Chapter 9 O&M Ideas for Major Equipment Types

9.1 Introduction

At the heart of all O&M lies the equipment. Across the Federal sector, this equipment varies greatly in age, size, type, model, fuel used, condition, etc. While it is well beyond the scope of this guide to study all equipment types, we tried to focus our efforts on the more common types prevalent in the Federal sector. The objectives of this chapter are the following:

- Present general equipment descriptions and operating principles for the major equipment types.
- Discuss the key maintenance components of that equipment.
- Highlight important safety issues.
- Point out cost and energy efficiency issues.
- Highlight any water-related efficiency impacts issues.
- Provide recommended general O&M activities in the form of checklists.
- Where possible, provide case studies.

The checklists provided at the end of each section were complied from a number of resources. These are not presented to replace activities specifically recommended by your equipment vendors or manufacturers. In most cases, these checklists represent industry standard best practices for the given equipment. They are presented here to supplement existing O&M procedures, or to merely serve as reminders of activities that should be taking place. The recommendations in this guide are designed to supplement those of the manufacturer, or, as is all too often the case, provide guidance for systems and equipment for which technical documentation has been lost. As a rule, this guide will first defer to the manufacturer's recommendations on equipment operations and maintenance.

Actions and activities recommended in this guide should only be attempted by trained and certified personnel. If such personnel are not available, the actions recommended here should not be initiated.

9.1.1 Lock and Tag

Lock and tag (also referred to as lockout-tagout) is a widely accepted safety procedure designed to ensure equipment being serviced is not energized while being worked on. The system works by physically locking the potential hazard (usually an electric switch, flow valve, etc.) in position such that system activation is not possible. In addition to the lock, a tag is attached to the device indicating that work is being completed and the system should not be energized.

When multiple staff are working on different parts of a larger system, the locked device is secured with a folding scissors clamp (Figure 9.1.1) that has many lock holes capable of holding it closed. In this situation, each staff member applies their own lock to the scissor clamp; therefore, the locked-out device cannot be activated until all staff have removed their lock from the clamp.

Figure 9.1.1. Typical folding lock and tag scissor clamp. This clamp allows for locks for up to 6 different facility staff.

There are well-accepted conventions for lock-and-tag in the United States, these include:

- No two keys or locks should ever be the same.
- A staff member's lock and tag must not be removed by anyone other than the individual who installed the lock and tag unless removal is accomplished under the direction of the employer.
- Lock and tag devices shall indicate the identity of the employee applying the device(s).
- Tag devices shall warn against hazardous conditions if the machine or equipment is energized and shall include directions such as: ***Do Not Start. Do Not Open. Do Not Close. Do Not Energize. Do Not Operate.***
- Tags must be securely attached to energy-isolating devices so that they cannot be inadvertently or accidentally detached during use.
- Employer procedures and training for lock and tag use and removal must have been developed, documented, and incorporated into the employer's energy control program.

The Occupational Safety and Health Administration's (OSHA) standard on the Control of Hazardous Energy (Lockout-Tagout), found in **CFR 1910.147**, spells out the steps employers must take to prevent accidents associated with hazardous energy. The standard addresses practices and procedures necessary to disable machinery and prevent the release of potentially hazardous energy while maintenance or service is performed.

9.2 Boilers

9.2.1 Introduction

Boilers are fuel-burning appliances that produce either hot water or steam that gets circulated through piping for heating or process uses.

Boiler systems are major financial investments, yet the methods for protecting these investments vary widely. Proper maintenance and operation of boilers systems is important with regard to efficiency and reliability. Without this attention, boilers can be very dangerous (NBBPVI 2001b).

9.2.2 Types of Boilers (Niles and Rosaler 1998)

Boiler designs can be classified in three main divisions – fire-tube boilers, water-tube boilers, and electric boilers.

9.2.2.1 Fire-Tube Boilers

Fire-tube boilers rely on hot gases circulating through the boiler inside tubes that are submerged in water (Figure 9.2.1). These gases usually make several passes through these tubes, thereby transferring their heat through the tube walls causing the water to boil on the other side. Fire-tube boilers are generally available in the range 20 through 800 boiler horsepower (bhp) and in pressures up to 150 psi.

Boiler horsepower: As defined, 34.5 lb of steam at 212˚F could do the same work (lifting weight) as one horse. In terms of Btu output—1 bhp equals 33,475 Btu/hr.

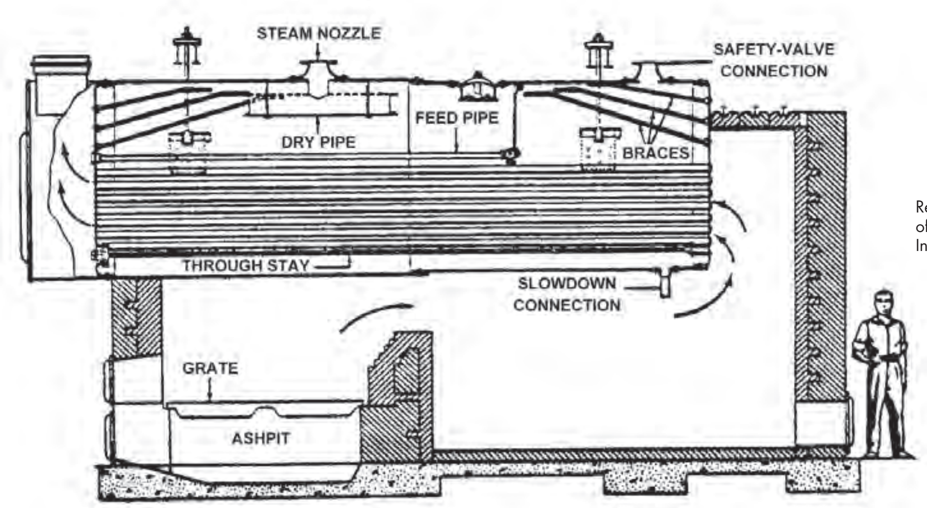

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Figure 9.2.1. Horizontal return fire-tube boiler (hot gases pass through tube submerged in water).

9.2.2.2 Water-Tube Boilers

Most high-pressure and large boilers are of this type (Figure 9.2.2). It is important to note that the small tubes in the water-tube boiler can withstand high pressure better than the large vessels of a fire-tube boiler. In the water-tube boiler, gases flow over water-filled tubes. These water-filled tubes are in turn connected to large containers called drums.

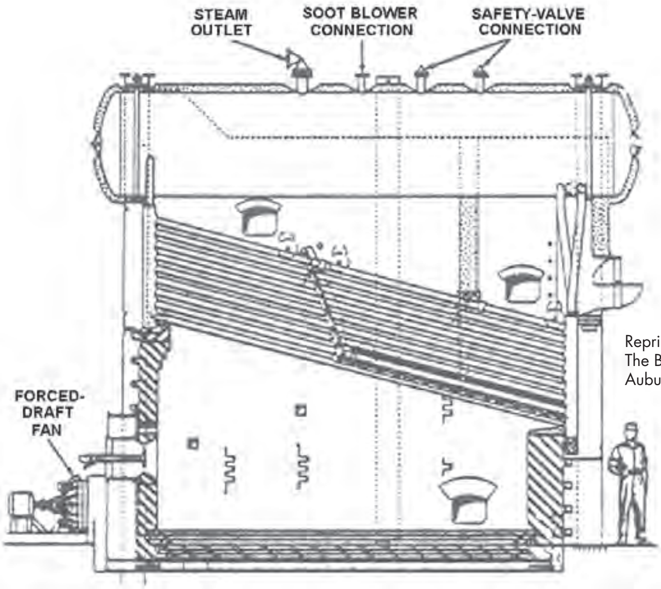

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Figure 9.2.2. Longitudinal-drum water-tube boiler (water passes through tubes surrounded by hot gases).

Water-tube boilers are available in sizes ranging from smaller residential type to very large utility class boilers. Boiler pressures range from 15 psi through pressures exceeding 3,500 psi.

9.2.2.3 Electric Boilers

Electric boilers (Figure 9.2.3) are very efficient sources of hot water or steam, which are available in ratings from 5 to over 50,000 kW. They can provide sufficient heat for any HVAC requirement in applications ranging from humidification to primary heat sources.

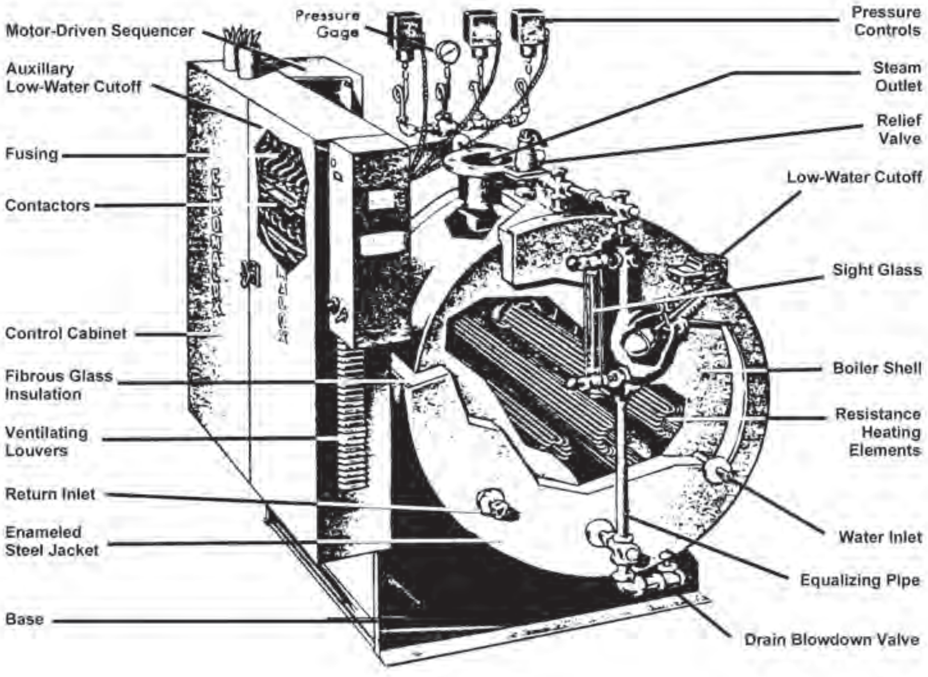

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Figure 9.2.3. Electric boiler

9.2.3 Key Components (Nakonezny 2001)

9.2.3.1 Critical Components

In general, the critical components are those whose failure will directly affect the reliability of the boiler. The critical components can be prioritized by the impact they have on safety, reliability, and performance. These critical pressure parts include:

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Most people do not realize the amount of energy that is contained within a boiler. Take for example, the following illustration by William Axtman: "If you could capture all the energy released when a 30-gallon home hot-water tank flashes into explosive failure at 332°F, you would have enough force to send the average car (weighing 2,500 pounds) to a height of nearly 125 feet. This is equivalent to more than the height of a 14-story apartment building, starting with a lift-off velocity of 85 miles per hour!" (NBBPVI 2001b)

- **Drums** – The steam drum is the single most expensive component in the boiler. Consequently, any maintenance program must address the steam drum, as well as any other drums, in the convection passes of the boiler. In general, problems in the drums are associated with corrosion. In some instances, where drums have rolled tubes, rolling may produce excessive stresses that can lead to damage in the ligament areas. Problems in the drums normally lead to indications that are seen on the surfaces – either inside diameter (ID) or outside diameter (OD).

  Assessment: Inspection and testing focuses on detecting surface indications. The preferred nondestructive examination (NDE) method is wet fluorescent magnetic particle testing (WFMT). Because WFMT uses fluorescent particles that are examined under ultraviolet light, it is more sensitive than dry powder type-magnetic particle testing (MT) and it is faster than liquid dye penetrant testing (PT) methods. WFMT should include the major welds, selected attachment welds, and at least some of the ligaments. If locations of corrosion are found, then ultrasonic thickness testing (UTT) may be performed to assess thinning due to metal loss. In rare instances, metallographic replication may be performed.

- **Headers** – Boilers designed for temperatures above 900°F (482°C) can have superheater outlet headers that are subject to creep – the plastic deformation (strain) of the header from long-term exposure to temperature and stress. For high temperature headers, tests can include metallographic replication and ultrasonic angle beam shear wave inspections of higher stress weld locations. However, industrial boilers are more typically designed for temperatures less than 900°F (482°C) such that failure is not normally related to creep. Lower temperature headers are subject to corrosion or possible erosion. Additionally, cycles of thermal expansion and mechanical loading may lead to fatigue damage.

  Assessment: NDE should include testing of the welds by MT or WFMT. In addition, it is advisable to perform internal inspection with a video probe to assess water side cleanliness, to note any buildup of deposits or maintenance debris that could obstruct flow, and to determine if corrosion is a problem. Inspected headers should include some of the water circuit headers as well as superheater headers. If a location of corrosion is seen, then UTT to quantify remaining wall thickness is advisable.

- **Tubing** – By far, the greatest number of forced outages in all types of boilers are caused by tube failures. Failure mechanisms vary greatly from the long term to the short term. Superheater tubes operating at sufficient temperature can fail long term (over many years) due to normal life expenditure. For these tubes with predicted finite life, Babcock & Wilcox (B&W) offers the NOTIS® test and remaining life analysis. However, most tubes in the industrial boiler do not have a finite life due to their temperature of operation under normal conditions. Tubes are more likely to fail because of abnormal deterioration such as water/steam-side deposits retarding heat transfer, flow obstructions, tube corrosion (ID and/or OD), fatigue, and tube erosion.

  Assessment: Tubing is one of the components where visual examination is of great importance because many tube damage mechanisms lead to visual signs such as distortion, discoloration, swelling, or surface damage. The primary NDE method for obtaining data used in tube assessment is contact UTT for tube thickness measurements. Contact UTT is done on accessible tube surfaces by placing the UT transducer onto the tube using a couplant, a gel or fluid that transmits the UT sound into the tube. Variations on standard contact UTT have been developed due to access limitations. Examples are internal rotating inspection system (IRIS)-based techniques in which the UT signal is reflected from a high rpm rotating mirror to scan tubes from the ID – especially in the area adjacent to drums; and B&W's immersion UT where a multiple transducer probe is inserted into boiler bank tubes from the steam drum to provide measurements at four orthogonal points. These systems can be advantageous in the assessment of pitting.

- **Piping**
  - **Main Steam** – For lower temperature systems, the piping is subject to the same damage as noted for the boiler headers. In addition, the piping supports may experience deterioration and become damaged from excessive or cyclical system loads.

    Assessment: The NDE method of choice for testing of external weld surfaces is WFMT. MT and PT are sometimes used if lighting or pipe geometry make WFMT impractical. Non-drainable sections, such as sagging horizontal runs, are subject to internal corrosion and pitting. These areas should be examined by internal video probe and/or UTT measurements. Volumetric inspection (i.e., ultrasonic shear wave) of selected piping welds may be included in the NDE; however, concerns for weld integrity associated with the growth of subsurface cracks is a problem associated with creep of high-temperature piping and is not a concern on most industrial installations.

  - **Feedwater** – A piping system often overlooked is feedwater piping. Depending upon the operating parameters of the feedwater system, the flow rates, and the piping geometry, the pipe may be prone to corrosion or flow assisted corrosion (FAC). This is also referred to as erosion-corrosion. If susceptible, the pipe may experience material loss from internal surfaces near bends, pumps, injection points, and flow transitions. Ingress of air into the system can lead to corrosion and pitting. Out-of-service corrosion can occur if the boiler is idle for long periods.

    Assessment: Internal visual inspection with a video probe is recommended if access allows. NDE can include MT, PT, or WFMT at selected welds. UTT should be done in any location where FAC is suspected to ensure there is not significant piping wall loss.

- **Deaerators** – Overlooked for many years in condition assessment and maintenance inspection programs, deaerators have been known to fail catastrophically in both industrial and utility plants. The damage mechanism is corrosion of shell welds, which occurs on the ID surfaces.

  Assessment: Deaerators' welds should have a thorough visual inspection. All internal welds and selected external attachment welds should be tested by WFMT.

9.2.3.2 Other Components (Williamson-Thermoflo Company 2001)

- **Air openings**

  Assessment: Verify that combustion and ventilation air openings to the boiler room and/or building are open and unobstructed. Check operation and wiring of automatic combustion air dampers, if used. Verify that boiler vent discharge and air intake are clean and free of obstructions.

- **Flue gas vent system**

  Assessment: Visually inspect entire flue gas venting system for blockage, deterioration, or leakage. Repair any joints that show signs of leakage in accordance with vent manufacturer's instructions. Verify that masonry chimneys are lined, lining is in good condition, and there are not openings into the chimney.

- **Pilot and main burner flames**

  Assessment: Visually inspect pilot burner and main burner flames.

  \- Proper pilot flame

    - Blue flame.
    - Inner cone engulfing thermocouple.
    - Thermocouple glowing cherry red.

