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Power Plant Cycling Costs

April 2012

N. Kumar, P. Besuner, S. Lefton, D. Agan,
and D. Hilleman
Intertek APTECH
Sunnyvale, California

NREL Technical Monitor: Debra Lew

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Preface

This report has been produced by Intertek APTECH for the National Renewable Energy Laboratory (NREL) and Western Electricity Coordinating Council (WECC) to support their renewable integration studies.

This report provides a detailed review of the most up to date data available on power plant cycling costs. Increasing variable renewable generation on the electric grid has resulted in increased cycling of conventional fossil generation. Previous studies by NREL and WECC have corroborated this fact and the purpose of Intertek APTECH's task was to provide generic lower bound power plant cycling costs to be used in production cost simulations. The inclusion of these costs in production cost simulations would result in accounting for some of the increased costs (system aggregate) and reduced reliability of conventional generation due to cycling.

The results of this report are only indicative of generic lower bound costs of cycling conventional fossil generation power plants. The primary objective of this report is to increase awareness of power plant cycling cost, the use of these costs in renewable integration studies and to stimulate debate between policymakers, system dispatchers, plant personnel and power utilities.

About Intertek APTECH

Intertek APTECH is in Intertek's Industry and Assurance Division and is an internationally-known engineering consulting firm specializing in performance optimization of equipment and the prediction and extension of the remaining useful life of piping, boilers, turbines, and associated utility equipment, structures, industrial equipment, and materials.

Intertek APTECH has been examining the cycling damage to power plant components for over two decades and has pioneered the development of numerous condition assessment methods for power plant equipment. They have been working closely with several clients with increasing renewable resources to assess the integration cost impacts on conventional generation.

Executive Summary

Competition and increasing penetration of variable renewable generation are having a far-reaching impact on the operation of conventional fossil generation. For many utilities and plant operators, plant operations and maintenance (O&M) expenditures are the one cost area that is currently rising at a rate faster than inflation. To stay competitive, utilities need to better understand the underlying nature of their plant O&M costs, and take measures to use this knowledge to their advantage. A major root cause of this increase in O&M cost for many fossil units is unit cycling. Power plant operators and utilities have been forced to cycle aging fossil units that were originally designed for base load operation.

Cycling refers to the operation of electric generating units at varying load levels, including on/off, load following, and minimum load operation, in response to changes in system load requirements. Every time a power plant is turned off and on, the boiler, steam lines, turbine, and auxiliary components go through unavoidably large thermal and pressure stresses, which cause damage. This damage is made worse for high temperature components by the phenomenon we call creep-fatigue interaction. While cycling-related increases in failure rates may not be noted immediately, critical components will eventually start to fail. Shorter component life expectancies will result in higher plant equivalent forced outage rates (EFOR) and/or higher capital and maintenance costs to replace components at or near the end of their service lives. In addition, it may result in reduced overall plant life. How soon these detrimental effects will occur will depend on the amount of creep damage present and the specific types and frequency of the cycling.

Several renewable integration studies, including those performed by NREL and WECC have recognized increased power plant cycling due to renewables. Additionally, most reports also list the need for more flexible generation in the generation mix to meet the challenge of ramping and providing reserve requirements. Intertek APTECH has provided generic lower bound cycling costs for conventional fossil generation in this report. The report also lists the typical cycling cost of the “flexible” power plants, as it is important to realize that while such plants are built for quick start and fast ramping capabilities, they are not inexpensive to cycle. There is still a cost to cycle such plants. Modern combined cycle plants also have constraints with HRSG reliability and have a cost to cycle. Finally, Intertek APTECH has provided an overview of systems and components commonly affected by cycling and mitigation strategies to minimize this cost.

The electricity market has appreciably changed over the past decade, especially with the introduction of large amounts of non-dispatchable wind and solar power in some regional markets. Cycling a plant may be required for numerous business reasons and is not necessarily a bad practice; however it does increase maintenance costs and forced outages. 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. Every power plant is designed and operated differently. Therefore the cost of cycling of every unit is unique. Managing the assets to a least cost option is the business opportunity while responding to a changing market.

Overview

1. Asset management of a fleet must include all the costs including cycling costs some of which are often latent and not clearly recognized by operators and marketers.
2. Most small and, especially, large coal units were designed for baseload operation and hence, on average are higher cycling cost units. Thermal differential stresses from cycling result in early life failures compared to base load operation
3. There are some important economies of scale for large coal (and other fossil Units), that lower their costs. So the highest costs per megawatt capacity, as plotted here, occur in some “abused” smaller coal units, especially for cold starts.
4. Once all operating costs including cycling are accounted for, the best system mix of generation can be matched to changing loads and market opportunities.

Start Cost Impacts

5. Cycling start costs have a very large spread or variation.
6. Median Cold Start cost for each of the generation types is about 1.5 to 3 times the Hot Start Capital and Maintenance Cost. For the lower bound 75th percentile this ratio of Cold Start Cost versus Hot Start Cost is only slightly higher.
7. The Gas Aero Derivative combustion turbine (CT) units have almost the same relatively low costs for hot, warm, and cold starts. That is because for many key components in these designed-to-cycle units, every start is cold.
8. Typically, large supercritical power plants are operated at baseload and do not cycle much. Thus the units we have examined have not cycled often and thus have not suffered the high costs of cycling operations. This is not to say that we believe that

cycling these units can be done without sustaining high costs. Operating these units in cycling mode can often result in unit trips and cycling related failures. As a result of the false starts and trips, the real cost of cycling these units is significantly high. Moreover, these units cannot easily be brought online under these circumstances (say, a trip) and such factors are not fully captured in this dataset.

9. Older combined cycle units were a step change in lower operating costs due to cycling efficiencies and were designed and operated as baseload units. Changing markets have resulted in variable operation and when operated in cycling mode these combined cycle units can have higher cycling costs compared to a unit specifically designed for cycling which can be seen from the distribution of costs

Reliability Impacts [EFOR]

10. While a unit's reliability during its early life has little indication of cycling damage and costs, long term costs and life consumption that leads to failures reach a point of very rapid increases in failure rates due to cyclic operation. We see a better statistical fit of cycling (starts) and costs when EFOR costs are included in the regression.
11. There is an inherent "tradeoff" relation between higher capital and maintenance expenditure and corresponding lower EFOR. While this is not conclusive from the plots themselves, the huge variation in EFOR impacts in these results may be attributed to this phenomenon. However, further research in this area is required.

Baseload Variable Operations and Maintenance (VOM) Cost

12. The higher operating and maintenance costs of supercritical units can be observed from the baseload VOM cost data.
13. Gas Aero Derivative CT units were found to have the least base load VOM cost, but these units typically operate in a cycling environment as peaking units (which have high "total" VOM Cost). Based on our methodology described in Figure 1-6, we attributed a significant portion of industry standard total VOM cost to cycling.

Load Following and Ramping Costs

14. The coal fired small and large units were the expensive load following units. Most of these units were designed for base load operation and undergo significant damage due to change in operations. Damage from cycling operations can be limited to acceptable rates, but unit specific damage mechanisms must be well understood to manage and reduce the damage rates.

15. Increasing ramp rates during load following can be expensive for normal operations. Still, the costs of increased ramp rate calculated for this report include only those fully attributed to load follow cycling. It is impossible to increase load following ramp rates by themselves without having some impact on unit trips and start/shutdown cycles. So the fast ramp rate results in this report probably understate their costs.
16. Higher ramp rates result in higher damage and this is most easily seen on the coal fired units. While not a linear relationship, additional research is required to get further detail.
17. The combined cycle units also have a higher ramp rate cost, due to the operational constraints on the Heat Recovery Steam Generator (HRSG) and Steam Turbine (ST). Emissions requirements often limit the ability of a CC unit to load follow below 50% or even 75% for some designs. These costs need to be quantified.
18. Intertek APTECH has seen a growing trend of minimum generation to maximum capacity type load follow cycling, due to increased renewable generation on the grid. This will result in higher costs and should be analyzed in a future study.

Startup Fuel Input and Other Start Costs

19. Supercritical units have a significantly higher fuel input cost than other unit types.
20. The same is true for other start cost inputs for supercritical units that include water, chemicals, additives and auxiliary power.

Heat Rate Impacts

21. Cycling’s effect on heat rate is the greatest for small coal units.
22. Newer, combined cycle units as well as simple cycle gas fired units see a much lower impact.
23. Moreover, plant heat rate is commonly monitored and plant operators often make capital investments to improve the heat rates of their power plants. This results in frequent replacement of components damaged by cycling.

Mitigation Strategies

24. How can we avoid “system” cycling costs?
    a. Cycling costs can be avoided by the obvious method of not cycling a unit and that may include staying on line at a small market loss price.
    b. Cycling costs may be managed by understanding the issues and managing the unit to reduce the damage rates

    c. Cycling costs may be managed by modifying the operation procedures or process (for example, keeping the unit "hot")
    d. Cycling cost may be reduced by capital or O&M projects to modify the base load designs to be better suited for cycling
25. Detailed component analysis allows for targeted countermeasures that address the root cause of the cycling damage to manage and even reduce the cost of future cycling duty. Some examples are:
    e. Air/Gas Side Operational Modifications – Reduces rapid transients in boiler flue gas
    f. Steam bypass – Matches steam temperature to turbine controls start up steam temperature in Superheater/Reheater (SH/RH)
    g. Feedwater bypass to condenser – Controls startup temperature ramp rates to feedwater heaters and economizers
    h. Condenser tube replacement – Improves plant chemistry and reliability and prevents turbine copper deposits.
    i. Motorized valve for startup – Reduces temperature ramp rates in boiler and reduces fatigue while providing a rapid and repeatable operation of critical components including drains.
    j. Motor driven boiler feed pump – Reduces fatigue of economizer and feedwater heaters and allows lower stress and faster, reliable start up.

Further research

26. This analysis of cycling costs is dependent of various assumptions that are detailed in the report. A sensitivity analysis should be performed to measure the impact of assumptions such as fuel cost, generation mix, retirement costs, baseload unit modification costs, and cost of additional flexible resources.
27. Further detailed investigation of mitigation and solution costs for increased power system flexibility.
28. Determine cost to retrofit existing units to improve cycling capabilities.
29. Identifying additional or enhanced operational practices and procedures to integrated variable generation.
30. Defining the characteristics of the system (e.g., ramping requirements, minimum load levels, resource mix, etc.) to maintain reliability with increased variable generation.

31. Developing a universally accepted measure or index of flexibility to allow comparison across systems.
32. Developing a set of best practices to mitigate impacts of increased cycling.
33. Estimating the impacts of cycling on reduced life
34. Develop a way to compare different methodologies of integration costs analysis.
35. Evaluating how integration costs change with changes to scheduled maintenance outages.
36. Transmission expansion modeling should not only include congestion and other physical constraints but also power plant cycling. Aggregating cycling costs at the system level results in ignoring the “flash flood” situation of heavy cycling on individual units on the grid.

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Section 1
Power Plant Cycling Costs

1.1 Introduction

This report presents generic industry historical data on power plant cycling costs for several types of electric generation units, as specified by National Renewable Energy Laboratory (NREL) and Western Electricity Coordinating Council (WECC). Intertek APTECH has organized the cycling cost data in consultation with NREL and WECC by the following eight generator plant types:

1. Small coal-fired sub-critical steam (35-299 MW)
2. Large coal-fired sub-critical steam (300-900 MW)
3. Large coal-fired supercritical steam (500-1300 MW)
4. Gas-fired combined cycle (CT-ST and HRSG)
5. Gas-fired simple cycle large frame CT (GE 7/9, N11, V94.3A, 501 and similar models)
6. Gas-fired simple cycle aero-derivative CT (LM 6000, 5000, 2500 and similar models)
7. Gas-fired steam (50-700 MW)
8. Lowest Cycling Cost Units from the above 7 groups (Low cycling due to specific design and operation procedures).

Additionally this power plant cycling cost data has been reported in two separate data sets:

- Lower-bound estimates of cycling costs – this data is for release to the general public and is reported in this document.
- Upper-bound cycling costs and cost distributions – this dataset is being produced by Intertek APTECH as their price participation in the project.
    - This dataset has been designated as limited rights data, which will not be released to the general public by NREL or WECC or anyone and is not included in this report.

NREL and WECC are both investigating the operational impacts of increasing energy penetration of wind, photovoltaics (PV), and concentrating solar power (CSP) on the power system (primarily the western interconnection). The Phase 1 of the WWSIS study received feedback from stakeholders, including the importance to account for fossil generation cycling costs in future wind integration studies. The main comments from the stakeholders were[1]:

- Increased cycling and ramping of fossil assets will increase O&M expenses. Obtain these costs and include them in modeling.
- Increased cycling and load following of fossil assets causes units to operate at suboptimal emissions conditions. Capture non-linear relationship between emissions and generation level, especially when cycling/ramping. Increase accuracy of emissions analysis.
- Review cycling implications on fossil assets associated with sub-hourly scheduling. Characterize impact including shutdowns and frequency of increased cycling. How will planning for maintenance outages change?
- Provide more accurate characterization of non-renewable generation portfolio (min gen, startup time, ramp rate, etc).

At the request of NREL and WECC, Intertek APTECH conducted a comprehensive analysis to aggregate power plant cycling costs inputs (to production cost models) with high and low bounds for the eight distinct groups described above. These costs are:

1. Hot, Warm, and Cold Start Costs
2. Forced Outage Rates as a function of start type
3. Base-load Variable operation and maintenance (VOM) costs
4. Load Following Costs (significant load follows)
5. Startup Cost – Fuel and (Aux. Power + Chemicals + Water)
6. Heat Rate effects due to Power Plant Cycling

The data Intertek APTECH have provided as a part of this report are based on the most appropriate and detailed cost-of-cycling studies Intertek APTECH has done on several hundred units for many different clients. The development of the cost of cycling data input analysis has utilized the greatest sample size possible from Intertek APTECH's database of generators tested and analyzed in the United States.

All costs have been calculated in 2011 US dollars. Also, to provide realistic cycling cost inputs, the sample of plants included in each of the groups has been carefully chosen to represent the variation of cycling costs for each group. For example, the first group (small coal fired units),

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[1] NREL Technical Review Committee (TRC) Slides

lower bound cycling costs represent the entire sample of sub-critical coal plants of unit size 35 MW to 299 MW. As mentioned earlier, our goal is to capture the cost of cycling based on generation type and size only. However, in each group there are other variations, such as past operation, equipment manufacturer, fuel quality, unit design, etc., which affect cycling costs but are not disclosed in this report.

From these past studies, APTECH has extracted typical data on costs for each unit type that is representative of units that NREL, WECC and their stakeholders may evaluate. The methods used in these past studies for developing the original cost of cycling estimates are briefly described in the following sections.

1.2 Approach to Estimating Cycling Costs

Power plant cycling damage mechanisms leading to component failures are complex and usually involve multiyear time lagging. Intertek APTECH started working on this problem more than 25 years ago by modeling life expenditure of individual critical components as a function of varying cycling operations. Since then, Intertek APTECH has developed a multi-faceted approach that provides cycling cost estimates at a reasonable cost. Our approach uses multiple methods to derive and bound cycling cost estimates so that results can be validated. Figure 1-1 shows a simplified flowchart of this approach. Intertek APTECH has used this methodology for hundreds of generation units owned by many utility clients throughout the world. The results and key power plant operating costs from these projects have been aggregated in the Intertek APTECH Power Plant Cycling Database. For the purpose of this project, only the North American power plants were aggregated. Figure 1-2 presents the various sources of data for this cycling cost database and how this data is reported for this project. The outputs presented in this report are a subset of the information held in this comprehensive database.

We utilized unit/plant-specific information, industry data, and our experience on similar units, so as much relevant information as possible can be brought to bear. In our analysis, APTECH uses two primary parallel approaches to analyzing cycling-related costs: (1) top-down analyses using unit composite damage accumulation models and statistical regression; and (2) modified bottom-up component-level studies using real-time monitoring data at key locations, prior engineering assessments of critical components, and a survey of plant personnel. [See Appendix B for details]

The results reported in this report, quantify the increase in capital, and operations and maintenance (O&M) costs (including fuel costs) of power plants due to increased cyclic operation.

