Summary

Large, complex and widely used, industrial boilers are major consumers of fuel. Proper operations and maintenance (O&M) procedures must be followed to ensure safe and efficient operations.

It is often assumed that good O&M provides no energy savings because it is simply “what should be done.” Actually, without proper O&M energy consumption can increase dramatically—as much as 10 to 20 percent as the system slowly gets out of adjustment. Thus, savings from energy-efficient O&M strategies can be thought of as avoided consumption.

Maintenance includes keeping physical components in good working order and within design specifications. This includes cleaning heat transfer surfaces, controls tuning and maintaining insulation. Before boiler tune-ups, system diagnostics should be performed and any deficient equipment brought back to specifications. Changes to design specifications can be made, but all implications of the change must first be considered.

Operational practices include equipment adjustments, handling and analysis of boiler log information and identification of boiler performance goals. Operations and maintenance practices overlap and greatly influence each other.

Due to the complexity and importance of efficient operation of industrial boilers, specialists are often contracted to perform some or all O&M functions.
How Operations and Maintenance Strategies Save Energy

Proper operation and maintenance of boilers will help derive useful work from as much of the fuel as practical, by avoiding unnecessary efficiency losses and matching boilers to loads. It is important to establish operational goals and to maintain accurate logs for each boiler so that variances can be quickly identified and remedied.

Efficiency losses are avoided by maintaining clean heat transfer surfaces, optimizing the air-to-fuel ratio\(^1\) of the burner, keeping steam vessels and pipes properly insulated, minimizing steam and boiler gas leakage, following good blowdown procedures, and minimizing steam pressure in keeping with load requirements.

It is also important to match the boilers in use to the steam or hot water load. For facilities with multiple boilers and variable loads, achieving the most efficient combination of boilers may mean occasionally shutting down some to allow others to operate at a more efficient firing rate. Controls must be properly adjusted and coordinated for continuous operation.

\(^1\) Bold-Italic words are defined in the section titled Definition of Key Terms.
delivery of steam or hot water to processes that are likely to be dynamic.

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**Energy-Saving Operations and Maintenance Strategies**

Boiler *maintenance* refers to keeping the boiler itself in efficient working condition. Boiler *operation* refers to adjustments and procedures that ensure the boiler meets its loads efficiently and safely. This document addresses operations and maintenance (O&M) strategies as they apply to energy considerations, not safety issues. Adding energy-saving equipment (e.g., economizers, air pre-heaters and deaerators) is not considered.

**Boiler Maintenance**

Boiler maintenance must be systematic. Applied properly, it minimizes energy consumption and downtime due to unanticipated failures. Responsibility should be assigned for performing and keeping written records of daily, weekly, monthly and annual maintenance tasks. Checklists should be used. They ensure the operator does not forget any tasks, serve as records of work done and are a way to communicate the boilers’ status. Completed checklists should be posted for all operators to review. Old checklists should be systematically filed for reference. A list of specific energy-related maintenance items follows.

**Boiler System Diagnostics and Inspection**

The *tune-up* of a fire-tube or smaller water-tube industrial boiler can usually be performed with only minimal advanced preparation, but large industrial boilers warrant diagnostic testing before formal tune-up. The primary aim here is to identify off-design equipment performance or undesirable site-specific operating practices/constraints. If maintenance, adjustment, calibration or modification of operating practices are needed, they should be completed before attempting to optimize boiler performance.

Before analyzing stack gas, *negative-draft boilers* should be checked for air leakage using smoke-generating sticks, the flame of a butane lighter or ultrasonic equipment. Leaks need to be sealed so the quantity of air supplied for combustion can be controlled; such control is essential if stack gas tests are to be accurate. High oxygen readings caused by air leaks can lead operators to reduce the air-to-fuel ratio, resulting in unburned combustibles (i.e., wasted fuel) in the stack. Note that air leakage from *positive-draft boilers* will be from the boiler to the surrounding area. This does not affect stack gas tests, but poses a potential hazard and should be remedied. Ultrasonic equipment can be used to detect such leaks.