  \- Improper pilot flame

    - Overfired – Large flame lifting or blowing past thermocouple.
    - Underfired – Small flame. Inner cone not engulfing thermocouple.
    - Lack of primary air – Yellow flame tip.
    - Incorrectly heated thermocouple.

  \- Check burner flames-Main burner

  \- Proper main burner flame

  \- Yellow-orange streaks may appear (caused by dust)

    - Improper main burner flame
      - Overfired - Large flames.
      - Underfired - Small flames.
      - Lack of primary air - Yellow tipping on flames (sooting will occur).

- **Boiler heating surfaces**

  Assessment: Use a bright light to inspect the boiler flue collector and heating surfaces. If the vent pipe or boiler interior surfaces show evidence of soot, clean boiler heating surfaces. Remove the flue collector and clean the boiler, if necessary, after closer inspection of boiler heating surfaces. If there is evidence of rusty scale deposits on boiler surfaces, check the water piping and control system to make sure the boiler return water temperature is properly maintained. Reconnect vent and draft diverter. Check inside and around boiler for evidence of any leaks from the boiler. If found, locate source of leaks and repair.

- **Burners and base**

  Assessment: Inspect burners and all other components in the boiler base. If burners must be cleaned, raise the rear of each burner to release from support slot, slide forward, and remove. Then brush and vacuum the burners thoroughly, making sure all ports are free of debris. Carefully replace all burners, making sure burner with pilot bracket is replaced in its original position and all burners are upright (ports up). Inspect the base insulation.

9.2.4 Safety Issues (NBBPVI 2001c)

Boiler safety is a key objective of the National Board of Boiler and Pressure Vessel Inspectors. This organization tracks and reports on boiler safety and "incidents" related to boilers and pressure vessels that occur each year. Figure 9.2.4 details the 1999 boiler incidents by major category. It is important to note that the number one incident category resulting in injury was poor maintenance/operator error. Furthermore, statistics tracking loss-of-life incidents reported that in 1999, three of seven boiler-related deaths were attributed to poor maintenance/operator error. The point of relaying this information is to suggest that through proper maintenance and operator training these incidents may be reduced.

At atmospheric pressure, 1 ft^3 of water converted to steam expands to occupy 1,600 ft^3 of space. If this expansion takes place in a vented tank, after which the vent is closed, the condensing steam will create a vacuum with an external force on the tank ***of 900 tons***! Boiler operators must understand this concept (NTT 1996).

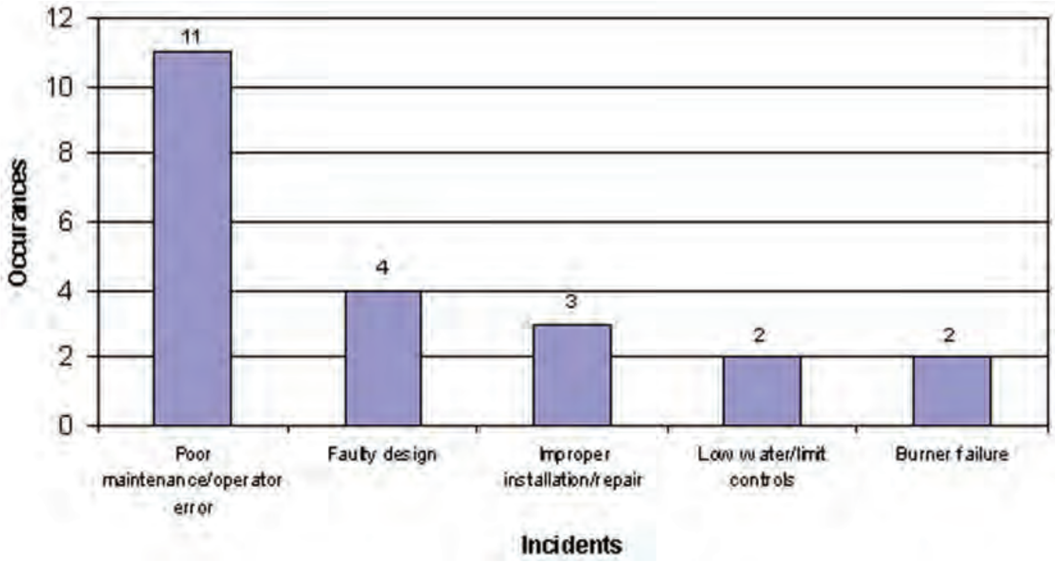

Figure 9.2.4. Adapted from 1999 National Board of Boiler and Pressure Vessel Inspectors incident report summary.

Boiler inspections should be performed at regular intervals by certified boiler inspectors. Inspections should include verification and function of all safety systems and procedures as well as operator certification review.

9.2.5 Cost and Energy/Water Efficiency (Dyer and Maples 1988)

9.2.5.1 Efficiency, Safety, and Life of the Equipment

It is impossible to change the efficiency without changing the safety of the operation and the resultant life of the equipment, which in turn affects maintenance cost. An example to illustrate this relation between efficiency, safety, and life of the equipment is shown in Figure 9.2.5. The temperature distribution in an efficiently operated boiler is shown as the solid line. If fouling develops on the water side due to poor water quality control, it will result in a temperature increase of the hot gases on the fire side as shown by the dashed line. This fouling will result in an increase in stack temperature, thus decreasing the efficiency of the boiler. A metal failure will also change the life of the boiler, since fouling material will allow corrosion to occur, leading to increased maintenance cost and decreased equipment reliability and safety.

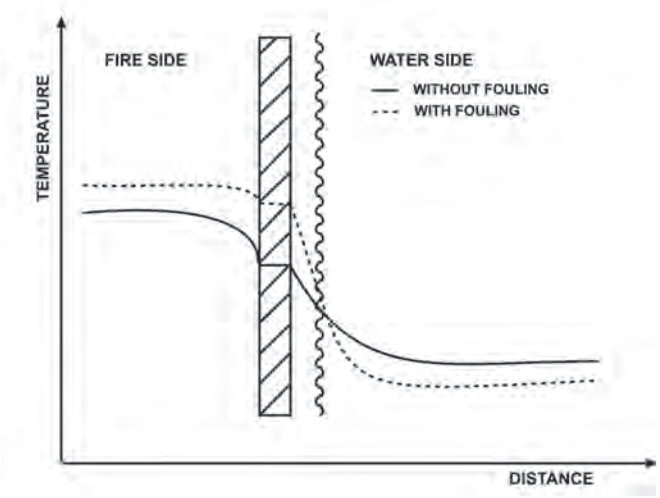

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Figure 9.2.5. Effect of fouling on water side

9.2.5.2 Boiler Energy Best Practices

In a study conducted by the Boiler Efficiency Institute in Auburn, Alabama, researchers have developed eleven ways to improve boiler efficiency with important reasons behind each action.

- **Reduce excess air** – Excess air means there is more air for combustion than is required. The extra air is heated up and thrown away. The most important parameter affecting combustion efficiency is the air/fuel ratio.
  - *Symptom* – The oxygen in the air that is not used for combustion is discharged in the flue gas; therefore, a simple measurement of oxygen level in the exhaust gas tells us how much air is being used. **Note**: It is worth mentioning the other side of the spectrum. The so called "deficient air" must be avoided as well because (1) it decreases efficiency, (2) allows deposit of soot on the fire side, and (3) the flue gases are potentially explosive.

  - *Action Required* – Determine the combustion efficiency using dedicated or portable combustion analysis equipment. Adjustments for better burning include:
    - Cleaning
    - New tips/orifices
    - Damper repair
    - Control repair
    - Refractory repair
    - Fuel pressure
    - Furnace pressure
    - Swirl at burner inlet
    - Atomizing pressure
    - Fuel temperature
    - Burner position
    - Bed thickness
    - Ratio under/overfire air
    - Undergrate air distribution.

- **Install waste heat recovery** – The magnitude of the stack loss for boilers without recovery is about 18% on gas-fired and about 12% for oil- and coal-fired boilers. A major problem with heat recovery in flue gas is corrosion. If flue gas is cooled, drops of acid condense at the acid dew temperature. As the temperature of the flue gas is dropped further, the water dew point is reached at which water condenses. The water mixes with the acid and reduces the severity of the corrosion problem.
  - *Symptom* – Flue gas temperature is the indicator that determines whether an economizer or air heater is needed. It must be remembered that many factors cause high flue gas temperature (e.g., fouled water side or fire side surfaces, excess air).
  - *Action Required* - If flue gas temperature exceeds minimum allowable temperature by 50°F or more, a conventional economizer may be economically feasible. An unconventional recovery device should be considered if the low-temperature waste heat saved can be used to heating water or air. ***Cautionary Note:*** *A high flue gas temperature may be a sign of poor heat transfer resulting from scale or soot deposits. Boilers should be cleaned and tuned before considering the installation of a waste heat recovery system.*

- **Reduce scale and soot deposits** – Scale or deposits serve as an insulator, resulting in more heat from the flame going up the stack rather than to the water due to these deposits. Any scale formation has a tremendous potential to decrease the heat transfer.
  - *Symptom* – The best indirect indicator for scale or deposit build-up is the flue gas temperature. If at the same load and excess air the flue gas temperature rises with time, the effect is probably due to scale or deposits.
  - *Action Required* – Soot is caused primarily by incomplete combustion. This is probably due to deficient air, a fouled burner, a defective burner, etc. Adjust excess air. Make repairs as necessary to eliminate smoke and carbon monoxide.

    Scale formation is due to poor water quality. First, the water must be soft as it enters the boiler. Sufficient chemical must be fed in the boiler to control hardness.

Scale deposits on the water side and soot deposits on the fire side of a boiler not only act as insulators that reduce efficiency, but also cause damage to the tube structure due to overheating and corrosion.

- **Reduce blowdown** – Blowdown results in the energy in the hot water being lost to the sewer unless energy recovery equipment is used. There are two types of blowdown. Mud blow is designed to remove the heavy sludge that accumulates at the bottom of the boiler. Continuous or skimming blow is designed to remove light solids that are dissolved in the water.
  - *Symptom* – Observe the closeness of the various water quality parameters to the tolerances stipulated for the boiler per manufacturer specifications and check a sample of mud blowdown to ensure blowdown is only used for that purpose. Check the water quality in the boiler using standards chemical tests.
  - Action Required – Conduct proper pre-treatment of the water by ensuring makeup is softened. Perform a "mud test" each time a mud blowdown is executed to reduce it to a minimum. A test should be conducted to see how high total dissolved solids (TDS) in the boiler can be carried without carryover.
- **Recover waste heat from blowdown** – Blowdown contains energy, which can be captured by a waste heat recovery system.
  - *Symptom and Action Required* – Any boiler with a significant makeup (say 5%) is a candidate for blowdown waste heat recovery.

Typical uses for waste heat include:

- Heating of combustion air
- Makeup water heating
- Boiler feedwater heating
- Appropriate process water heating
- Domestic water heating.

- **Stop dynamic operation on applicable boilers**
  - *Symptom* – Any boiler which either stays off a significant amount of time or continuously varies in firing rate can be changed to improve efficiency.
  - *Action Required* – For boilers which operate on and off, it may be possible to reduce the firing rate by changing burner tips. Another point to consider is whether more boilers are being used than necessary.
- **Reduce line pressure** – Line pressure sets the steam temperature for saturated steam.
  - *Symptom and Action Required* – Any steam line that is being operated at a pressure higher than the process requirements offers a potential to save energy by reducing steam line pressure to a minimum required pressure determined by engineering studies of the systems for different seasons of the year.
- **Operate boilers at peak efficiency** – Plants having two or more boilers can save energy by load management such that each boiler is operated to obtain combined peak efficiency.
  - *Symptom and Action Required* – Improved efficiency can be obtained by proper load selection, if operators determine firing schedule by those boilers, which operate "smoothly."
- **Preheat combustion air** – Since the boiler and stack release heat, which rises to the top of the boiler room, the air ducts can be arranged so the boiler is able to draw the hot air down back to the boiler.
  - *Symptom* – Measure vertical temperature in the boiler room to indicate magnitude of stratification of the air.
  - *Action Required* – Modify the air circulation so the boiler intake for outside air is able to draw from the top of the boiler room.

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General Requirements for a Safe and Efficient Boiler Room

1. Keep the boiler room clean and clear of all unnecessary items. The boiler room should not be considered an all-purpose storage area. The burner requires proper air circulation in order to prevent incomplete fuel combustion. Use boiler operating log sheets, maintenance records, and the production of carbon monoxide. The boiler room is for the boiler!
2. Ensure that all personnel who operate or maintain the boiler room are properly trained on all equipment, controls, safety devices, and up-to-date operating procedures.
3. Before start-up, ensure that the boiler room is free of all potentially dangerous situations, like flammable materials, mechanical, or physical damage to the boiler or related equipment. Clear intakes and exhaust vents; check for deterioration and possible leaks.
4. Ensure a thorough inspection by a properly qualified inspector.
5. After any extensive repair or new installation of equipment, make sure a qualified boiler inspector re-inspects the entire system.
6. Monitor all new equipment closely until safety and efficiency are demonstrated.
7. Use boiler operating log sheets, maintenance records, and manufacturer's recommendations to establish a preventive maintenance schedule based on operating conditions, past maintenance, repair, and replacement that were performed on the equipment.
8. Establish a checklist for proper startup and shutdown of boilers and all related equipment according to manufacturer's recommendations.
9. Observe equipment extensively before allowing an automating operation system to be used with minimal supervision.
10. Establish a periodic preventive maintenance and safety program that follows manufacturer's recommendations.

- **Switch from steam to air atomization** – The energy to produce the air is a tiny fraction of the energy in the fuel, while the energy in the steam is usually 1% or more of the energy in the fuel.
  - *Symptom* – Any steam-atomized burner is a candidate for retrofit.
  - *Action Required* – Check economics to see if satisfactory return on investment is available.

9.2.6 Maintenance of Boilers (NBBPVI 2001a)

A boiler efficiency improvement program must include two aspects: (1) action to bring the boiler to peak efficiency and (2) action to maintain the efficiency at the maximum level. Good maintenance and efficiency start with having a working knowledge of the components associated with the boiler, keeping records, etc., and end with cleaning heat transfer surfaces, adjusting the air-to-fuel ratio, etc (NBBPVI 2001a). Sample steam/hot-water boiler maintenance, testing and inspection logs, as well as water quality testing log can be found can be found at the end of this section following the maintenance checklists.

9.2.7 Diagnostic Tools

- **Combustion analyzer** – A combustion analyzer samples, analyzes, and reports the combustion efficiency of most types of combustion equipment including boilers, furnaces, and water heaters. When properly maintained and calibrated, these devices provide an accurate measure of combustion efficiency from which efficiency corrections can be made. Combustion analyzers come in a variety of styles from portable units to dedicated units.

- **Thermography** – An infrared thermometer or camera allows for an accurate, non-contact assessment of temperature. Applications for boilers include insulation assessments on boilers, steam, and condensate-return piping. Other applications include motor/bearing temperature assessments on feedwater pumps and draft fan systems. More information on thermography can be found in Chapter 6.

9.2.8 Available Software Tools

- **Steam System Tool Suite**

Description: If you consider potential steam system improvements in your plant, the results could be worthwhile. In fact, in many facilities, steam system improvements can save 10% to 20% in fuel costs.

To help you tap into potential savings in your facility, DOE offers a suite of tools for evaluating and identifying steam system improvements. The tools suggest a range of ways to save steam energy and boost productivity. They also compare your system against identified best practices and the self-evaluations of similar facilities.

- **Steam System Scoping Tool**

This tool is designed to help steam system energy managers and operations personnel to perform initial self-assessments of their steam systems. This tool will profile and grade steam system operations and management. This tool will help you to evaluate your steam system operations against best practices.

- **Steam System Assessment Tool (SSAT)** *Version 3*

SSAT allows steam analysts to develop approximate models of real steam systems. Using these models, you can apply SSAT to quantify the magnitude—energy, cost, and emissions-savings—of key potential steam improvement opportunities. SSAT contains the key features of typical steam systems.

New to Version 3 includes a set of templates for measurement in both English and metric units. The new templates correct all known problems with Version 2, such as an update to the User Calculations sheet, which allows better access to Microsoft Excel functionality. Version 3 is also now compatible with Microsoft Vista and Microsoft Excel 2007.

- **3E Plus® *Version 4.0***

The program calculates the most economical thickness of industrial insulation for user input operating conditions. You can make calculations using the built-in thermal performance relationships of generic insulation materials or supply conductivity data for other materials.

Availability: To download the Steam System Tool Suite and learn more about DOE Qualified Specialists and training opportunities, visit the Industrial Technology Program Web site: **www1.eere.energy.gov/industry/bestpractices**.

9.2.9 Relevant Operational/Energy Efficiency Measures

There are many operational/energy efficiency measures that could be presented for proper boiler operation and control. The following section focuses on the most prevalent O&M recommendations having the greatest energy impacts at Federal facilities. These recommendations are also some of the most easily implemented for boiler operators and O&M staff/contractors.