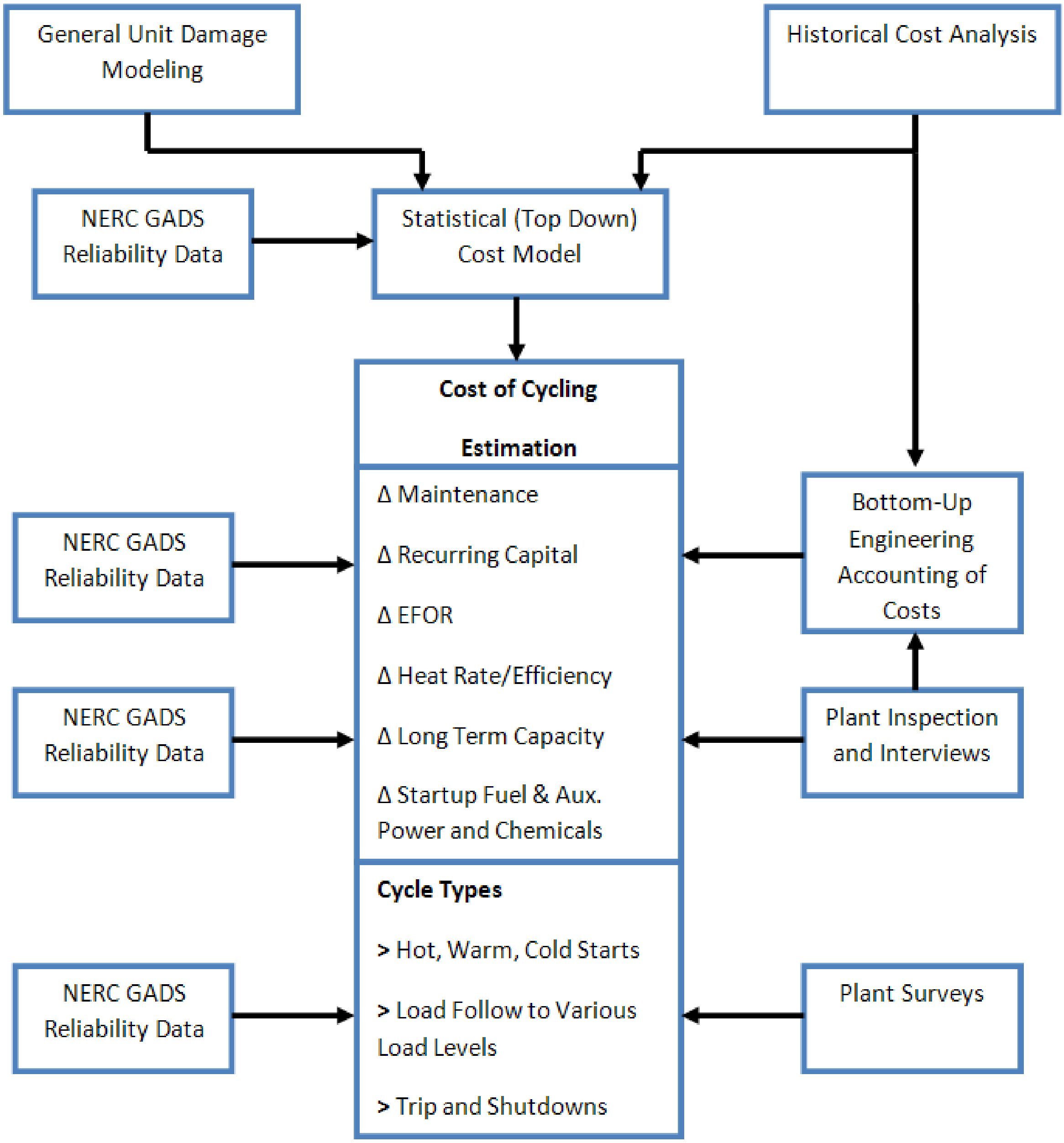

Figure 1-1: Cost of Cycling Estimation Procedure

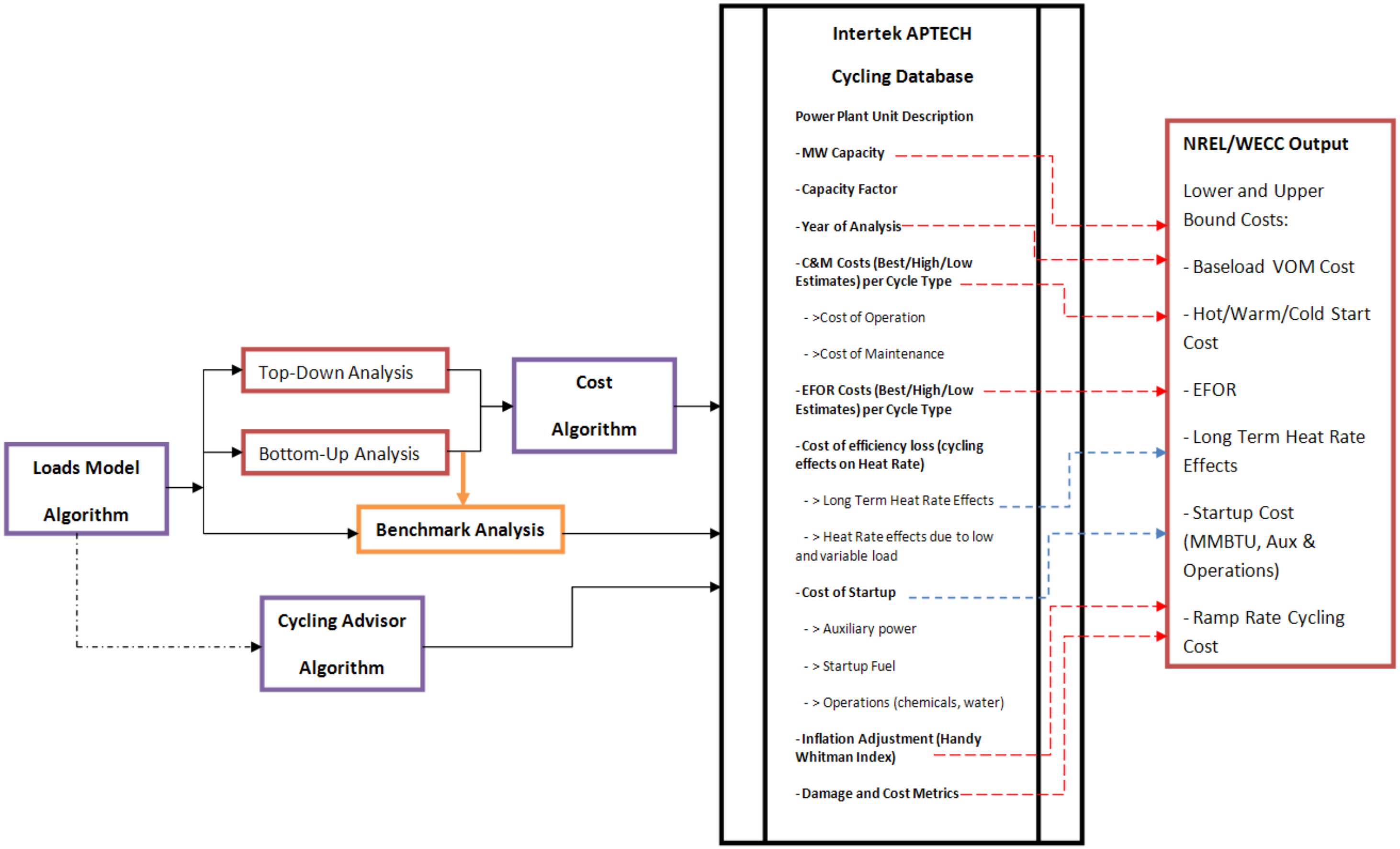

Figure 1-2: Intertek APTECH Cost of Cycling Database

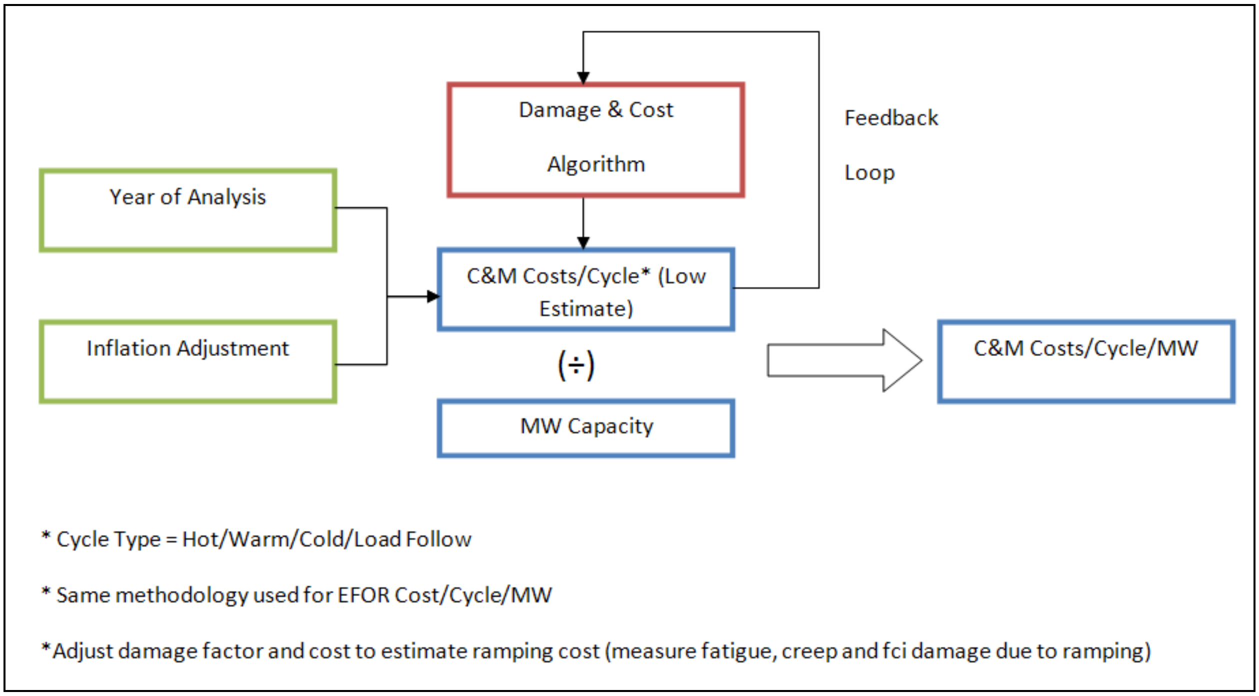

Figure 1-3: Estimating Lower Bound Start Cost

Figure 1-3 is the flowchart for generating the inflation adjusted cycling start costs and EFOR impacts. The Hot/Warm/Cold start cost was reported on per MW capacity basis and is the capitalized maintenance cost of cycling. This cost is the additional cost attributed to each additional on/off cycle. The feedback loop in the figure represents steps taken to update current plant operation from the time when a cycling study was originally performed. As mentioned before, cycling cost is directly dependent on power plant operation and on some occasions Intertek APTECH had to recalibrate the cost of cycling estimated in older studies. Therefore, we believe that the lower bound cycling cost inputs reported in this document are reliable and typical averages for units that have been operated in conditions seen over the last 10 to 20 years[2].

Power plant operators are well aware that load cycling causes accelerated damage to many unit components, causing increased equipment failures with resulting higher equipment forced outage rates (EFOR) and higher non-routine maintenance and capital replacement costs. With increased cycling, operators are putting their assets at increased risk of increased forced outages and High Impact Low Probability (HILP) events that they wish to minimize and avoid if

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[2] Future operating conditions with increased power plant cycling due to recent trends to add variable renewable generation will most likely result in higher cycling cost for existing generation.

possible (Figure 1-4). Figure 1-5 was generated using NERC-GADS data and shows that the Actual Plant Data Reflects Creep Fatigue Interaction Design Curve[3].

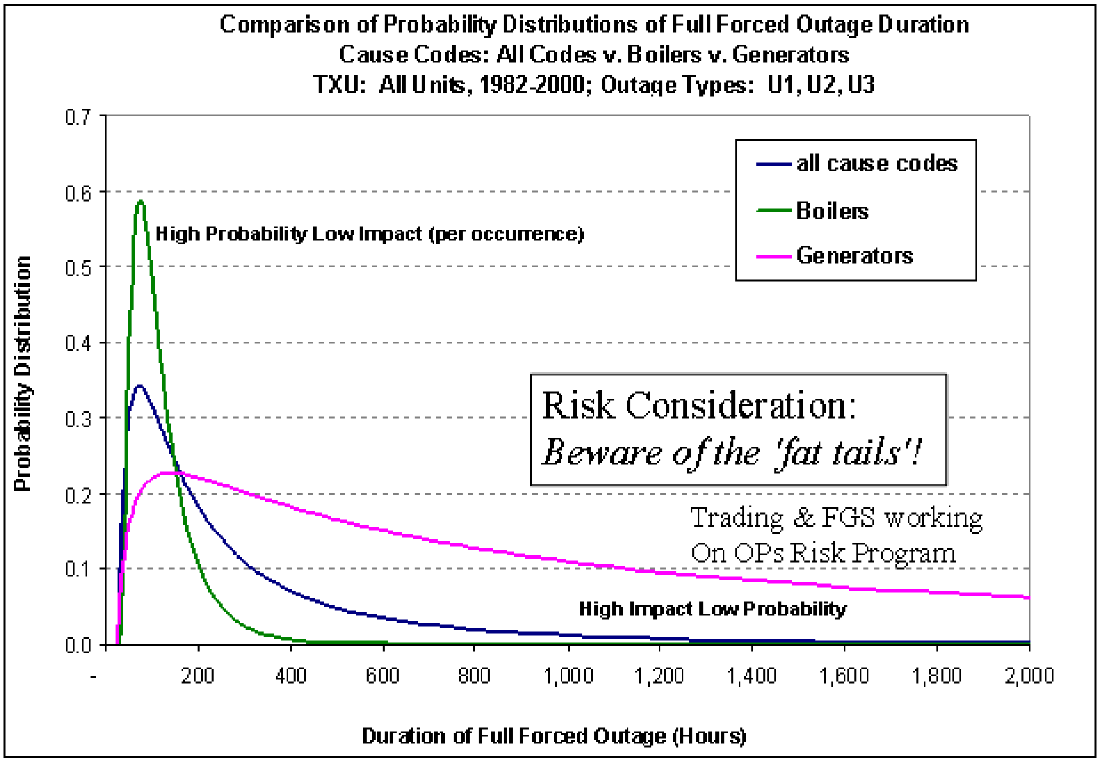

Figure 1-4: High Impact Low Probability Events

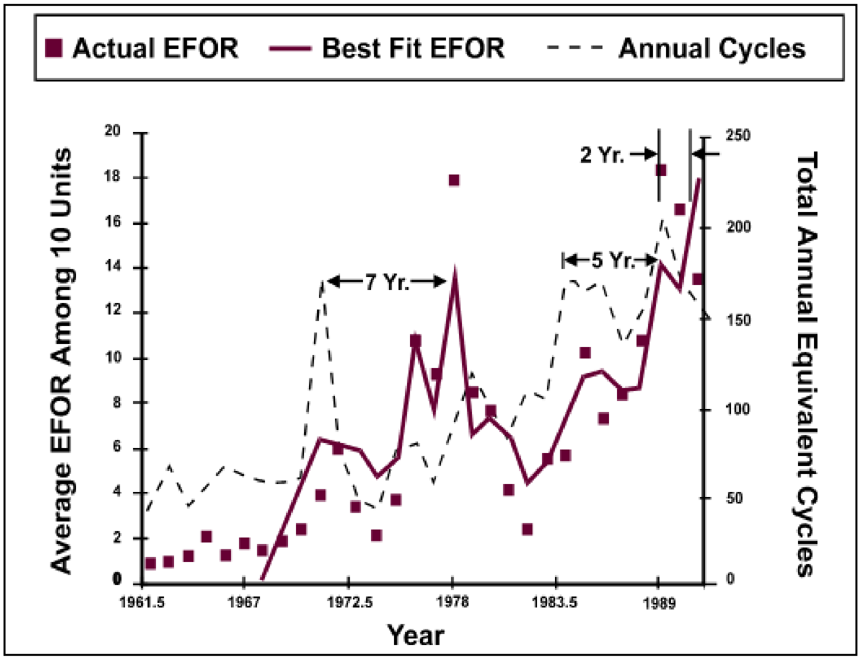

Figure 1-5: Cycling effect on plant reliability

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[3] ASME creep-fatigue interaction curves

Figure 1-6 presents a flowchart to generate the baseload variable operations and maintenance (VOM) cost. Intertek APTECH determines the cycling related O&M cost and subtracts that from industry standard and plant provided total O&M costs to generate a baseload VOM cost. These costs assume a power plant running at steady load without any on/off cycling.

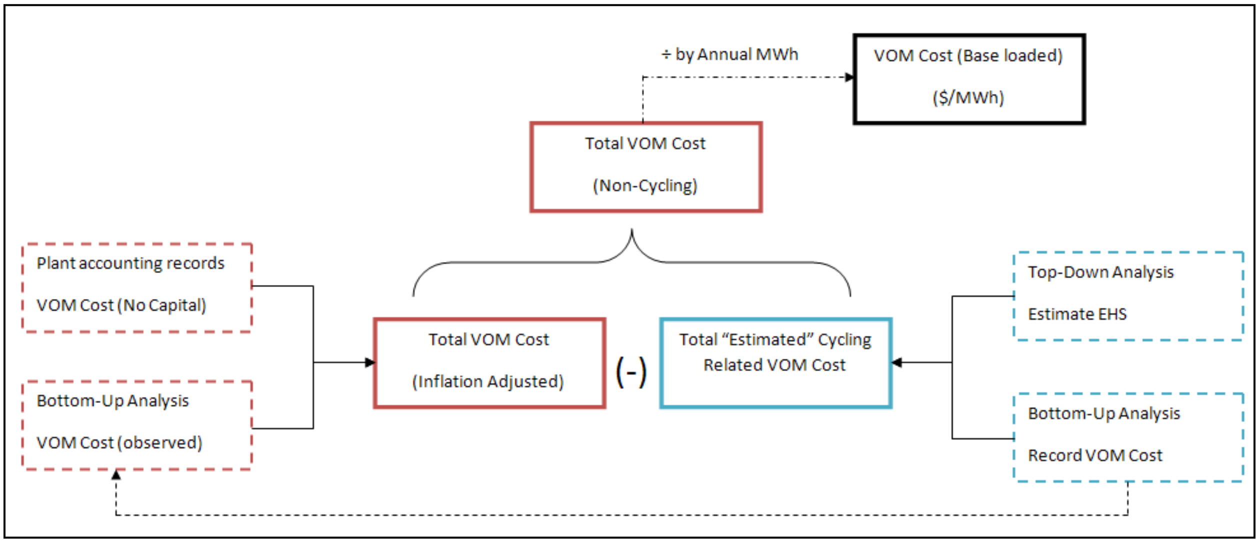

Figure 1-6: Estimating Baseload VOM Cost

What makes APTECH's methodology especially powerful is our top-down method's ability to capture the effects of operator error and other obscure factors in its estimates of unit-wide cycling costs. The bottom-up accounting and modeling techniques are then used to break down the unit-wide cycling costs into component-specific costs. This detailed component analysis allows for targeted countermeasures that address the root cause of the cycling damage to manage and even reduce the cost of future cycling duty. Intertek APTECH has leveraged its database of power plant cycling costs, as well as products of our rich and detailed methodology, to develop high level – "generic" cost inputs for NREL and WECC as part of the Western Wind and Solar Integration Study (WWSIS) Phase 2 and Transmission Expansion Planning Policy Committee (TEPPC) studies. The data input costs will be distributed to NREL and WECC stakeholders to include power plant cycling costs in their economic dispatch and transmission and capacity expansion models.

While our main goal has been to estimate cycling costs as accurately as available data permits, we believe it is also important to quantify the uncertainty of such estimates by calculating both low and high bound cycling costs. Since low bounds are the key deliverable in this report, we have included Appendix A to discuss how these bounds are estimated. These costs are ultimately the inputs for planning including the justification of cycling related countermeasures to manage the asset reliability and cost of future cycling. Countermeasures include both equipment and procedural changes to reduce the accumulated damage rates when cycling.

1.3 Results

Table 1-1 presents the lower bound cycling cost results for each unit type. It should be emphasized that there are large variations in costs between individual units of each type, and that the numbers provided by Intertek APTECH are *generic low bounds*[4]. All cost numbers in this report have been adjusted for calendar year 2011$.

Table 1-1 also presents other basic data for each unit type such as: (1) Warm Start "Offline" Hours (2) Load Following Cost (Typical Ramp Rates and Faster[5] ($/MW Capacity per Load Follow), and (3) non-cycling related baseload variable O&M costs ($/MWH).

Use of the cycling cost numbers without accounting for actual unit operations can result in significant under/over estimation of power plant cycling costs.

The typical ranges of "hour offline" for warm starts for each unit type are also presented - any start duration below this range would be a hot start, and any above this range would be a cold start.

Intertek APTECH uses the same EFOR definition as described by the North American Electric Reliability Council (NERC). APTECH's typical cycling cost project usually derives a dollar cost of added EFOR; however, for our deliverable to NREL and WECC, we provide the expected increase in EFOR (in added percentage for a single year[6]) due to each cycle type. Thus, it is up to the user of this data to determine the "value lost" due to this increase in EFOR by calculating

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[4] Care should be taken to implement the lower bound cycling cost. For example if a unit goes through 200 starts per year and the start cost is underestimated by $1000/start, then the annual cost of this erroneous number can be significant. Moreover if this unit is indeed cycled on/off more often due to the lower cost estimate, then it would accumulate damage at a significantly higher rate.

[5] Fast ramp rate results are preliminary and under review as of Apr 2012

[6] For example, Table 1-1 shows a median (lower bound) EFOR impact of 0.0086% per hot start for small sub critical coal units. Assume that the EFOR = 2% for some near-future year and the Unit typically sees 10 hot starts annually. If 5 additional hot starts are imposed, the EFOR will be raised to 2.043% (2 + 0.0086*5) for a single near-future year.

the replacement cost of generation lost to forced outages, typically in units of present dollars per MWh. NREL and WECC will utilize production cost models to include escalating EFOR, and these models will subsequently find replacement resources to meet requirements.

As described, a power plant cycling can be classified either as on/off cycling or load follow cycling, which refers to a change in generation from maximum capacity to lower or minimum load. The load follow cycling is further classified by Intertek APTECH as significant load following and shallow load following. Table 1-1 provides the estimates for the costs of the "significant" load follow cycles. Depending on the unit, Intertek APTECH regards all cycles of MW range greater than 15-20% gross dependable capacity (GDC) as significant. The typical load following MW range is also presented in the table.

Intertek APTECH has plant signature data of temperature and other transients during typical ramp rates and has also evaluated the cost of ramping up/down power plants faster than these normal rates. Typically, older power plants have maintained steady ramp rates during load follows and only over the last few years have these plants ramped faster due to variable renewable generation or new market conditions. Due to this, Intertek APTECH had a relatively smaller sample size of actual signature data on these faster ramp rates. To overcome the limited sample size, Intertek APTECH has calibrated its damage models to determine the increased cost of load following due to these faster ramp rates and has presented a "multiplying factor" to increase the damage from a typical ramp rate load follow. However, it should be noted that several small and large coal or combined cycle plants have constraints on operation which do not allow much faster ramp rates without incurring a huge penalty to do so. Therefore, damage due to faster ramp rates, will depend on past operation of these units (i.e. accumulated creep and fatigue damage) as well as their physical limitations.

Table 1-1: Typical lower bound costs of cycling and other data for various generation types

Unit Types	Coal - Small Sub Critical	Coal - Large Sub Critical	Coal - Super Critical	Gas - CC [GT+HRSG+ST]	Gas - Large Frame CT	Gas - Aero Derivative CT	Gas - Steam
Cost Item/							
Typical Hot Start Data							
-C&M cost ($/MW cap.)							
Median	94	59	54	35	32	19	36
~25th_centile	79	39	39	28	22	12	25
~75th_centile	131	68	63	56	47	61	42
-EFOR Impact							
Median	0.0086%	0.0057%	0.0037%	0.0025%	0.0020%	0.0073%	0.0029%
~25th_centile	0.0045%	0.0035%	0.0030%	0.0021%	0.0007%	0.0038%	0.0016%
~75th_centile	0.0099%	0.0082%	0.0065%	0.0070%	0.0142%	0.0186%	0.0060%
Typical Warm Start Data							
-C&M cost ($/MW cap.)							
Median	157	65	64	55	126	24	58
~25th_centile	112	55	54	32	26	12	36
~75th_centile	181	78	89	93	145	61	87
-EFOR Impact							
Median	0.0123%	0.0070%	0.0054%	0.0039%	0.0027%	0.0073%	0.0048%
~25th_centile	0.0058%	0.0041%	0.0037%	0.0023%	0.0007%	0.0038%	0.0026%
~75th_centile	0.0156%	0.0081%	0.0095%	0.0083%	0.0162%	0.0186%	0.0081%
Typical Cold Start Data							
-C&M cost ($/MW cap.)							
Median	147	105	104	79	103	32	75
~25th_centile	87	63	73	46	31	12	54
~75th_centile	286	124	120	101	118	61	89
-EFOR Impact							
Median	0.0106%	0.0088%	0.0088%	0.0055%	0.0035%	0.0088%	0.0060%
~25th_centile	0.0085%	0.0047%	0.0059%	0.0033%	0.0007%	0.0038%	0.0043%
~75th_centile	0.0163%	0.0150%	0.0101%	0.0088%	0.0116%	0.0195%	0.0123%
Startup Time (hours)							
-Typical (Warm Start Offline Hours)	4 to 24	12 to 40	12 to 72	5 to 40 (ST Different)	2 to 3	0 to 1	4 to 48

Table 1-1: Continued

Unit Types	Coal - Small Sub Critical	Coal - Large Sub Critical	Coal - Super Critical	Gas - CC [GT+HRSG+ST]	Gas - Large Frame CT	Gas - Aero Derivative CT	Gas - Steam
Typical Load Follows Data							
-C&M cost ($/MW cap.) - Typical Ramp Rate							
Median	3.34	2.45	1.96	0.64	1.59	0.63	1.92
~25th_centile	1.91	1.40	1.52	0.30	0.94	0.42	1.17
~75th_centile	3.84	3.10	2.38	0.74	2.80	1.70	2.32
Range of Load Follow (%GDC)							
-Typical Range (%GDC)	32%	35%	30%	20%	27%	20% (Some 50%)	32%
-Multiplying Factor - Faster Ramp Rate (1.1 to 2x)							
Range*	2 to 8	1.5 to 10	1.5 to 10	1.2 to 4	1.2 to 4	1 to 1.2	1.2 to 6
Note: Multiplying factor - increase in load follow cost (damage) from a faster ramp rate							
Typical Non-cycling Related Costs							
- Baseload Variable Cost ($/MWH)							
Median	2.82	2.68	2.96	1.02	0.57	0.66	0.92
~25th_centile	1.52	1.62	2.48	0.85	0.48	0.27	0.66
~75th_centile	3.24	3.09	3.40	1.17	0.92	0.80	1.42

Table 1-2 presents the cycling costs for the Type 8 units, which were defined in the Introduction as a collection of the best cycling units in the Intertek APTECH database. These plants were chosen to represent the lowest cost cycling units within each generation type. Reasons for the low cycling cost can be several, some of which are listed below:

- Better operating procedures, such as
  - Better layup procedures
  - Standard and relatively gentle operating procedures for startup and shutdown
  - Low thermal ramp rates, especially on critical components
- Design considerations or modifications to key components and materials like::
  - Drains
  - Mills/Pulverizers
  - Bypass valves
  - Waterwall tubing
  - Boiler superheater and reheater tube modifications to reduce peak tube temperatures
  - Turbine hood spray design
  - Turbine water induction system
  - Turbine HP and IP valves and first stage components
  - Turbine steam to metal temperature differentials and thermal growth management

Table 1-2: Typical lower bound costs of cycling and other data for various generation types [TYPE 8]

Unit Types	Coal - Small Sub Critical	Coal - Large Sub Critical	Coal - Super Critical	Gas - CC [GT+HRSG+ST]	Gas - Large Frame CT	Gas - Aero Derivative CT	Gas - Steam
Cost Item/							
Typical Hot Start Data							
-C&M cost ($/MW cap.)							
Median	58	39	38	31	22	12	26
-EFOR Impact (in %)							
Median	0.0055%	0.0056%	0.0027%	0.0023%	0.0019%	0.0038%	0.0025%
Typical Warm Start Data							
-C&M cost ($/MW cap.)							
Median	95	61	56	44	28	12	46
-EFOR Impact (in %)							
Median	0.0089%	0.0075%	0.0034%	0.0038%	0.0025%	0.0038%	0.0040%
Typical Cold Start Data							
-C&M cost ($/MW cap.)							
Median	94	89	99	60	38	12	58
-EFOR Impact (in %)							
Median	0.0081%	0.0098%	0.0065%	0.0053%	0.0033%	0.0038%	0.0063%
Startup Time (hours)							
-Typical (Warm Start Offline Hours)	4 to 24	12 to 40	12 to 72	5 to 40 (ST Different)	2 to 3	0 to 1	4 to 48

Table 1-2: Continued

Unit Types	Coal - Small Sub Critical	Coal - Large Sub Critical	Coal - Super Critical	Gas - CC [GT+HRSG+ST]	Gas - Large Frame CT	Gas - Aero Derivative CT	Gas - Steam
Typical Load Follows Data							
-C&M cost ($/MW cap.) - Typical Ramp Rate							
Median	2.26	1.99	1.72	0.33	0.88	0.47	1.56
Range of Load Follow (%GDC)							
-Typical Range (%GDC)	32%	35%	30%	20%	27%	20% (Some 50%)	32%
-Multiplying Factor - Faster Ramp Rate (1.1 to 2x)							
Range*	2 to 5	1.5 to 8	1.5 to 8	1.2 to 4	1.2 to 4	1 to 1.2	1.2 to 6
Note: Multiplying factor - increase in load follow cost (damage) from a faster ramp rate							
Typical Non-cycling Related Costs							
- Baseload Variable Cost ($/MWH)							
Median	2.66	3.01	3.22	1.1	0.76	0.8	1.09

Figures 1-7 shows the spread of start costs for all units included in this project. It is apparent from these plots that power plant cycling costs have a large variation and depend on several factors such as:

- Design
- Vintage
- Age
- Operation and maintenance history and procedure

We use a combination of these factors to define a generating unit's cycling susceptibility. For instance, units in a given generation type of similar age, vintage, design and O&M history and procedures should have somewhat similar damage from cycling operation.