The boiler should also be checked for steam and water leaks. Ultrasonic probes can be used to detect steam leaks in water-tube boilers. For any boiler with a water storage tank leakage can be checked by shutting off the make-up water supply and observing the water level in the tank over a specified period of time. A decrease is symptomatic of a potential tube leak. Prior to testing, the operator must be absolutely certain low-water cutoff controls are in place and functioning properly.
Large industrial boilers (100,000 - 500,000 lb/hr steam flow) tend to have particular design and operating characteristics that make diagnostics and tuning more complex. For example, they are generally field-erected to customized designs and component selection. Multiple burners are common. Combustion controls tend to be more complex and auxiliary equipment such as economizers and air preheaters is more likely to be present. Older balanced-draft units may have significant air leakage. For these reasons it is often desirable to hire a specialist to perform diagnostic and tuning work.

Combustion non-uniformity should be tested as part of the diagnosis. Identifying and eliminating non-uniform combustion requires a very disciplined approach; methods are discussed in the Boiler Operations section.

**Maintain Clean Heat Transfer Surfaces - Fire Side**

Although it is unlikely to be significant for gas boilers, soot can build up on the fire side of heat transfer surfaces, inhibiting heat transfer. Less heat is transferred to the water and more heat is carried out in the flue gases. Elevated stack temperatures may indicate *fouling* of heat transfer surfaces. It is estimated that each 40°F rise in stack temperature cuts efficiency 1 percentage point. Before assuming stack temperature increases are due to fouling, changes to firing rates, exhaust gas composition and combustion air temperature should be considered. As a general rule, stack gas temperature should not be more than 150°F above the temperature of saturated steam at the boiler operating pressure.

Fire side fouling is not likely when natural gas is being burned. The most likely causes are low air-to-fuel ratios, improper fuel preparation or malfunctioning burners. Gas-burning fire-tube boilers should have their tubes inspected at least once a year, more frequently for systems with problematic combustion. The tubes should be cleaned (or "punched") as needed. Many devices are available to do this; they may include a vacuum or water attachment to remove the loosened soot.

A 1/32-inch layer of soot reduces boiler efficiency an estimated 2.5 percent, a 1/8-inch layer an estimated 8.5 percent.

To illustrate, consider a boiler generating 200 psig/500°F steam at a rate of 50,000 lb/hr and an 85 percent efficiency using $.50/therm natural gas. Generation costs would be approximately $6.00 per 1,000 pounds of steam. Assuming 7,000 annual operating hours and average annual soot buildup of 1/16-inch, the annual cost of the resulting 4.5 percent efficiency loss would be approximately $84,000.

**Maintain Clean Heat Transfer Surfaces - Water Side**

*Scale* deposits on the water side of boiler tubes present problems similar to those described above. One difference is that the fire side may still be clean, allowing the tubes to absorb heat without any means of dissipation. This can lead to tube failure, especially in water-tube boilers.

The relationship between scale thickness and efficiency losses is similar to those for soot buildup, although losses may be twice those for soot, depending on the type of scale. The best way to deal with scale is not to let it form in the
first place. This is accomplished by a combination of properly treating the boiler water in water softeners before it enters the boiler, by the injection of chemicals into the boiler water and by blowing down the system. Table 1 provides acceptable concentration limits of common impurities. Scale formation is likely beyond these limits.

Removing scale that has already formed can be accomplished by mechanical means, water treatment or acid cleaning. Mechanical and acid cleaning require care to avoid damaging the tubes; water cleaning requires care not to remove scale too quickly. Removing scale too quickly can result in large pieces of removed scale restricting water flows, leading to localized overheating and possible catastrophic failure.

**Maintenance of Insulation**

The primary mechanism for heat loss through the skin of an uninsulated boiler is radiant heat loss. The higher the temperature of the boiler skin (insulated or not), the greater the radiant heat loss to the surroundings. Note that a boiler at partial load has a skin temperature the same as if it were at full load, as long as the steam it is generating stays at the same temperature; thus radiant losses are the same at either load. However, the losses are a higher percentage of the fuel consumed at the lower firing rate. Therefore, in boilers that run at lower loads for significant periods, good insulation is more important.