9.2.9.1 Boiler Measure #1: Boiler Loading, Sequencing, Scheduling, and Control

The degree to which a boiler is loaded can be determined by the boiler's firing rate. Some boiler manufacturers produce boilers that operate at a single firing rate, but most manufacturers' boilers can operate over a wide range of firing rates. The firing rate dictates the amount of heat that is produced by the boiler and consequently, modulates to meet the heating requirements of a given system or process. In traditional commercial buildings, the hot water or steam demands will be considerably greater in the winter months, gradually decreasing in the spring/fall months and finally hitting its low point during the summer. A boiler will handle this changing demand by increasing or decreasing the boiler's firing rate. Meeting these changing loads introduces challenges to boiler operators to meet the given loads while loading, sequencing and scheduling the boilers properly.

Any gas-fired boiler that cycles on and off regularly or has a firing rate that continually changes over short periods can be altered to improve the boiler's efficiency. Frequent boiler cycling is usually a sign of insufficient building and/or process loading. Possible solutions to this problem (Dyer 1991) include adjusting the boiler's high and low pressure limits (or differential) farther apart and thus keeping the boiler on and off for longer periods of time. The second option is replacement with a properly sized boiler.

O&M Tip:
Load management measures, including optimal matching of boiler size and boiler load, can save as much as 50% of a *boiler's* fuel use.

The efficiency penalty associated with low-firing stem from the operational characteristic of the boiler. Typically, a boiler has its highest efficiency at high fire and near full load. This efficiency usually decreases with decreasing load.

The efficiency penalty related to the boiler cycle consists of a pre-purge, a firing interval, and a post-purge, followed by an idle (off) period. While necessary to ensure a safe burn cycle, the pre- and post-purge cycles result in heat loss up the exhaust stack. Short cycling results in excessive heat loss. Table 9.2.1 indicates the energy loss resulting from this type of cycling (Dyer 1991).

Table 9.2.1. Boiler cycling energy loss

Number of Cycles/Hour	Percentage of Energy Loss
2	2
5	8
10	30

Based on equal time between on and off, purge 1 minute, stack temp = 400°F, airflow through boiler with fan off = 10% of fan forced airflow.

Opportunity Identification

Boiler operators should record in the daily log if the boiler is cycling frequently. If excessive cycling is observed, operators should consider the options given above to correct the problem.

Boiler operators should also record in the daily log the firing rate to meet the given hot water or steam load. If the boiler's firing rate continuously cycles over short periods of time and with fairly small variations in load – this should be noted. Seasonal variations in firing rate should be noted with an eye for sporadic firing over time. Corrections in firing rates require knowledge of boiler controls and should only be made by qualified staff.

Diagnostic Equipment

Data Loggers. The diagnostic test equipment to consider for assessing boiler cycling includes many types of electric data logging equipment. These data loggers can be configured to record the time-series electrical energy delivered to the boiler's purge fan as either an amperage or wattage measurement. These data could then be used to identify cycling frequency and hours of operation.

Other data logging options include a variety of stand-alone data loggers that record run-time of electric devices and are activated by sensing the magnetic field generated during electric motor operation. As above, these loggers develop a times-series record of on-time which is then used to identify cycling frequency and hours of operation.

Energy Savings and Economics

Estimated Annual Energy Savings. Using Table 9.2.1 the annual energy savings, which could be realized by eliminating or reducing cycling losses, can be estimated as follows:

$$Energy\ Savings = \left[\left(\frac{BL \times RFC}{EFF \times \left(1 - \frac{EL_1}{100}\right)}\right) - \left(\frac{BL \times RFC}{EFF \times \left(1 - \frac{EL_2}{100}\right)}\right)\right] \times H$$

$$Annual\ Energy\ Savings = \sum_{i=1}^{n} Energy\ Savings$$

where:

BL = current boiler load or firing rate, %/100

RFC = rated fuel consumption at full load, MMBtu/hr

EFF = boiler efficiency, %/100

EL_1 = current energy loss due to cycling, %

EL_2 = tuned energy loss due to cycling, %

H = hours the boiler operates at the given cycling rate, hours

Estimated Annual Cost Savings. The annual cost savings, which could be realized by eliminating or reducing cycling losses, can be estimated as follows:

$$Annual\ Cost\ Savings = Annual\ Energy\ Savings \times FC$$

where: FC = fuel cost, $/MMBtu

Boiler Loading Energy Savings and Economics Example

Example Synopsis: A boiler's high pressure set point was increased to reduce the cycling losses of a given boiler. Before the change was implemented, the boiler cycled on and off 5 times per hour, during low load conditions. With the new set point, the boiler only cycles on and off 2 times per hour. The boiler operates at this low load condition approximately 2,500 hours per year, and has a firing rate at this reduced loading of 20%. The rated fuel consumption at full load is 10 MMBtu/hr, with an efficiency of 82%. The average fuel cost for the boiler is $9.00/MMBtu.

The annual energy savings can be estimated as:

$$Energy\ Savings = \left[\left(\frac{0.2 \times 10}{0.82 \times \left(1 - \frac{8}{100}\right)} \right) - \left(\frac{0.2 \times 10}{0.82 \times \left(1 - \frac{2}{100}\right)} \right) \right] \times 2{,}500$$

$$Energy\ Savings = 405.78\ MMBtu/yr$$

The annual cost savings can be estimated as:

$$Annual\ Cost\ Savings = (405.78\ MMBtu/yr) \times (\$9.00/MMBtu)$$

$$Annual\ Cost\ Savings = \$3{,}652/yr$$

An associated energy conservation measure that should be considered, in relation to boiler sequencing and control, relates to the number of boilers that operate to meet a given process or building load. The more boilers that operate to meet a given load, results in lower firing rates for each boiler. Boiler manufacturers should be contacted to acquire information on how well each boiler performs at a given firing rate, and the boilers should be operated accordingly to load the boilers as efficiently as possible. The site should also make every possible effort to reduce the number of boilers operating at a given time.

Operation and Maintenance – Persistence

Most boilers require daily attention including aspects of logging boiler functions, temperatures and pressures. Boiler operators need to continuously monitor the boiler's operation to ensure proper operation, efficiency and safety. For ideas on persistence actions see the Boiler Operations and Maintenance Checklist at the end of this section.

9.2.9.2 Boiler Measure #2: Boiler Combustion Efficiency

The boiler combustion process is affected by many variables including the temperature, pressure, and humidity of ambient air; the composition of the fuel and the rate of fuel and air supply to the process. It is important to note that the theoretical representation of the combustion process is just that – theoretical. It is important to consider all of the real-world inefficiencies and how the fuel and air actually come together when making combustion efficiency estimates.

O&M Tip:
A comprehensive tune-up with precision testing equipment to detect and correct excess air losses, smoking, unburned fuel losses, sooting, and high stack temperatures can result in *boiler* fuel savings of 2% to 20%.

Opportunity Identification

The efficiency of the combustion process is typically measured through the percent oxygen (O_2) in the exhaust gas. The amount of oxygen (or excess air as it is often referred to) in the exhaust gas is defined as the amount of air, above that which is theoretically required for complete combustion. It is imperative that boilers are operated with some excess air to ensure complete and safe combustion. Yet, the amount of excess air needs to be controlled so to minimize the losses associated with the heat that is expelled in the exhaust gases. Table 9.2.2 summarizes the typical optimum excess air requirements of conventional boilers (Doty and Turner 2009).

Table 9.2.2. Optimum excess air

Fuel Type	Firing Method	Optimum Excess Air (%)	Equivalent O_2 (by volume)
Natural gas	Natural draft	20 to 30	4 to 5
Natural gas	Forced draft	5 to 10	1 to 2
Natural gas	Low excess air	0.4 to 0.2	0.1 to 0.5
No. 2 oil	Rotary cup	15 to 20	3 to 4
No. 2 oil	Air-atomized	10 to 15	2 to 3
No. 2 oil	Steam-atomized	10 to 15	2 to 3
No. 6 oil	Steam-atomized	10 to 15	2 to 3

The tuned combustion efficiency values specific to the subject boiler are typically published by the manufacturer. These values, usually published as easy to use charts, will display the optimum combustion efficiency compared to the boiler load or firing rate. Using this information, site personnel can determine the maximum combustion efficiency at the average load of the subject boiler.

If the boiler has large variances in load (firing rate) throughout the year, and the given boiler combustion efficiency varies significantly with load (firing rate), the equation referenced below can be calculated for each season, with the appropriate efficiency and fuel consumption for the given season.

Tuning the Boiler. The boiler can be tuned by adjusting the air to fuel ratio linkages feeding the boiler burner. Experienced boiler operators will need to adjust the air to fuel linkages accordingly to increase or decrease the given ratios to achieve the optimum excess air and resulting combustion efficiency.

Diagnostic Equipment. To accurately measure combustion efficiency, excess air and a host of other diagnostic parameters, a combustion analyzer is recommended. These devices, made by a number of different manufacturers, are typically portable, handheld devices that are quick and easy to use. Most modern combustion analyzers will measure and calculate the following:

- Combustion air ambient temperature, T_a
- Stack temperature of the boiler, T_s
- Percent excess air, %
- Percent O_2, %
- Percent CO_2, %
- Percent CO, %
- Nitric Oxide, NX ppm
- Combustion efficiency, EF

A typical combustion analyzer is shown below in Figure 9.2.6. The probe seen in the picture is inserted in a hole in the exhaust stack of the boiler. If the boiler has a heat recovery system in the boiler exhaust stack, such as an economizer, the probe should be inserted above the heat recovery system. Figure 9.2.7 provides example locations for measurement of stack temperature and combustion air temperature readings (Combustion Analysis Basics 2004).

Figure 9.2.6. Combustion analyzer

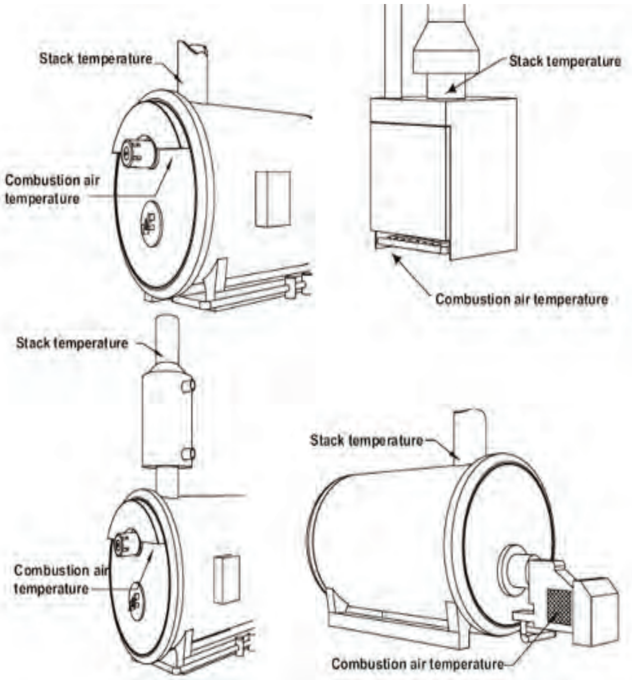


Figure 9.2.7. Example locations – combustion analysis

Energy Savings and Economics

Estimated Annual Energy Savings. The annual energy savings, which could be realized by improving combustion efficiency, can be estimated as follows:

$$\mathit{Annual\ Energy\ Savings} = \left[1 - \left(\frac{EFF_1}{EFF_2}\right)\right] \times AFC$$

where

EFF_1 = current combustion efficiency, %

EFF_2 = tuned combustion efficiency, %

AFC = annual fuel consumption, MMBtu/yr

Estimated Annual Cost Savings. The annual cost savings, which could be realized by improving combustion efficiency, can be estimated as follows:

$$\mathit{Annual\ Cost\ Savings} = \mathit{Annual\ Energy\ Savings} \times FC$$

where FC = fuel cost, \$/MMBtu

Combustion Efficiency Energy Savings and Economics Example

Example Synopsis: A boiler has an annual fuel consumption of 5,000 MMBtu/yr. A combustion efficiency test reveals an excess air ratio of 28.1%, an excess oxygen ratio of 5%, a flue gas temperature of 400°F, and a 79.5% combustion efficiency. The boiler manufacturer's specification sheets indicate that the boiler can safely operate at a 9.5% excess air ratio, which would reduce the flue gas temperature to 300°F and increase the combustion efficiency to 83.1%. The average fuel cost for the boiler is $9.00/MMBtu.

The annual energy savings can be estimated as:

$$\mathit{Annual\ Energy\ Savings} = \left[1 - \left(\frac{79.5}{83.1}\right)\right] \times 5{,}000$$

$$\mathit{Annual\ Energy\ Savings} = 216.61\ \mathit{MMBtu/yr}$$

The annual cost savings can be estimated as:

$$\mathit{Annual\ Cost\ Savings} = (216.61\ \mathit{MMBtu/yr})\ (\$9.00/\mathit{MMBtu}$$

$$\mathit{Annual\ Cost\ Savings} = \$1{,}949/\mathit{yr}$$

Operation and Maintenance – Persistence

Combustion analysis measurements should be taken regularly to ensure efficient boiler operation all year. Depending on use, boilers should be tuned at least annually; high use boilers at least twice annually.

Boilers that have highly variable loads throughout the year should consider the installation of online oxygen analyzers. These analyzers will monitor the O_2 in the exhaust gas and provide feedback to the linkages controlling the air to fuel ratios into the boilers burner (DOE 2002). This type of control usually offers significant savings by continuously changing the air to fuel linkages and maintaining optimum combustion efficiencies at all times. It should be noted that even if the boiler has an oxygen "trim" system, the boiler operators should periodically test the boilers with handheld combustion analyzers to ensure the automated controls are calibrated and operating properly.

9.2.9.3 Boiler Measure #3: Trending Boiler Stack Temperature

Trending the boiler stack temperature ensures the minimum amount of heat is expelled with the boiler's exhaust gases. This essentially minimizes the total thermal mass flowing with the exhaust air out of the boiler. A lower boiler stack temperature means more of the heat is going into the water or steam serving the process load or HVAC system in the building.

The stack temperature of the boiler can be optimized and maintained by making sure all heat transfer surfaces (both on the fire-side and on the water side) are clean. This is accomplished through an effective water treatment program (water side affect) and a fire-side cleaning program.

A final method of stack-gas temperature optimization can be accomplished through the use of a heat recovery system such as an economizer. An economizer places an air to water heat exchanger in the exhaust stack that uses the heat in the exhaust gases to preheat the feed water into the boiler.

9.2.9.4 Opportunity Identification

This section will focus on maintaining an effective water side maintenance/cleaning, and fire side cleaning program as these are no-low cost measures to implement, that should be part of the Operations and Maintenance program for the building.

Fire side Cleaning and Maintenance Program. Fire side cleaning consists of manually cleaning the particulates that accumulate on the fire side of the boiler. Reducing the residue on the fire side of the boiler increases the amount of heat that gets absorbed into the water, and helps maintain proper emissions from the boiler. Some particulate accumulation is normal for continuously operating boilers, but excessive fire side residue can be an indication of failed internal components that are expelling unburned fuel into the combustion chamber, causing excess sooting. Excess sooting can also be the result of incomplete combustion due to inadequate excess air.

Water side Cleaning and Maintenance Program. Hot water boilers are usually closed loop systems, therefore the boiler water is treated before it enters the boiler and piping, and does not require any additional chemicals or daily water treatment tests. Steam boilers on the other hand, lose steam due to a variety of circumstances and therefore require additional water to maintain consistent water levels. Boiler water-side maintenance for steam boilers consists of maintaining "soft water" for the feed-water and eliminating as much dissolved oxygen as possible. The first requires daily chemical monitoring and treatment of the feed-water. The presence of "hard-water" can create a "scale" buildup on the pipes. Once built up, the scale acts as an insulator and inhibits heat transfer into the boiler water. This creates excess heat in the combustion chamber that gets vented with the exhaust gases rather than absorbing into the process water.

O&M Tip:
Every 40°F reduction in net stack temperature (outlet temperature minus inlet combustion air temperature) is estimated to save 1% to 2% of a boiler's fuel use.

Scale formation on the water side of the boiler is due to poor water quality, as such, water must be treated before it enters the boiler. Table 9.2.3 presents the chemical limits recommended for Boiler-Water Concentrations (Doty and Turner 2009).

The table columns highlight the limits according to the American Boiler Manufacturers Association (ABMA) for ***total solids, alkalinity, suspended solids,*** and ***silica***. For each column heading the ABMA value represents the target limit while the column headed "Possible" represents the upper limit.

