Power Plant Asset Management

Cost Analysis and Cost-Based Power Plant Asset Management – Thermal Power Plant Cycling Costs

Presented by
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Power Plant Asset Management

- Know Your Costs- Hot, warm, cold starts, load follow and regulation/AGC costs
- Reduce Costs of O&M
- Reduce Operational Damage
  - Results in Lower O&M
- Reduce Outages and Lost Capacity
  - Reduce Cycles and Optimize Full Load Operations 80-110% of MCR Maximum Rated Capacity
- Know Plant Component Condition
  - Monitor Plant and Component Life
- Maximize Plant Value
  - Know Your Market/Mission
- Compete Based on Costs – Dispatch fleet on costs
Problem Definition

Generation Units Originally Designed for Baseload Operations Running in Cycling Modes

Current System Operations are Likely to be Very NON-Optimal in Terms of Minimizing Long-Term Revenue Requirements

• Increased Maintenance costs
• Higher EFOR and Higher Probability plant will not return to service as scheduled.
• HILP High impact Low Probability events
Typical Cycling Cost Breakdown for Two Large Units
Typical Cost Breakdown – Large Coal Unit

- Startup fuel and auxiliary power costs
- Extra fuel costs from low- and variable-load operation (@ $1.57/mbtu)
- Forced outage replacement power cost
- Maintenance and Capital Cost
Typical Production Cost Components

- Heat Rates Increased
- Start-Up Fuel Used
- Dynamic Heat Rate Increased
- Cycling Related Degradation

Cost components affected by cycling:
- Capital
- Depreciation
- O&M
- Other
- Fuel
Breakdown of Cycling-Related C&M Costs 1990-97

- Boiler, 57%
- Turbine, 27%
- Balance of Plant, 9%
- Controls, 2%
- Fuel Handling, 5%
Breakdown of Cycling-Related C&M Costs 1990-97

- Boiler, 52%
- Turbine, 22%
- Balance of Plant, 15%
- Controls, 3%
- Fuel Handling, 8%
Load Cycling Definitions

**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 On-Line
Equivalent Hot Start (EHS) Damage measured

Standard EHS - Actual ramp rates and maximum load measured
ABB 11N – 3 Starts Cold, Warm, Hot
Ramp Rate: 2870°F/hr Cold, 1955°F Warm, and 1452°F/hr Hot

![Graph showing temperature and ramp rate over time for ABB 11N starts.](image-url)
Hot Gas Parts Fall Out
Overall System Costs vs. Average Cycles Per Year for Utility Power Plants

Plant View

- Total Capital and Maintenance Costs Resulting from Cycling Equipment (Wear and Tear Costs)
Overall System Costs vs. Average Cycles Per Year for Utility Power Plants

Reduced Fuel and Production Costs Incurred by a Unit Cycling to Respond to Real-Time Load Dispatch Needs
Overall System Costs vs. Average Cycles Per Year for Utility Power Plants

- Capital and Maintenance Costs Resulting from Cycling Equipment (Wear and Tear)
- Cost Incurred by Inability to Respond to Real-Time Load Dispatch Needs

"Optimum"
How Do We Measure the Costs of Increased Cycling?

Total Cost of Cycling

\[ \text{Total Cost of Cycling} = \Delta \text{Maintenance and Capital Spending} + \Delta \text{Replacement Power Cost Due to Forced Outages} + \Delta \text{Long-Term Heat Rate Impacts} + \Delta \text{Operational Heat Rate Impacts} + \Delta \text{Startup Auxiliary Power and Chemicals} + \Delta \text{Startup Fuel and Manpower} + \Delta \text{Capital Cost Impacts Due to Unit Life Shortening} \]

Here, \( \Delta \) Refers Only to Those Costs Attributed to Cycling
Cycling Effects

Equivalent Forced Outage Rate (%)

- 600 MW Baseloaded
- 600 MW Cycling and Upgraded for Cycling
- 600 MW Cycling - No Upgrades for Cycling
- 600 MW Cycling and Designed for Cycling
- 600 MW Cycling Arrows Show Infusion of Capital Spending

Unit Upgraded (Capital Added)

Reduced Plant Life

Cycling Begins

Shaded Area = Cycling-Related Lost Generation
Creep Fatigue Interaction (CFI) Design
Curves for Several Materials

CFI adds significant damage! And shortens life!
Cycling Effect on Plant Reliability

Actual Plant Data Reflects Creep Fatigue Interaction Design Curve
Cycling Effects on Heat Rate

10% Increase Partially Due to Cycling
1-5% Reasonably Attributable to Cycling
Cycling Effects

Accelerated Boiler Failures Due to Cycling

- Boiler Seals Degradation
- Tube Rubbing
- Boiler Hot Spots
- Drum Humping/Bowing
- Downcomer to Furnace Sub cooling
- Expansion Joint Failures
Cycling Effects

Accelerated Boiler Failures Due to Cycling (cont’d.)

