**

37



- “These additional costs should be evaluated in future resource planning analysis.”
- Funding to support the operation and maintenance of load following is an iterative process to find the optimum solution(s).

## **Conclusion**

- ▶ **Xcel Energy is committed to renewable energy.**
- ▶ **Variable non-dispatchable wind will require Xcel Energy baseload coal units to cycle more (deep load follow).**
- ▶ **Deep load following causes cyclic damage.**
- ▶ **Cycling damage cost mitigation will require resources**

**Questions?**