Table 9.2.3. Recommended limits for boiler-water concentrations

Drum Pressure (psig)	Total Solids		Alkalinity		Suspended Solids		Silica
	ABMA	Possible	ABMA	Possible	ABMA	Possible	ABMA
0 to 300	3,500	6,000	700	1,000	300	250	125
301 to 450	3,000	5,000	600	900	250	200	90
451 to 600	2,500	4,000	500	500	150	100	50
601 to 750	2,000	2,500	400	400	100	50	35
751 to 900	1,500	--	300	300	60	--	20
901 to 1,000	1,250	--	250	250	40	--	8
1,001 to 1,500	1,000	--	200	200	20	--	2

The second water-side maintenance activity requires an operational de-aerator to remove excess oxygen. Excess oxygen in the feed-water piping can lead to oxygen pitting and ultimately corrosion which can cause pipe failure. As seen in Figures 9.2.8 through 9.2.13, proper de-aerator operation is essential to prevent oxygen pitting which can cause catastrophic failures in steam systems (Eckerlin 2006).

Diagnostic Equipment

Diagnostic equipment consists of a boiler-stack thermometer and water treatment test equipment necessary to properly analyze the boiler water. Local water treatment companies should be contacted to determine the appropriate additives and controlling agents needed for the particular water compositions that are unique to the given community or region.

Figure 9.2.8. Boiler tube – scale deposit

Figure 9.2.9. Boiler tube – failure (rupture)

Energy Savings and Economics

Figure 9.2.14 presents energy loss percentage as a function of scale thickness. This information is very useful in estimating the resulting energy loss from scale build-up.

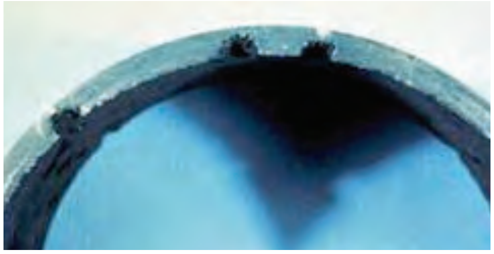


Figure 9.2.10. Feed-water pipe – oxygen pitting

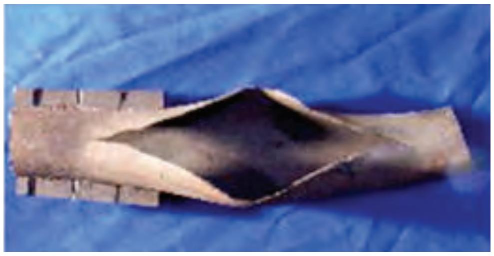


Figure 9.2.11. Boiler tube – failure (rupture)

Figure 9.2.12. Condensate pipe – oxygen pitting

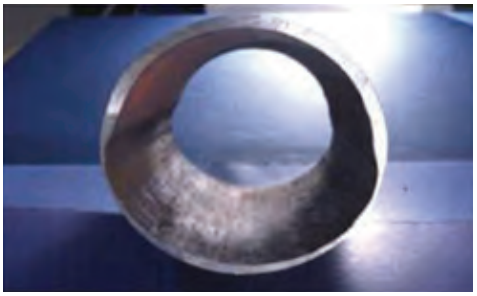


Figure 9.2.13. Condensate pipe – acidic corrosion

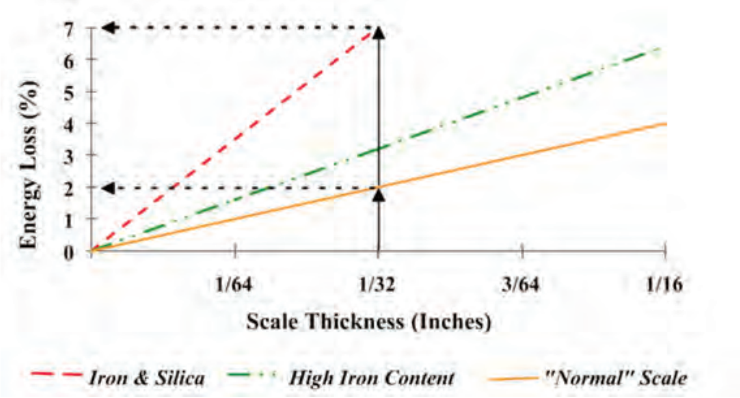


Figure 9.2.14. Boiler energy losses versus scale thickness

Estimated Annual Energy Savings

The annual energy savings, which could be realized by removing scale from the water side of the boiler, can be estimated as follows:

$$Annual\ Energy\ Savings = \left[\left(\frac{BL \times RFC}{EFF \times \left(1 - \frac{EL_1}{100}\right)} \right) - \left(\frac{BL \times RFC}{EFF \times \left(1 - \frac{EL_2}{100}\right)} \right) \right] \times H$$

where

BL = current boiler load or firing rate, %/100

RFC = rated fuel consumption at full load, MMBtu/hr

EFF = boiler efficiency, %/100

EL_1 = current energy loss due to scale buildup, %

EL_2 = tuned energy loss with out scale buildup, %

H = hours the boiler operates at the given cycling rate, hours

Estimated Annual Cost Savings

The annual cost savings, which could be realized by removing scale from the water side of the boiler, can be estimated as follows:

$$\textit{Annual Cost Savings} = \textit{Annual Energy Savings} \times FC$$

where

FC = fuel cost, \$/MMBtu

Boiler Tube Cleaning Energy Savings and Economics Example

Example Synopsis: After visually inspecting the water side of a water tube boiler, normal scale 3/64 inch thick was found on the inner surface of the tubes resulting in an estimated 3% efficiency penalty (see Figure 9.2.14). On-site O&M personnel are going to manually remove the scale. The boiler currently operates 4,000 hrs per year, at an average firing rate of 50%, with a boiler efficiency of 82% and a rated fuel consumption at full load of 10 MMBtu/hr. The average fuel cost for the boiler is $9.00/MMBtu.

The annual energy savings can be estimated as:

$$\textit{Annual Energy Savings} = \left[\left(\frac{0.5\times 10}{0.82\times\left(1-\frac{3}{100}\right)}\right)-\left(\frac{0.5\times 10}{0.82\times\left(1-\frac{0}{100}\right)}\right)\right]\times 2{,}000$$

$$\textit{Annual Energy Savings} = 377.17\ \textit{MMBtu/yr}$$

The annual cost savings can be estimated as:

$$\textit{Annual Cost Savings} = (377.17\ \textit{MMBtu/yr})(\$9.00/\textit{MMBtu})$$

$$\textit{Annual Cost Savings} = \$3{,}394/\textit{yr}$$

Operation and Maintenance – Persistence

- Boiler operators should record the results of the boiler water-chemistry tests daily. The water-chemistry tests should be recorded and benchmarked to determine the necessary treatment.
- Boiler operators should complete daily records of the de-aerator's operation to ensure continuous and proper operation.
- Boiler operators should take daily logs of stack temperature for trending purposes as this is a highly diagnostic indication of boiler heat-transfer-surface condition. An increasing stack temperature can be indicative of reduced heat transfer.
- The fire side of the boiler should be cleaned once a year, and is usually mandated by local emission regulatory committee.

The Boiler Operations and Maintenance Checklist, sample boiler maintenance log, and water quality test report form are provided at the end of this section for review and consideration.

9.2.10 Boiler Rules of Thumb

In the report, *Wise Rules for Industrial Energy Efficiency*, the EPA develops a comprehensive list of rules-of-thumb relating to boiler efficiency improvements. Some of these rules are presented below (EPA 2003):

- **Boiler Rule 1**. Effective boiler load management techniques, such as operating on high fire settings or installing smaller boilers, can save over 7% of a typical *facility's* total energy use with an average simple payback of less than 2 years.
- **Boiler Rule 2**. Load management measures, including optimal matching of boiler size and boiler load, can save as much as 50% of a *boiler's* fuel use.
- **Boiler Rule 3**. An upgraded boiler maintenance program including optimizing air-to-fuel ratio, burner maintenance, and tube cleaning, can save about 2% of a *facility's* total energy use with an average simply payback of 5 months.
- **Boiler Rule 4**. A comprehensive tune-up with precision testing equipment to detect and correct excess air losses, smoking, unburned fuel losses, sooting, and high stack temperatures can result in *boiler* fuel savings of 2% to 20%.
- **Boiler Rule 5**. A 3% decrease in flue gas O_2 typically produces *boiler* fuel savings of 2%.
- **Boiler Rule 6**. Every 40°F reduction in net stack temperature (outlet temperature minus inlet combustion air temperature is estimated to save 1% to 2% of a boiler's fuel use.
- **Boiler Rule 7**. Removing a 1/32 inch deposit on boiler heat transfer surfaces can decrease a boiler's fuel use by 2%; removal of a 1/8 inch deposit can decrease boiler fuel use by over 8%.
- **Boiler Rule 8**. For every 11°F that the entering feedwater temperature is increased, the boiler's fuel use is reduced by 1%.

9.2.10.1 Boiler Water-Use Best Practices

Boilers and steam generators are not only used in comfort heating applications, they are also used in institutional kitchens, or in facilities where large amounts of process steam are used. These systems use varying amounts of water depending on the size of the system, the amount of steam used, and the amount of condensate returned.

To maintain optimal equipment performance and minimized water use, the following guidelines are suggested:

- Install meters on boiler system make up lines to track system water use and trend.
- Install meters on make-up lines to recirculating closed water loop heating systems so that leaks can be easily detected.
- Boiler blowdown is the periodic or continuous removal of water from a boiler to remove accumulated dissolved solids and/or sludges and is a common mechanism to reduce contaminant build-up. Proper control of blowdown is critical to boiler operation. Insufficient blowdown may lead to efficiency reducing deposits on heat transfer surfaces. Excessive blowdown wastes water, energy, and chemicals. The American Society of Mechanical Engineers (ASME 1994) has developed a consensus on operating practices for boiler feedwater and blowdown that is related to operating pressure, which applies for both steam purity and deposition control.
- Consider obtaining the services of a water treatment specialist to prevent system scale, corrosion and optimize cycles of concentration. Treatment programs should include periodic checks of boiler water chemistry and automated chemical delivery to optimize performance and minimize water use.
- Develop and implement a routine inspection and maintenance program to check steam traps and steam lines for leaks. Repair leaks as soon as possible.
- Develop and implement a boiler tuning program to be completed a minimum of once per operating year.
- Provide proper insulation on piping and on the central storage tank.
- Develop and implement a routine inspection and maintenance program on condensate pumps.
- Regularly clean and inspect boiler water and fire tubes. Reducing scale buildup will improve heat transfer and the energy efficiency of the system.
- Employ an expansion tank to temper boiler blowdown drainage rather than cold water mixing.
- Maintain your condensate return system. By recycling condensate for reuse, water supply, chemical use, and operating costs for this equipment can be reduced by up to 70 percent. A condensate return system also helps lower energy costs as the condensate water is already hot and needs less heating to produce steam than water from other make-up sources.
- Install an automatic blowdown system based on boiler water quality to better manage the treatment of boiler make-up water.

9.2.11 Case Studies

Combustion Efficiency of a Natural Gas Boiler (OIT 2001)

A study of combustion efficiency of a 300 hp natural-gas-fired heating boiler was completed. Flue gas measurements were taken and found a temperature of 400°F and a percentage of oxygen of 6.2%. An efficient, well-tuned boiler of this type and size should have a percent oxygen reading of about 2% – corresponding to about 10% excess air. This extra oxygen in the flue gas translates into excess air (and its heat) traveling out of the boiler system – a waste of energy.

The calculated savings from bringing this boiler to the recommended oxygen/excess air level was about $730 per year. The cost to implement this action included the purchase of an inexpensive combustion analyzer costing $500. Thus, the cost savings of $730 would pay for the implementation cost of $500 in about 8 months. Added to these savings is the ability to tune other boilers at the site with this same analyzer.

9.2.12 Boiler Checklist, Sample Boiler Maintenance Log, and Water Quality Test

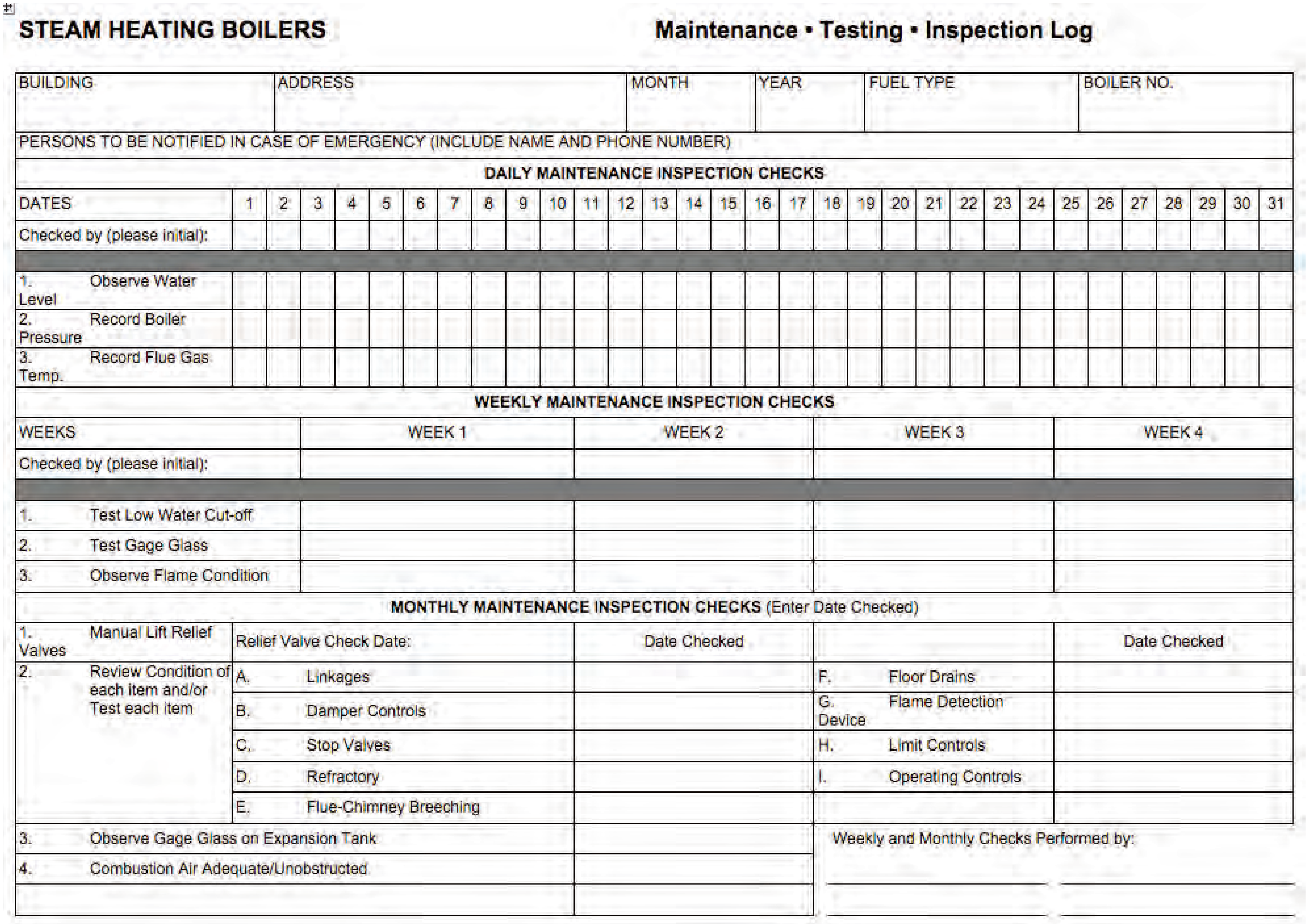
Description	Comments	Maintenance Frequency			
		Daily	Weekly	Monthly	Annually
Boiler use/sequencing	Turn off/sequence unnecessary boilers	X			
Overall visual inspection	Complete overall visual inspection to be sure all equipment is operating and safety systems are in place	X			
Follow manufacturer's recommended procedures in lubricating all components	Compare temperatures with tests performed after annual cleaning	X			
Check steam pressure	Is variation in steam pressure as expected under different loads? Wet steam may be produced if the pressure drops too fast	X			
Check unstable water level	Unstable levels can be a sign of contaminates in feedwater, overloading of boiler, equipment malfunction	X			
Check burner	Check for proper control and cleanliness	X			
Check motor condition	Check for proper function temperatures	X			
Check air temperatures in boiler room	Temperatures should not exceed or drop below design limits	X			
Boiler blowdown	Verify the bottom, surface and water column blow downs are occurring and are effective	X			

Boiler Checklist (contd)