The first inch of insulation reduces heat loss by about 90 percent. Each additional inch obviously will have much less impact. One rule of thumb is that any surface above 120°F should be insulated, including boiler surfaces, steam or condensate piping and fittings. Removable insulating jackets are available for valves, flanges, pressure-reducing valves, steam traps and other fittings. Note that a 6-inch gate valve may have

<table>
<thead>
<tr>
<th>Boiler Pressure Range (psig)</th>
<th>Total Solids (ppm)</th>
<th>Total Alkalinity (ppm)</th>
<th>Suspended Solids (ppm)</th>
<th>Silica (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 300</td>
<td>3,500</td>
<td>700</td>
<td>300</td>
<td>125</td>
</tr>
<tr>
<td>301 - 450</td>
<td>3,000</td>
<td>600</td>
<td>250</td>
<td>90</td>
</tr>
<tr>
<td>451 - 600</td>
<td>2,500</td>
<td>500</td>
<td>150</td>
<td>50</td>
</tr>
<tr>
<td>601 - 750</td>
<td>2,000</td>
<td>400</td>
<td>100</td>
<td>35</td>
</tr>
<tr>
<td>751 - 900</td>
<td>1,500</td>
<td>300</td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>901 - 1,000</td>
<td>1,250</td>
<td>250</td>
<td>40</td>
<td>8</td>
</tr>
<tr>
<td>1,001 - 1,500</td>
<td>1,000</td>
<td>200</td>
<td>20</td>
<td>2.5</td>
</tr>
</tbody>
</table>

*Table 1: Acceptable Concentration Limits of Boiler Water Solids*
more than 6 square feet of surface area over which to radiate heat from the system.

Damaged, missing or wet insulation should be repaired or replaced. The insulating value of wet insulation is vastly compromised and what is making it wet needs to be identified and removed before replacing it. Common causes of wet insulation are leaking valves, external piping leaks, tube leaks or leakage from adjacent equipment.

**Boiler Operations**

Natural gas-fired boiler operational problems commonly fall into three major categories:

- Operation at non-optimum air-to-fuel ratios
- Lack of combustion uniformity
- Combustion controls/instrumentation placement issues

These types of problems are discussed in this section to aid in their identification. Other operational issues are also discussed.

**Air-to-Fuel Ratio**

Efficient operation of any combustion equipment is highly dependent on a proper air-to-fuel ratio. Due to the mechanics of combustion, it is necessary to provide more air than would be required to provide exactly the right quantity of oxygen ($O_2$) to burn all the fuel without any $O_2$ left over. Because air is comprised of approximately 21 percent $O_2$ and 79 percent nitrogen ($N_2$), in delivering the right amount of $O_2$, nearly four times as much $N_2$ is also delivered. Nitrogen absorbs heat and carries it out the stack, resulting in a loss to the system. Minimizing excess air, consistent with complete combustion, minimizes this heat loss.

Complete carbon combustion forms carbon dioxide ($CO_2$) and heat is released. Incomplete combustion forms carbon monoxide (CO) and less than one-third as much heat is released, although CO does have the potential for completing combustion to form $CO_2$ if another oxygen atom can be found. CO is an unburned combustible and, in the stack gas, an efficiency loss to the system. Figure 2 shows the relationship of excess (or deficient) air to unburned combustibles, $CO_2$ and $O_2$ in the flue gas.

Excess air is determined from the concentration of either $CO_2$ or $O_2$ in the stack gas, but $O_2$ provides more accurate results. Many stack gas analyzers combine the measurement of either $O_2$ or $CO_2$ with the concentration of CO. Most systems will also display a calculated combustion efficiency value.

Even with continuous monitoring of the flue gas, non-optimum air-to-fuel ratios may result due to air leaking in upstream of the analyzer; infrequent or incorrect analyzer calibration; insufficient combustion air supply at full load; or an analyzer placed at a non-representative location.

Air in-leakage in large industrial boilers is often a consequence of their balanced-draft design. Air that enters the boiler after the combustion zone will cause high $O_2$ readings at the analyzer and the operator may adjust the air-to-
fuel ratio downward, resulting in oxygen-starved, inefficient combustion.