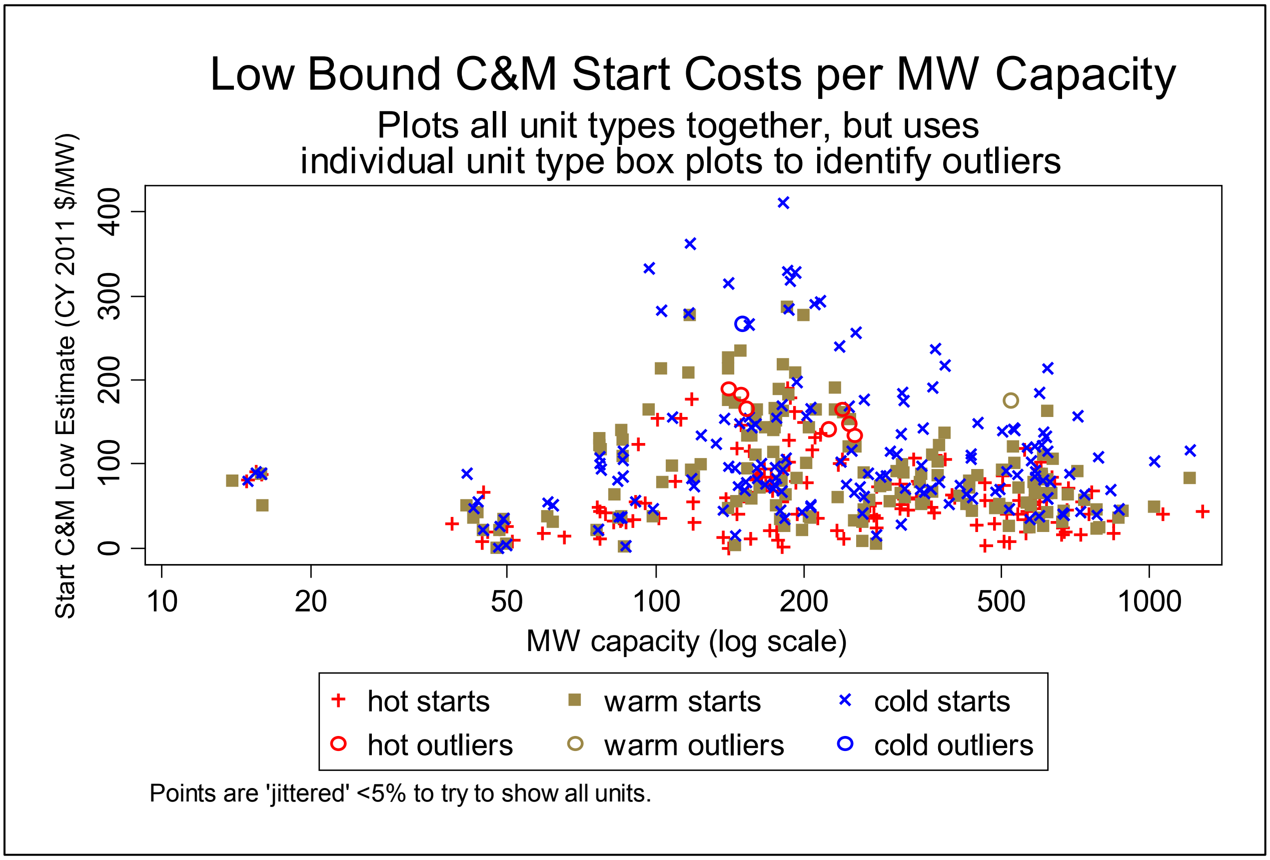

Figure 1-7: Lower Bound – Capital and Maintenance Start Costs per MW Capacity

Start Cost and EFOR Impacts

One of the key outputs of the report is the Capital and Maintenance - Hot, Warm and Cold start costs[7]. Typical definitions of the cycling related costs are:

Cost of operation, maintenance and capital–

- Cost includes:
    - operator non-fixed labor,
    - general engineering and management cost (including planning and dispatch);
- Cost excludes:
    - fixed labor,
    - fixed maintenance and overhaul maintenance expenditures for boiler, turbine, generator, air quality control systems and balance of plant key components

Cost of operation –

- Cost includes:
    - operator non-fixed labor,
    - general engineering and management cost (including planning and dispatch);
- Cost excludes:
    - excludes fixed labor

Cost of maintenance –

- Cost includes:
    - maintenance and overhaul maintenance expenditures for boiler, turbine, generator, air quality control systems and balance of plant key components

Cost of capital maintenance –

- Cost includes:
    - overhaul capital maintenance expenditures for boiler, turbine, generator, air quality control systems and balance of plant key components

Additionally Intertek APTECH records the following costs separately:

- Cost of forced outage and derate effects, including forced outage time, replacement energy, and capacity.

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[7] Note that these costs do not include the fuel cost required for the startup, which is being reported separately.

There is a difference between traditional utilities and market-based operation. Traditional utilities may or may not have to purchase replacement power to meet their needs during an outage. If power is "hedged" (sold in long-term commitments) in a market-based economy, then the cost of increased EFOR includes both (1) lost revenue and (2) an obligation to procure replacement capacity on the spot market. Again, it is up to the user of this data to determine the "value lost" due to this increase in EFOR by calculating the replacement cost of generation lost to forced outages, typically in units of present dollars per MWh.

Figures 1-8 to 1-13 use box plots[8] to present the cycling cost per MW capacity for hot, warm and cold cycles (with and without outliers). It is important to note the huge spread of power plant cycling cost when we closely examine the plots – with outliers. Figures 1-14 to 1-19 present the percent EFOR impact from each of these cycle types using units defined above. Again we include plots with and without outliers to show the spread of our results.

These results in Figures 1-8 through 1-19 (and Tables 1-1 and 1-2) are a major deliverable in this project, which represent typical lower bound cycling cost values and spread that have been observed in our more than 20 years of cycling studies.

Note that supercritical units are generally run baseload and the lower start costs in our database reflect this scenario. However, it is important to note that cyclic tendency of both existing and new supercritical plants will be further exacerbated as a result of increasing variable renewable generation on the grid. There is thus a need to further study plant cycling issues on supercritical units, and in particular the cost issues[9].

---

[8] Box plots are statistical tools often used to explore data and illustrate and compare both central tendency and variation of grouped data. A good description of box plot symbols used in this report is available on several websites, including http://mathworld.wolfram.com/Box-and-WhiskerPlot.html

[9] Damage to Power Plants Due to Cycling, EPRI, Palo Alto, CA: 2001. 1001507

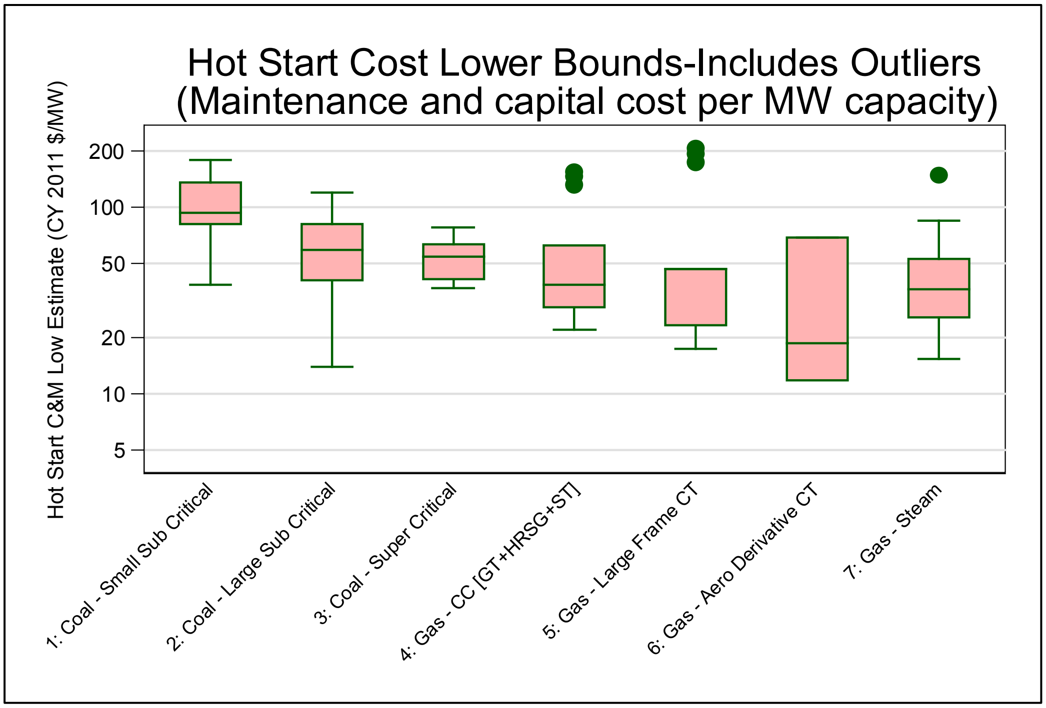


Figure 1-8: Hot Start, Maintenance & Capital Cost per MW Capacity (including outliers)

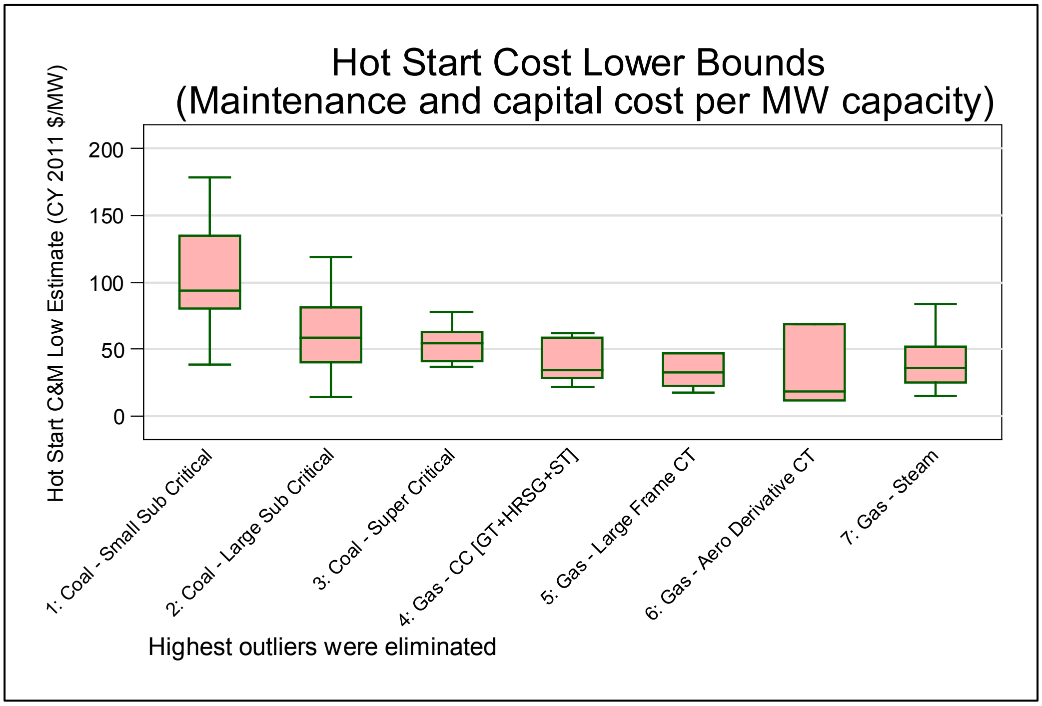


Figure 1-9: Hot Start, Maintenance & Capital Cost per MW Capacity (highest outliers eliminated)

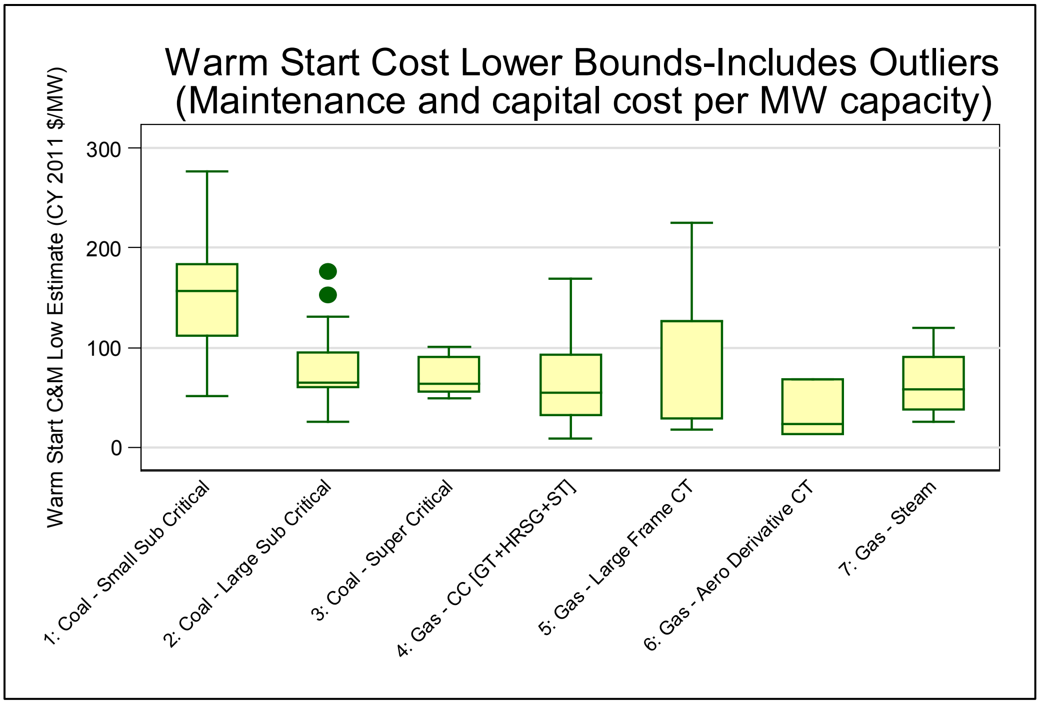


Figure 1-10: Warm Start, Maintenance & Capital Cost per MW Capacity (including outliers)

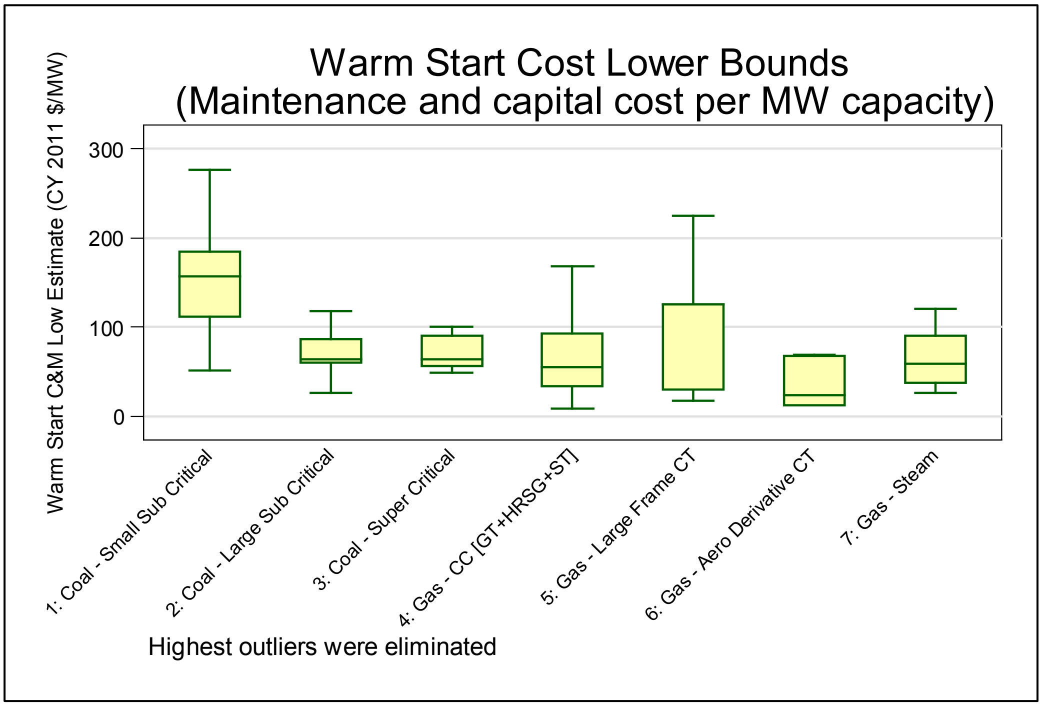


Figure 1-11: Warm Start, Maintenance & Capital Cost per MW Capacity (highest outliers eliminated)

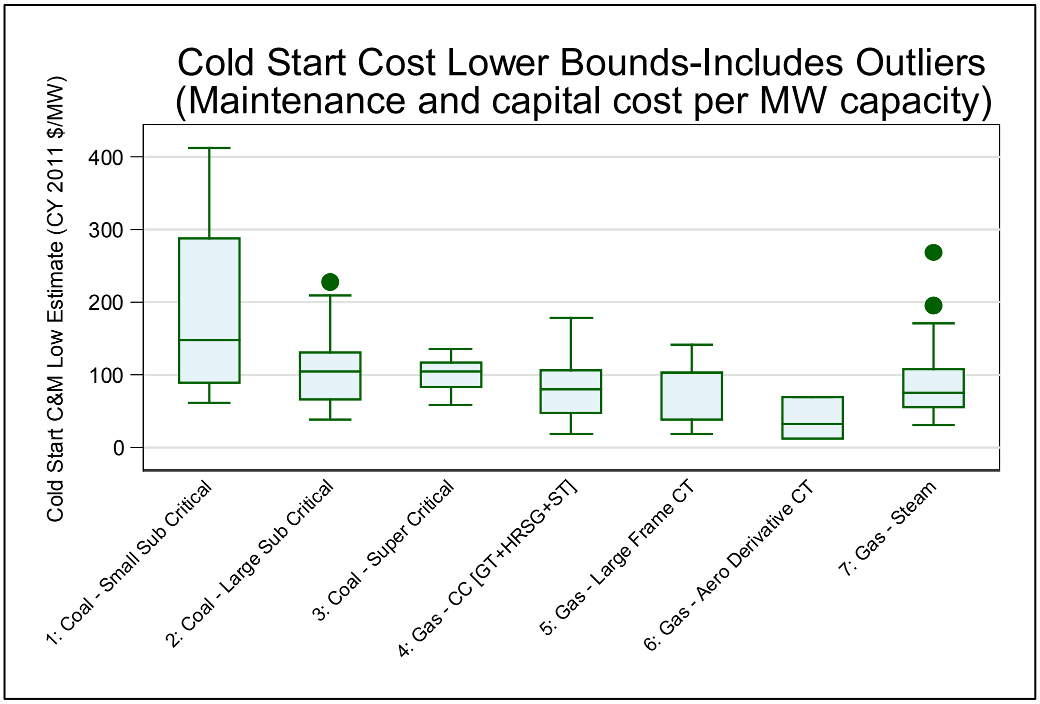


Figure 1-12: Cold Start, Maintenance & Capital Cost per MW Capacity (including outliers)

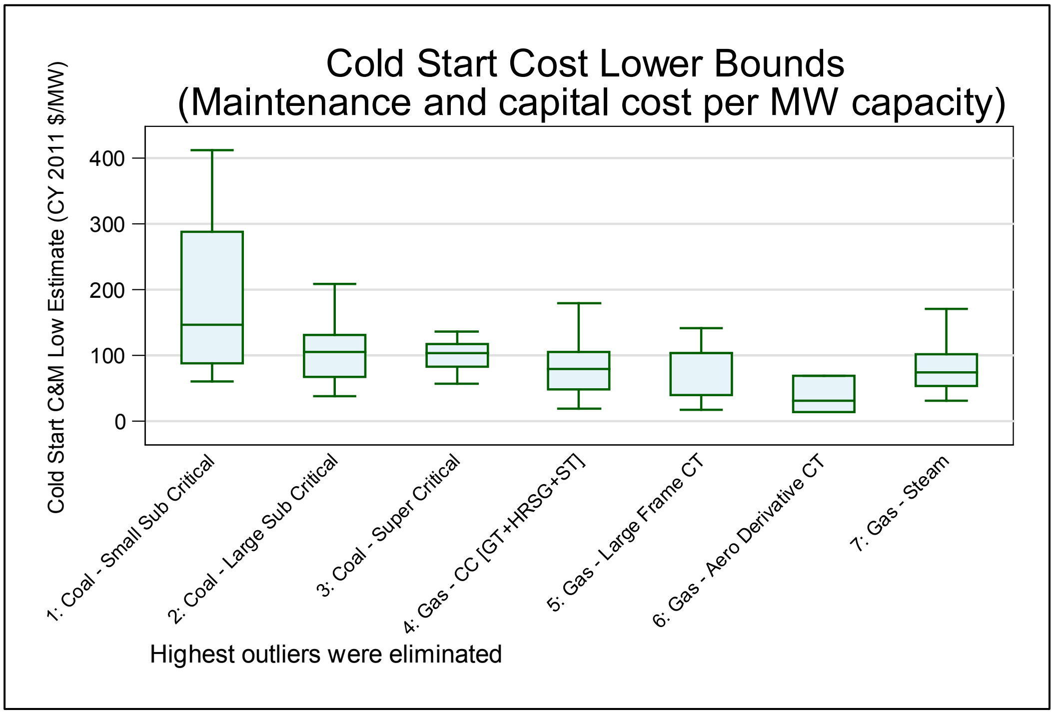


Figure 1-13: Cold Start, Maintenance & Capital Cost per MW Capacity (highest outliers eliminated)

