Flexible Operations and Heat Rate

Technical Brief — *Heat Rate Improvement Program of Generation Sector*

Most coal-fired power boilers were originally designed for base load operation. Their optimum heat rate occurs at or near full load. Today, however, the market conditions dictate that many of these units operate in a continuous transient mode, following the generation demand. As such, they often experience large load changes throughout the day and may be requested to cycle off and return to service shortly thereafter. This new mode of flexible operation presents multiple problems for the aging fossil fleet, including a poorer plant heat rate and increased wear and tear requiring larger expenditures for maintenance and potentially increasing the frequency of force outages and derates.

These actions increase costs, and reduce time online and total generation. The unit's incremental cost increases, which pushes the unit further down on the dispatch order. That increases the amount of load following and number of on-off cycles, which decreases the average operating load level and further increases the wear and tear. The operating costs continue to rise as this "death spiral" continues until the unit reaches the point of being uneconomical to operate.

This paper will explore some of the reasons behind the decreased efficiency, describe actions to mitigate those problems, and identify the technology gaps to further improve part load heat rate. This discussion is meant to both inform and define further potential research to ultimately improve the economic health and viability of thermal power plants. A bibliography is included at the end of this paper providing a partial listing of reports related to EPRI research on this topic.

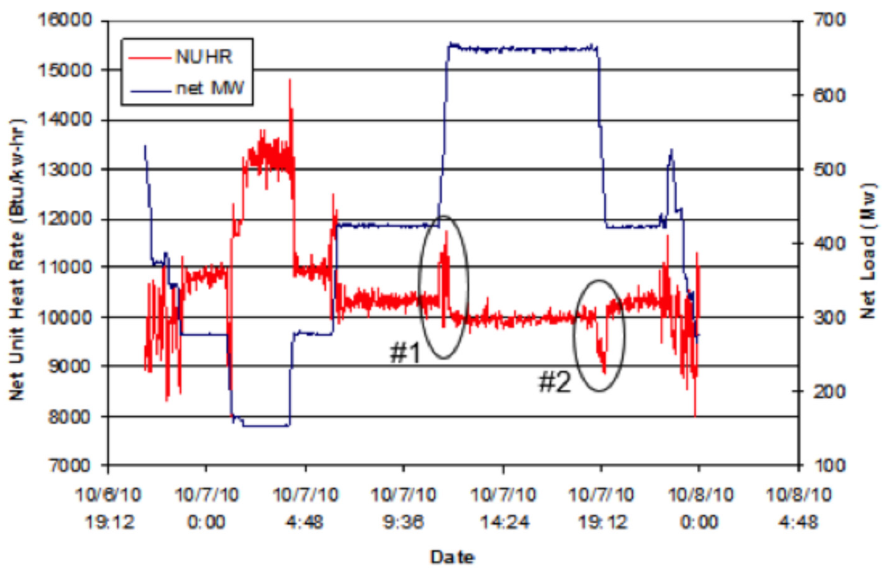

Figure 1 – Heat Rate Effects of Discrete Unit Load Changes
Notes:
#1 Load Increase – Temporary heat rate jump, but lower in long-term
#2 Load Decrease – Temporary heat rate drop, but higher in long-term

EPRI has conducted several projects to quantify the heat rate increase and identify its cause(s) during part load operation and load following. A series of tests were conducted at operating power plants to provide more detailed information.

Figure 1 shows the results of a day of load following but all taken in discrete steps. The heat rate is expectedly greater (poorer) during period of low load and lower (better) during period of high load. But a few heat rate spikes were observed during this test series. Those spikes occurred during the short time periods when load ramped up or down. The upward heat rate spike corresponds to time periods of increasing loads when additional fuel had to be added to the boiler to generate more steam. The downward spike corresponds to time periods of decreasing loads when the unit was "thermally coasting" on residual energy until it attained its lower level of steam generation.

After further investigation, the thermal lag and associated inefficiency associated with increasing load was found to be caused by several concurrent events. During time periods of increasing load:

- Main steam temperature often sagged below the design or expected levels
- Superheat spray flow rate increased
- Reheat spray flow rate increased
- Stack (exhaust) gas temperature increased
- Oxygen levels (excess O_2) increased