- Superheater/Reheater Tube Leg Flexibility Failures
- Superheater/Reheater Dissimilar Metal Weld Failures
- Startup-Related Tube Failures in Waterwall, Superheater, and Reheater Tubing
- Burner Refractory Failure Leading to Flame Impingement and Short-Term Tube Overheating
Best “Simple” Fit of Annual Number of Cycling-Related Tube Failures
(During 1982 through 2003)

Considers only one variable; starts from previous year raised to the 4th power

- Annual cycling-related tube failures
- Prediction from Poisson regression of (past starts)^4
Corrosion Fatigue Damage of Subcritical Boiler Waterwall Tubing

Note oval tube resulting from restrained expansion
Boiler corrosion fatigue
Waterwall Cracking at Membrane
Superheat/Reheat Attachment Fatigue
Cycling Effects

Turbine Effects Due to Cycling

- Water Induction to Turbine
- Increased Thermal Fatigue Due to Steam Temperature Mismatch
- Steam Chest Fatigue Cracking
- Steam Chest Distortion
- Bolting Fatigue Distortion/Cracking
- Blade, Nozzle Block, Solid Particle Erosion
- Rotor Stress Increase
- Rotor Defects (Flaws) Growth
HP rotor bore surface stresses as computed from 1st stage temperatures

Stresses at highest rate multiples are limited only because no ramp rate is allowed to exceed the original maximums.
To reduce file size, a random 5% of all 50000+points are plotted
Cycling effects on Turbine due to cycling

- Seals/Packing Wear/Destruction
- Blade Attachment Fatigue
- Disk Bore and Blade Fatigue/Cracking
- Silica and Copper Deposits
- Lube Oil/Control Oil Contamination
- Shell/Case Cracking
- Wilson Line Movement
- Bearing Damage
- Reduced Life
Turbine fatigue failures Dominate Data Base

Causes of Casing Failures

<table>
<thead>
<tr>
<th>Condition</th>
<th>Percent Observed</th>
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<tr>
<td>Low Cycle Fatigue</td>
<td>70</td>
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<tr>
<td>Brittle Fracture</td>
<td>20</td>
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<tr>
<td>Creep</td>
<td>5</td>
</tr>
<tr>
<td>Brittle/Low Cycle</td>
<td>15</td>
</tr>
<tr>
<td>Low Cycle/Creep</td>
<td>10</td>
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</tbody>
</table>
Cycling effects on Chemistry due to Cycling

- Corrosion Fatigue
- Oxygen Pitting
- Corrosion Transport to Boiler and Condenser
- Air, Carbon Dioxide, Oxygen Inleakage (Require NH3 Countermeasures)
- NH3 - Oxygen Attack on Admiralty Brass
Cycling effects on Chemistry due to Cycling (contd.)

- Grooving of Condenser/Feedwater Heater Tubes at Support Plates
- Increased Need for Chemical Cleaning
- Phosphate Hideout Leading to Acid and Caustic Attack
- Silica, Iron, and Copper Deposits
- Out of Service Corrosion
Cycling Effects on Electrical and Control System due to Cycling

- Increased Controls Wear and Tear
- Increased Hysteresis Effects that Lead to Excessive Pressure, Temperature, and Flow
- Controls Not Repeatable
- Motor Control Fatigue
- Motor Insulation Fatigue
- Motor Insulation Failure Due to Moisture Accumulation
Cycling Effects on Electrical and Control System due to Cycling (contd.)

- Motor Mechanical Fatigue Due to Increased Starts/ Stops
- Wiring Fatigue
- Insulation Fatigue Degradation
- Increased Hydrogen Leakage in Generator
- Fatigue of Generator Leads
Cycling Effects on Electrical and Control System due to Cycling (contd.)

- Generator Retaining Ring Failures
- Generator End Turn Fatigue and Arching
- Bus Corrosion When Cool (i.e., low amps)
- Breaker Fatigue
- Transformer Fatigue Degradation
Cycling Effects

- Increased Risk of Personnel Errors Due to Cycling
  - Implosion
  - Explosion
  - Low Water in the Boiler
  - Water Induction into the Turbine
  - Low Load Instability
  - Improper Valve Alignment
  - Other Man/Machine Interface Problems during starts and load follows
How Do We Measure the Possible Long-Term Costs of Excessive Cycling?

Total Cost of Cycling

- Maintenance/Overhaul Costs
- Maintenance/Overhaul Time
- Forced Outage Rates
- Plant Performance (efficiency)

System Production Cost

- In Short Term
- Over Long Term

- Emissions Per kWh Generated
- Unit Life Expectancies
- Long-Term Capacity Costs
Factors Affecting Cycling Cost

- Unit Design
- Operator Care
- Already Performed Upgrades for Cycling
- O&M, and Capital Expenditures vs. EFOR
- System Marginal Energy and Capacity Costs
- Cost of New Capacity
- Past Annual Maintenance and Capital Costs
- Past Cycles
Cost of Cycling Analysis Methods

**Top-Down Method**
Annual Cycling
damage regression of
EHS vs. Costs

**Bottom-Up Method**
Detailed analysis of 7-10 years of Work orders
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
Annual Damage Accumulation- EHS