Another common cause of operation at a non-optimum $O_2$ level is infrequent or incorrect analyzer calibration. Routine scheduled analyzer calibration is critical. Note that even when following manufacturer’s instructions, improperly labeled calibration gas cylinders or plugged lines may bias the calibration.

Occasionally, boilers operate at below normal excess air levels because there is insufficient combustion air supply at full load. High CO emissions can result. Partially plugged or leaking air preheaters can starve the burners for air. Leaking air preheater seals can lead to erroneously high $O_2$ readings if the inlet combustion air leaks over into the flue gases. For these reasons, diagnostic testing prior to a boiler tune-up should include an air preheater leakage and efficiency test. For further information on potential air-to-fuel ratio problems and solutions, see Reference 4.

**Combustion Uniformity**

Complete combustion at efficient excess air levels requires the fuel and air to be uniformly mixed throughout the primary combustion zone. In multi-burner gas boilers, non-uniform combustion can result if the fuel and air are not evenly distributed. Just one misadjusted or malfunctioning burner spoils the boiler efficiency effort. The natural tendency when encountering noticeable CO levels is to raise excess air levels for the whole boiler, causing the other burners to operate at unnecessarily high $O_2$ levels.

Uniform combustion can quite often be achieved by simple adjustments (e.g., to the air register or damper settings). In other cases, further diagnostic testing is required. Considerable insight into combustion uniformity can be obtained by mapping the $O_2$ profile at the economizer.
mizer exit (or a duct location in close proximity to the boiler O$_2$ analyzer probe, if one exists). Systems exist that will automatically measure and map O$_2$ concentrations on a continuous basis. A complete combustion uniformity assessment typically involves an evaluation of combustibles and oxides of nitrogen (NO$_x$) emissions. For further information regarding combustion uniformity, see Reference 4.

**Oxygen Analyzer Location**

Occasionally, boilers with O$_2$ analyzers have them placed at a non-representative location in the flue gas duct. This can be identified by diagnostic tests where the O$_2$ analyzer sample plane is traversed with a probe connected to a portable O$_2$ analyzer. Another approach is to install a grid of sample probes in the duct to obtain a composite average gas sample. Either approach can be valuable in evaluating combustion uniformity in a large multiple-burner unit.

**Reduce Steam Pressure**

To the extent practical, steam should be generated at the lowest pressure that will meet the highest-pressure demand. Less fuel is required and lower stack temperatures result, improving efficiency. Savings may be as much as 1 or 2 percent, but actual savings depend on the starting pressure and the pressure reduction that is realized. For example, a 50 psi drop from 150 psig saturated steam will reduce the steam (and stack) temperature by 28°F, saving approximately 0.7 percent. A 50 psi drop from 400 psig saturated steam, however, will result in only a 12°F drop for an approximate 0.3 percent saving.

**Blowdown Management**

Blowdown is essential for maintaining low concentrations of dissolved solids in the water (skimming blowdown) or removing solids that have settled out of the water (bottom blowdown). Both practices result in unavoidable energy losses as hot water is wasted to the drain, and a balance must be maintained between acceptable results and energy losses. Skimming blowdown is best used as a continuous process, bottom blowdown is best done periodically as several short blowdowns. Continuous blowdown makes the use of heat recovery devices more feasible.

**Load Management**

In many industrial facilities, loads vary with production schedules or seasons. When multiple boilers serve many loads, it is important to manage them as efficiently as possible.

Individual boilers achieve maximum efficiency over a specific firing range. Units with high excess air requirements or significant radiation losses at low loads will have peak efficiency at a high load. Boilers with constant excess air levels and small radiation losses over the load range will exhibit peak efficiency at a lower load. Efficiencies should be determined over the full range of firing rates. More efficient boilers should be brought on line first as loads increase, and less efficient units should be taken off-line first as loads drop. Where possible, scheduling of loads can help achieve optimum system performance.
Applicability

All strategies presented in this Application Note are applicable to all boilers, although the method of implementation will vary: Large installations will benefit from automated systems; smaller or fire-tube systems may employ manual methods.