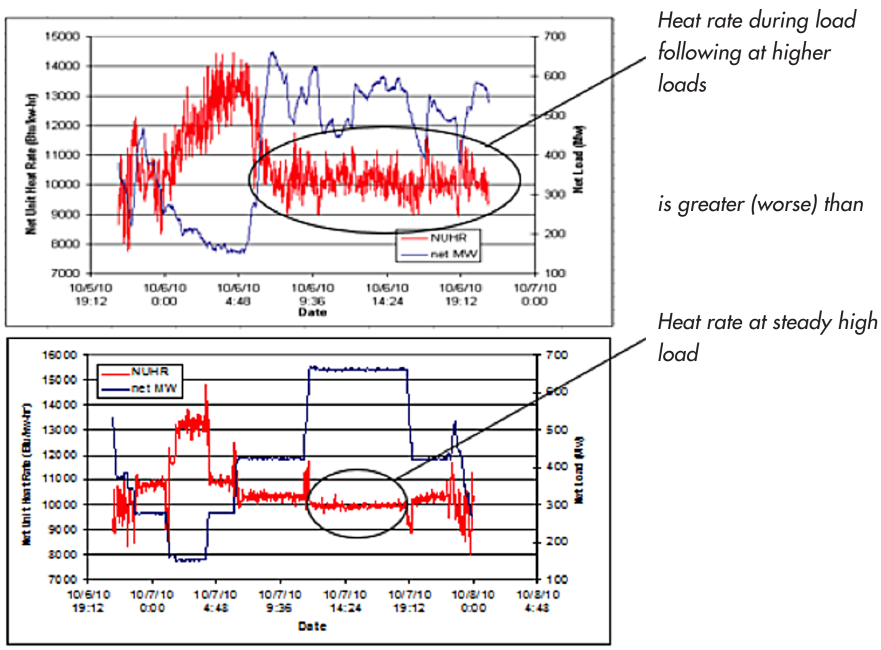

Figure 2 – Heat Rate Effects Comparison

The temporary spike can be attributed to the inefficiencies brought by these off-design conditions. Depending upon the combustion control system and based on these parameters, one would expect the level of unburned carbon to also have temporarily increased.

The upper trend plot of Figure 2 depicts a period of time during which the unit load was varied upon demand of the system dispatcher. It is compared to the trends plot containing the results of the discrete load changes. The lower load heat rate is higher (poorer) in both cases, and the higher load heat rate is lower (better) in both cases. But as depicted in the comparison of the two trend plots, the higher load heat rate is better when the unit is at steady state. The results are similar to fuel efficiency obtained on the highway when using cruise control compared to manually adjusting your vehicle's speed.

Tests conducted tests by a power company yielded similar results. While those tests were not part of an EPRI project, their results were reported at several EPRI events. The power company staff conducted heat rate tests at several different loads, while the unit was at steady state. These were followed by tests during which the dispatch center varied load based on demand. The staff identified test periods during which the average load/generation level was close to that observed during a steady state test run. They observed about a 2% increase in heat rate during the load following tests compared to those conducted at steady state. That difference is similar to that observed in the highlighted areas on Figure 2.

Potential Resolutions

Options are available to attempt to stabilize the increasing costs and pull out of the previously mentioned death spiral. Those require a commitment of plant staff and leadership. Some options are operational in nature and others may require hardware modifications.

Reducing Minimum Load

Reducing the minimum load at which a unit can operate stably will reduce the number of on-off cycles. The on-off cycle adds costs due to equipment wear and tear, as the components experience large variations in temperatures and therefore harmful expansions and contractions. Unit startups increase overall heat rate as fuel is fired in the process during which no or very little power is generated.

Design/expected heat rate is already high at low load and increases as minimum load decreases. For example, boiler efficiency drops due to increased dry gas losses caused by grossly excessive excess air mandated by NFP code to prevent explosions and other related safety issues. Some power companies have modified their units to fire natural gas, either throughout the entire load range or co-firing with coal at low loads to stabilize the combustion process. Firing gas can reduce emissions and aux power requirements, which both reduce unit operating costs. Boiler efficiency is poorer while firing gas, but that loss is partially offset by the reduction in aux power as coal and ash handling activities subside. Emission control systems are challenged at very low loads, specifically SCRs as the backend gas temperatures may be reduced to unacceptable levels for effective SCR performance.

Employing Best Practices

As the plants age and fall down the dispatch order, staffing levels are often decreased as a cost cutting measure. That action trims down many of the best practices that can improve plant performance, which is crucial to maintaining reasonable operating costs. The first best practice is that of conducting periodic/preventive maintenance in lieu of break down maintenance. Since this is a discussion on plant performance, we won't go into details on reliability issues, but degraded equipment tends to operate less efficiently, so those PMs can help keep efficiency from falling off so quickly. Calibration based PMs are also needed to ensure reliable information is provided to plant performance monitoring systems and unit controls. The unit control systems should be monitored and tuned to optimize startups, but that's only possibly with accurate and reliable data.