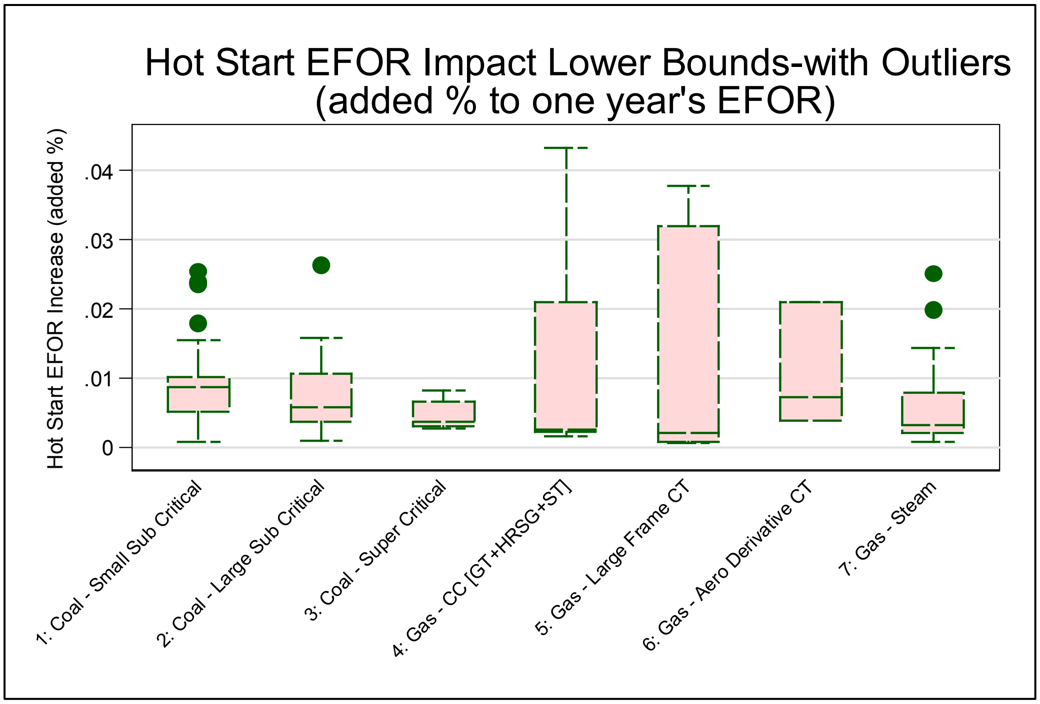


Figure 1-14: Hot Start EFOR Impact - added % to 1 year's EFOR (including outliers)

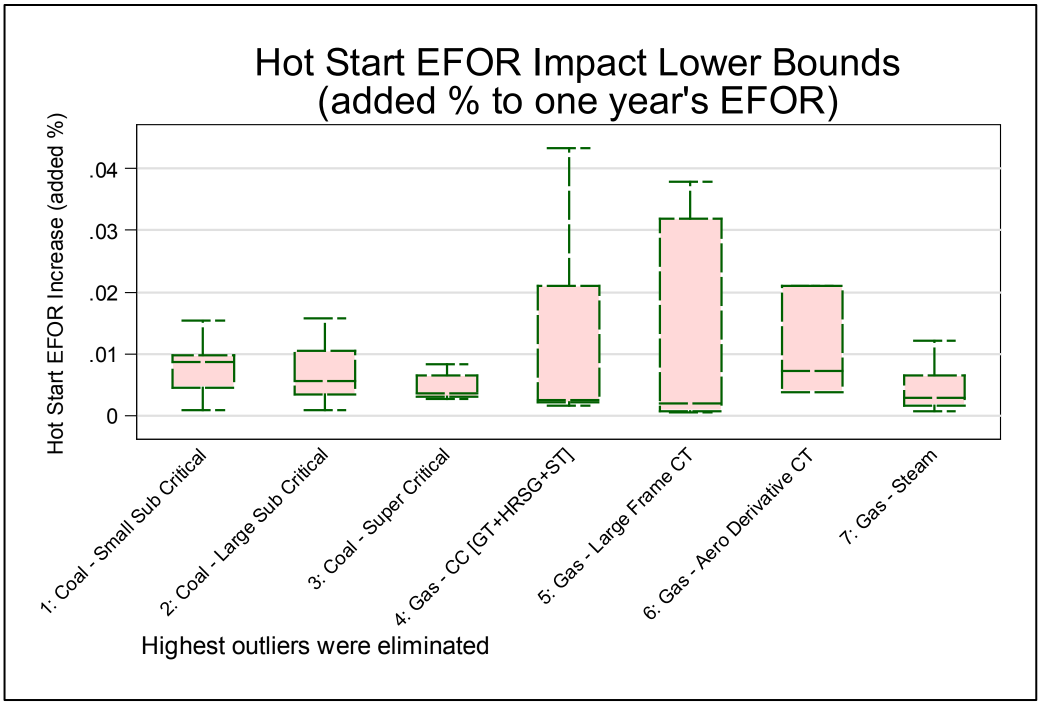


Figure 1-15: Hot Start EFOR Impact - added % to 1 year's EFOR (highest outliers eliminated)

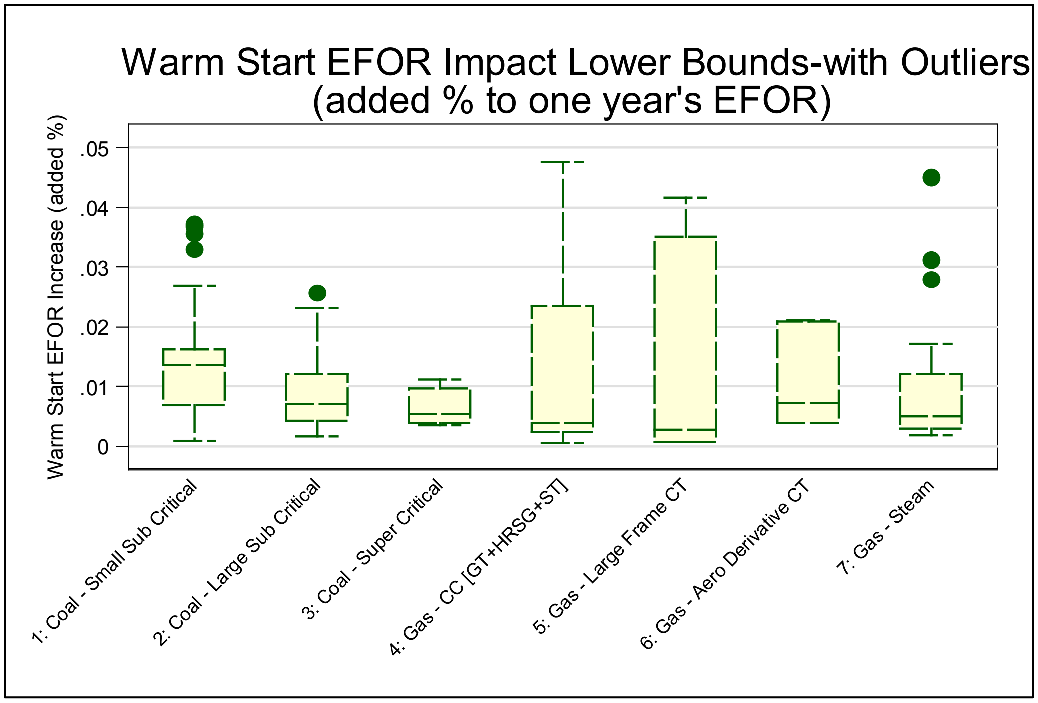


Figure 1-16: Warm Start EFOR Impact - added % to 1 year's EFOR (including outliers)

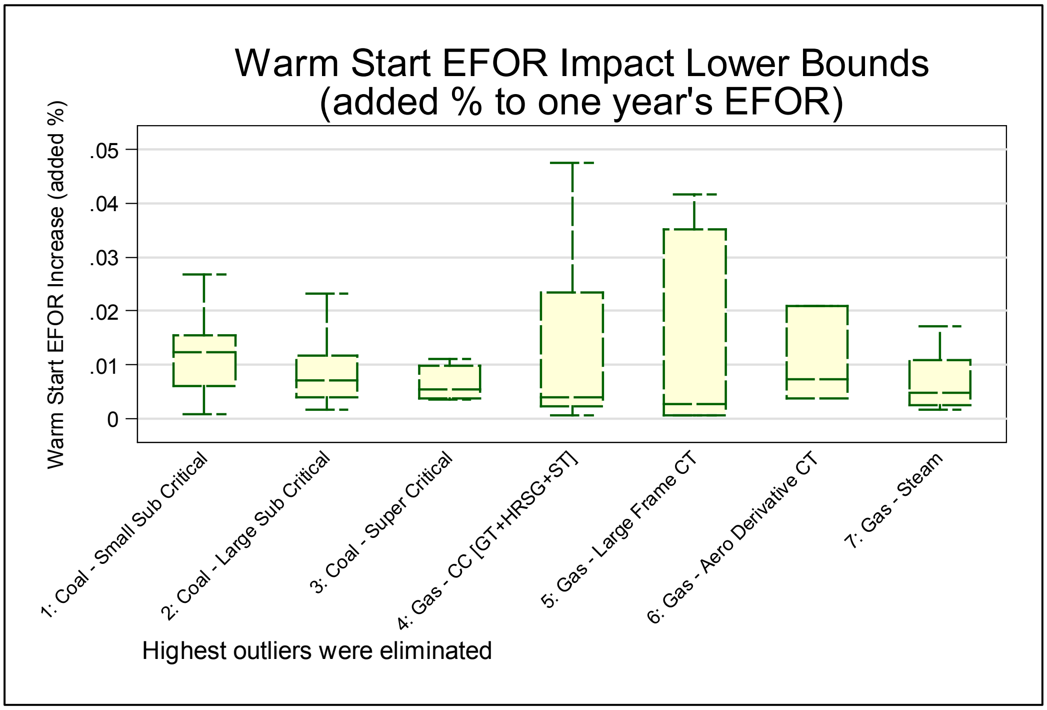


Figure 1-17: Warm Start EFOR Impact - added % to 1 year's EFOR (highest outliers eliminated)

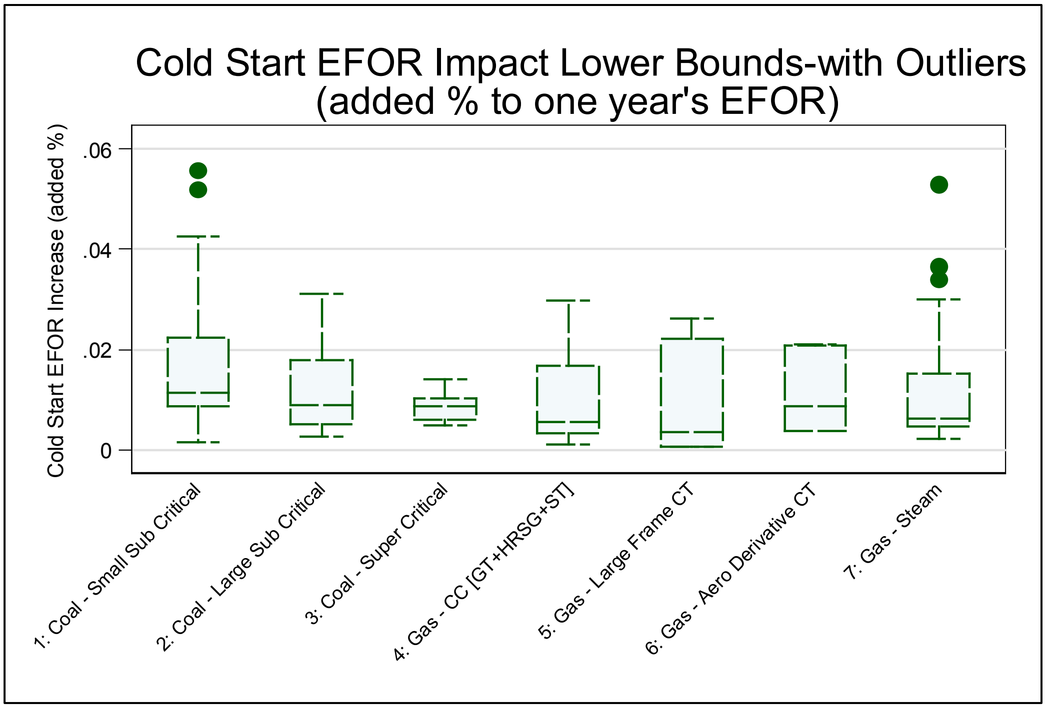


Figure 1-18: Cold Start EFOR Impact - added % to 1 year's EFOR (including outliers)

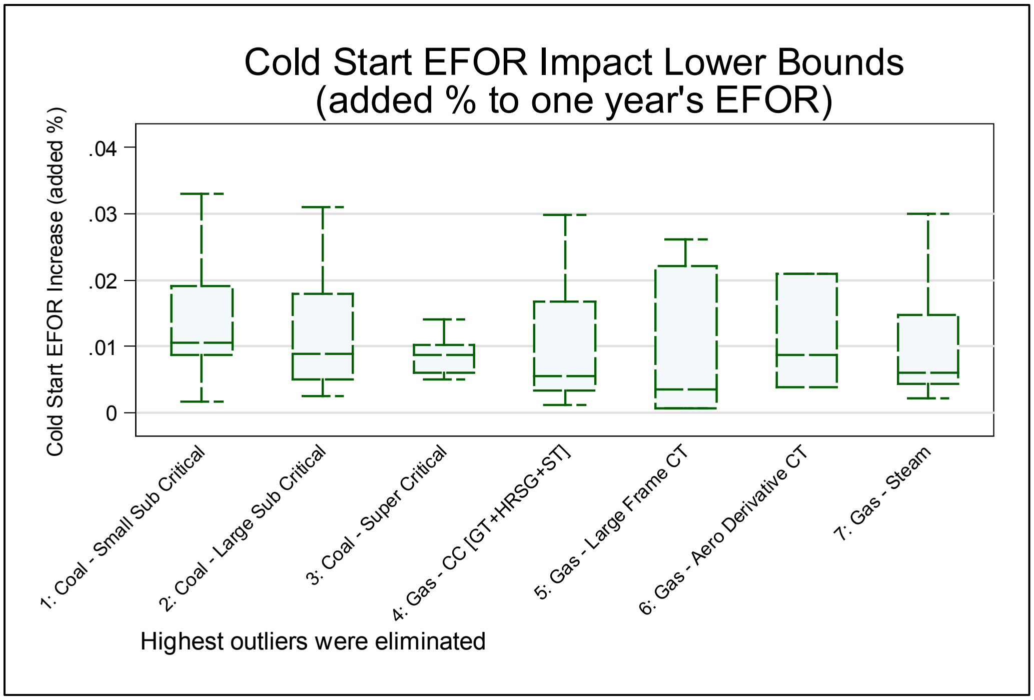


Figure 1-19: Cold Start EFOR Impact - added % to 1 year's EFOR (highest outliers eliminated)

Baseload VOM Cost

Figure 1-20 and 1-21 have the baseload variable O&M costs ($/MWh) distribution for the power plant groups. Non-cycling-related O&M costs include equipment damage due to base-load operation, chemicals, and other consumables used during operations. Supercritical units tend to operate baseloaded and hence have the highest median baseload VOM cost as well as have a low outlier in our database. Again, since the Gas-Steam units represent a large set of units with varying capacities, the spread on these costs is the highest. The CT units, both large frame and aero-derivative, typically run as intermediate or peaker units and are not operated baseload resulting in lower overall baseload VOM costs. Gas aero derivative CT units were found to have the least base load VOM cost, but these units typically operate in a cycling environment as peaking units (which have high “total” VOM Cost). Based on our methodology described in Figure 1-6, we attributed a significant portion of industry standard total VOM cost to cycling.

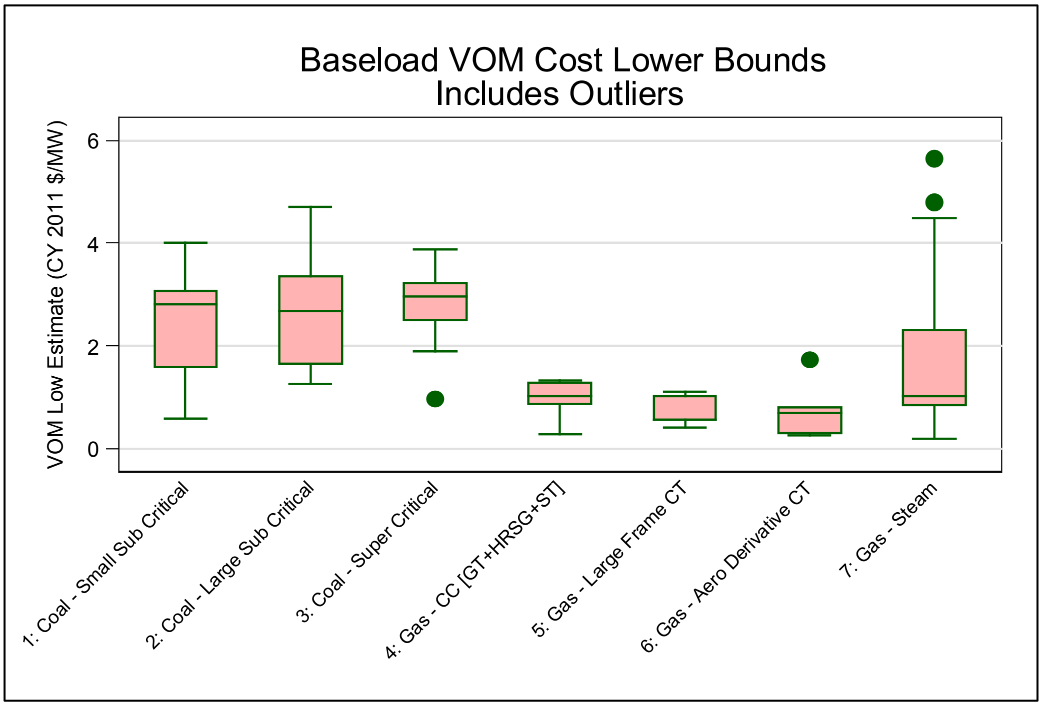


Figure 1-20: Baseload VOM Cost $/MWh (including outliers)

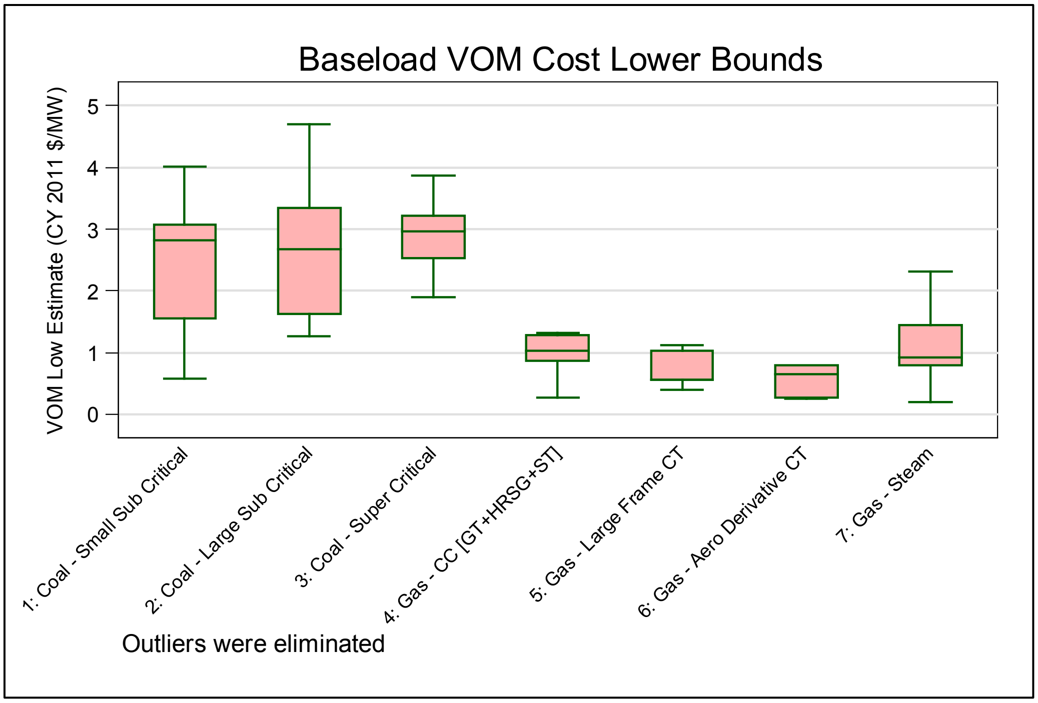


Figure 1-21: Baseload VOM Cost $/MWh (outliers eliminated)

Load Following Cost

The load following cost for a typical normal ramp rate for each of the power plant groups is presented in Figures 1-22 and 1-23. The load following cost is presented as a $/MW capacity per load follows. The preliminary data for faster ramp rate costs was presented in Table 1-1. Load following cost increases due to faster ramp rates are difficult to quantify since both design and operation constraints have to be included in this assessment. Several units are simply incapable of ramping much faster than their typical ramp rates and hence applying a penalty for faster ramp rates has to be carefully included in production cost models. For example on the combined cycle units, the Gas turbines have traditionally compromised their fast-loading capabilities to accommodate the limitations of the HRSG and steam turbine.

The costs represented in these figures are the average cost for all significant load follows. Typically larger units may have several significant load follows but only a few cycles that represent a minimum generation to maximum operating capacity type load follow cycle (deep load follow). Intertek APTECH has seen this trend change of late with increased renewable generation on the grid. This will result in higher costs and should be analyzed in a future study.