Description	Comments	Maintenance Frequency			
		Daily	Weekly	Monthly	Annually
Boiler logs	Keep daily logs on: • Type and amount of fuel used • Flue gas temperature • Makeup water volume • Steam pressure, temperature, and amount generated Look for variations as a method of fault detection	X			
Check oil filter assemblies	Check and clean/replace oil filters and strainers	X			
Inspect oil heaters	Check to ensure that oil is at proper temperature prior to burning	X			
Check boiler water treatment	Confirm water treatment system is functioning properly	X			
Check flue gas temperatures and composition	Measure flue gas composition and temperatures at selected firing positions – recommended O_2% and CO_2% Fuel — O_2% — CO_2% Natural gas — 1.5 — 10 No. 2 fuel oil — 2.0 — 11.5 No. 6 fuel oil — 2.5 — 12.5 Note: percentages may vary due to fuel composition variations		X		
Check all relief valves	Check for leaks		X		
Check water level control	Stop feedwater pump and allow control to stop fuel flow to burner. Do not allow water level to drop below recommended level.		X		
Check pilot and burner assemblies	Clean pilot and burner following manufacturer's guidelines. Examine for mineral or corrosion buildup.		X		
Check boiler operating characteristics	Stop fuel flow and observe flame failure. Start boiler and observe characteristics of flame.		X		
Inspect system for water/ steam leaks and leakage opportunities	Look for: leaks, defective valves and traps, corroded piping, condition of insulation		X		
Inspect all linkages on combustion air dampers and fuel valves	Check for proper setting and tightness		X		
Inspect boiler for air leaks	Check damper seals		X		
Check blowdown and water treatment procedures	Determine if blowdown is adequate to prevent solids buildup			X	
Flue gases	Measure and compare last month's readings flue gas composition over entire firing range			X	

Boiler Checklist (contd)

Description	Comments	Maintenance Frequency			
		Daily	Weekly	Monthly	Annually
Combustion air supply	Check combustion air inlet to boiler room and boiler to make sure openings are adequate and clean			X	
Check fuel system	Check pressure gauge, pumps, filters and transfer lines. Clean filters as required.			X	
Check belts and packing glands	Check belts for proper tension. Check packing glands for compression leakage.			X	
Check for air leaks	Check for air leaks around access openings and flame scanner assembly.			X	
Check all blower belts	Check for tightness and minimum slippage.			X	
Check all gaskets	Check gaskets for tight sealing, replace if do not provide tight seal			X	
Inspect boiler insulation	Inspect all boiler insulation and casings for hot spots			X	
Steam control valves	Calibrate steam control valves as specified by manufacturer			X	
Pressure reducing/regulating	Check for proper operation valves			X	
Perform water quality test	Check water quality for proper chemical balance			X	
Clean water side surfaces	Follow manufacturer's recommendation on cleaning and preparing water side surfaces				X
Clean fire side	Follow manufacturer's recommendation on cleaning and preparing fire side surfaces				X
Inspect and repair refractories on fire side	Use recommended material and procedures				X
Relief valve	Remove and recondition or replace				X
Feedwater system	Clean and recondition feedwater pumps. Clean condensate receivers and deaeration system				X
Fuel system	Clean and recondition system pumps, filters, pilot, oil preheaters, oil storage tanks, etc.				X
Electrical systems	Clean all electrical terminals. Check electronic controls and replace any defective parts.				X
Hydraulic and pneumatic valves	Check operation and repair as necessary				X
Flue gases	Make adjustments to give optimal flue gas composition. Record composition, firing position, and temperature.				X
Eddy current test	As required, conduct eddy current test to assess tube wall thickness				X



STEAM HEATING BOILERS

Maintenance • Testing • Inspection Log

BUILDING	ADDRESS	MONTH	YEAR	FUEL TYPE	BOILER NO.

PERSONS TO BE NOTIFIED IN CASE OF EMERGENCY (INCLUDE NAME AND PHONE NUMBER)

DAILY MAINTENANCE INSPECTION CHECKS

DATES	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Checked by (please initial):																															
1. Observe Water Level																															
2. Record Boiler Pressure																															
3. Record Flue Gas Temp.																															

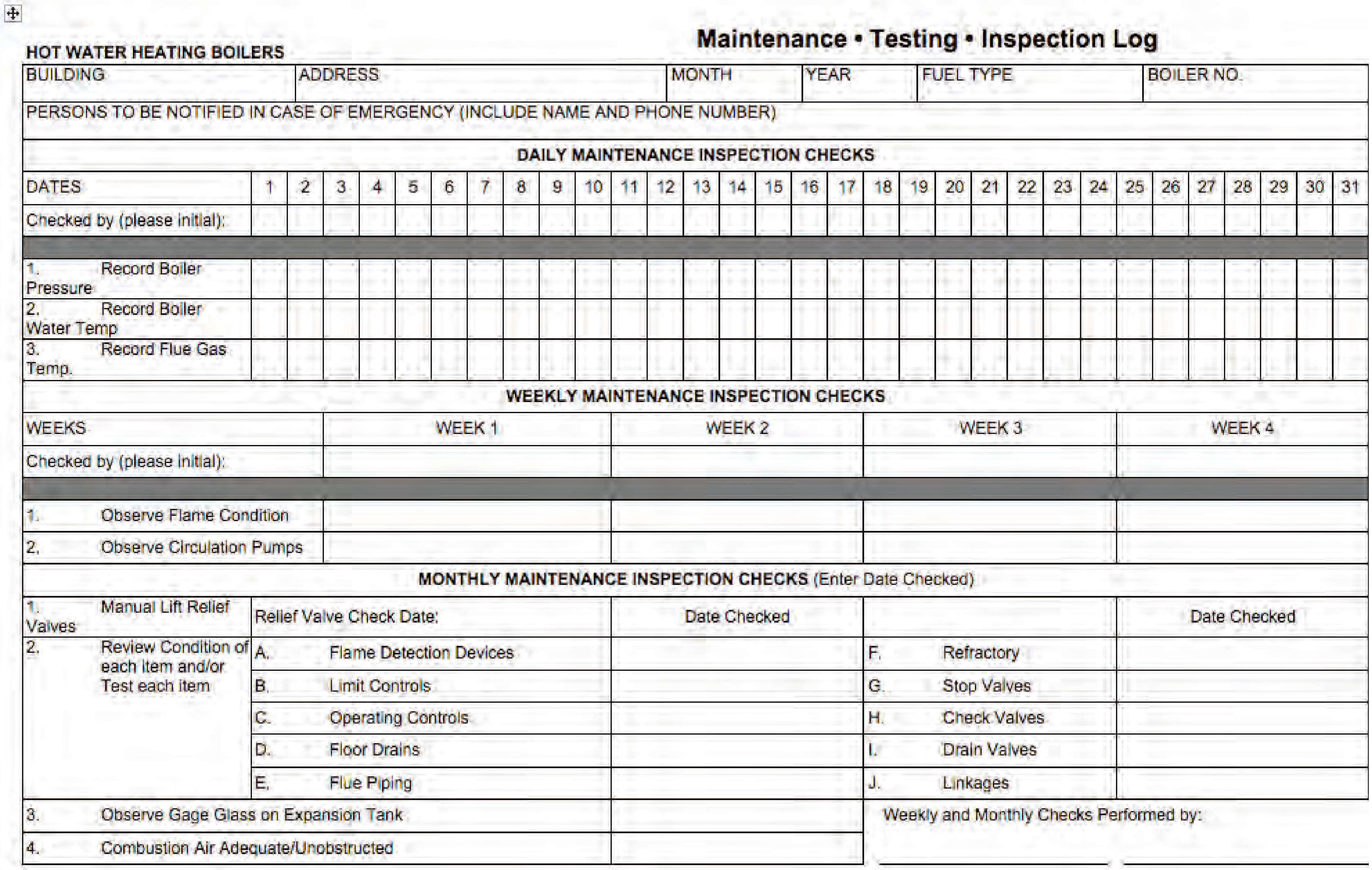
WEEKLY MAINTENANCE INSPECTION CHECKS

WEEKS	WEEK 1	WEEK 2	WEEK 3	WEEK 4
Checked by (please initial):				
1. Test Low Water Cut-off				
2. Test Gage Glass				
3. Observe Flame Condition				

MONTHLY MAINTENANCE INSPECTION CHECKS (Enter Date Checked)

1. Manual Lift Relief Valves	Relief Valve Check Date:	Date Checked		Date Checked
2. Review Condition of each item and/or Test each item	A. Linkages		F. Floor Drains	
	B. Damper Controls		G. Flame Detection Device	
	C. Stop Valves		H. Limit Controls	
	D. Refractory		I. Operating Controls	
	E. Flue-Chimney Breeching			
3. Observe Gage Glass on Expansion Tank			Weekly and Monthly Checks Performed by:	
4. Combustion Air Adequate/Unobstructed				

Boilers Checklist (contd)



HOT WATER HEATING BOILERS

Maintenance • Testing • Inspection Log

BUILDING	ADDRESS	MONTH	YEAR	FUEL TYPE	BOILER NO.
PERSONS TO BE NOTIFIED IN CASE OF EMERGENCY (INCLUDE NAME AND PHONE NUMBER)					

DAILY MAINTENANCE INSPECTION CHECKS

DATES	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Checked by (please initial):																															
1. Record Boiler Pressure																															
2. Record Boiler Water Temp																															
3. Record Flue Gas Temp.																															

WEEKLY MAINTENANCE INSPECTION CHECKS

WEEKS	WEEK 1	WEEK 2	WEEK 3	WEEK 4
Checked by (please initial):				
1. Observe Flame Condition				
2. Observe Circulation Pumps				

MONTHLY MAINTENANCE INSPECTION CHECKS (Enter Date Checked)

1. Manual Lift Relief Valves	Relief Valve Check Date:	Date Checked		Date Checked
2. Review Condition of each item and/or Test each item	A. Flame Detection Devices		F. Refractory	
	B. Limit Controls		G. Stop Valves	
	C. Operating Controls		H. Check Valves	
	D. Floor Drains		I. Drain Valves	
	E. Flue Piping		J. Linkages	
3. Observe Gage Glass on Expansion Tank			Weekly and Monthly Checks Performed by:	
4. Combustion Air Adequate/Unobstructed				

Sample Water Quality Test Form

Date	Softener	Feedwater			Boiler Water Test						Condensate		Lbs products fed/day			Operator Initials
	Total Hardness	TDS or Cond.	Total Hardness	pH	Bir. No.	O-Alk	TDS or Cond.	SiO_2	SO_3	Poly or PO_4	pH	TDS or Cond.				

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9.3 Steam Traps

9.3.1 Introduction

Steam traps are automatic valves that release condensed steam (condensate) from a steam space while preventing the loss of live steam. They also remove non-condensable gases from the steam space. Steam traps are designed to maintain steam energy efficiency for performing specific tasks such as heating a building or maintaining heat for process. Once steam has transferred heat through a process and becomes hot water, it is removed by the trap from the steam side as condensate and either returned to the boiler via condensate return lines or discharged to the atmosphere, which is a wasteful practice (Gorelik and Bandes 2001).

9.3.2 Types of Steam Traps (DOE 2001a)

Steam traps are commonly classified by the physical process causing them to open and close. The three major categories of steam traps are 1) mechanical, 2) thermostatic, and 3) thermodynamic. In addition, some steam traps combine characteristics of more than one of these basic categories.

9.3.2.1 Mechanical Steam Trap

The operation of a mechanical steam trap is driven by the difference in density between condensate and steam. The denser condensate rests on the bottom of any vessel containing the two fluids. As additional condensate is generated, its level in the vessel will rise. This action is transmitted to a valve via either a "free float" or a float and connecting levers in a mechanical steam trap. One common type of mechanical steam trap is the inverted bucket trap shown in Figure 9.3.1. Steam entering the submerged bucket causes it to rise upward and seal the valve against the valve seat. As the steam condenses inside the bucket or if condensate is predominately entering the bucket, the weight of the bucket will cause it to sink and pull the valve away from the valve seat. Any air or other non-condensable gases entering the bucket will cause it to float and the valve to close. Thus, the top of the bucket has a small hole to allow non-condensable gases to escape. The hole must be relatively small to avoid excessive steam loss.

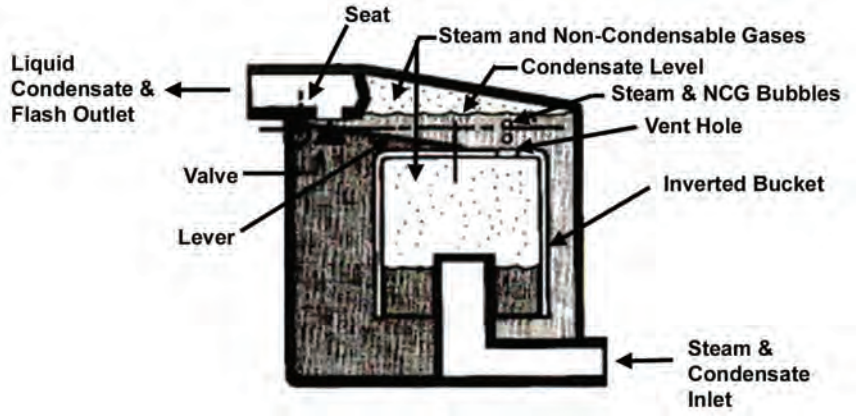

Figure 9.3.1. Inverted bucket steam trap

9.3.2.2 Thermostatic Steam Trap

As the name implies, the operation of a thermostatic steam trap is driven by the difference in temperature between steam and sub-cooled condensate. Valve actuation is achieved via expansion and contraction of a bimetallic element or a liquid-filled bellows. Bimetallic and bellows thermostatic traps are shown in Figures 9.3.2 and 9.3.3. Although both types of thermostatic traps close when exposure to steam expands the bimetallic element or bellows, there are important differences in design and operating characteristics. Upstream pressure works to open the valve in a bimetallic trap, while expansion of the bimetallic element works in the opposite direction. Note that changes in the downstream pressure will affect the temperature at which the valve opens or closes. In addition, the nonlinear relationship between steam pressure and temperature requires careful design of the bimetallic element for proper response at different operating pressures. Upstream and downstream pressures have the opposite affect in a bellows trap; an increase in upstream pressure tends to close the valve and vice versa. While higher temperatures still work to close the valve, the relationship between temperature and bellows expansion can be made to vary significantly by changing the fluid inside the bellows. Using water within the bellows results in nearly identical expansion as steam temperature and pressure increase, because pressure inside and outside the bellows is nearly balanced.

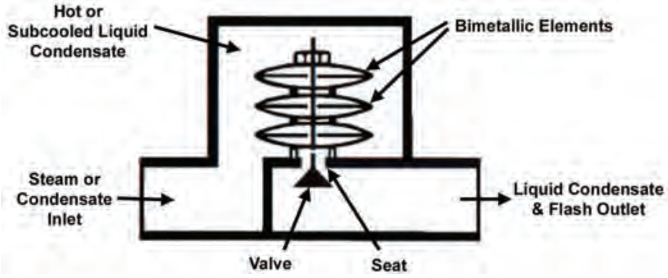

Figure 9.3.2. Bimetallic steam trap

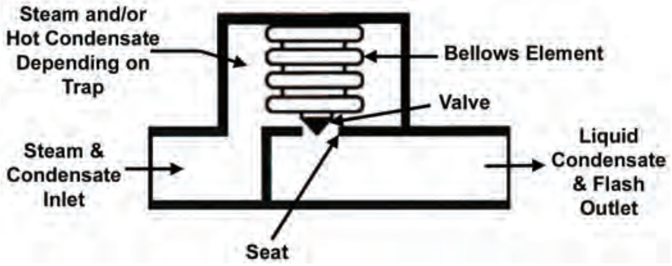

Figure 9.3.3. Bellows steam trap

In contrast to the inverted bucket trap, both types of thermostatic traps allow rapid purging of air at startup. The inverted bucket trap relies on fluid density differences to actuate its valve. Therefore, it cannot distinguish between air and steam and must purge air (and some steam) through a small hole. A thermostatic trap, on the other hand, relies on temperature differences to actuate its valve. Until warmed by steam, its valve will remain wide open, allowing the air to easily leave. After the trap warms up, its valve will close, and no continuous loss of steam through a purge hole occurs. Recognition of this deficiency with inverted bucket traps or other simple mechanical traps led to the development of float and thermostatic traps. The condensate release valve is driven by the level of condensate inside the trap, while an air release valve is driven by the temperature of the trap. A float and thermostatic trap, shown in Figure 9.3.4, has a

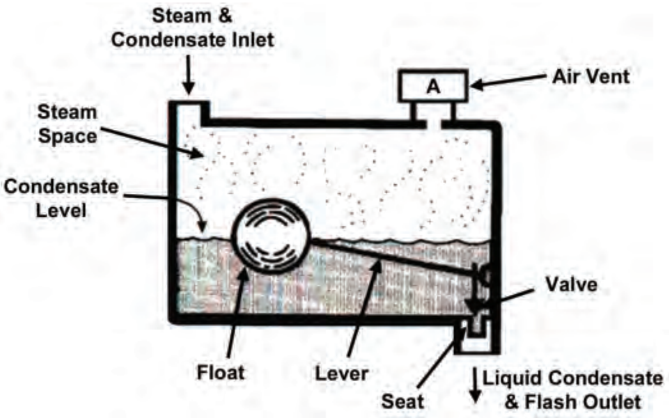

Figure 9.3.4. Float and thermostatic steam trap

float that controls the condensate valve and a thermostatic element. When condensate enters the trap, the float raises allowing condensate to exit. The thermostatic element opens only if there is a temperature drop around the element caused by air or other non-condensable gases.