Performance monitoring systems have been a main component of well performing plants. Those systems have become more autonomous, requiring less care and providing more timely information on which to base actions. Many power companies have remote monitoring facilities, usually focused on catching incipient reliability issues, but can easily incorporate the thermal performance applications.

Support from management is crucial both in the form of budget to employ these best practices and the placement of priority to monitor and resolve heat rate issues. One plant studied by EPRI, experienced a 12% drop in generation in conjunction with a large increase of load following, but experienced a negligible heat rate increase ~15 Btu/kWh. They credit the reduced adverse effects to the formation of an active heat rate improvement team that increased monitoring and brought issues to the forefront instead of suffering through extended period of efficiency penalties. Establishing plant heat rate/performance goals and communicating the goals, the heat rate values, and the reasons behind the actions, can enlarge the ad hoc heat rate improvement team to include the entire staff instead of a few isolated individuals. Investing in operator heat rate awareness training is another low cost method to improve plant performance.

Actions should be fully evaluated to ensure the total cost and full potential benefits are accounted for. For example, adding several staff members to monitor heat rate may not be cost effective, but adding an automated performance monitoring system that alerts the existing staff of inefficient operation or equipment degradation may be more cost effective. Fully accounting for all the costs involved in cycling a unit on and off is crucial to ensuring the cycling is justified. The startup costs should include wear and tear costs in addition to the traditional costs for fuel, power, material, and incremental labor.

Cycle Alignment

Cycle alignment programs are a key ingredient of successful plant performance improvement programs. Maintaining proper cycle alignment, also known as cycle isolation, can provide large heat rate gains for a small investment.

Cycle alignment refers to the alignment of the steam cycle through the positioning and maintenance of the steam and water paths to ensure the high energy fluid is travels to locations as designed and any leakage is minimized. This fluid absorbed energy from burning a fuel or in an HRSG. Any energy that goes into heating the water in these cycles that does not get used for generating electricity is wasted. If less fluid is available for generation, either the fuel burn increases to meet the generation requirements or the plant generates less power. Increased fuel consumption adversely effects heat rate.

Often cycle alignment losses go undetected. For example, leakage is often to the condenser and is not readily apparent. If the leakage exhausts to the atmosphere through a drain, vent, or relief valve it is usually quickly noticed and identified for repair. Unintended leakage to the condenser and blowdown tanks is hidden within the piping and the vessel shell and may be undetected for a significant amount of time unless methods are taken to identify and monitor the potential leakage.

Power plants initiating cycle alignment programs often see heat rate improvements in the range of 0.5–2.0%. These programs become more important during times of frequent on-off cycling and load following as many valves will be cycling open and closed, and may start leaking through or be inadvertently left open leading to a waste of thermal energy.

Key areas to be monitored as part of a cycle alignment program include emergency drain valves, startup drain valves, blowdown valves, and equipment bypass valves. A parallel action can be undertaken to ensure the steam supplied to various plant components is that with the lowest available energy. For example, deaerators and other devices require pegging steam. Using cold reheat, if possible, instead of main steam or hot reheat steam, decreases the load on the steam generator and increases the power generating capabilities of the unit's steam turbine. Another way to think about it is to use the steam source at the lowest enthalpy or pressure for heating and other non-power generating requirements.

Steam Turbine Performance

Steam turbines are the workhorse of a power plant and their performance is directly affected by steam conditions and other factors external to their influence. A steam turbine's efficiency drops as the unit load drops. The key factors resulting turbine efficiency penalties include throttling losses, steam temperature, lower steam flows, and condenser backpressure. Flexible operation will adversely affect throttling losses as the turbine control valves close as the load drops. Often steam generators cannot maintain design steam temperatures at part load, resulting in poorer steam turbine performance. The steam path is designed to be optimum with design (full) steam flow rate. As that flow rate drops off, the turbine efficiency drops as the aerodynamics of the steam and the steam path no longer match. But on a positive side condenser pressure drops at lower loads, reducing the backpressure on the low pressure turbine improving its performance.