• Count and Classify Load Changes Based on Duration, Previous Offline Period, and MW Output
• Each Classification of Cycling Type has Different Level of Damage
• Accumulate the Amounts of Damage that Grow Over Time
• Count all cycles using Rainflow techniques
Rainflow Method: Counting and Classifying Cycles

- Rotate Load Curve 90 Degrees
- Imagine Raindrops Rolling down a Roof
- Circle the Start of the drop
- Circle the Node when a drop falls past a rooftop
- Delete all un-circled nodes and label them cycles
- Define these cycles based on criteria
- Repeat and count all smaller cycles
Top-Down Analysis Procedure

- Annual Damage Accumulation Rates
- Filtered Capital and Maintenance Costs
- EFOR History and Costs

Statistical "Top-Down" Model

Estimates of Maintenance, Capital, and EFOR Costs Per Equivalent Hot Start
Effective Damage and Load History Estimates

- Actual Hot Starts
- Regression Results

Bar chart showing annual equivalent hot starts from 1970 to 1994.
Regression Analysis of Relevant Maintenance, Capital, and EFOR Costs for Oil Units 1, 2, and 3

Regression-Based Total Cost per Equivalent Hot Start = $34,000 (1995)
Regression Analysis of Relevant Maintenance, Capital, and EFOR Costs for Oil and Gas Units 1, 2, and 3

Regression-Based Total Cost per Equivalent Hot Start = $6,000 (1995)
Best Estimate of Smoothed Colorado River Unit 5 Maintenance and Capital Costs

- Smoothed Annual Maintenance and Capital Costs in 1999 $
- Best Fit of Annual Costs (Approximates $32.8K per Equivalent Hot Start and a COV = 14%)

Assumes 153 EHS/Year for cycling in the future
Fitting and smoothing favored data after 1989

Best Estimate of Smoothed Colorado River Unit 5 Forced Outage, Maintenance and Capital Costs

- Smoothed Annual Outage, Maintenance and Capital Costs in 1999 $
- Best Fit of Annual Costs (Results in $43.4K per Equivalent Hot Start and a COV = 10%)

Assumes 153 EHS/Year for cycling in the future
Fitting and smoothing favored data after 1989
Captain Hook Regulation Damage/costs

Shows the Much Greater AGC Regulation and Other High-Frequency Cycling Damage at Captain Hook Units 1 and 2 (Summer 1998) than at Eight Other-Utility Units (27 months starting in January 1994) Modeled by Aptech

All Units are extrapolated to a six-second interval using similar regression models
Best Estimate of Smoothed Sunnyvale Units 1 and 2 Maintenance and Capital Costs
Best Estimate of Sunnyvale Units 1 and 2 Forced Outage, Maintenance and Capital Costs

- Smoothed Annual Outage, Maintenance and Capital Costs in 1999 $
- Best Fit of Annual Costs (Results in $41.6K per Equivalent Hot Start and a COV=12%)

Assumes 291 EHS/Year for the SUM of Sunnyvale 1 and 2 cycling in the future
Increased EFOR with Increased Cycling

- **Benchmarking**
  - EFOR vs. Equivalent Hot Starts for Palo Alto Hills Units 1 and 2. Compares Palo Alto Hills Plant with 266 Other (237<MW<1000) Coal Primary Subcritical Units Not Designated by NERC as Daily Cyclers (excludes 20 "Outliers")
Bottom-Up Methodology

1. Detailed Audit of Maintenance and Capital Costs (90-95% of plant work orders W/O)
2. In-Plant Investigations (Q&A regarding W/O)
3. Detailed Review of boiler/HRSG Tube Failures/all major maintenance reviewed
4. Analysis of Cycling-Related Costs for all key plant components:
   - Boiler, Turbine, generator, GT, condensers, feedwater heaters, BOP
Intertek APTECH Flowchart to Estimate Future Cycling Cost

START

Fossil Plant Hourly MW Data

APTECH’s Plant Damage Model Based on Hourly Generation

Engineering Damage Model Phase II Improved model

Plant Test Signature Data:
- Startup
- Hot Start
- Warm Start
- Cold Start
- Ramp MW/min
- Low Loads
- Peak Loads
- Typical Load Following
- Atypical Load Following
- Trip
- Shutdown

NERC GADS Data

Cost Data:
- Capital Costs
- Maintenance Costs
- Planned and Forced

Survey of Plant Personnel

Statistical Analysis to Solve for Unknown in Model

Industry Data on Similar Units

Future Cycles From Planning Group and APTECH Recommendations

Cost Algorithm

Bottom-Up Analysis of O&M Costs

Check Model Prediction of Past Costs

Current Cycling Cost Estimates

Future Costs of Cycling

NO

Costs Minimized?

YES

STOP
How Total Cycling Cost Information Can be Used

Cost of Cycling Results

Unit Mission Statements

Plant Operations
- Better Real-Time Monitoring
- Fine-Tune Cycling Operations

Plant Budgeting
- Capital Projects
- O&M Cost Levels

System Dispatch & Planning
- Optimal System Dispatch Including “Total” Costs
- System Planning, i.e., New Acquisitions
- Regulation Costs