9.3.2.3 Thermodynamic Steam Traps

Thermodynamic trap valves are driven by differences in the pressure applied by steam and condensate, with the presence of steam or condensate within the trap being affected by the design of the trap and its impact on local flow velocity and pressure. Disc, piston, and lever designs are three types of thermodynamic traps with similar operating principles; a disc trap is shown in Figure 9.3.5. When sub-cooled condensate enters the trap, the increase in pressure lifts the disc off its valve seat and allows the condensate to flow into the chamber and out of the trap. The narrow inlet port results in a localized increase in velocity and decrease in pressure as the condensate flows through the trap, following the first law of thermodynamics and the Bernoulli equation. As the condensate entering the trap increases in temperature, it will eventually flash to steam because of the localized pressure drop just described. This increases the velocity and decreases the pressure even further, causing the disc to snap close against the seating surface. The moderate pressure of the flash steam on top of the disc acts on the entire disc surface, creating a greater force than the higher pressure steam and condensate at the inlet, which acts on a much smaller portion on the opposite side of the disc. Eventually, the disc chamber will cool, the flash steam will condense, and inlet condensate will again have adequate pressure to lift the disc and repeat the cycle.

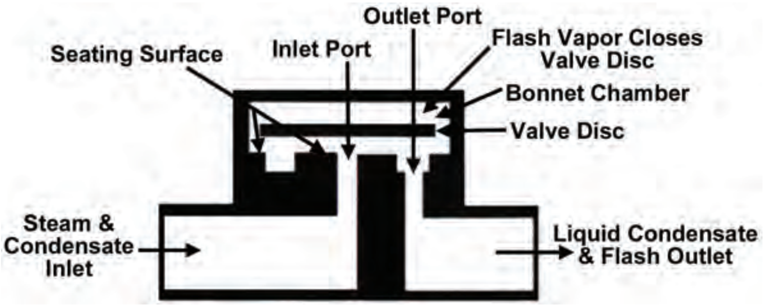

Figure 9.3.5. Disc steam trap

9.3.2.4 Other Steam Traps

Another type of steam trap is the fixed orifice steam trap. Fixed orifice traps contain a set orifice in the trap body and continually discharge condensate. They are said to be self-regulating. As the rate of condensation decreases, the condensate temperature will increase, causing a throttling in the orifice and reducing capacity due to steam flashing on the downstream side. An increased load will decrease flashing and the orifice capacity will become greater (Gorelik and Bandes 2001). Orifice steam traps function best in situations with relatively constant steam loads. In situations where steam loads vary, the orifice trap either is allowing steam to escape or condensate to back up into the system. Varying loads, such as those found in most steam heating systems, are usually not good candidates for orifice steam traps. Before an orifice trap is specified, a careful analysis of appropriateness is recommended – preferably done by someone not selling orifice steam traps!

9.3.3 Safety Issues

When steam traps cause a backup of condensate in a steam main, the condensate is carried along with the steam. It lowers steam quality and increases the potential for water hammer. Not only will energy be wasted, equipment can be destroyed. Water hammer occurs as slugs of water are picked up at high speeds in a poorly designed steam main, in pipe coils, or where there is a lift after a steam trap. In some systems, the flow may be at 120 feet per second, which is about 82 mph. As the slug of condensate is carried along the steam line, it reaches an obstruction, such as a bend or a valve, where it is suddenly stopped. The effect of this impact can be catastrophic. It is important to note that the damaging effect of water hammer is due to steam velocity, not steam pressure. It can be as damaging in low-pressure systems as it can in high. This can actually produce a safety hazard, as the force of water hammer can blow out a valve or a strainer. Condensate in a steam system can be very destructive. It can cause valves to become wiredrawn (worn or ground) and unable to hold temperatures as required. Little beads of water in a steam line can eventually cut any small orifices the steam normally passes through. Wiredrawing will eventually cut enough of the metal in a valve seat that it prevents adequate closure, producing leakage in the system (Gorelik and Bandes 2001).

9.3.4 Cost and Energy Efficiency (DOE 2001a)

Monitoring and evaluation equipment does not save any energy directly, but identifies traps that have failed and whether failure has occurred in an open or closed position. Traps failing in an open position allow steam to pass continuously, as long as the system is energized. The rate of energy loss can be estimated based on the size of the orifice and system steam pressure using the relationship illustrated in Figure 9.3.6. This figure is derived

The use of Figure 9.3.6 is illustrated via the following example. Inspection and observation of a trap led to the judgment that it had failed in the fully open position and was blowing steam. Manufacturer data indicated that the actual orifice diameter was 3/8 inch. The trap operated at 60 psia and was energized for 50% of the year. Boiler efficiency was estimated to be 75%. Calculation of annual energy loss for this example is illustrated below.

Estimating steam loss using Figure 9.3.6.

Assume: 3/8-inch diameter orifice steam trap, 50% blocked, 60 psia saturated steam system, steam system energized 4,380 h/yr (50% of year), 75% boiler efficiency.

- Using Figure 9.3.6 for 3/8-inch orifice and 60 psia steam, steam loss = 2,500 million Btu/yr.
- Assuming trap is 50% blocked, annual steam loss estimate = 1,250 million Btu/yr.
- Assuming steam system is energized 50% of the year, energy loss = 625 million Btu/yr.
- Assuming a fuel value of $5.00 per million cubic feet (1 million Btu boiler input).

Annual fuel loss including boiler losses = [(625 million Btu/yr)/(75% efficiency) ($5.00/million Btu)] = $4,165/yr.

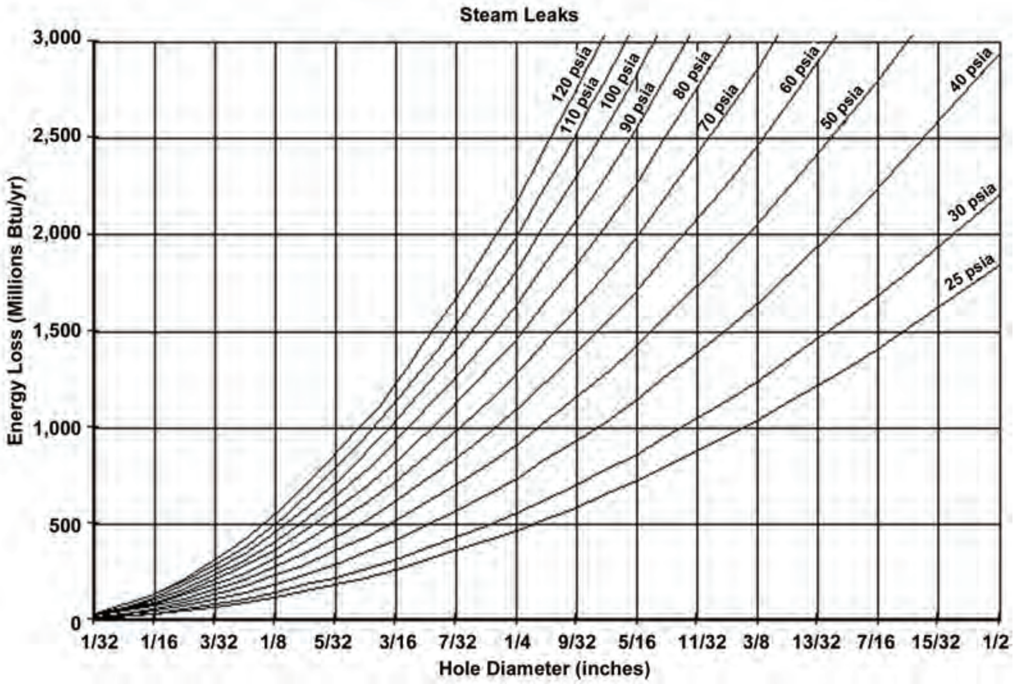

Figure 9.3.6. Energy loss from leaking steam traps.

from Grashof's equation for steam discharge through an orifice (Avallone and Baumeister 1986) and assumes the trap is energized (leaks) the entire year, all steam leak energy is lost, and that makeup water is available at an average temperature of 60°F. Boiler losses are not included in Figure 9.3.6, so must be accounted for separately. Thus, adjustments from the raw estimate read from this figure must be made to account for less than full-time steam supply and for boiler losses.

The maximum steam loss rate occurs when a trap fails with its valve stuck in a fully opened position. While this failure mode is relatively common, the actual orifice size could be any fraction of the fully opened position. Therefore, judgment must be applied to estimate the orifice size associated with a specific malfunctioning trap. Lacking better data, assuming a trap has failed with an orifice size equivalent to one-half of its fully-opened condition is probably prudent.

9.3.4.1 Other Costs

Where condensate is not returned to the boiler, water losses will be proportional to the energy losses noted above. Feedwater treatment costs (i.e., chemical to treat makeup water) will also be proportionately increased. In turn, an increase in make-up water increases the blowdown requirement and associated energy and water losses. Even where condensate is returned to the boiler, steam bypassing a trap may not condense prior to arriving at the deaerator, where it may be vented along with the non-condensable gases. Steam losses also represent a loss in steam-heating capacity, which could result in an inability to maintain the indoor design temperature on winter days or reduce production capacity in process heating applications. Traps that fail closed do not result in energy or water losses, but can also result in significant capacity reduction (as the condensate takes up pipe cross-sectional area that otherwise would be available for steam flow). Of generally more critical concern is the physical damage that can result from the irregular movement of condensate in a two-phase system, a problem commonly referred to as "water hammer."

9.3.5 Maintenance of Steam Traps

Considering that many Federal sites have hundreds if not thousands of traps, and that one malfunctioning steam trap can cost thousands of dollars in wasted steam per year, steam trap maintenance should receive a constant and dedicated effort.

Excluding design problems, two of the most common causes of trap failure are oversizing and dirt.

- Oversizing causes traps to work too hard. In some cases, this can result in blowing of live steam. As an example, an inverted bucket trap can lose its prime due to an abrupt change in pressure. This will cause the bucket to sink, forcing the valve open.
- Dirt is always being created in a steam system. Excessive build-up can cause plugging or prevent a valve from closing. Dirt is generally produced from pipe scale or from over-treating of chemicals in a boiler.

9.3.5.1 Characteristics of Steam Trap Failure (Gorelik and Bandes 2001)

- ***Mechanical Steam Trap (Inverted Bucket Steam Trap)*** – Inverted bucket traps have a "bucket" that rises or falls as steam and/or condensate enters the trap body. When steam is in the body, the bucket rises closing a valve. As condensate enters, the bucket sinks down, opening a valve and allowing the condensate to drain. Inverted bucket traps are ideally suited for water-hammer conditions but may be subject to freezing in low temperature climates if not insulated. Usually, when this trap fails, it fails open. Either the bucket loses its prime and sinks or impurities in the system may prevent the valve from closing.
- ***Thermostatic Steam Trap (Bimetallic and Bellows Steam Traps)*** – Thermostatic traps have, as the main operating element, a metallic corrugated bellows that is filled with an alcohol mixture that has a boiling point lower than that of water. The bellows will contract when in contact with condensate and expand when steam is present. Should a heavy condensate load occur, such as in start-up, the bellows will remain in a contracted state, allowing condensate to flow continuously. As steam builds up, the bellows will close. Therefore, there will be moments when this trap will act as a "continuous flow" type while at other times, it will act intermittently as it opens and closes to condensate and steam, or it may remain totally closed. These traps adjust automatically to variations of steam pressure but may be damaged in the presence of water hammer. They can fail open should the bellows become damaged or due to particulates in the valve hole, preventing adequate closing. There can be times when the tray becomes plugged and will fail closed.

Checklist Indicating Possible Steam Trap Failure

- Abnormally warm boiler room.
- Condensate received venting steam.
- Condensate pump water seal failing prematurely.
- Overheating or underheating in conditioned space.
- Boiler operating pressure difficult to maintain.
- Vacuum in return lines difficult to maintain.
- Water hammer in steam lines.
- Steam in condensate return lines.
- Higher than normal energy bill.
- Inlet and outlet lines to trap nearly the same temperature.

- ***Thermodynamic Steam Trap (Disc Steam Trap)*** – Thermodynamic traps have a disc that rises and falls depending on the variations in pressure between steam and condensate. Steam will tend to keep the disc down or closed. As condensate builds up, it reduces the pressure in the upper chamber and allows the disc to move up for condensate discharge. This trap is a good general type trap where steam pressures remain constant. It can handle superheat and "water hammer" but is not recommended for process, since it has a tendency to air-bind and does not handle pressure fluctuations well. A thermodynamic trap usually fails open. There are other conditions that may indicate steam wastage, such as "motor boating," in which the disc begins to wear and fluctuates rapidly, allowing steam to leak through.
- ***Other Steam Traps (Thermostatic and Float Steam Trap and Orifice Steam Trap)*** – Float and thermostatic traps consist of a ball float and a thermostatic bellows element. As condensate flows through the body, the float rises or falls, opening the valve according to the flow rate. The thermostatic element discharges air from the steam lines. They are good in heavy and light loads and on high and low pressure, but are not recommended where water hammer is a possibility. When these traps fail, they usually fail closed. However, the ball float may become damaged and sink down, failing in the open position. The thermostatic element may also fail and cause a "fail open" condition.

  For the case of fixed orifice traps, there is the possibility that on light loads these traps will pass live steam. There is also a tendency to waterlog under wide load variations. They can become clogged due to particulate buildup in the orifice and at times impurities can cause erosion and damage the orifice size, causing a blow-by of steam.

General Requirements for Safe and Efficient Operation of Steam Traps

(Climate Technology Initiative 2001)

1. Every operating area should have a program to routinely check steam traps for proper operation. Testing frequency depends on local experiences but should at least occur yearly.
2. All traps should be numbered and locations mapped for easier testing and record-keeping. Trap supply and return lines should be noted to simplify isolation and repair.
3. Maintenance and operational personnel should be adequately trained in trap testing techniques. Where ultrasonic testing is needed, specially trained personnel should be used.
4. High maintenance priority should be given to the repair or maintenance of failed traps. Attention to such a timely maintenance procedure can reduce failures to 3% to 5% or less. A failed open trap can mean steam losses of 50 to 100 lb/hr.
5. All traps in closed systems should have atmospheric vents so that trap operation can be visually checked. If trap headers are not equipped with these, they should be modified.
6. Proper trap design should be selected for each specific application. Inverted bucket traps may be preferred over thermostatic and thermodynamic-type traps for certain applications.
7. It is important to be able to observe the discharge from traps through the header. Although several different techniques can be used, the most foolproof method for testing traps is observation. Without proper training, ultrasonic, acoustical, and pyrometric test methods can lead to erroneous conclusions.
8. Traps should be properly sized for the expected condensate load. Improper sizing can cause steam losses, freezing, and mechanical failures.
9. Condensate collection systems should be properly designed to minimize frozen and/or premature trap failures. Condensate piping should be sized to accommodate 10% of the traps failing to open.

9.3.6 Performance Assessment

Methods

Steam trap performance assessment is basically concerned with answering the following two questions: 1) Is the trap working correctly or not? 2) If not, has the trap failed in the open or closed position? Traps that fail open result in a loss of steam and its energy. Where condensate is not returned, the water is lost as well. The result is significant economic loss, directly via increased boiler plant costs, and potentially indirectly, via decreased steam heating capacity. Traps that fail closed do not result in energy or water losses, but can result in significantly reduced heating capacity and/or damage to steam heating equipment.

There are three basic methods for evaluating a steam trap that are commonly discussed in the literature: sight, sound, and temperature. Because of the challenges associated with steam trap assessment, at least two of the three methods should be used to increase the chances of correctly identifying the condition of a steam trap.

Sight Method

The sight method is usually based on a visual observation of the fluid downstream of the trap. This is possible if there is no condensate recovery system or if test valves have been installed to allow a momentary discharge of the downstream fluid from the condensate recovery system. In either case, the steam trap evaluator must be able to distinguish between “flash” steam, which is characteristic of a properly working trap, and “live” steam, which is characteristic of a trap that has failed open and is leaking or blowing a significant amount of steam. Flash steam is created when a portion of the condensate flashes to vapor upon expansion to atmospheric pressure. Flash steam is characterized by a relatively lazy, billowy plume. Live steam, on the other hand, will form a much sharper, higher velocity plume that may not be immediately visible as it exits the test valve or steam trap. The difference between live steam and flash steam is illustrated in Figure 9.3.7.

Figure 9.3.7. Live steam (left) versus flash steam (right)

Sight glasses can also be used for a visual observation, but have some drawbacks that must be overcome or avoided. First, steam and condensate are both expected to exist upstream and downstream of the trap (live steam on the upstream side and flash steam on the downstream side). Second, the view through a sight glass tends to deteriorate over time because of internal or external fouling. Third, both steam and condensate will appear as clear fluids within the pipe. In response to the first and third concerns, sight glasses have been developed with internal features that allow the proportion of steam and condensate to be identified.