Since the control valves create a large penalty when operating less than full load, the recommendations involve actions to reduce that throttling loss. The first is to operate in partial arc admission. The turbine control system can drive all the turbine control valves open or shut simultaneously. This is known as full arc or single valve operation. The steam is throttled across all the valves which creates a loss of

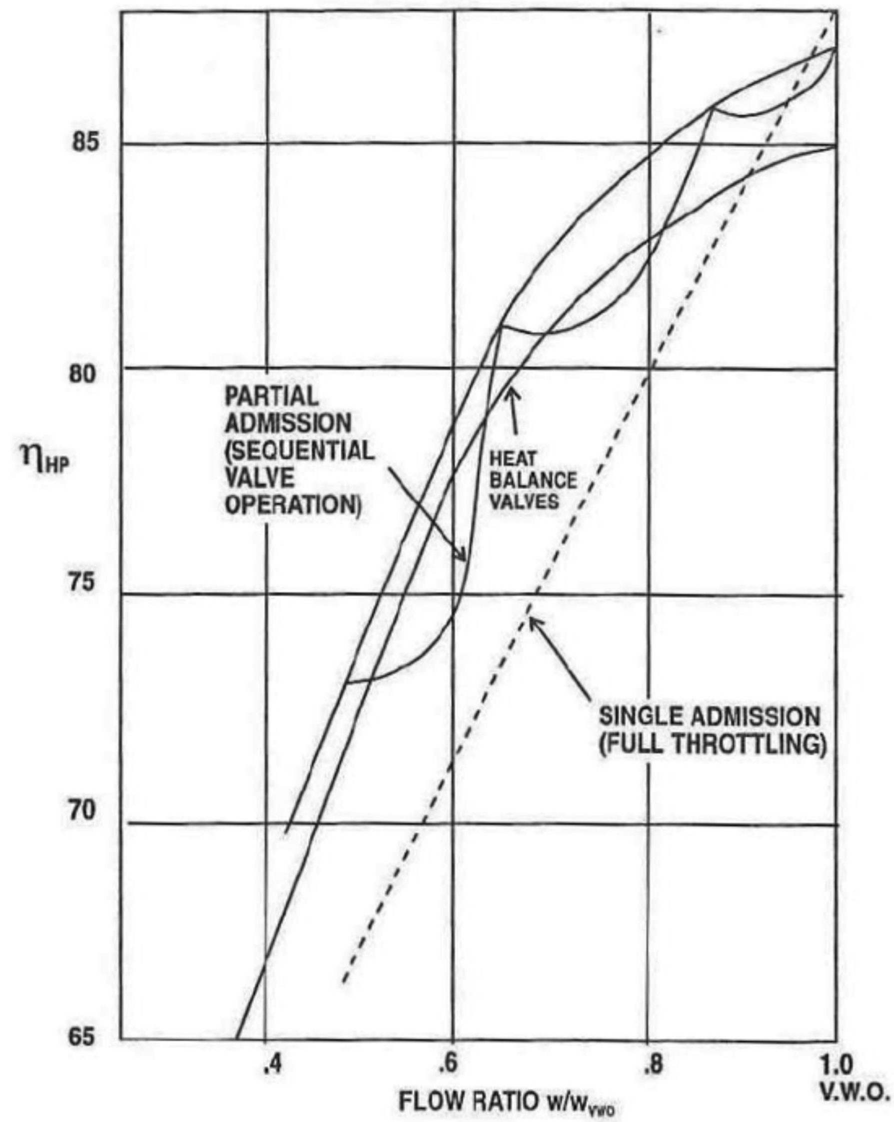

Figure 3 – Expected HP turbine section efficiency for full arc and partial arc admission schemes

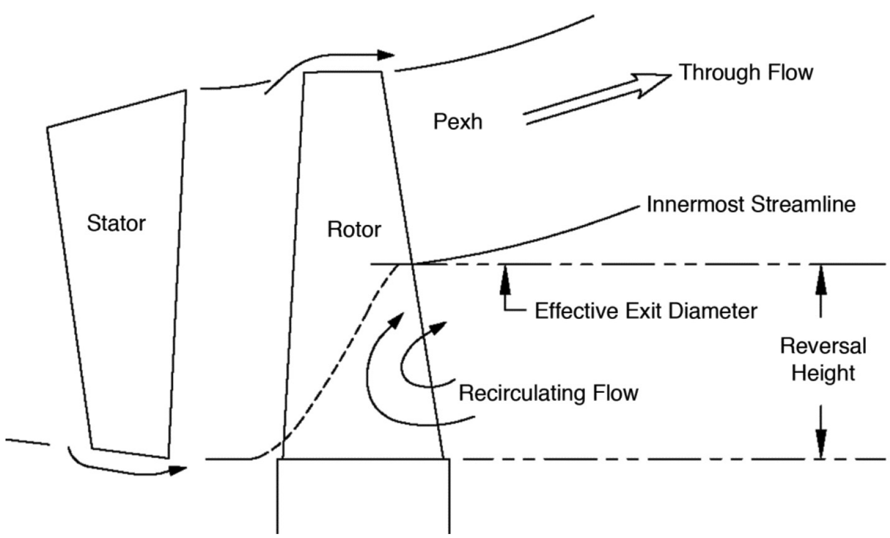

Figure 4 – Potential last stage steam recirculation (not drawn to scale)

available energy to produce work in the turbine. The other control option is drive the control valves to open or shut sequentially, one at a time. This is known as sequential valve or partial arc admission. Independent of load the steam is throttled only by the one valve not fully open, reducing the overall throttling losses.