Field Observations to Assess Feasibility

This section discusses field observations and checks that will ensure that O&M procedures are allowing efficient system operation.

Related to Applicability

O&M needs to be performed on all boiler systems. The strategies in this Application Note can enhance the performance of any system not already practicing them. The following general observations apply:

- For boilers over 100,000 lbs/hr steam capacity, check to see if automated systems to achieve operational objectives (e.g., O₂-trim controls, blowdown systems) are installed. It is probably easiest to just ask the operator.

- Review of boiler maintenance logs will quickly reveal the frequency with which critical functions are carried out. If some are seldom or never performed, they should be added to the list of regular maintenance items.

- Too much excess air will show up as elevated stack temperatures, because the hot gases are being forced through the boiler too quickly, without time for adequate heat transfer. Generally, stack temperature should not be more than 150°F above the temperature of saturated steam at the boiler operating pressure.

- Boiler operation logs should indicate whether excess air is too far out of limits of good practice. Gas-fired boilers should be able to operate at 5 to 10 percent excess air. This range corresponds to 1 to 2 percent O₂, 11.9 to 12.3 percent CO₂, and, depending on stack temperature, efficiencies of 85.2 to 85.4 percent.

- On balanced-draft boilers, normal O₂ readings coupled with high combustibles and/or low stack temperatures may indicate air leakage into the system or air preheater seal leakage, situations that need to be remedied. Air leakage may also be indicated if high O₂ readings are coupled with normal or even low stack temperatures.

- Missing or degraded insulation on boiler, steam and condensate lines and fittings.

- Multiple boilers running at low fire simultaneously may indicate potential improvements through load management. Low-fire conditions can be determined by asking the operator or comparing steam flow rates, as indicated by gauges or readouts at a control panel, to boiler ratings.

Related to Energy Savings
Related to Implementation Cost

- The size of the boiler and the number of burners will influence the costs of maintaining proper air-to-fuel ratios and fuel pretreatment. Not only do multi-burner systems have more units to maintain, they must also be coordinated to achieve optimum efficiencies.

- Stack gas characteristics may influence the type of stack gas analyzer purchased. If the analyzer requires extractive stack gas samples, systems may need to be installed to remove moisture or particulates before analysis is performed.

Estimation of Energy Savings

Unlike adding energy conserving equipment like economizers or oxygen trim control, no energy savings will be reflected in a facility’s utility bills when ongoing O&M is practiced. The value of ongoing O&M is in the avoidance of unnecessary fuel consumption. It is difficult, if not impossible, to quantify this avoided consumption as there is not a good baseline (i.e., how the system would consume fuel without O&M) for comparison.

Whether the strategies employed result in combustion improvements, reductions in radiant losses or better load management, all can be measured in terms of improved efficiencies. The fuel savings (or fuel consumption avoidance) realized are determined from a ratio of the change in efficiency to the original efficiency.

\[
Fractional\_Savings = \frac{(E_N - E_O)}{E_O}
\]

where \( E_N = \text{New Efficiency obtained by implementing the strategy} \)
\( E_O = \text{Pre-Implementation (Old) Efficiency} \)

Note that savings are greater than just the number of efficiency percentage points gained, because the starting efficiency will be less than one. For example, if a boiler’s efficiency is improved from 75 to 80 percent, the operating efficiency point gain will be 5 percent, but the savings will be 5 percent divided by 0.75—6.7 percent savings.

In general, properly applied boiler O&M can be expected to save 5 to 10 percent of the energy that would otherwise be consumed. This reduction is difficult to quantify as it is an avoided, rather than a reduced, consumption. The only way to determine savings would be to establish a baseline by stopping O&M functions—clearly unacceptable.

In a typical gas boiler plant, maintaining proper air-to-fuel ratios and water quality are probably the two most important O&M procedures. They are both essential and are generally well attended to, although opportunities for improvement often exist. Closely related to the air-to-fuel ratio are air leakage, \(O_2\) analyzer location and combustion uniformity issues.