Sound Method

Mechanisms within steam traps and the flow of steam and condensate through steam traps generate sonic (audible to the human ear) and supersonic sounds. Proper listening equipment, coupled with the knowledge of normal and abnormal sounds, can yield reliable assessments of steam trap working condition. Listening devices range from a screwdriver or simple mechanic's stethoscope that allow listening to sonic sounds to more sophisticated electronic devices that allow "listening" to sonic or sonic and ultrasonic sounds at selected frequencies. The most sophisticated devices compare measured sounds with the expected sounds of working and non-working traps to render a judgment on trap condition.

Temperature Method

Measuring the temperature of the steam trap is generally regarded as the least reliable of the three basic evaluation techniques. Saturated steam and condensate exist at the same temperature, of course, so it's not possible to distinguish between the two based on temperature. Still, temperature measurement provides important information for evaluation purposes. A cold trap (i.e., one that is significantly cooler than the expected saturated steam temperature) indicates that the trap is flooded with condensate, assuming the trap is in service. A flooded trap could mean several things, but barring measurement during startup, when flooding can be expected, generally indicates a problem that needs to be addressed. Downstream temperature measurement may also yield useful clues in certain circumstances. For example, the temperature downstream of a trap should drop off relatively quickly if the trap is working properly (mostly condensate immediately past the trap). On the other hand, the temperature downstream of the trap will be nearly constant if significant steam is getting past the trap. Care must be taken not to use this technique where other traps could affect downstream conditions, however. Temperature measurement methods, like sound measurement, vary tremendously in the degree of sophistication. At the low-end, spitting on the trap and watching the sizzle provides a general indication of temperature. For the more genteel, a squirt bottle filled with water will serve the same purpose. Alternatively, a glove-covered hand can provide a similar level of accuracy. More sophisticated are various types of temperature sensitive crayons or tapes designed to change color in different temperature ranges. Thermometers, thermocouples, and other devices requiring contact with the trap offer better precision. Finally, non-contact (i.e., infrared) temperature measuring devices (sensing thermometers and cameras) provide the precision of thermometers and thermocouples without requiring physical contact. Non-contact temperature measurement makes it easier to evaluate traps that are relatively difficult or dangerous to access closely.

Automated Diagnostics

In recent years a number of manufacturers have devised self-diagnosing steam trap routines. In most cases these are based on absence or presence of condensate in the trap as measured by either temperature and/or conductivity. These systems can be connected to an energy management and control system to notify facilities staff of condition or failure. While the remote and self diagnosing aspects of these systems is quite attractive, the vendor should make the facility manager aware that once the sensing element is compromised, the system may be outputting incorrect information and thus lead to a false sense of security. While these systems hold great promise, the user needs to be aware that they are another item that needs to be maintained for proper function.

Recommended time schedule for testing steam traps

- Process steam traps: Every 3 months
- High pressure steam traps: Every 6 months
- Low to medium pressure steam traps: Every 6 months
- Building heating steam traps: Twice a heating season

At an absolute minimum, all steam traps should be surveyed and tested at least once per year

9.3.7 Diagnostic Equipment

- Thermography – An infrared thermometer or camera allows for an accurate, non-contact assessment of temperature. Applications for steam traps include testing for proper function and insulation assessments around the traps. More information on thermography can be found in Chapter 6.
- Ultrasonic analyzer – Steam traps emit very distinct sound patterns; each trap type is said to have a particular signature. These sounds are not audible to the unaided ear. Using an ultrasonic detector, the analyst is able to isolate the frequency of sound being emitted by the steam trap, compare it to trended sound signatures, and make an assessment. Changes in these ultrasonic wave emissions are indicative of changes in steam trap function. More information on ultrasonic analysis can be found in Chapter 6.

9.3.8 Relevant Operational/Energy Efficiency Measures

There are many operational/energy efficiency measures that could be presented for proper steam trap operation and control. The following section focuses on the most prevalent O&M recommendations having the greatest energy impacts at Federal facilities. These recommendations are also some of the most easily implemented for boiler operators and O&M contractors.

Steam Trap Measure: Cost Evaluation of Failed Steam Trap

Table 9.3.1 below can be used to approximate the energy loss from a failed-open steam trap (DOE 2006).

Table 9.3.1. Steam trap discharge rate

Trap Orifice Diameter (in.)	Steam Loss (lb/hr)			
	Steam Pressure (psig)			
	15	100	150	300
1/32	0.85	3.3	4.8	–
1/16	3.40	13.2	18.9	36.2
1/8	13.7	52.8	75.8	145
3/16	30.7	119	170	326
¼	54.7	211	303	579
3/8	123	475	682	1,303

Estimated Annual Energy Savings. The annual energy savings, which could be realized by repairing a failed steam trap, can be estimated as follows (DOE 2006).

$$\textit{Annual Energy Savings} = \frac{DR \times H}{1{,}000}$$

where

DR = discharge rate of steam, lb/hr

H = annual hours of operation, hours

Estimated Annual Cost Savings. The annual cost savings, which could be realized by repairing a failed steam trap, can be estimated as follows:

$$\textit{Annual Cost Savings} = \textit{Annual Energy Savings} \times FCS$$

where

FCS = average fuel cost of steam, $/1,000 lb of steam

It should be noted that this cost savings calculation assumes on-site personnel have benchmarked the fuel cost of steam production. This will display how much the site is paying to produce steam, on a $/1,000 lb of steam basis.

Steam Trap Replacement Energy Savings and Economics Example

Example Synopsis

A steam system audit reveals a failed steam trap in a steam line pressurized to 100 psig. The steam trap has an orifice diameter of 1/8 of an inch and results in a loss rate of 52.8 lb/hr (see Table 9.3.1). The line is energized 8,000 hrs/yr and the current fuel costs are $10/1,000 lb of steam.

The annual energy savings can be estimated as:

$$\textit{Annual Energy Savings} = \frac{52.8 \times 8{,}000}{1{,}000}$$

$$\textit{Annual Energy Savings} = 422.4(1{,}000\ \textit{lb/yr})$$

The annual cost savings can be estimated as:

$$\textit{Annual Cost Savings} = (422.4(1{,}000\ \textit{lb/yr}))(\$10.00/1{,}000\ \textit{lb})$$

$$\textit{Annual Cost Savings} = \$4{,}224/\textit{yr}$$

9.3.8.1 Steam Trap Water-Use Best Practices

The predominant impact steam traps have on water use relates to proper function. A steam trap that is failed open coupled to distribution system with a leaky or non-existent condensate return will be losing water, via condensed steam, at a significant rate. Whether failed open or closed an improperly functioning steam trap impacts the entire system by introducing inefficiency. Any inefficiency results in a less-than-optimal operation leading to increased resource use – water is one of those resources.

9.3.9 Case Studies

1986 Event at a Major Research Government Facility (DOE 2001b)

On October 10, 1986, a condensate-induced water hammer at a major research government facility injured four steamfitters–two of them fatally. One of the steamfitters attempted to activate an 8-inch steam line located in a manhole. He noticed that there was no steam in either the steam line or the steam trap assembly and concluded that the steam trap had failed. Steam traps are devices designed to automatically remove condensate (liquid) from steam piping while the steam system is operating in a steady state. Without shutting off the steam supply, he and another steamfitter replaced the trap and left.

Later the first steamfitter, his supervisor, and two other steamfitters returned and found the line held a large amount of condensate. They cracked open a gate valve to drain the condensate into an 8-inch main. They cracked the valve open enough to allow water to pass, but this was too far open to control the sudden movement of steam into the main after all the condensate had been removed. A series of powerful water hammer surges caused the gaskets on two blind flanges in the manhole to fail, releasing hot condensate and steam into the manhole. A photograph of one failed gasket is shown in Figure 9.3.8. All four steamfitters suffered external burns and steam inhalation. Two of them died as a result.

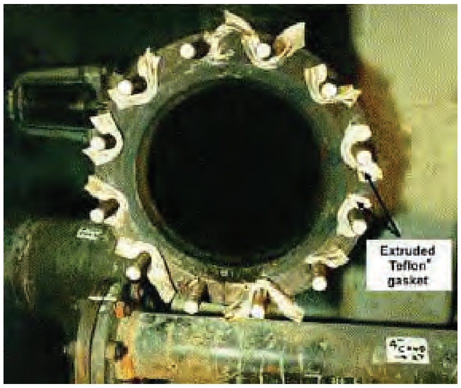

Figure 9.3.8. Failed gasket on blind flange

A Type A Accident Investigation Board determined that the probable cause of the event was a lack of procedures and training, resulting in operational error. Operators had used an in-line gate valve to remove condensate from a steam line under pressure instead of drains installed for that purpose.

The board also cited several management problems. There had been no Operational Readiness Review prior to system activation. Laboratory personnel had not witnessed all the hydrostatic and pressure testing, nor had all test results been submitted, as required by the contract. Documentation for design changes was inadequate.

1991 Event at a Georgia Hospital (DOE 2001c)

In June 1991, a valve gasket blew out in a steam system at a Georgia hospital. Operators isolated that section of the line and replaced the gasket. The section was closed for 2 weeks, allowing condensate to accumulate in the line. After the repair was completed, an operator opened the steam valve at the upstream end of the section. He drove to the other end and started to open the downstream steam valve. He did not open the blow-off valve to remove condensate before he opened the steam valve. Water hammer ruptured the valve before it was 20% open, releasing steam and condensate and killing the operator.

Investigators determined that about 1,900 pounds of water had accumulated at the low point in the line adjacent to the repaired valve, where a steam trap had been disconnected. Because the line was cold, the incoming steam condensed quickly, lowering the system pressure and accelerating the steam flow into the section. This swept the accumulated water toward the downstream valve and may have produced a relatively small steam-propelled water slug impact before the operator arrived. About 600 pounds of steam condensed in the cold section of the pipe before equilibrium was reached.

When the downstream valve was opened, the steam on the downstream side rapidly condensed into water on the upstream side. This flow picked up a 75 cubic foot slug of water about 400 feet downstream of the valve. The slug sealed off a steam pocket and accelerated until it hit the valve, causing it to rupture.

Investigators concluded that the accident could have been prevented if the operator had allowed the pipe to warm up first and if he had used the blow-off valve to remove condensate before opening the downstream valve.

Maintenance of Steam Traps

A steam trap assessment of three VA hospitals located in Providence, RI, Brockton, MA, and West Roxbury, MA was conducted with help of FEMP's SAVEnergy Program. The facilities are served by 15, 40, and 80 psig steam lines. The Providence system alone includes approximately 1,100 steam traps.

The assessment targeted steam trap performance and the value of steam losses from malfunctioning traps. The malfunctioning traps were designated for either repair or replacement. Included in this assessment was a training program on steam trap testing.

The cost of the initial steam trap audit was $25,000 for the three facilities. Estimated energy savings totaled $104,000. The cost of repair and replacement traps was about $10,000. Thus, the cost savings of $104,000 would pay for the implementation cost of $35,000 in about 4 months.

9.3.10 Steam Traps Checklist

Description	Comments	Maintenance Frequency			
		Daily	Weekly	Monthly	Annually
Test steam traps	Daily/weekly test recommended for high-pressure traps (250 psig or more)	X			
Test steam traps	Weekly/monthly test recommended for medium-pressure traps (30-250 psig)		X		
Test steam traps	Monthly/annually test recommended for low-pressure traps			X	
Repair/replace steam traps	When testing shows problems. Typically, traps should be replaced every 3-4 years.			X	
Replace steam traps	When replacing, take the time to make sure traps are sized properly.				X

9.3.11 References

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9.4 Chillers

9.4.1 Introduction

A chiller can be generally classified as a refrigeration system that cools water. Similar to an air conditioner, a chiller uses either a vapor-compression or absorption cycle to cool. Once cooled, chilled water has a variety of applications from space cooling to process uses.

9.4.2 Types of Chillers

9.4.2.1 Mechanical Compression Chiller (Dyer and Maples 1995)

The refrigeration cycle of a simple mechanical compression system is shown in Figure 9.4.1. The mechanical compression cycle has four basic components through which the refrigerant passes: (1) the evaporator, (2) the compressor, (3) the condenser, and (4) the expansion valve. The evaporator operates at a low pressure (and low temperature) and the condenser operates at high pressure (and temperature).

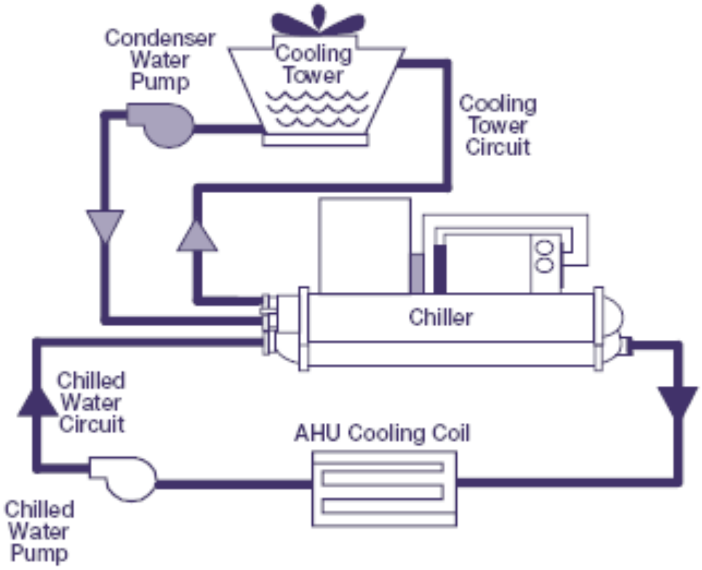

Figure 9.4.1. Typical chiller plant

The chiller cycle begins in the evaporator coils located in the chiller where the liquid refrigerant flows over the evaporator tube bundles and evaporates, absorbing heat from the chilled water circulating through the tube bundle. The refrigerant vapor, which is somewhat cooler than the chilled water temperature, is drawn out of the evaporator by the compressor. The compressor "pumps" the refrigerant vapor to the condenser by raising the refrigerant pressure (and thus, temperature). The refrigerant condenses on the cooling water coils of the condenser giving up its heat to the cooling water. The high-pressure liquid refrigerant from the condenser then passes through the expansion device that reduces the refrigerant pressure (and temperature) to that of the evaporator. The refrigerant again flows over the chilled water coils absorbing more heat and completing the cycle. Mechanical compression chillers are generally classified by compressor type: reciprocating, centrifugal, and screw (Dyer and Maples 1995).

- **Reciprocating** – This is a positive displacement machine that maintains fairly constant volumetric flow over a wide range of pressure ratios. They are almost exclusively driven by fixed speed electric motors.
- **Centrifugal** – This type of compressor raises the refrigerant pressure by imparting momentum to the refrigerant with a spinning impeller, then stagnating the flow in a diffuser section around the impeller tip. They are noted for high capacity with compact design. Typical capacities range from 100 to 10,000 tons.
- **Screw** – The screw or helical compressor is a positive displacement machine that has a nearly constant flow performance characteristic. The machine essentially consists of two mating helically grooved rotors, a male (lobes) and a female (gullies), in a stationary housing. As the helical rotors rotate, the gas is compressed by direct volume reduction between the two rotors.

9.4.2.2 Absorption Chiller (Dyer and Maples 1995)

The absorption and the mechanical compression cycles have the evaporation and condensation of a refrigerant in common. In both cycles, the refrigerant evaporates at low pressure (and low temperature) to absorb heat and then condenses at higher pressure (and higher temperature) to reject heat to the atmosphere. Both cycles require energy to raise the temperature of the refrigerant for the heat rejection process. In the mechanical compression cycle, the energy is supplied in the form of work to the compressor whereas in the absorption cycle, heat is added (usually steam) to raise the refrigerant temperature.

The absorption cycle requires two working fluids: a refrigerant and an absorbent. Of the many combinations of refrigerant and absorbent that have been tried, only lithium bromide-water and ammonia-water cycles are commonly used today.

9.4.3 Key Components (Dyer and Maples 1995)

9.4.3.1 Mechanical Compression Chillers

- **Evaporator** – Component in which liquid refrigerant flows over a tube bundle and evaporates, absorbing heat from the chilled water circulating through the tube bundle.
- **Compressor** – “Pumps” the refrigerant vapor to the condenser by raising the refrigerant pressure (and thus, temperature).
- **Condenser** – Component in which refrigerant condenses on a set of cooling water coils giving up its heat to the cooling water.
- **Expansion Valve** – The high-pressure liquid refrigerant coming from the condenser passes through this expansion device, reducing the refrigerant’s pressure (and temperature) to that of the evaporator.