Refer to Figure 3 to compare the efficiency effects of each of these two turbine admission modes. The dotted line reflects the high pressure turbine section efficiency with single valve / full arc admission. The line containing the loops reflects the high pressure turbine section efficiency with sequential valve/partial arc admission. Full arc admission out performs partial arc admission only at the very top end of the turbine load range. At loads under ~90% MCR, the performance penalty increases as the load drops and can reach 5%.

Another method to reduce the throttling losses is to reduce pressure as load drops. Sliding pressure keeps the control valves at wider open position(s) reducing the throttling experience as part load. This is commonly done for units that only operate with full arc admission schemes. EPRI sponsored research identified about a 2% heat rate improvement by using sliding pressure during part load operation. A slight decrease in the unit ramp rate occurs with sliding pressure operation.

For those units that never will operate near or at full rated load, the steam path can be physically modified to reduce the flow area permitting the control valves to open wider without a ramp rate penalty. This is a permanent and expensive hardware modification that requires a lengthy outage.

Low pressure turbines are designed with relatively large flow areas. During very low load operation the voluminous steam path may not be 100% filled with steam, which may permit a small fraction of the steam exhausted to be drawn into the lower portions of the last stage blades and recirculated. That action can cause blade flutter, an increase heat load on those blades, and an efficiency penalty on the low pressure turbine. Refer to Figure 4 for an approximation of the low pressure turbine steam flow path at low load.

Reduce Auxiliary Power Consumption

EPRI has been involved in a multi-year and multi-site project to reduce auxiliary power consumption. At each of the site visited a large number of opportunities have been identified to reduce aux power. Many of the opportunities were found to be at part load. Risks may be involved with certain actions to reduce aux power. Cycling a piece of equipment on and off increases its wear and tear, and increases the opportunity for failure and/or increased maintenance costs. Those risks are identified as part of this project and their associated effects have been estimated. It is recommended to conduct a thorough cost/benefit analysis prior to taking actions to reduce aux power.

Some of the largest potential gains (reductions in aux power) could come from the installation and use of VFD (variable speed drives) on certain pieces of rotating equipment. ID and FD fans, feedpumps, and other large components could potentially drop their aux power consumption significantly, potentially more than 50% while operating at part loads. VFDs have been successfully used on cooling tower fans, ID and FD fans. They are much more expensive than standard drives and may require a larger footprint.

Technical Gaps and Future Research

This section identifies the areas requiring technical advances that may reduce the adverse heat rate effects of flexible operation.

Lower load operation results in additional moisture formation in the low pressure sections of the steam turbine. Advanced materials and/or coatings could reduce the damage caused by the impingement of the water droplets on the steam path components. If those surfaces could be made hydrophobic, permitting the shedding of smaller droplets, less impact damage would occur downstream. To be successful, the hydrophobic coatings would be required to withstand the high steam velocities and temperatures.

A similar problem is the occasional off-design operation of pumps occurring during transients or very low flow situations when cavitation occurs. Those events can damage the pump impellors resulting in poorer performance and increased maintenance costs. Coatings, advanced materials, and improved designs may reduce the onset of cavitation and/or the damage it incurs.

Turbines, pump, fans, and other pieces of rotating equipment while designed for good performance are also built very substantially with minimal moving parts. Gas turbines and some fans have adjustable inlet guide vanes to improve efficiency over a wider range of operation. Research should be conducted to determine if adjustable vanes could be more widely employed without adversely affecting equipment reliability.

Optimal heat rates at part load operation are already higher than those at full load and any deviation from normal operation conditions can make that situation even less efficient. More fully automating and optimizing the integrated power plant controls to ensure the operation is closer to design will improve heat rate. Neural net optimizers were used successfully over 25 years ago to maintain the complex combustion process near its optimum and reduce the need for costly hardware modifications to comply with clean air act amendment requirements. The application of machine learning and optimizers beyond the combustion systems have the potential to improve part load and transient heat rate.

Variable speed drives (VFD) were mentioned as a currently available technology to reduce auxiliary power consumption, but due to their size and cost, are not widely used. Additional research should be conducted to determine options to reduce the cost and physical size of VFDs.

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