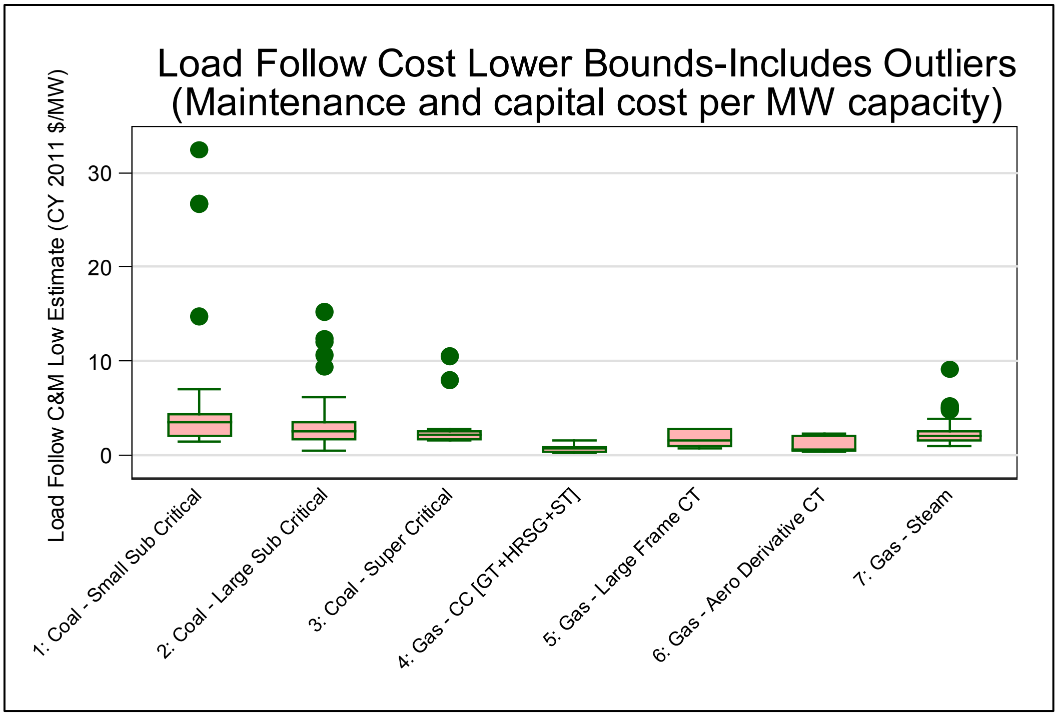


Figure 1-22: Load Follows Cost $/MW – Typical Ramp Rate (including outliers)

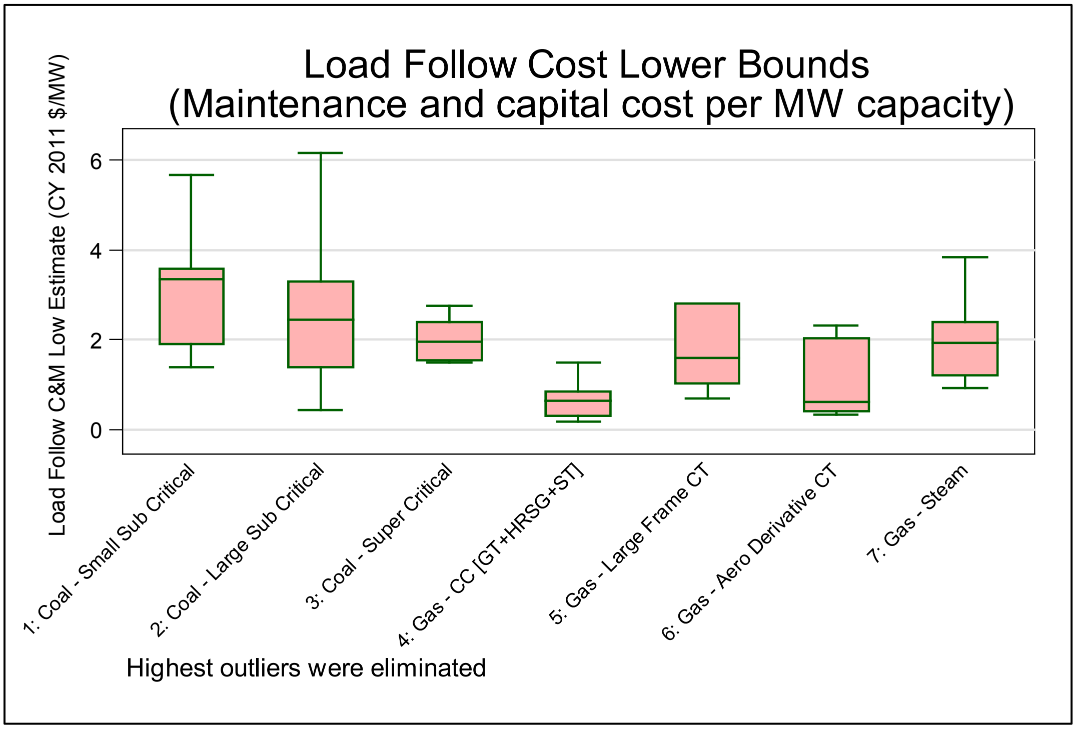


Figure 1-23: Load Follows Cost $/MW – Typical Ramp Rate (outliers eliminated)

Start-up Fuel and Other Start Costs

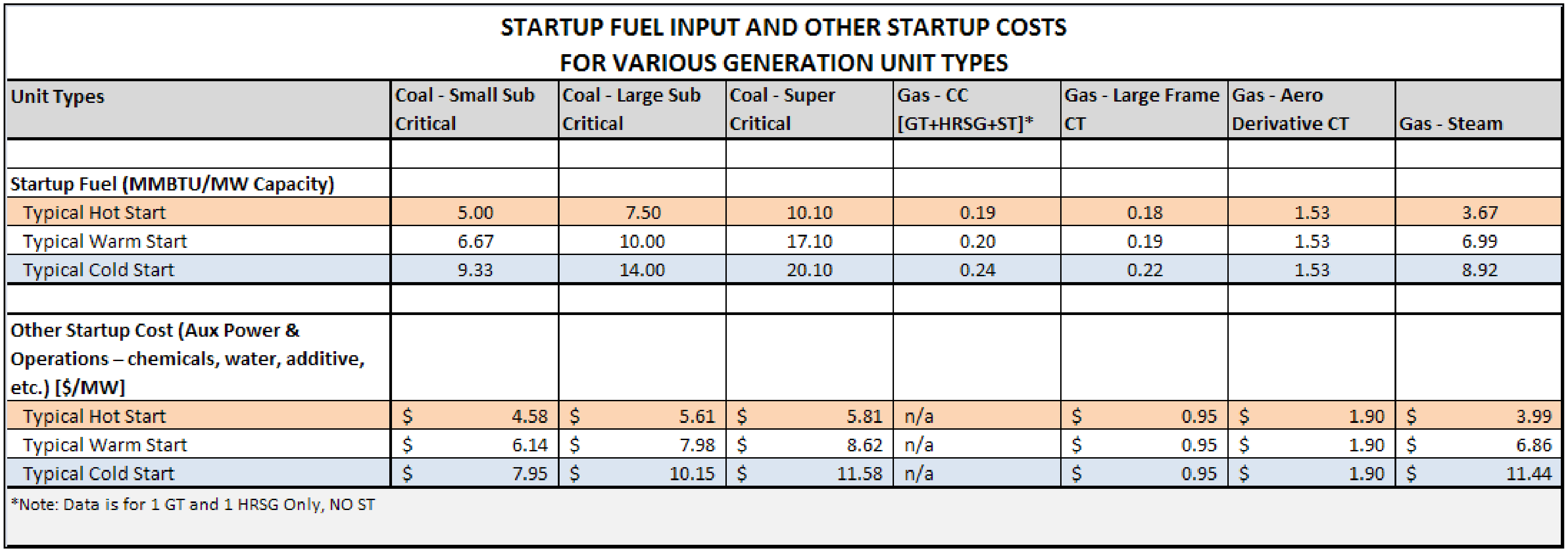
The Startup Cost of a power plant has other components other than Cycling Capital and Maintenance Cost. They are:

- Cost of startup auxiliary power
- Cost of startup fuel
- Cost of startup (Operations – chemicals, water, additive, etc.)

The startup fuel cost inputs are presented in Table 1-3 as MMBTU (fuel input) per startup. This will allow NREL/WECC to utilize a more generic approach to calculate and compare startup fuel costs. The startup cost per start (Hot/Warm/Cold) for [Auxiliary Power + Water + Chemicals] is presented on a $/MW Capacity basis.

Supercritical coal units have a significantly higher startup fuel requirement compared to other generation types. Intertek APTECH did not have a large enough data set to determine the other start cost values for combined cycles units and has not reported the same.

Table 1-3: Startup Fuel Input and Other Startup Costs



STARTUP FUEL INPUT AND OTHER STARTUP COSTS
FOR VARIOUS GENERATION UNIT TYPES

Unit Types	Coal - Small Sub Critical	Coal - Large Sub Critical	Coal - Super Critical	Gas - CC [GT+HRSG+ST]*	Gas - Large Frame CT	Gas - Aero Derivative CT	Gas - Steam
Startup Fuel (MMBTU/MW Capacity)							
Typical Hot Start	5.00	7.50	10.10	0.19	0.18	1.53	3.67
Typical Warm Start	6.67	10.00	17.10	0.20	0.19	1.53	6.99
Typical Cold Start	9.33	14.00	20.10	0.24	0.22	1.53	8.92
Other Startup Cost (Aux Power & Operations – chemicals, water, additive, etc.) [$/MW]							
Typical Hot Start	$ 4.58	$ 5.61	$ 5.81	n/a	$ 0.95	$ 1.90	$ 3.99
Typical Warm Start	$ 6.14	$ 7.98	$ 8.62	n/a	$ 0.95	$ 1.90	$ 6.86
Typical Cold Start	$ 7.95	$ 10.15	$ 11.58	n/a	$ 0.95	$ 1.90	$ 11.44

*Note: Data is for 1 GT and 1 HRSG Only, NO ST

Heat Rate Impacts

Intertek APTECH prepared heat rate curves for each of the seven unit types (not "low cycling" units), based on past studies of various units as well as approximately 10 years of updated hourly EPA CEMS data. The supplementary input of the additional 10 years of Heat Rate data was required to support historical report results. The effects of cycling on heat rate for each of the unit types were investigated and reported in this section.

Methodology

Figure 1-24 summarizes the results of the cycling heat rate, hourly fuel burn analysis for an example unit. In this plot, the green points show all actual hourly data, excluding data near zero hourly MW and a few outliers[10]. The red data points are model "curve fits" using an advanced nonlinear regression tool[11]. The reason the polynomial fit (red points) do not lie on a single heat rate vs. hourly MW curve, and why they model much of the variability inherent in the green data points, is because they are fit to many other variables. These variables are:

- All hourly readings above 30 MW (number varies depending on unit size)
- Each month of the year (individually) to model seasonal effects
- Calendar year to model aging, occasional equipment modifications, and other long term changes
- Number of starts (0, 1, or 2) each day
- Number of daily shutdowns

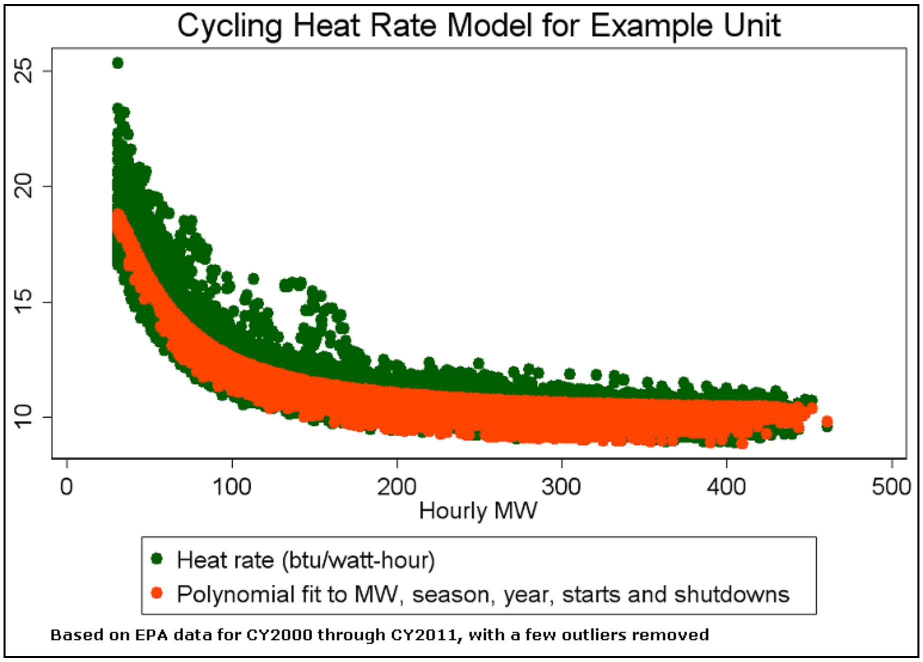
The MW and calendar age variables above are each fit using nonlinear polynomials with four coefficients. The other variables are handled using linear terms. The average "fit error" of these highly scattered hourly readings is about 4%, an acceptable result of EPA data for conventional steam units.

---

[10] Using APTECH's proprietary screening algorithm, all units were moderately screened and had fewer than 5% of hourly readings removed as outliers; an acceptably low percentage based on previous studies using EPA hourly data for natural gas units.

[11] The "multivariable fractional polynomial (mfp)" model was implemented using computer program Stata, "a … statistical package designed for researchers of all disciplines." See http://www.stata.com and more specifically, see http://www.stata.com/help.cgi?mfp.

Our general approach was to fit heat rate data using advanced regression tools detailed below. Included among the independent variables were starts and shutdowns. By knowing the average effect of these cycles on daily heat rates and fuel usage, and the current per million BTU fuel price, we then estimated the extra fuel cost associated with start-shutdown cycles.



Based on EPA data for CY2000 through CY2011, with a few outliers removed

Figure 1-24: Cycling Heat Rate Model for example unit.

Heat Rate Effects

Intertek APTECH runs its regression by controlling for various independent variables. Some of the effects we typically examine are as follows:

- Seasonal Effects
- Time or Aging Effects
- Cycling Effects

This report specifically discusses the “cycling effects” on power plant heat rates.

Immediate Cycling Effects: Start counts are explicitly included in the nonlinear regression model of heat rate, again while properly accounting for all the other listed heat rate effects including average weekly MW itself. The differences among startup fuel costs for hot, warm, and cold starts are quite large, but the differences among the start types on immediate heat rate effects are usually not. In this particular analysis, there are not enough data to differentiate the immediate heat rate costs of hot, warm, and cold starts, so the relatively small heat rate-based cost estimates above are applied to all shutdown/start cycles, with only a small adjustment for shutdown length (start type).

The effects of long-term degradation can and often are countered by maintenance practices and spending to replace the degraded equipment, e.g., replacing worn seals at the turbine overhaul, cleaning the condenser of corrosion deposits, replacing air heater baskets, etc. However, as shown in Figure 1-25[12], the long-term heat rate of ten identical units can degrade by as much as 10% over a 30-year period. We believe that approximately 1-5% loss in efficiency is attributable to cycling. While this is one of the largest long-term impacts we have observed, we note that a 1% increase in unit heat rate over 4 to 5 years is not uncommon.

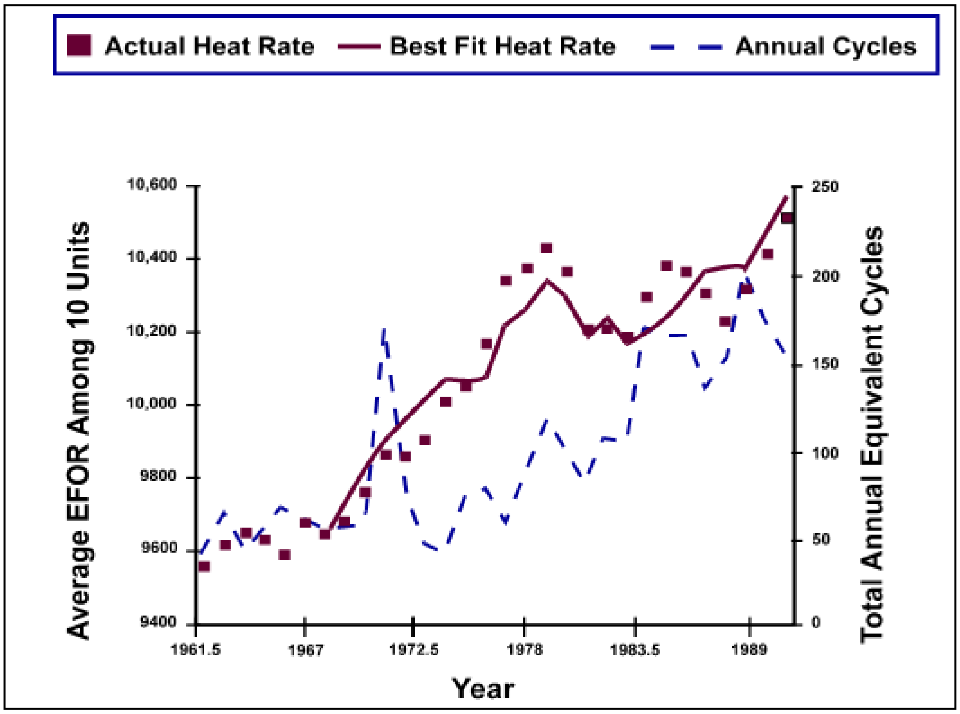


Figure 1-25: Cycling effects on Heat Rate

The typical unit may increase 4% to 5% in the period but regain all but 1% after a good major turbine overhaul. We typically find that most of this 1% degradation is due to cycling operations. We observe turbine efficiencies degrading from 88 –91% to the low 80s between overhauls.

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[12] "Power Plant Cycling Operations and Unbundling Their Effect on Plant Heat Rate", Steven A. Lefton and Philip M. Besuner, Rocky Mountain Electric League, Operations Seminar, Denver CO (2001)

Table 1-4 below shows the impacts of one cycle (any type) on the unit's weekly heat rate. Typically small coal units have the greatest effect of cycling on their heat rates. Newer, combined cycle units as well as simple cycle gas fired units see a much lower impact. Intertek APTECH observed a fairly small impact of cycling on heat rate in the case of the gas aero-derivative CT units. Note that enough care was taken to ensure that startup fuel input was eliminated from this analysis.

While we have given a large range for the heat rate effects due to cycling operations, these effects are strongly dependent on the unit, control systems, past spending to test and maintain heat rate, test data, load follow depth, rate of change, and total load shed. Such scenarios can quite easily be seen over a multi-year study. However, for our analysis we have isolated such long term scenarios and isolated the impact on heat rate due to additional cycling.

Table 1-4: Heat Rate Impacts

% INCREASE IN EFFECTIVE WEEKLY HEAT RATE DUE TO ADDING ONE STARTUP SHUTDOWN CYCLE							
Unit Types	**Coal - Small Sub Critical**	**Coal - Large Sub Critical**	**Coal - Super Critical**	**Gas - CC [GT+HRSG+ST]***	**Gas - Large Frame CT**	**Gas - Aero Derivative CT**	**Gas - Steam**
Heat Rate (% Increase per start)							
Typical Start	0.62%	0.44%	0.44%	0.20%	0.20%	0.00%	0.20%

1.4 Using Power Plant Cycling Costs in Simulation Models

Intertek APTECH suggests that the cycling cost data in this report be used in NREL/WECC simulation models based on perception of the target unit's past cycling history and its cycling susceptibility. Intertek APTECH suggests using its Loads Model[13] to more accurately account for power plant cycles (using the Rainflow counting method). This will allow Intertek APTECH to provide the best suggestion for using these costs. For instance, units will fall into various percentiles based on past and future usage, including cycles.

- Units with typical usage and cycling susceptibility (for a given generation type) should be assigned median values from Table 1-1.
- If a Unit is judged to have more than typical cycling usage and susceptibility compared to the generation type, use of the 75th percentile values of Table 1-1 bounds is more appropriate.
- Similarly, if a Unit is judged to be less susceptible to cycling costs or low cycling usage compared to other units in the generation type population, a 25th percentile value of these bounds could be used.

Still, for units with exceptionally high or low cycling susceptibility, even the use of the 75th and 25th percentile costs is not appropriate. For such atypical units, we recommend using Intertek APTECH to produce appropriate Unit-specific cycling cost estimates.

A paper by J. Larson of Northern States Power (NSP)[14][15] addresses the concern about economic penalties of dispatching generation units using the wrong cycling cost data. This paper presents the results of a study quantifying the cost penalties of using incorrect cycling cost data in a Unit Commitment model (a model used to optimize dispatch schedules). The study used a typical five-weekday medium load period at NSP. The dispatch problem involved determining which small coal-fired units to run and cycle, and which purchases to buy. Figure

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[13] The Loads Model includes the methodology and software Intertek APTECH has been developing since the late

1980s to quantify cycling intensity from hourly generation and other data and background information, such as thermal signature and remaining useful life data. Loads Model software is simplified and converted to subroutines within the Cycling Advisor computer program (Production Cost Model), ensuring that our best cycling models are simulated.

[14] Cited in: "Operational aspects of generation cycling", IEEE Transactions on Power Systems (Volume: 5, Issue: 4, Page(s): 1194 - 1203) [Nov 1990]

[15] Technical Paper: "Economics of Cycling 101: What Do You Need To Know About Cycling Costs and Why?", by G. Paul Grimsrud and Steven A. Lefton

1-25 summarizes the results of this study by presenting the cost penalties to the system as a function of the degree of error in the startup cost estimate. The curve given in Figure 1-25 provides some very interesting insights. The first is that moderate errors in cycling cost information (e.g., plus or minus 50%) can be tolerated, as the cost penalties are relatively small. The second, more significant insight is that the penalties of using a cycling cost estimate that is much too low is much worse than for estimates that are much too high. Given the information on cycling costs, most utilities are using cycling costs in the range of 10% to 30% of what APTECH has found to be the "true" cost of cycling. Thus, we believe most utilities may be in this high cost penalty regime.

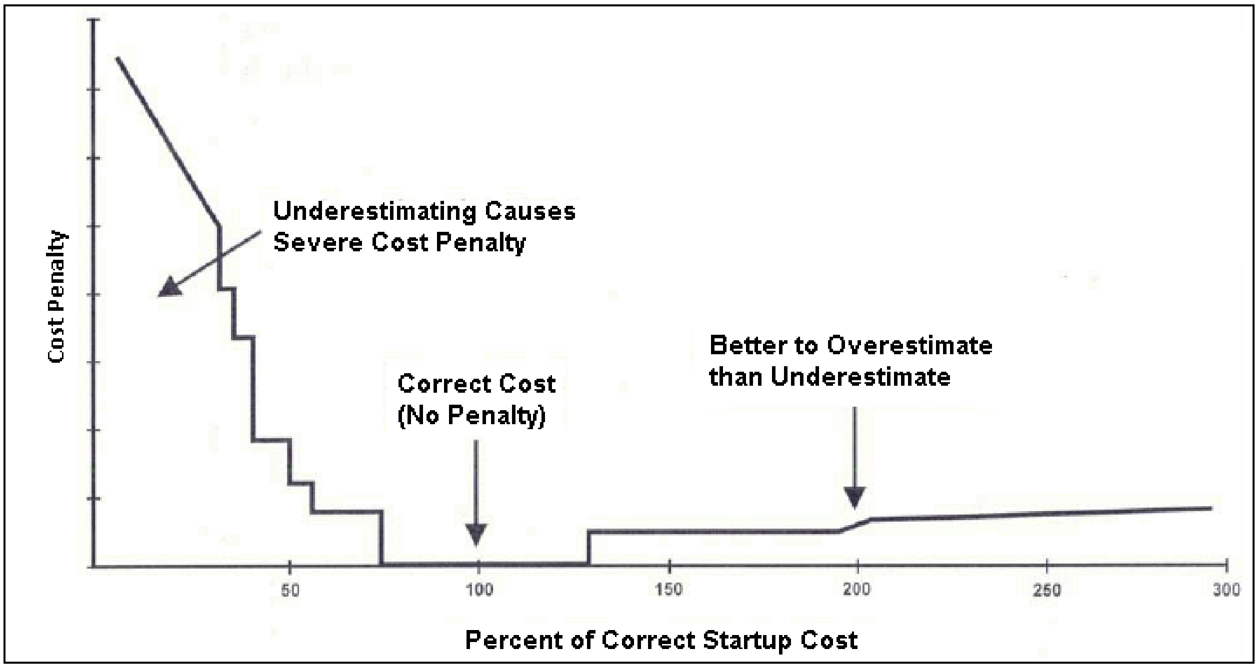

Figure 1-26: Calculated System Penalty for Using Incorrect Startup Cost

1.5 Components and Systems Affected by Cycling

Cycling operation increases the concern for creep-fatigue damage caused by thermal stresses, especially in units designed for baseload operation. The creep-fatigue is a dominant failure mode for damage and failures of many fossil plant components. A sample list of these is summarized in Table 1-5. From this list several observations can be made. Creep-fatigue damage often locally occurs at stress concentration such as rotor grooves, header bore holes, ligaments, etc. involving large plastic strain. It may also involve elastic strain combined with stress relaxation like in combustion turbine blades. Creep-fatigue damage usually occurs because of thermal stress in constrained components during thermal transients. The constraints can be in internal cooling of components that incur rapid heating at the surface, like gas turbine blades, or internally in the case of heavy sections components like rotors, headers, drums, etc. where thermal gradients come about between the surface and the interior. The constraint can also be external such as in the case of joining thick to thin section or materials of different coefficients of expansion as in dissimilar metal welds. All of these stresses are thermally induced and occur in a relatively low number of cycles.