Depending on conditions at the site, reduced steam pressure, blowdown and load management may offer opportunities for significant savings. In most
situations, insulation improvements offer few opportunities for large savings.

Factors That Influence Operations and Maintenance Costs

As mentioned earlier, boiler size and complexity dictate the level of O&M for optimum performance. Besides those items, this section provides other considerations that will influence the cost of an O&M program aimed at energy reduction.

- **The availability of labor is a prime consideration.** It is necessary to determine whether existing staff have the ability or the time to perform additional O&M duties, and if not, whether to hire those abilities or to contract for them.

- **The frequency with which the new tasks are to be performed** bears directly on whether existing staff has time available. Contractors will definitely figure frequency of site visits into any cost estimates.

- **Another labor-related issue is the time required to analyze** information from O&M logs and any measurements that are taken. This becomes more important as the cost of energy increases as a percentage of the cost of production. That is, in an industry where energy accounts for 1 percent of the cost of production, the incentive to reduce energy costs will be less than at one in which energy costs are 10 percent. In the latter case, it is more likely time for data analysis will be found.

- **Depending on the strategies involved,** consumables may be required. Many of these costs are incidental and are not generally a major contributor to strategy costs. Items for consideration are chemical cells used in gas analyzers, hardcopy charts and calibration gases. Cost of maintenance for the analyzers themselves should also be considered.

- **Hot, wet, dirty stack gases may require special treatment before being analyzed;** additional equipment may have to be added to a stack gas analysis system.

Laws, Codes, and Regulations

It is assumed that ASME Pressure Vessel and Piping Codes were followed at the time of boiler installation. Energy-saving O&M procedures should not affect any periodic inspections required under existing regulations.

While the Clean Air Act Amendments of 1990 apply in California, the state’s own 37 air quality control districts each have their own regulations, generally among the most restrictive in the country. Of special concern are stringent NOx emission requirements; burner manufacturers have developed special low-NOx burners to address them. Other strategies include modifications to the combustion equipment, flue gas recirculation and downstream treatment of the flue gas to convert NOx to nitrogen and water.
Definitions of Key Terms

- **Air Register:** A device surrounding a burner used to direct the combustion air flow.

- **Air-to-Fuel Ratio:** The weight (solid or liquid fuels) or volume (gaseous fuels) ratio of air to fuel delivered to the combustion process.

- **Balanced-Draft:** The operation of a forced draft fan and an induced draft fan, balanced to create a slight negative pressure in the furnace.

- **Blowdown:** The act of releasing some of the water from an operating boiler to maintain a low level of suspended solids in the water. Since solids are not carried away by the steam, they will build up in the water if action is not taken. Blowdown can also refer to the water thus released.

- **Excess Air:** That amount of air introduced to the combustion process that is in addition to the exact amount required for all the fuel to burn with no oxygen left over.

- **Fouling:** The accumulation of deposits on the surface of heat exchange surfaces.

- **Negative Draft Boiler:** A boiler in which the combustion chamber and hot gas passages are maintained at a pressure less than the air pressure surrounding the boiler. This is accomplished by means of a downstream fan (i.e., and induced-draft fan) that pulls the hot gases through the passages.

- **Positive Draft Boiler:** A boiler in which the combustion chamber and hot gas passages are maintained at a pressure higher than the air pressure surrounding the boiler. This is accomplished by means of an upstream fan (i.e., and forced-draft fan) that pushes the hot gases through the passages.

- **Scale:** A deposit of medium to extreme hardness occurring on water heating surfaces of a boiler because of an undesirable condition in the boiler water.

- **Tune-up:** The adjustment of air-to-fuel ratios, reduction of stack losses and adjustment of forced and induced draft fans to optimize boiler energy performance.

References to More Information


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**Trade Organizations**

Further information may be obtained from:

The Combustion Institute  
5001 Baum Blvd  #635  
Pittsburgh, PA  15238  
Tel (412) 687-1366  
Fax (412) 687-0340

Amer. Boiler Mfrs. Assoc.  
950 N. Glebe Rd.  #160  
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