For gas turbines, the impacts of startup, shutdown, and part load cyclic operation on the component life, maintenance cost, emission compliance, unit reliability and availability are significant. Starts and shutdowns can induce excessive thermal fatigue damage, especially to the combustion system and hot gas path components, which lead to premature life and more forced outages. Fast cycling during load following can require transitions from one combustion mode to another which can reduce flame stability and increase combustion pressure dynamics. Both of these reduce reliability. Also, the high exhaust temperatures during transients mode transfers cause creep damage to expansion joints and of course the HRSG.

For each unit type, Intertek APTECH presents in Table 1-5 a list of specific components that are typically adversely affected by cycling and the primary damage mechanisms causing the damage.

Table 1-5: Specific components typically affected by cycling

Unit Types	Plant Equipment with Most Significant Adverse Impacts from Cycling	Primary Damage Mechanism	Backup Paper (if available)
Small and Large Sub-Critical Coal	Boiler Waterwalls	Fatigue Corrosion fatigue due to outages oxygen and high starts up oxygen Chemical deposits	The Cost of Cycling Coal Fired Power Plants, Coal Power Magazine, 2006 - S. Lefton, P. Besuner
	Boiler Superheaters	High temperature differential and hot spots from low steam flows during startup, long term overheating failures	
	Boiler Reheaters	High temperature differential and hot spots from low steam flows during startup, long term overheating failures, tube exfoliation damages IP turbines	
	Boiler Economizer	Temperature transient during startups	
	Boiler Headers	Fatigue due to temperature ranges and rates, thermal differentials tube to headers	
	LP Turbine	Blade erosion	
	Turbine shell and rotor clearances	Non uniform temperatures result in rotor bow and loss of desired clearance and possible rotor rubs with resulting steam seal damages	
	Feedwater Heaters	High ramp rates during starts, not designed for rapid thermal changes	
	Air Heaters	Cold end basket corrosion when at low loads and start up, acid dew point	
	Water/Chemistry Water Treatment Chemistry	Cycling results in peak demands on condensate supply and oxygen controls	

Unit Types	Plant Equipment with Most Significant Adverse Impacts from Cycling	Primary Damage Mechanism	Backup Paper (if available)
	Fuel System/ Pulverizers	Cycling of the mills occurs from even load following operation as iron wear rates increase from low coal flow during turn down to minimum	Power Magazine, August 2011, S Lefton & D. Hilleman, Making your Plant Ready for Cycling Operation. Also: Coal Power Mag, Improved Coal Fineness Improves Performance
Supercritical Coal (600-700 MW)	Same as subcritical coal except added temperatures in furnace tubing		
	Large supercritical furnace subject to uneven temperatures and distortion	Fatigue due to temperature ranges and rates, thermal differentials tube to headers	
Large Frame 7 or Frame 9 CT	Compressor Blades	Erosion/corrosion fatigue. Thermal fatigue. Fatigue crack growth. Higher temperature gradients.	Erosion and Fatigue Behavior of Coated Titanium Alloys for Gas Turbine Compressors. Milton Levy, et. al. 1976.
	Turbine Nozzles/Vanes	Variable amplitude loading.	
	Turbine Buckets/Blades	Erosion/corrosion fatigue. Thermal fatigue. Fatigue crack growth.	Failure Analysis of Gas Turbine Blades. Microscopy Society of America. 2005. Rybnikov A.I., et al.

Unit Types	Plant Equipment with Most Significant Adverse Impacts from Cycling	Primary Damage Mechanism	Backup Paper (if available)
	Thermal Barrier Coatings on hot gas path parts	Higher temperature gradients. Sintering of blade coatings. Thermal fatigue cracking. Loss of thermal barrier coating and frequent replacements	
	Turbine Rotor	Variable amplitude loading. Erosion/corrosion fatigue. Thermal fatigue. Fatigue crack growth. Higher temperature gradients.	Potential Issues in Cycling of Advanced Power Plants, OMMI, April 2002. F. Starr
	Combustor Liner	Erosion/corrosion fatigue. Thermal fatigue. Creep-fatigue interaction	Combustion Turbine Hot Section Life Management, OMMI August 2002. M. Kemppainen, J. Scheibel, and R. Viswanathan.
	Fuel Injectors	Erosion fatigue. Thermal fatigue	Gas Turbine Handbook: Principles and Practice. Tony Giampalo 2003.
Aero-Derivative CT (LM 6000)	Turbine Nozzles/Vanes	Variable amplitude loading. Erosion/corrosion fatigue. Thermal fatigue. Fatigue crack growth.	
	Turbine Buckets/Blades	Erosion/corrosion fatigue. Thermal fatigue. Fatigue crack growth.	
	Turbine Rotor	Variable amplitude loading. Erosion/corrosion fatigue. Thermal fatigue. Fatigue crack growth. Higher temperature gradients.	
	Combustor Liner	Erosion/corrosion fatigue. Thermal fatigue. Creep-fatigue interaction	
Combined Cycle Unit	HRSG Tube to Header Connections	Spatial (between tubes) differential temperatures High temporal temperature ramp rates & differential tube temperatures tube to tube. Thermal shock from un-drained Condensate during a startup or forced cooling purge cycles	

Unit Types	Plant Equipment with Most Significant Adverse Impacts from Cycling	Primary Damage Mechanism	Backup Paper (if available)
	Headers and drum	High ramp rates when cycling, thermal quench of bottom headers from un-drained condensate	Analysis Of Cycling Impacts On Combined Cycle, ASME Power Proceedings 2008 - S. Lefton, P. Grimsrud, P Besuner, D. Agan, J. Grover
CT, HRSG and ST	HRSG Tubes	High temporal temperature ramp rates and high stress from uneven flow rates, from laning of gas and low steam flows during cycling. Overheating (temperatures too high) in duct fired units Feedwater heater tube failures from thermal differentials in adjacent tubes during startups	Heat Recovery Steam Generators And Evaluating Future Costs Of Countermeasures To Reduce Impacts
	Condensate Piping, LP evaporator and Economizer/ Feedwater heater Tubing For CT (see Large Frame Unit below)	FAC Flow Assisted Corrosion in carbon steel tubes, headers and piping in low temperature sections including the LP or IP evaporator, economizers and feedwater heaters.	

1.6 Mitigation strategies for power plant cycling

In units that have large amounts of cycling and cycling damage, the mitigation strategy will include a higher level of scheduled inspections or replacements for the components susceptible to creep-fatigue failures to reduce the risks of failure. If failures such as leaks, unacceptable cracks, unacceptable wall loss, and peeling of coatings are detected appropriate action should be taken: replacement or repair.

Understanding cycling costs and including them in dispatch is the first step, however it is equally important to control and mitigate these costs. Below, we discuss steps from a power plant operator's perspective to mitigating cycling impacts.

Mitigation Strategies for Small/Large Coal Units

Cycling cost can be avoided by:

- obvious method of not cycling a unit and that may include staying on line at a small market loss price
- keeping the unit hot thereby reducing delta temperature transients
- by understanding the issues and managing the unit to reduce the damage rates
- modifying the operation procedures or process, specifically keeping ramp rates modest
- capital or O&M projects to modify the base load designs to make units designs more adept to cycling

Detailed component analysis allows for targeted countermeasures that address the root cause of the cycling damage to manage and even reduce the cost of future cycling duty. Some examples are:

- Air/Gas Side Operational Modifications – Reduces rapid transients in boiler flue gas
- Steam bypass – Matches steam temperature to turbine controls start up steam temperature in SH/RH
- Feedwater bypass to condenser – Controls startup temperature ramp rates to feedwater heaters and economizers
- Condenser tube replacement – Improves plant chemistry and reliability and prevents turbine copper deposits.
- Motorized valve for startup – Reduces temperature ramp rates in boiler and reduces fatigue

- Motor driven boiler feed pump – Reduces fatigue of economizer and feedwater heaters and allows faster, reliable start up.

Mitigation Strategies for Gas Turbines

The GT mitigation strategies for controlling and reducing the risks of high cycling are strongly dependent on many factors including manufacturer, model, design (such as one-shaft or two-shaft design), rating, vintage, combustor type, fuel type, emission regulations, environmental factors, and operating profile. The major original equipment manufacturers (OEMs) are GE, Alstom, and Siemens. The hardware and software modifications that are required or even possible for units with a high cycling operation are diverse. The schedules for combustion inspections, hot gas path inspections/overhauls, and major overhauls are all highly dependent on how much the unit cycles: starts, shutdowns, fast starts, trips, part load operation, etc. The operator of the unit must keep track of these transient operations. Software can be installed to work in conjunction with the unit's digital control system to track such cycling. Intertek APTECH's Cycling Advisor and COSTCOM are software systems to track cycling damage for units.

Mitigation strategies for retrofit vs. new application are also very different. Once an asset is designed and purchased to meet specific load requirements, it cannot be easily changed without large expenditures. For example, GE large turbines with advanced technology (7FA, 7EA, 9FA, and 9EA with Dry Low NOx (DLN) combustion systems) would have different modification strategies compared to a Siemens F-Class younger than 2003 with FACY technologies or Alstom GT24/KA24 combined cycles.

Modifications in the design of the GT hardware, software and operations practices can mitigate the harmful impacts. For example, an automated Distributed Control System (DCS) logic system for start sequencing can reduce the time for various auxiliaries to startup and reduce startup preparation from 70 minutes to 35 minutes. These types of automatic systems also reduce chance of operator error.

The regulations for low emissions in GTs have become more stringent resulting in the development of DLN systems. These systems are designed for good performance at full load. At part load and transient operations flame stability, heat rates, and emissions compliance can be a problem. The combustion mode changes required in DLN systems often cause high combustion dynamics (pressure fluctuations and vibration) during cycling operations. These have caused fatigue cracking in the combustion liner, transition piece, and thermal barrier coatings with increased erosion and corrosion in the hot gas path components. Monitoring and tuning of the mode transfer sequencing is required to reduce the magnitude of the dynamic. The liner may also require modifications to withstand the vibration.

On some GTs that use DLN combustors, incidence of high vibrations has been experienced during hot starts. Modifications to the tie bolt and compressor disk are necessary if a cool down period before restart is not observed.

1.7 Conclusions

Some of the observations from the figures and tables in the report are as follows:

- Figure 1-7 clearly shows the large spread of cycling start cost observed.
- Median Cold Start Cost for each of the generation types is about 1.5 to 3 times the Hot Start Capital and Maintenance Cost. For the lower bound 75th percentile this ratio of Cold Start Cost versus Hot Start Cost is only slightly higher.
- The Gas aero derivative CT units have almost the same relatively low costs for hot, warm, and cold starts. That is because in these designed-to-cycle units, every start is cold.
- Most small and, especially, large coal units were designed for baseload operation and hence, on average are higher cycling cost units.
- There are some important economies of scale for large coal (and other fossil Units), that lower their costs. So the highest costs per MW capacity, as plotted here, occur in some “abused” smaller coal units, especially for cold starts.
- Typically, large supercritical power plants are operated at baseload and do not cycle much. Thus the units we have examined have not cycled often and have not suffered the high costs of cycling operations. This is not to say that we believe that cycling these units can be done without sustaining high costs. Operating these units in cycling mode can result in unit trips and cycling failures. As a result of the false starts and trips, the real cost of cycling these units is significantly high. Moreover, these units cannot easily be brought online under these circumstances and such factors are not fully captured in this dataset.

- There is an inherent “tradeoff” relation between higher capital and maintenance expenditure and corresponding lower EFOR. While this is not conclusive from the plots themselves, the huge variation in EFOR impacts in these results may be attributed to this phenomenon. However, further research in this area is required.
- Older combined cycle units were designed for baseload operation and when operated in cycling mode can have higher cycling costs, which can be seen from the distribution of costs.
- The coal fired small and large units were the expensive load following units. Most of these units were designed for base load operation and undergo significant damage due to change in operations.
- Increasing ramp rates during load following is expensive. Still, the costs of increased ramp rate calculated for this report include only those fully attributed to load follow cycling. It is impossible to increase ramp rates of load following by itself without having some impact on start/shutdown cycles. So the fast ramp rate results in this report probably understate their costs.
    - Higher ramp rates result in higher damage and this is most easily seen on the coal fired units. While not a linear relationship, additional research is required to get further detail.
    - The combined cycle units also have a higher ramp rate cost, due to the operational constraints on the HRSG and ST.
    - Combined cycle units have a limited load following range while maintaining emissions compliance.
- The higher operating and maintenance costs of supercritical units can be observed from the baseload VOM cost data.
- Gas Aero Derivative CT units were found to have the least base load VOM cost, but these units typically operate in a cycling environment as peaking units (which have high “total” VOM Cost). Based on our methodology described in Figure 1-6, we attributed a significant portion of industry standard total VOM cost to cycling.
- Aggregating cycling costs at the system level results in ignoring the “flash flood” situation of heavy cycling on individual units on the grid. Transmission expansion studies should include power plant cycling as an input.

Appendix A

Intertek APTECH'S Method for Determining Bounds for Cycling Cost Estimates

Intertek APTECH believes it is important to determine the bounds for the top-down cycling cost estimates. This is done by assessing the uncertainty in the cycling cost regression due to the combination of:

- Limited sample size
- Noise inherent in variations of annual cost and cycling characteristics
- Both standard and heuristic numerical procedures

Uncertainty is estimated in several steps:

- **Step 1** — Compute the best estimate of cycling cost (dC/de)[16] as the one that best fits annual cost data and "soft regression constraints." This answer must also satisfy any "hard" regression constraints imposed by data limitations and by Intertek APTECH's engineering judgment (such as, on the "A coefficient", which represents that portion of costs that is independent of Unit loads). A hard constraint is one that must be satisfied unconditionally. A soft constraint need not be totally satisfied. Still, a penalty is imposed on the regression that increases according to how much the soft constraint is violated.
- **Step 2** — Rerun the analysis several times while forcing cycling cost (dC/de) "answers" that differ by various amounts from the best estimate of Step 1. The greater this forced deviation from the best-fit cycling cost, the worse the fit.
- **Step 3** — Study the negative impact of changing the answer on the regression fit and constraints in the following two ways:
  - Visually and subjectively, comparing the fits "by eye"
  - More objectively by comparing statistical measures of the "goodness" of both fit and ability to satisfy soft constraints
- **Step 4** — The bounds are set where the deviation from the best fit cannot be explained solely by randomness in the sample.

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[16] Here "C" is wear and tear cost, including cycling cost, and "e" represents a specified cycle. A more complete description of APTECH's top down cycling cost equations will be incuded in the final report.

One Hard Constraint

As described above, for baseloaded units, typically a 50% to 75% range is imposed on the top-down analysis A coefficient to reflect the portion of wear and tear costs that have no relation to unit loading variations. This is a hard constraint. To implement it, the numerical analysis routine is prohibited from using values of A outside this range. The routine will arrive at its best regression solution by choosing any A value it wants to within the constraint, but it is forbidden to "wander" outside of the 50% to 75% range.

Two Soft Constraints

Soft constraints are more tolerant. They allow the numerical analysis routine to wander wherever it wants in search of a best regression fit. Soft constraints do not prohibit such wandering but severely "penalize" the routine if it wanders too far from the soft constraints.

In our first example of soft constraints, APTECH uses a smoothing algorithm for many of its top-down regressions. The smoothing is done to cope with large year-to-year variations in maintenance, capital, and outage spending that may be the result of economic and political decisions, as opposed to how the unit is loaded. The smoothing algorithm uses one or more soft constraints. To implement these we defined "loss functions" (a term in the mathematics and statistics literature on regression) and place them into the function that the analysis routine is attempting to minimize. The loss function allows us to tolerate some small violation beyond a typical ±50% limit for smoothing annual cost data, if it results in a better regression fit.

The second example of a soft constraint is even more creative. After completing a top-down regression cycling cost estimate for one large unit, the client believed the estimate to be too low, as only past expenditures had been used as input and no accounting was made for large future capital costs that were certain to occur within the next 5 years. Certain boiler-tube sections were in need of replacement at a projected cost of $10 million (±30%). To account for this, a soft constraint on future capital spending was added to the regression model. The added loss function stayed at zero whenever the regression search predicted about $10 million capital spending over the next 5 years. This "future-spending loss function" was designed specifically to grow rapidly for models that differed by more than 30% from the predicted $10 million.

Even with this modification, however, the new cycling cost estimates increased by only about 15% over those from the original model. The reason was that the original model had "anticipated" some of these extraordinary future capital costs because it "noticed" annual past costs had been rapidly accelerating. Therefore, the aging part of the original regression model had done a good job modeling this unit's cost history.

Two measures are used in Step 3, Part 2, to calculate the deviations from perfect fit. The first is a measure of fit error alone. It is symbolized by "COV" because it is similar to, but considered more robust than, the standard statistical measure called "coefficient of variation." Specifically:

$$\mathrm{COV} = \%100 * \mathrm{AAAFE} / \mathrm{AAC} \quad \textbf{(A-1)}$$

where,

AAAFE = Average annual absolute fit error

AAC = Average annual cost

The second measure is a function developed by APTECH that depends on the type and completeness of available data. We call this second measure equivalent COV or "ECOV." It depends on several measures of uncertainty including COV, maximum annual fit error, and the degree any soft constraints are violated by the regression result. The numerical value of ECOV is always expressed as a percentage and we define it such that ECOV is always larger than COV.

Appendix B

The Basic Premise

The underlying premise of the APTECH's approach is that cycling directly causes a significant proportion of annual non-fuel unit costs. For economic modeling, the independent cycling-related variable was taken to be equivalent hours of operation.

As detailed earlier in this section, APTECH first screens total costs to eliminate only those costs that bear no relation to unit loading, like buildings and grounds expenses. Costs remaining after this initial screen are called "candidate" costs. These costs represent the total candidate annual capital, maintenance, and forced outage cost, independent of whether the cost was actually due to cycling or not.

Costs per Start

The final desired result is an estimate of the cycling cost elements combined to determine the effect of an additional equivalent start. APTECH's methodology brings all future forecasted costs to their present value using the client's discount rate, cost escalation factor (or simply inflation rate), and aging effects. The present value of future wear-and-tear cycling costs for the plant equipment is the sum of two components: adding costs and hastening costs. Specifically, the first component, adding costs, is the cost of extra cycling-related maintenance necessary to avoid shortening of the component's life caused by an additional start. The second component, hastening costs, is the cost of "moving up" future maintenance costs in time (i.e., maintenance costs occur sooner) caused by adding one "start". Adding a "start" to a unit's operation will cause the time required before maintenance is needed to decrease. Thus, this second component represents the present value of the acceleration of costs incurred for ordinary maintenance costs due to an additional start, especially overhaul costs and other large non-annual costs.

Determining bounds for the cycling cost estimates

APTECH believes it is important to report the high and low bounds for the top-down cycling cost estimates. These are determined by assessing the uncertainty in the estimates of costs and the inputs to our damage models. Much of this uncertainty assessment is done heuristically, by inputting APTECH's and the client's best, high, and low estimates of key input data into our cost calculations.

Heat Rate at Low Load and during Variable Load Operation

For most steam boiler fossil units and GTs, efficiency as measured by heat rate tests can degrade markedly due to cycling. Poor efficiency comes from low-load operations like load following and shutdowns. The cumulative effect of long-term usage can also increase the heat rate from causes like fouled heat exchangers and worn seals. This trend can often be shown by heat rate test data taken over time. However, heat rate tests do not tell nearly the whole story about the relation between efficiency and operation. The tests measure fuel burn efficiency only under ideal conditions reflecting a full constant load and, typically, a "tuned" and optimized mode of operation. This is why we make use of actual fuel burn data to estimate heat rate costs due to variable- and low-load operation.

Life Shortening Costs of Cycling

Increased cycling may have a significant life-shortening impact on certain units. This cost element can be significant for units that are near their end-of-life, but less important in cases of planned obsolescence. We believe that as long as capital and maintenance expenditures are made to counter cycling effects, this cost element will be small compared to such costs as maintenance and extra fuel. It is important to note that since not all subsystems have the same life expectancy; targeted spending patterns for critical subsystems are required. APTECH looks at both total spending and spending patterns to determine if current and projected critical subsystem spending is sufficient to maintain efficiency and reliability.

Overview of Cycling Costs and General Calculation Method

Calculated cycling costs for typical load cycles of any power plant unit are recorded by Intertek APTECH as the total present-valued future cost of the next "incremental" cycle. These numbers are best estimates based on the assumption that the overall amount of cycling (i.e., EHS per year) continues at no more than 75% of the level of past operations. If the amount of cycling of a given unit increases dramatically, the cost per cycle would also increase due to nonlinear creep-fatigue interaction effects. These cycling cost numbers result from the combination of bottom-up and benchmarking analyses introduced in this section, as well as consideration of the unit operation and maintenance history, results of signature data analysis, and confidential cycling studies done by APTECH for other utilities.

Intertek APTECH has developed an equation that defines the total cost of cycling as the sum of the following distinct elements:

1. Increases in maintenance, operation (excluding fixed costs), and overhaul capital expenditures
2. Cost of heat rate changes due to low load and variable load operation
3. Cost of startup fuel, auxiliary power, chemicals, and extra manpower for startups
4. Cost of long-term heat rate increases (i.e., efficiency loss)
5. Long-term generation capacity cost increases due to unit life shortening

Additionally we capture the cost of replacement power (associated with EFOR), but has not been reported in our study for NREL/WECC.

The first cost element listed above, namely cycling-related maintenance, operation, and overhaul capital costs, is typically the largest cycling cost element for most fossil generating units. This is also true for GT cogeneration and combined cycle units.

Intertek APTECH is bound by client requirements to report power plant cycling costs. As part of this project, Intertek APTECH is reporting the above mentioned elements of costs separately.

Methodology: Determining Cycling Costs

Intertek APTECH performs a comprehensive analysis of the plant operations and maintenance metrics, including a detailed audit of plant costs to determine the cost of cycling. As mentioned earlier the two key tasks in this analysis are the 'top-down' and 'bottom-up' steps. Typically, Intertek APTECH performs the following tasks to determine its final cycling cost values:

- Review and Analysis of Plant Signature Data
- Engineering Assessment and Operations Review
- Survey of Selected Plant Personnel
- Damage Modeling
- Top-Down Cycling Cost Estimation
- Bottom-Up Cycling Cost Estimation
- Evaluate Unit Cycling Costs for Future Operations Scenarios

REVIEW AND ANALYSIS OF PLANT SIGNATURE DATA

Objectives: To determine the relative stresses and damage to key unit components using available signature data (i.e., real-time data points on pressures and temperatures at key points in each unit).

The following will be done for the selected unit for detailed cost of cycling analysis.

First, Intertek APTECH develops a critical equipment list. The critical equipment list will include those components that are currently known to cause major outages and costs from the startup of a power plant and from similar units. Past reliability and outage data obtained from the unit under review will be analyzed. This analysis and review of major component outage cost contributors will assist in defining the critical cycling-related components. We will also make use of our past studies of cycling power plants to assist in identifying the critical equipment and the anticipated damage mechanisms.

For selected critical components, we will use available signature data, specifically, temperature and pressure transient data, to develop relative cycling damage. Examples of the analysis of plant hot start data are shown in Figures B-1 and B-2 and the temperature change rates are shown in Figure B-3. This is done by type of cycling (e.g., cold start, warm start, hot start, load swing to minimum load, unit trip, and normal shutdown). This data is shown in Tables B-2 and

B-3 and an example of the damage model input data by component is shown in Figures B-4 and B-5. This analysis will be used as input to the damage modeling and the overall statistical/engineering analysis.

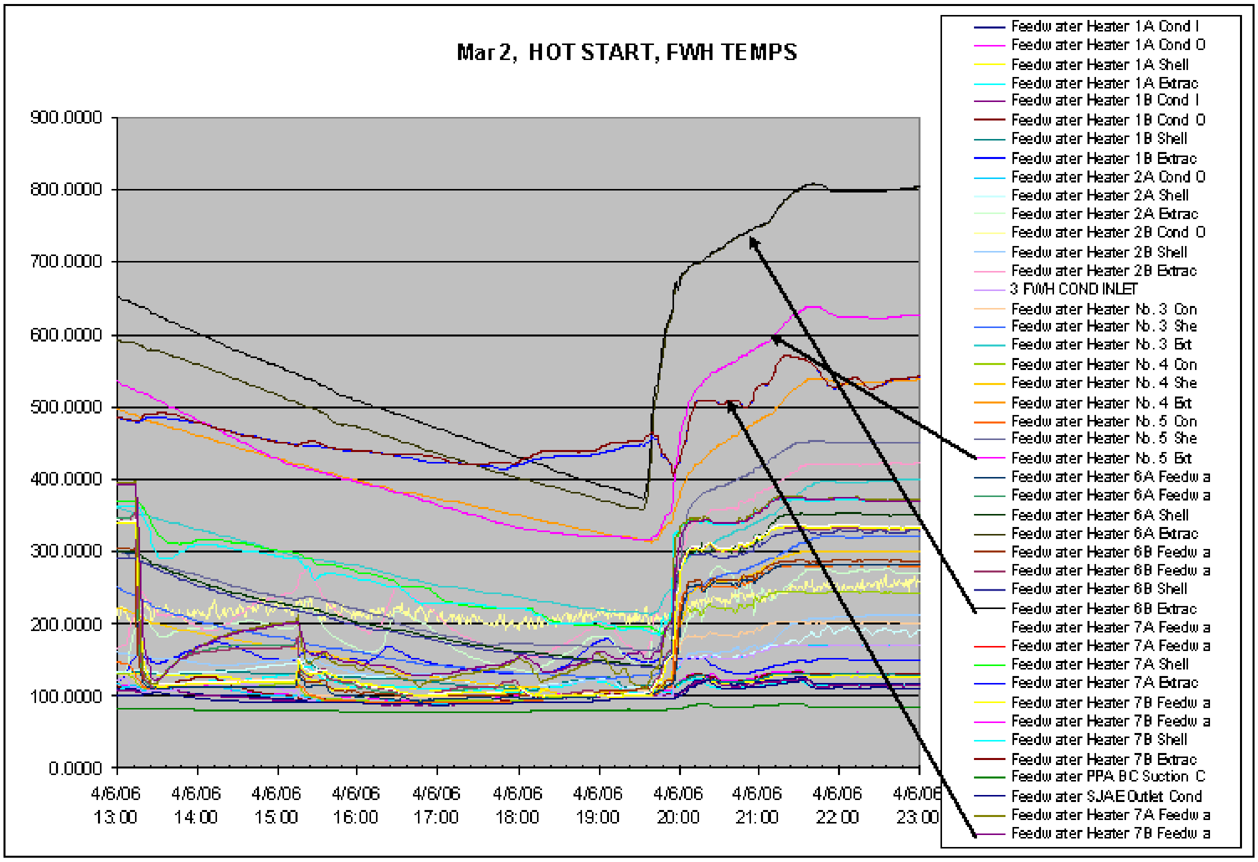

Figure B-1: Example of Plant Hot Start Data.

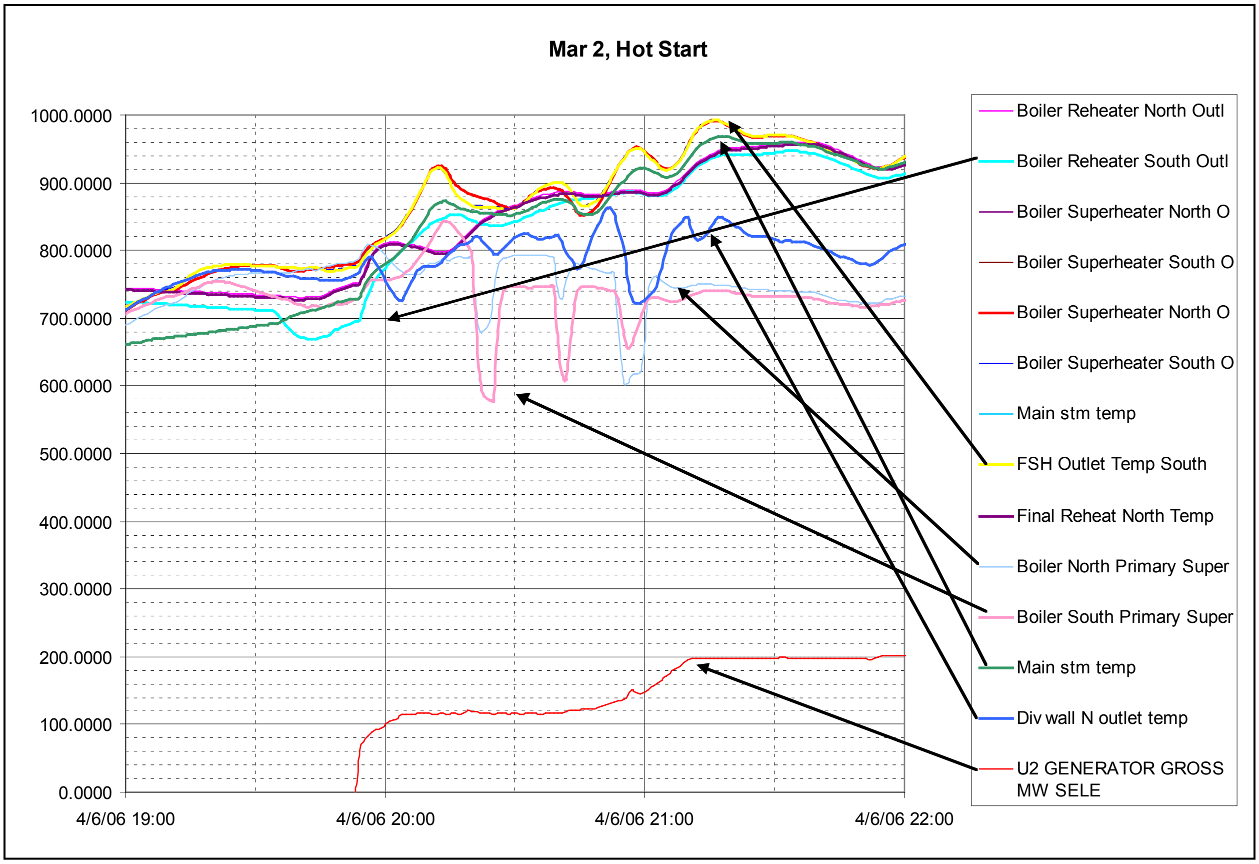

Figure B-2: Another example of Plant Hot Start Data.

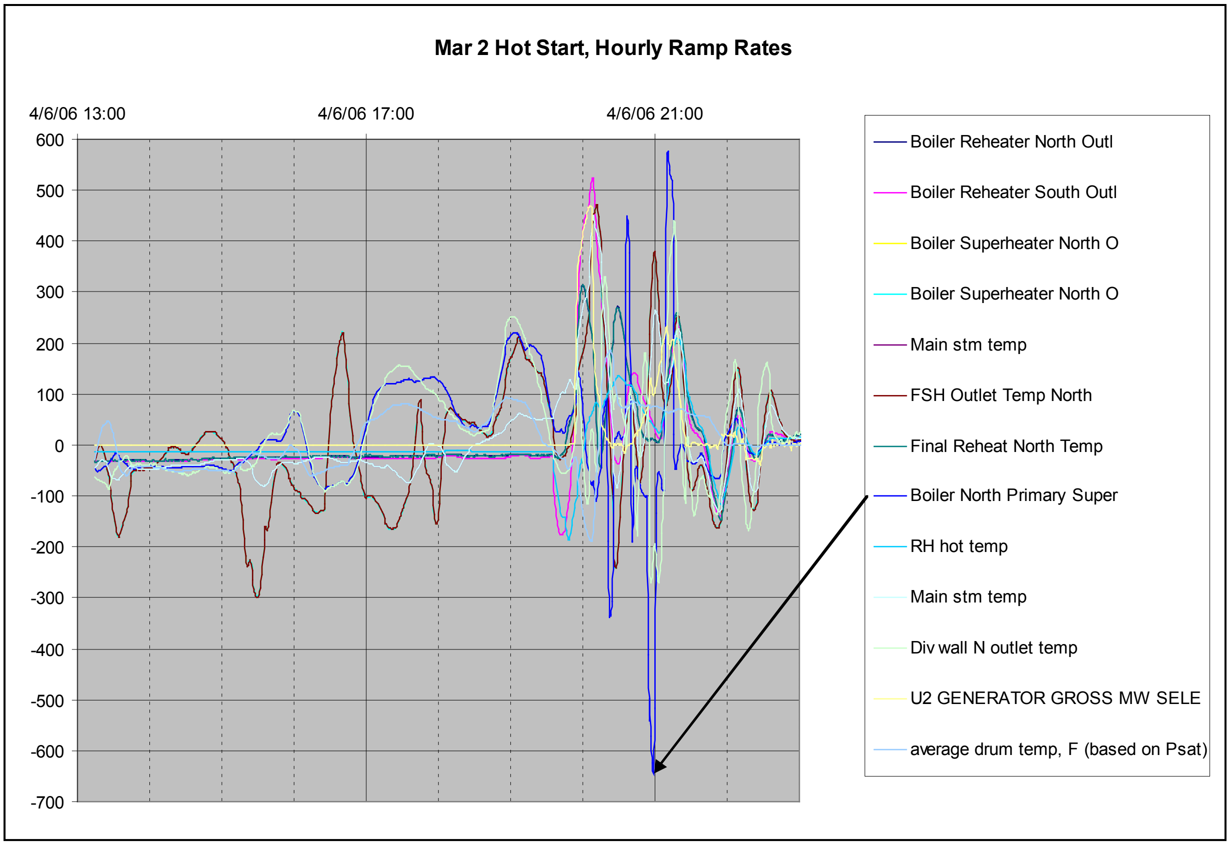

Figure B-3: Example of Hourly Temperature Changes Corresponding to Figure B-1

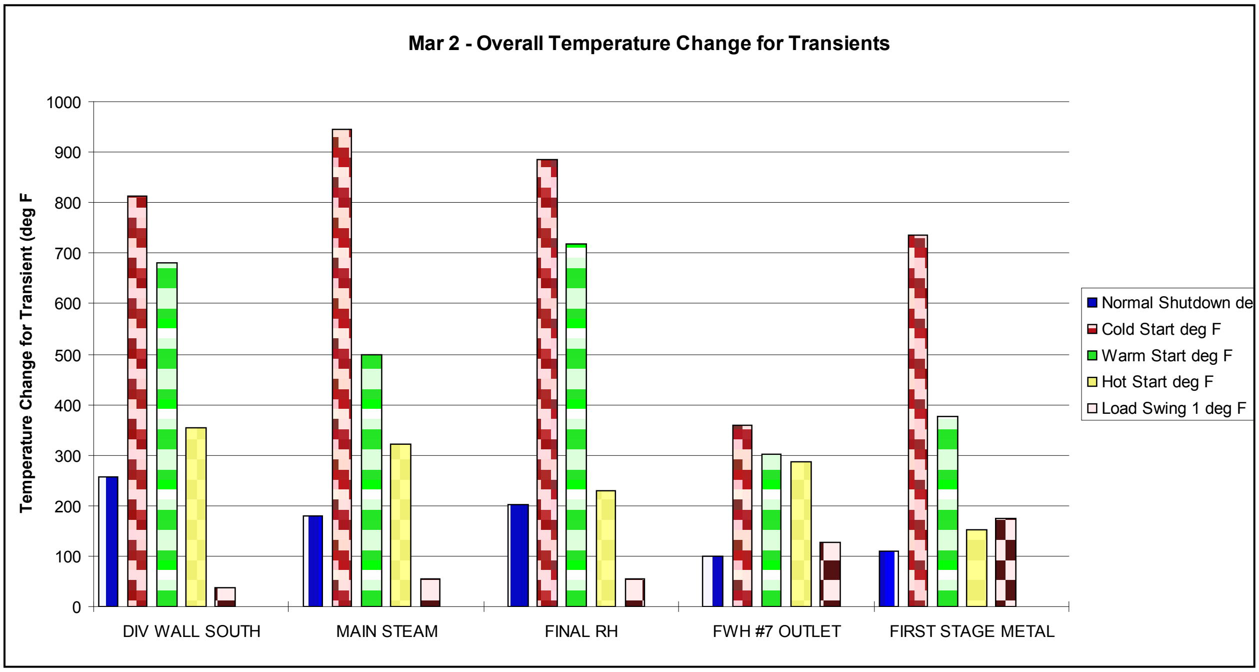

Figure B-4: Example of maximum temperature change for components

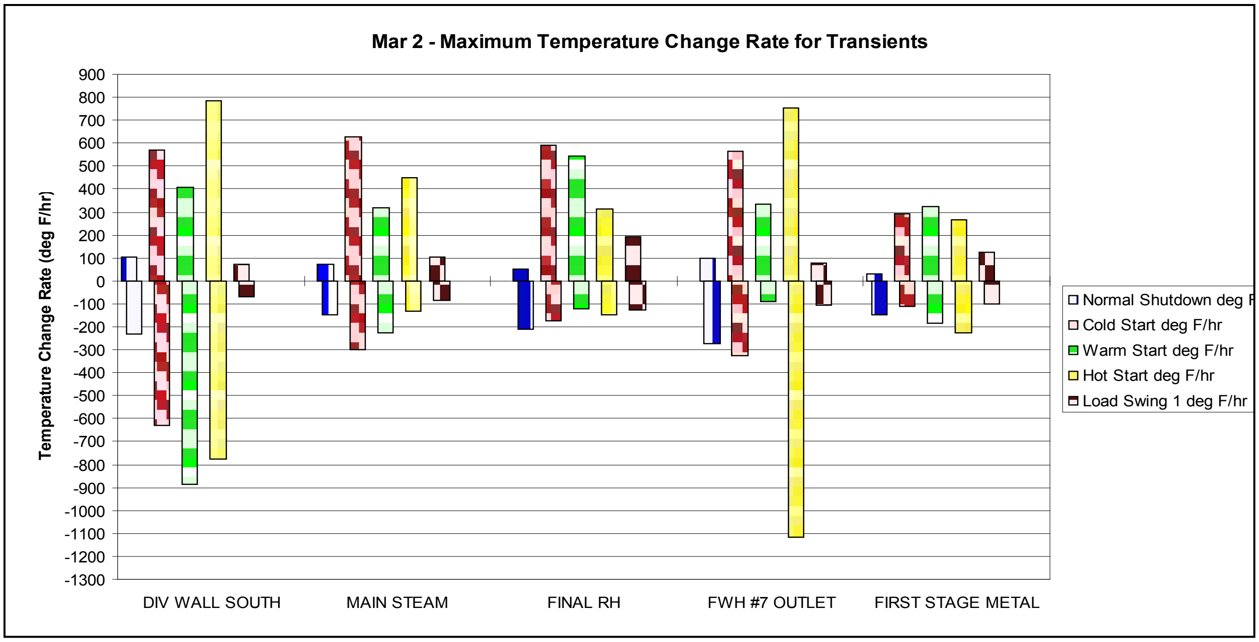

Figure B-5: Example of overall temperature change for components

ENGINEERING ASSESSMENT AND OPERATIONS REVIEW

Objectives: To assess cycling damage based on equipment outage and inspection data that is independent from top-down analysis. To provide insights on which component and operation practices contribute most to cycling costs.

Intertek APTECH investigates and assesses the major causes of failures at the selected units, and determines whether they are wholly or partially caused by cycling or low load operation. Specific activities in this task will include:

1. Design review of current unit design including equipment lists, piping and instrument diagrams, and startup-related equipment limitations.
2. Review major failure modes of critical boiler, turbine, generator, fans, pumps, feedwater heater, and condenser equipment that we know are cycling-related.
3. Review all work orders to include 95% of all the work orders for the last 7 years and assign a percent cycling to these work orders and total by major component and system.
4. Review the history of the cycling-related failures with other similar units “in the industry” we have studied.

5. Review of plant operational procedures from the minute-by-minute analysis of the plant signature data, written procedures, and evaluate options for improved operational and maintenance procedures for cycling operations.
6. Provide a preliminary list of improvement options soon after the completion of the field trip.
7. Provide a list of concerns and recommendations.
8. Review unit condition assessment and remaining useful life data.

SURVEY OF SELECTED PLANT PERSONNEL

Objectives: To provide a check on cost of cycling estimates using a survey of the selected power plant unit experts in the field and obtain plant personnel input on cycling-related problems.

Intertek APTECH has found that a good way of checking the cost of cycling estimates made by regression analysis is to do a qualitative survey of experts, including primarily plant personnel, who are very familiar with the operating histories and problems at the plants. An interview process Intertek APTECH has developed for other cost of cycling studies will be adapted and customized for use in this project. The interviews are designed to utilize the knowledge of at least six key selected plant personnel to discuss past cycling costs and to foresee what future effects different unit operation modes (e.g., types and intensities of cycling) will have on their units [example for a coal unit]. Ideally, the six people should consist of the following:

Plant Management
Operations
General Maintenance
Turbine Maintenance Expert
Boiler Maintenance Expert
Plant Chemistry Expert

DAMAGE MODELING

Objectives: To adapt Intertek APTECH's unit-wide damage model to develop unit damage histories for the selected units.

Intertek APTECH adapts its existing damage models for assessing the damage accumulation and reliability impact on the critical equipment. The damage model starts with a previouslydeveloped Intertek APTECH power plant damage model, called the “Loads Model,” which is based on hourly MW generation. We request all hourly data for the unit to be studied. We have proven methods to extrapolate loads model results backward in time using annual generation, service hour, and start data.

The damage model calculates total unit baseload (creep) and cyclic (fatigue) damage. Therefore, the model has the ability to apportion and discriminate between baseload and cyclic damage. It also can incorporate the effects of poor fuel quality (e.g., increased erosion), which is not expected to have an impact on costs for oil and gas-fired units. The model calculates damage under cyclic and steady loads of any magnitude that interact with each other in a nonlinear fashion. It accounts for any combination of load peaks and valleys, times at load, ramp rates (load changes with time), and differences among hot, warm, and cold starts. Thus, it handles all sorts of cycling in combination with normal, derated, or uprated steady loads.

TOP-DOWN CYCLING COST ESTIMATION

Objectives: To develop best estimates and upper and lower bounds of the largest cycling cost components, which are capital and maintenance costs, and outage costs.

We use Intertek APTECH’s proprietary regression techniques, along with the output of previous tasks (e.g., annual damage accumulation histories), to develop cycling cost estimates for what is typically the largest cycling cost components — namely, increased capital and maintenance spending, increased outages leading to more expensive replacement power, and increased heat rates due to low and variable load operation. This analysis will result in best estimates, and upper and lower bounds for these cost components, and with plots of the regression fit model against historical records of actual cost/outage data.

BOTTOM-UP CYCLING COST ESTIMATION

Objective: To allocate the total unit cycling costs by primary unit systems and components (e.g., boiler, turbine, generator, piping, etc.).

Intertek APTECH collects, and reviews detailed accounting data on specific capital and non-routine maintenance expenditures. This may include the accounting of major work orders that relate to projects to repair or mitigate adverse cycling impacts. We estimate the percent of each expenditure that is caused by cycling. We use this accounting to estimate the breakdown of unit-wide cycling costs into major systems and components, as shown in Figure B-6.

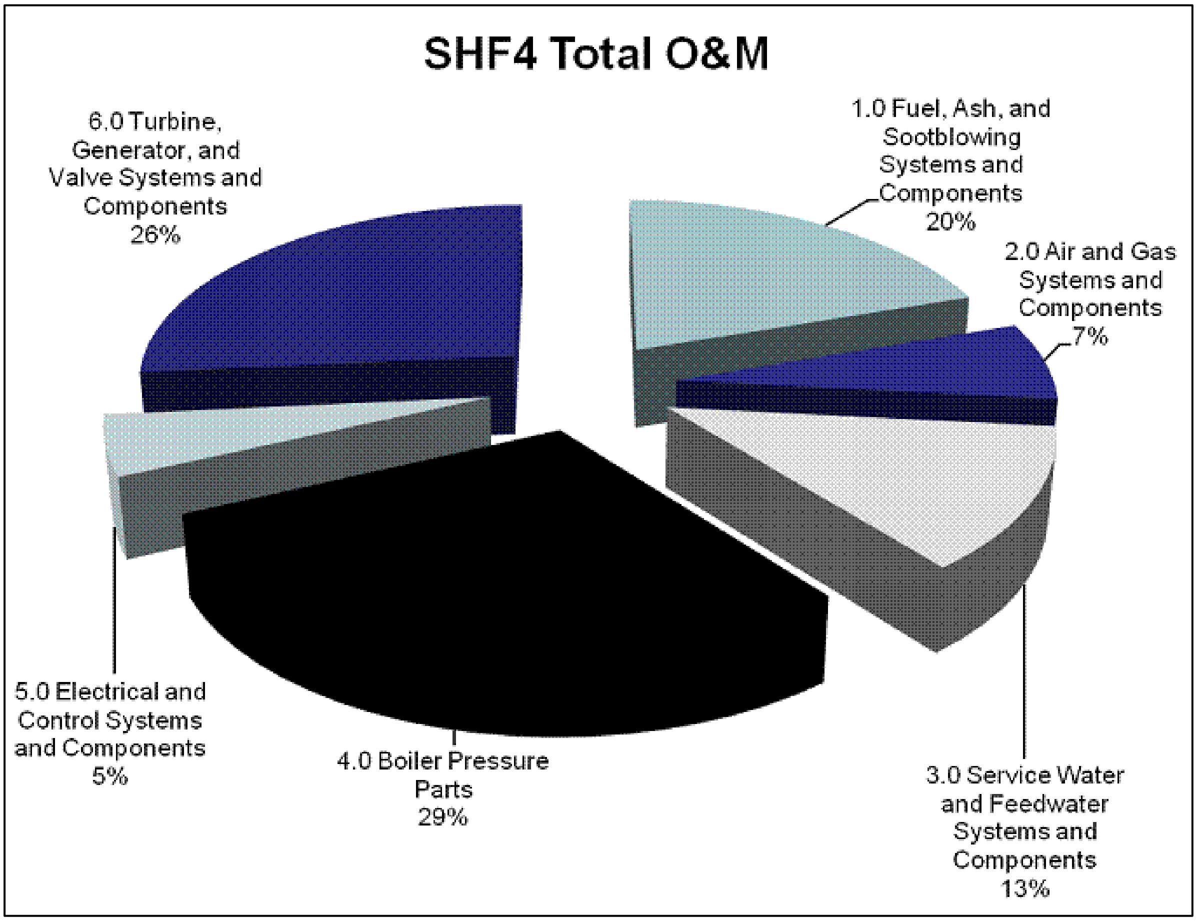

Figure B-6: Work Orders Broken Out by Component and System for Cycling Costs

We also use our industry databases, both NERC-GADS data and data from similar units Intertek APTECH has already studied in detail, to broaden and bolster the bottom-up accounting of outages and costs for the selected unit. We collect and summarize subsystem level cost data from our previous and current cycling studies and collect industry wide outage, maintenance, and other data collected by NERC-GADS for similar units. We use the GADS "pedigree" file and detailed descriptions of plant equipment of the unit under review to determine both similarities and differences from the subject unit.

EVALUATE UNIT CYCLING COSTS FOR FUTURE OPERATIONS SCENARIOS

Objective: To project the reliability and capital/maintenance cost impacts of future operations scenarios.

Intertek APTECH develops a set of graphs that show how the reliability and capital/maintenance costs of the selected unit will vary in the future under the different operation scenarios identified by the subject unit. An example of such a graph is shown in Figure B-7. It resulted from an actual Cycling Model for large units. We computed cycling damage for the four plotted future scenarios and used these to model past and future costs.

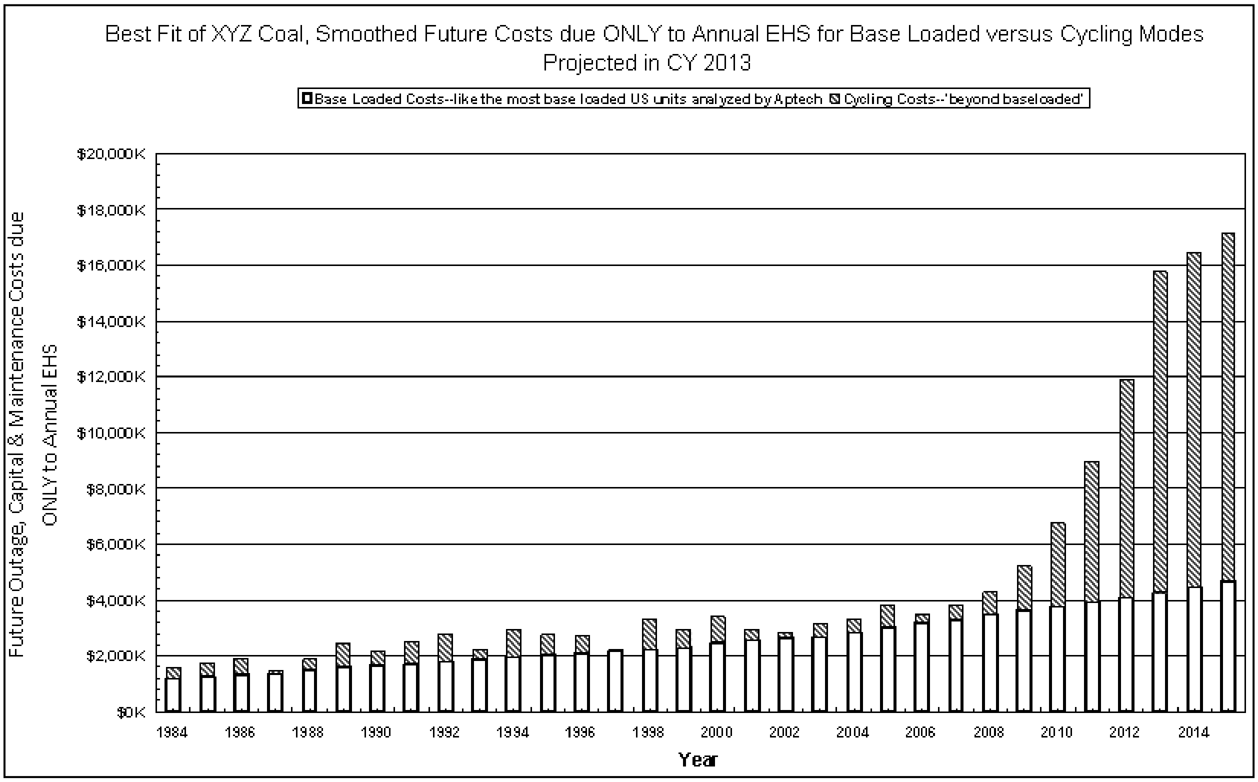

Figure B-7: Best Estimate of XYZ Cycling Maintenance and Capital Costs.

Note: Based on Large Power Plant No Cycling Countermeasures and Increases Due to Increased Load Cycling Only

Results from the Cost of Cycling Study

The total cost of cycling is broken down into nine different elements (E1 through E9). The composite of these nine cost elements (E1 through E9) are totaled to determine the cost of each type of cycling (hot starts, warm starts, cold starts, and significant load follows). For example, for a combined cycle unit, the hot, warm, and cold starts are defined by the metal temperature of the heat recovery steam generator (HRSG), gas turbine, and steam turbine when the start is initiated. A significant load follow is defined as a load change (typically 20% of maximum continuous rating or more) that results in a substantial amount of wear-and-tear damage as defined by Intertek APTECH's Loads Model (very small MW load changes are not considered). Table B-1 shown below provides an example break down of cycling costs for a steam turbine.

Table B-1: Cost Elements for Hot Start/Shutdown cycles at Steam Generator

1 Steam Turbine Hot Starts for 2002	**Baseline Data ($/ cycle) [1]**			**Baseline Data ($/MW-hr) [2]**		
	Best Estimate	*Low*	*High*	*Best Estimate*	*Low*	*High*
E1: Cost of operation – Includes operator non-fixed labor, general engineering and management cost (including planning and dispatch); excludes fixed labor	[redacted]	$ 1,600	[redacted]	[redacted]	$0.00094	[redacted]
E2: Cost of maintenance - includes maintenance and overhaul maintenance expenditures for boiler, turbine, generator, air quality control systems and balance of plant key components	[redacted]	$ 5,000	[redacted]	[redacted]	$ 0.0029	[redacted]
E3: Cost of capital maintenance - includes overhaul capital maintenance expenditures for boiler, turbine, generator, air quality control systems and balance of plant key components	[redacted]	$ 3,000	[redacted]	[redacted]	$ 0.0018	[redacted]
E4: Cost of forced outage and derate effects, including forced outage time, replacement energy, and capacity.	[redacted]	$ 18,000	[redacted]	[redacted]	$ 0.0106	[redacted]
E5: Cost of long-term heat rate change due to cycling wear and tear [3]	[redacted]	$ -	[redacted]	[redacted]	$ -	[redacted]
E6: Cost of heat rate change due to low load and variable load operation (process related)	[redacted]	$ -	[redacted]	[redacted]	$ -	[redacted]
E7: Cost of startup auxiliary power	[redacted]	$ -	[redacted]	[redacted]		[redacted]
E8: Cost of startup fuel	[redacted]	$ 40,000	[redacted]	[redacted]	$ 0.0235	[redacted]
E9: Cost of startup (Operations – chemicals, water, additive, etc.)	[redacted]	$ -	[redacted]	[redacted]		[redacted]
Total incremental cost of cycling (sum of E1 through E9)	[redacted]	$ 71,000	[redacted]	[redacted]	$ 0.0416	[redacted]

[1] Cost data refer to top down results for CY 2002, including fatigue-creep interaction effects, does not include adjustment for signature data analyses

[2] based on all analyzed starts and net MWh during CY 2002

[3] Over the last 5 years, maintenance and other activities have prevented discernible heat rate increase solely due to cycling

Note: Total best estimate = sum of individual ones; but this is not true of high and low totals

Top-Down Statistical Regression Method

Intertek APTECH has found that reasonably accurate estimates of total unit cycling costs can be derived using a regression analysis of historical unit damage with historical cost and equivalent forced outages, along with component-specific data that indicate the breakdown of cycling costs among various cycle types (e.g., hot, warm, and cold starts, load follows). This section briefly describes the various aspects of INTERTEK APTECH's top-down cycling cost methodology.

DAMAGE MODELING

Model Description

One way to model cycling-related damage for any component in a fossil power plant is by direct damage modeling. This type of modeling could combine physical measurements, taken while the component is on-line (e.g., temperature, strain, and heat flux), with state-of-the-art stress analyses and damage algorithms to produce a detailed estimate of the amount of damage suffered by the particular component.

However, this type of analysis would require substantial time, data collection, and funding. To limit the cost of analyzing all critical components in the unit, a general damage resources model, developed by Intertek APTECH, is employed. This model is intended to provide information on the cycling-related damage for the entire unit. It is founded on physical models and uses plant temperature and other signature data to provide cross validation with MW changes, but requires only hourly MW "loads" data to estimate damage. (Note: In this section of the report, the term "loads" refers to the MW output of the unit, not forces, moments, or temperatures.) Relying solely on hourly MW unit load data is an inherent advantage due to the fact that these types of data are more readily available. In addition, hourly MW data provide an accurate history of past unit operations.

The general damage model is based on an Intertek APTECH proprietary computer code that has been tested and employed on over 300 previous fossil plant cycling studies. The model is very flexible, adaptable, and general. It accounts for creep damage, fatigue damage, erosion, corrosion, and all other types of damage that are known to occur in fossil power plants.

The damage model has been calibrated several different ways. The two most important methods are:

Predicting later cycling costs from earlier ones. Benchmarking studies have been performed which ask the top-down model to predict later costs using only the early portion of cost data from the units' database. Comparison of the predicted costs with the actual past costs has helped to calibrate and improve the cycling damage and cost models. The model has been calibrated to accurately reflect past costs and should accurately predict future costs.

Comparing cycling cost estimates with "bottom-up" results. A bottom-up approach to calculating cycling costs requires a very detailed and comprehensive accounting. This accounting would include a diary of all past equipment failures and all maintenance activities. From this data and an understanding of the active damage mechanisms for each piece of equipment and their root causes, the costs of cycling as a function of cycling events can be developed for each piece of equipment. The cycling-related cost divided by the number of cycles (as defined later) results in a cost per cycle. This type of analysis has been performed for many different unit types at different power companies. Reasonably close agreement between the bottom-up and top-down estimates serves to confirm the models.

Damage Model Results and Operational Histories

The Loads Model is an MW-output-based damage model that counts all fatigue cycles, creep, and fatigue-creep interaction. The damage accumulation rates computed by Intertek APTECH's Loads Model are related to the fatigue damage emanating from an idealized gentle load transient known as an equivalent hot start (EHS). The model takes hourly MW data as input to calculate the EHS. Table B-2 gives the resulting quarterly damage estimates in equivalent hot starts (EHS) per quarter.

Using the hourly MW data the damage model is used to determine the relative damage of "typical" hot, warm, and cold start cycles of Example Units 5, 6, 7, 8, and 9 in relation to our normalized damage parameter, EHS. These are shown in Table B-3, along with the typical MW ramp rates used for all five units. The relative damage numbers for hot, warm, and cold start cycles are among the highest we've seen for coal-fired steam units. Table B-4 shows the computed relative damage rates of load follow cycles.

Table B-2: Loads Model Quarterly Data for Example Unit

Quarter	EHSs	op.	EHSs per	non	hot	ws	cs	lf	orat	pd	md	starts
		Days	op. day	op days								
1Q82	48.4	81.8	.592	7.2	3	4	0	26	26.96	90	1	7
2Q82	29.4	77.2	.489	12.8	2	4	1	31	8.21	91	1	7
3Q82	24.7	71.2	.445	13.8	0	2	3	32	5.67	92	7	5
4Q82	30	44.2	.482	44.8	1	1	3	16	11.29	92	3	5
1Q83	30.7	33.9	.529	56.1	1	0	5	5	8.08	90	0	6
2Q83	30.8	44.2	.55	44.8	2	1	4	29	11.25	91	2	7
3Q83	36.6	82.5	.53	9.5	2	3	1	11	29.46	92	0	6
4Q83	26.3	86.5	.493	5.5	0	0	1	2	27.46	92	0	1
1Q84	43.9	59.8	.517	31.2	4	5	3	21	9.38	91	0	12
2Q84	24.1	17.8	.542	73.2	2	0	2	3	4.21	91	0	4
3Q84	42.3	72.4	.547	19.6	1	2	4	33	13.5	92	0	7
4Q84	28.1	75.6	.529	15.4	0	2	1	6	22.12	92	1	3
1Q85	40	82.1	.525	7.9	2	4	1	12	21.25	90	0	7
2Q85	36.6	87.1	.515	3.9	2	3	0	5	31.88	91	0	5
3Q85	24.5	84.2	.496	5.8	1	2	1	20	3.75	92	2	4
4Q85	27.6	76	.487	14	0	1	2	10	12.29	92	2	3
1Q86	27.2	86.7	.474	3.3	1	0	1	5	27.04	90	0	2
2Q86	19.1	78.6	.459	12.4	0	1	0	9	14.5	91	0	1
3Q86	8.5	5.4	.464	84.6	0	1	1	1	2.83	92	2	2
4Q86	34.1	66.4	.467	18.6	3	2	0	6	40.88	92	7	5
1Q87	46.3	69.3	.477	17.7	2	1	4	9	37.25	90	3	7
2Q87	53	75.8	.488	12.2	5	6	1	17	23.62	91	3	12
4Q87	38.7	83.8	.487	8.2	1	2	1	20	31.83	92	0	4
1Q88	29.9	81.9	.481	8.1	0	1	1	17	47.12	91	1	2
2Q88	36.9	86.2	.478	4.8	1	3	0	21	42.12	91	0	4
3Q88	28.9	81.5	.473	10.5	1	0	1	27	39.29	92	0	2
4Q88	44.6	74.6	.477	15.4	2	3	3	10	44.75	92	2	8
1Q89	27.2	49.2	.479	40.8	0	0	3	4	25.88	90	0	3
2Q89	27	33.6	.485	57.4	2	4	3	23	8.29	91	0	9
3Q89	31.5	57	.487	32	2	1	3	36	11.62	92	3	6
4Q89	60	68.9	.499	20.1	4	4	3	32	25.58	92	3	11
1Q90	56.1	71.8	.508	17.2	7	1	3	65	15	90	1	11
2Q90	28	81.1	.502	2.9	1	2	0	21	17.33	91	7	3
3Q90	33.8	85.5	.499	6.5	0	2	1	8	44.75	92	0	3
4Q90	24	88.5	.49	2.5	0	0	0	10	25.96	92	1	0
1Q91	21.9	56.4	.488	33.6	1	1	2	30	0	90	0	4
2Q91	27.8	79.5	.484	9.5	2	1	1	39	0	91	2	4
3Q91	20.6	58.9	.481	31.1	0	2	1	26	0	92	2	3
4Q91	31.5	61.5	.482	30.5	1	2	1	36	1.46	92	0	4
1Q92	32.1	77.5	.48	13.5	0	1	2	38	3.33	91	0	3
2Q92	26.3	83.3	.475	6.7	1	2	1	30	1.25	91	1	4
3Q92	28.9	81.5	.472	10.5	0	3	1	50	.12	92	0	4
4Q92	26.5	83.9	.467	8.1	1	0	1	27	.79	92	0	2
1Q93	31.5	74.3	.466	15.7	0	2	3	32	.25	90	0	5
2Q93	37.5	75.8	.467	15.2	3	3	1	20	.42	91	0	7
3Q93	22.1	89.8	.461	2.2	0	1	0	23	.25	92	0	1
4Q93	11.2	42.9	.458	49.1	0	0	0	1	.17	92	0	0
1Q94	39.1	64	.461	26	4	3	2	22	.88	90	0	9
2Q94	32.8	83.1	.46	7.9	2	4	0	40	.08	91	0	6
3Q94	23.9	89.5	.455	2.5	0	2	0	38	.21	92	0	2
4Q94	25.4	87.2	.451	4.8	1	3	0	9	.08	92	0	4

Table B-2, Continued

Quarter	EHSs	op.	EHSs per	non	hot	ws	cs	lf	orat	pd	md	starts
				Days	op.	day	op	days				
1Q95	26.3	72.1	.449	17.9	0	2	2	1	.33	90	0	4
2Q95	22.1	83.8	.445	7.2	1	1	1	3	.29	91	0	3
3Q95	21.4	89.8	.44	2.2	0	2	0	4	.46	92	0	2
4Q95	30.6	80.2	.439	11.8	0	2	2	6	3.58	92	0	4
1Q96	18.9	66.9	.437	24.1	0	2	0	7	.71	91	0	2
2Q96	26.3	50.3	.438	40.7	1	3	1	23	.12	91	0	5
3Q96	29	80.6	.436	11.4	0	5	0	40	.08	92	0	5
4Q96	34.2	80.8	.436	11.2	1	2	1	25	21.62	92	0	4
1Q97	26	80.9	.434	9.1	1	1	2	39	.62	90	0	4
2Q97	30.9	77	.433	14	0	4	1	29	.04	91	0	5
3Q97	30.6	83.1	.432	7.9	0	4	0	21	.08	92	1	4
4Q97	23.8	87.1	.429	4.9	0	3	0	28	.38	92	0	3
1Q98	22.1	83.3	.426	4.7	0	0	1	39	.62	90	2	1
2Q98	28.4	90	.424	1	0	1	0	50	2.08	91	0	1
3Q98	31.2	82.1	.423	9.9	2	3	1	15	0	92	0	6
4Q98	20.8	82.1	.42	9.9	0	0	1	6	.92	92	0	1
1Q99	26	62.5	.42	27.5	0	0	3	9	.46	90	0	3
2Q99	23	81.5	.418	9.5	0	2	1	7	1.17	91	0	3
3Q99	23.7	88.7	.416	2.3	0	2	0	5	.75	92	1	2
4Q99	29	83.7	.415	8.3	1	4	0	4	0	92	0	5
1Q00	19.2	83.7	.412	6.3	0	1	1	7	.17	91	1	2
2Q00	19.4	26.9	.413	64.1	0	0	4	4	.42	91	0	4
3Q00	31	82.9	.413	9.1	2	0	1	4	1	92	0	3
4Q00	24.6	86.2	.411	4.8	0	2	1	2	.54	92	1	3
1Q01	25.8	77.5	.41	11.5	1	3	1	2	.21	90	1	5
2Q01	24.8	80	.408	11	0	3	1	9	.29	91	0	4
3Q01	20.1	86.7	.405	5.3	0	2	0	5	.21	92	0	2
4Q01	17.8	67.7	.404	24.3	0	2	1	4	.04	92	0	3
1Q02	26.2	80	.403	10	0	3	2	2	1.83	90	0	5
2Q02	23.4	77.5	.401	13.5	1	1	2	5	0	91	0	4
3Q02	31.6	85.3	.401	6.7	1	4	0	7	.92	92	0	5
4Q02	19.6	84.1	.399	7.9	0	0	2	5	0	92	0	2
1Q03	21.1	85.6	.397	4.4	0	1	1	3	0	90	0	2
2Q03	25.7	77.6	.396	13.4	1	1	1	0	.04	91	0	3
3Q03	18.8	83	.394	9	0	1	1	3	0	92	0	2
4Q03	25.9	76.3	.393	15.7	0	2	1	4	0	92	0	3
1Q04	21.8	40	.394	51	0	0	4	3	0	91	0	4
2Q04	24.8	85.5	.393	5.5	0	3	0	3	.58	91	0	3
3Q04	29.3	62	.393	30	0	1	4	6	.25	92	0	5
4Q04	18.7	63.4	.392	28.6	0	1	2	3	1.83	92	0	3
1Q05	14	47.6	.392	42.4	0	1	1	1	1.83	90	0	2
2Q05	23.8	68	.391	23	0	1	3	35	1.92	91	0	4
3Q05	27	83.9	.39	8.1	0	2	1	46	0	92	0	3
4Q05	16.1	85.5	.388	6.5	0	0	1	17	.17	92	0	1
1Q06	21.8	87.4	.386	2.6	0	1	0	13	.04	90	0	1
2Q06	18.6	86.7	.384	4.3	0	0	1	27	.04	91	0	1
3Q06	17.3	89.9	.382	2.1	0	1	0	32	0	92	0	1
4Q06	15.9	92	.379	0	0	0	0	11	.04	92	0	0
1Q07	23.1	73	.379	17	2	2	1	6	0	90	0	5

Statistical Regression on Damage Costs

Intertek APTECH has developed an equation that defines the total cost-of-cycling as the sum of the following five distinct elements:

- Increases in maintenance, operation (excluding fixed costs), and overhaul capital expenditures
- Increased time-averaged replacement energy and capacity cost due to increased equivalent forced outage rates (EFOR)
- Increase in the cost of heat rate changes due to low load and variable load operation
- Increase in the cost of startup fuel, auxiliary power, chemicals, and extra manpower for startups
- Cost of long-term heat rate increases (i.e., efficiency loss)

Intertek APTECH's top-down statistical method uses a mathematical regression technique to calculate the present value wear-and-tear cost of the next additional cycle. The basis for the top-down regression analysis is made by examining calendar time trends in maintenance (including capital) and EFOR-related costs, and obtaining an independent quantitative relation between cycling and these time-varying costs for the plant.

Table B-3: Damage statistics for typical starts

	Hot Starts				Warm Starts				Cold Starts			
Unit	Number in Database	Range (%GDC)	Ramp Rate (%/hr.)	Damage (%EHS)	Number in Database	Range (%GDC)	Ramp Rate (%/hr.)	Damage (%EHS)	Number in Database	Range (%GDC)	Ramp Rate (%/hr.)	Damage (%EHS)
5	82	105	53	216	152	102	52	311	110	96	48	450
6	88	103	52	206	182	101	51	292	133	98	48	469
7	101	107	50	200	170	100	54	311	111	94	50	467
8	95	107	48	197	191	102	52	309	109	96	50	478
9	72	103	53	211	157	102	51	299	118	96	50	480

Table B-4: Load Following Damage

Unit	Number in Database	Eff. Avg. Min. Load	Eff. Avg. Drop (% GDC)	Eff. Avg. Rate (%GDC/hr)	Damage (%EHS)
ki5	2075	126	29	33	5
ki6	1735	127	29	34	5
ki7	2382	128	28	35	5
ki8	2118	126	29	34	5
ki9	2164	127	28	34	5

Note: AVERAGE DAMAGE FROM LOAD-FOLLOWING DROPS OF MORE THAN 15% GROSS CAPACITY. BASED ON HOURLY GROSS MW DATA