9.4.3.2 Absorption Chiller

The absorption cycle is made up of four basic components:

- **Evaporator** – Where evaporation of the liquid refrigerant takes place.
- **Absorber** – Where concentrated absorbent is sprayed through the vapor space and over condensing water coils. Since the absorbent has a strong attraction for the refrigerant, the refrigerant is absorbed with the help of the cooling water coils.

- **Generator** – Where the dilute solution flows over the generator tubes and is heated by the steam or hot water.
- **Condenser** – Where the refrigerant vapor from the generator releases its heat of vaporization to the cooling water as it condenses over the condenser water tube bundle.

9.4.4 Safety Issues (TARAP 2001)

Large chillers are most commonly located in mechanical equipment rooms within the building they are air conditioning. If a hazardous refrigerant is used (e.g., ammonia), the equipment room must meet additional requirements typically including minimum ventilation airflows and vapor concentration monitoring.

In many urban code jurisdictions, the use of ammonia as a refrigerant is prohibited outright. For large chillers, the refrigerant charge is too large to allow hydrocarbon refrigerants in chillers located in a mechanical equipment room.

9.4.5 Cost and Energy Efficiency (Dyer and Maples 1995)

The following steps describe ways to improve chiller performance, therefore, reducing its operating costs:

- **Raise chilled water temperature** – The energy input required for any liquid chiller (mechanical compression or absorption) increases as the temperature lift between the evaporator and the condenser increases. Raising the chilled water temperature will cause a corresponding increase in the evaporator temperature and thus, decrease the required temperature lift.

On a centrifugal chiller, if the chilled water temperature is raised by 2°F to 3°F, the system efficiency can increase by as much as 3% to 5%.

- **Reduce condenser water temperature** – The effect of reducing condenser water temperature is very similar to that of raising the chilled water temperature, namely reducing the temperature lift that must be supplied by the chiller.

On a centrifugal chiller, if the condenser water temperature is decreased by 2°F to 3°F, the system efficiency can increase by as much as 2% to 3%.

- **Reducing scale or fouling** – The heat transfer surfaces in chillers tends to collect various mineral and sludge deposits from the water that is circulated through them. Any buildup insulates the tubes in the heat exchanger causing a decrease in heat exchanger efficiency and thus, requiring a large temperature difference between the water and the refrigerant.
- **Purge air from condenser** – Air trapped in the condenser causes an increased pressure at the compressor discharge. This results in increased compressor horsepower. The result has the same effect as scale buildup in the condenser.
- **Maintain adequate condenser water flow** – Most chillers include a filter in the condenser water line to remove material picked up in the cooling tower. Blockage in this filter at higher loads will cause an increase in condenser refrigerant temperature due to poor heat transfer.
- **Reducing auxiliary power requirements** – The total energy cost of producing chilled water is not limited to the cost of operating the chiller itself. Cooling tower fans, condenser water circulating pumps, and chilled water circulating pumps must also be included. Reduce these requirements as much as possible.

- **Use variable speed drive on centrifugal chillers** – Centrifugal chillers are typically driven by fixed speed electric motors. Practical capacity reduction may be achieved with speed reductions, which in turn requires a combination of speed control and prerotation vanes.
- **Compressor changeouts** – In many installations, energy saving measures have reduced demand to the point that existing chillers are tremendously oversized, forcing the chiller to operate at greatly reduced loads even during peak demand times. This causes a number of problems including surging and poor efficiency. Replacing the compressor and motor drive to more closely match the observed load can alleviate these problems.
- **Use free cooling** – Cooling is often required even when outside temperatures drop below the minimum condenser water temperature. If outside air temperature is low enough, the chiller should be shut off and outside air used. If cooling cannot be done with outside air, a chiller bypass can be used to produce chilled water without the use of a chiller.
- **Operate chillers at peak efficiency** – Plants having two or more chillers can save energy by load management such that each chiller is operated to obtain combined peak efficiency. An example of this is the use of a combination of reciprocating and centrifugal compressor chillers.
- **Heat recovery systems** – Heat recovery systems extract heat from the chilled liquid and reject some of that heat, plus the energy of compression, to warm water circuit for reheat and cooling.
- **Use absorption chilling for peak shaving** – In installations where the electricity demand curve is dominated by the demand for chilled water, absorption chillers can be used to reduce the overall electricity demand.
- **Replace absorption chillers with electric drive centrifugals** – Typical absorption chillers require approximately 1.6 Btu of thermal energy delivered to the chiller to remove 1 Btu of energy from the chilled water. Modern electric drive centrifugal chillers require only 0.2 Btu of electrical energy to remove 1 Btu of energy from the chilled water (0.7 kw/ton).
- **Thermal storage** – The storage of ice for later use is an increasing attractive option since cooling is required virtually year-round in many large buildings across the country. Because of utility demand charges, it is more economical to provide the cooling source during non-air conditioning periods and tap it when air conditioning is needed, especially peak periods.

9.4.6 Maintenance of Chillers (Trade Press Publishing Corporation 2001)

Similar to boilers, effective maintenance of chillers requires two activities: first, bring the chiller to peak efficiency and second, maintain that peak efficiency. There are some basic steps facility professionals can take to make sure their building's chillers are being maintained properly. Among them are:

- Inspecting the chiller as recommended by the chiller manufacturer. Typically, this should be done at least quarterly.
- Routine inspection for refrigerant leaks.
- Checking compressor operating pressures.
- Checking all oil levels and pressures.
- Examining all motor voltages and amps.

- Checking all electrical starters, contactors, and relays.
- Checking all hot gas and unloader operations.
- Using superheat and subcooling temperature readings to obtain a chiller's maximum efficiency.
- Taking discharge line temperature readings.

A sample chiller operations log useful for recording relevant operational efficiency metrics is provide at the end of this section following the chiller maintenance checklist.

9.4.7 Diagnostic Tools

- **Thermography** – An infrared thermometer or camera allows for an accurate, non-contact assessment of temperature. Applications for chillers include insulation assessments on chilled water piping as well as motor/bearing temperature assessments on compressors and pumping systems. More information on thermography can be found in Chapter 6.
- **Ultrasonic analyzer** – Most rotating equipment and many fluid systems emit sound patterns in the ultrasonic frequency spectrum. Changes in these ultrasonic wave emissions are indicative of changes in equipment condition. Analyzer applications for chillers include compressors, chilled water pumping systems (e.g., bearing wear) and refrigerant leak detection. More information on ultrasonic analysis can be found in Chapter 6.

9.4.8 Available Software Tool

Chilled Water System Analysis Tool (CWSAT) Version 2.3

Description: The DOE Chilled Water System Analysis Tool (CWSAT) is a software tool that is available at no charge to help optimize the performance of industrial chilled water systems. The tool allows the user to propose changes to existing equipment including chillers, pumps, and towers, and calculates how much energy and money the plant can save by implementing these changes.

The CWSAT uses inputs of the chilled water system equipment and operating parameters to calculate the system's energy consumption. The level of input detail is customized to the knowledge of the user. When specific equipment details are not known, catalog and default data are available in the CWSAT and can be readily utilized. The CWSAT allows users to analyze the impacts of implementing many system improvement measures by changing input data and comparing the revised system's energy consumption to the user's originally inputted system.

The tool can quickly calculate the potential energy savings opportunities that exist from measures such as increasing the chilled water temperature, decreasing the condenser water temperature, replacing the chillers, applying variable speed control to the circulation pump motors, and upgrading the tower motor controls to 2-speed or variable speed. Depending on the characteristics of the specific chilled water system being analyzed, the tool can examine additional system specific cost reduction measures. These measures include replacing the chiller refrigerant, installing a variable speed drive on centrifugal compressors, using free cooling, and sequencing chiller operation to minimize energy consumption.

Availability: To download CWSAT and learn more about training opportunities, visit the Industrial Technology Program Web site: **www1.eere.energy.gov/industry/bestpractices**.

9.4.9. Relevant Operational/Energy Efficiency Measures

There are a number of operational/energy efficiency measures that could be presented for proper chiller operation and control. The following section focuses on the most prevalent O&M recommendations having the greatest energy impacts at Federal facilities.

Chiller Measure #1: Chilled Water Temperature Control

Chillers are typically set to have a chilled water output temperature in the range of 42°F to 45°F. If the maximum cooling load on the chillers cause the chiller to operate at less than full load, the chiller operator could possibly increase the chilled water temperature and still meet the cooling loads of the building while saving energy.

O&M Tip:
Increasing chiller water temperature by 1°F reduces chiller energy use by 1.7% and 1.2% for centrifugal and reciprocating compressors, respectively.

Likewise, the energy input required for any chiller (mechanical compression or absorption) increases as the temperature lift between the evaporator and the condenser increases. Raising the chilled water temperature will cause a corresponding increase in the evaporator temperature and thus, decrease the required temperature lift. A decrease in temperature lift equates to a decrease in energy use.

Opportunity Identification

The basic chilled water control strategies for chillers using microprocessor-based controllers are presented below:

Return Temperature. A chiller controlled by return-water temperature will rely on preset operational instructions based on the return temperature. For example, if the return water temperature increases, indicating an increasing load, the chiller is preprogrammed to respond with greater capacity and thereby mitigating the increased load.

Supply Temperature. A chiller controlled by the supply-water temperature functions with a set of water temperatures pre-programmed based on chiller loading. For example, as a space or process calls for greater capacity (i.e., a space temperature is increasing with solar loading) the chiller response is proportional to the call for added capacity.

Constant Return. If the chiller is controlled to have a constant return water temperature, the chiller will modulate chilled water supply temperatures to achieve a certain return water temperature over a range of chiller loads. In this case, the chiller operator specifies the desired chilled water return temperature, and the chiller modulates the chilled water supply temperature accordingly to meet this temperature.

Outside Air. Water cooled chillers that are located indoors, usually require an outdoor temperature sensor wired into the chiller's control panel. Most chiller manufacturers provide outside air temperature sensors that are specific to their chillers, and easily be integrated into the chiller control panel. In this case, the chiller reads the outdoor wet-bulb temperatures and modulates the chilled water temperature based on predefined outdoor air temperatures and chilled-water set-points.

Zone Temperature. Some chillers come equipped with temperature sensors that read interior zone temperatures, or they have controls that can be integrated into the building automation system (BAS). In this case, the operators can apply chilled water reset strategies based on the interior zone temperatures. In each case, the chiller will usually step up the chilled water temperature to that of the reset value, even if the compressor is in the "off" cycle.

Chilled water reset strategies usually reset the chilled water temperature over a range of about 10°F (Webster 2003). Chiller operators should contact their local chiller manufacturers for information on setting appropriate chilled water temperatures. Manufacturers can provide guidance on chilled water modulation at partial loads, and outside air temperatures for the particular chiller.

Regardless of the control strategy used to modulate chilled water temperatures, the operators should always keep in mind the impacts on the entire chilled water system. Care should be taken to optimize the entire system, rather than just applying chilled water reset strategies blindly (Webster 2003).

It is also important to consider the implications on cooling coils and their ability to regulate the indoor relative humidity ratios within the building, at higher chilled water temperatures. As the chilled water temperatures are increased, the energy/facility managers should closely monitor indoor relative humidity (RH) levels to make sure they are staying in the 55% to 60% RH range.

Diagnostic Equipment

Opportunities with chillers rely on the use of the chiller controller and/or the BAS for diagnosis. There are situations where neither the controller nor the BAS are available or programmed properly for use. In these cases, portable data loggers for evaluating temperatures are most appropriate. In addition, chiller and chilled water distribution systems usually have temperature and pressure devices hard-mounted to the system. These devices, provided they are accurate, can be used in system diagnostics.

Energy Savings and Economics

Recognizing that the system efficiency can increase by as much as 2% to 5% by raising the chilled water supply temperature by 2°F to 3°F, the annual energy savings, which could be realized, can be estimated as follows:

$$Energy\ Savings = (CEU \times H) - \left[CEU \times H\left(1 - \frac{ES}{100}\right)\right]$$

$$Annual\ Energy\ Savings = \sum_{i=1}^{n} Energy\ Savings$$

where

CEU = chiller energy use, kW

H = hours of operation at a given load, h

ES = energy savings, %

Estimated Annual Cost Savings

The annual cost savings, which could be realized by increasing chilled water temperatures, can be estimated as follows:

$$\text{Annual Cost Savings} = \text{Annual Energy Savings} \times ER$$

where ER = electric energy rate, $/kWh

It should be noted that this cost savings calculation does not account for an electric peak demand reduction. If the facility has a peak demand charge, and the chiller operates everyday with on operational schedule that is coincident with the facilities peak demand, then this calculation could underestimates the cost savings.

Chilled Water Supply Temperature Energy Savings and Economics Example

Example Synopsis: A water cooled centrifugal chiller currently has a constant 42°F supply temperature. After inspection it was determined that the temperature controls can allow modulation up to 45°F during low load periods with an estimated energy savings of 2.25%. The operators estimate that the chiller can operate at 45°F for 3,000 hrs per year, and the chiller has an electrical load of 300 kW when operating at these low load conditions. The average electric rate is $0.10/kWh.

The annual energy savings can be estimated as:

$$\text{Energy Savings} = (300 \times 3{,}000) - \left[300 \times 3{,}000\left(1 - \frac{2.25}{100}\right)\right]$$

$$\text{Annual Energy Savings} = 20{,}250\ kWh/yr$$

The annual cost savings can be estimated as:

$$\text{Annual Cost Savings} = (20{,}250\ kWh/yr)(\$0.10/kWh)$$

$$\text{Annual Cost Savings} = \$2{,}025/yr$$

Chiller Measure #2: Condenser Water Temperature Control

The effect of reducing condenser water temperature (water-cooled chillers only) is very similar to that of raising the chilled water temperature on the supply side, namely reducing the temperature lift that must be supplied by the chiller. These temperatures can be reset downward as outdoor wet-bulb temperatures decrease and during low-load conditions (Webster 2003).

O&M Tip:
For each 1°F decrease in condenser cooling water temperature, until optimal water temperature is reached, there is a corresponding percentage decrease in chiller energy use.

It is important to note that the chiller operators need to make sure that the chiller is capable of handling lowered condenser water temperatures. Some chillers are not designed to handle lower condenser water temperatures and can encounter compressor oil return problems. *As a default, site personnel should always check with their local chiller manufacturers before lowering the condenser water temperatures.*

Opportunity Identification

Most chillers reach their maximum operating efficiency at the designed peak load. However, chillers operate at the part-load condition most of the time. Resetting the condenser water temperature normally decreases the temperature lift between the evaporator and the condenser, thus increasing the chiller operating efficiency. Therefore, to reset the condenser water temperature to the lowest possible temperature will allow the cooling tower to generate cooler condenser water whenever possible. Note that although lowering the condenser water temperature will reduce chiller energy, it may increase cooling tower energy consumption because the tower fan may have to run longer to achieve the lower condenser water temperature. In addition, some older chillers have condensing water temperature limitations. Consult the chiller manufacturer to establish appropriate guidelines for lowering the condenser water temperature.

Diagnostic Equipment

Opportunities with chillers rely on the use of the chiller controller and/or the BAS for diagnosis. There are situations where neither the controller not the BAS are available or programmed properly for use. In these cases, portable data loggers for evaluating temperatures are most appropriate. In addition, chiller and chilled water distribution systems usually have temperature and pressure devices hard-mounted to the system. These devices, provided they are accurate, can be used in system diagnostics.

Estimated Annual Energy Savings

Lowering the condenser water temperature 2°F to 3°F can increase system efficiency by as much as 2% to 3%. The annual energy savings, which could be realized by reducing condenser temperatures, can be estimated as follows:

$$Energy\ Savings = (CEU \times H) - \left[CEU \times H\left(1 - \frac{ES}{100}\right)\right]$$

$$Annual\ Energy\ Savings = \sum_{i=1}^{n} Energy\ Savings$$

where

CEU = chiller energy use, kW

H = hours of operation at a given load, h

ES = energy savings, %

Estimated Annual Cost Savings

The annual cost savings, which could be realized by reducing condenser temperatures, can be estimated as follows:

$$Annual\ Cost\ Savings = Annual\ Energy\ Savings \times ER$$

where ER = electric energy rate, $/kWh

It should be noted that this cost savings calculation does not account for an electric peak demand reduction. If the facility has a peak demand charge, and the chiller operates everyday with on operational schedule that is coincident with the facilities peak demand, then this estimate slightly underestimates the cost savings.

Condenser Temperature Reset Energy Savings and Economics Example

Example Synopsis: A water cooled centrifugal chiller currently has an entering condenser temperature of 55°F. After inspection it was determined that the temperature controls can allow modulation down to 52°F during low load periods. The operators estimate that the chiller can operate at 52°F for 3,000 hrs per year, and the chiller has an electrical load of 300 kW when operating at these low load conditions. The average electric rate is $0.10/kWh.

The annual energy savings can be estimated as:

$$\textit{Energy Savings} = (300 \times 3{,}000) - \left[300 \times 3{,}000\left(1 - \frac{3}{100}\right)\right]$$

$$\textit{Annual Energy Savings} = 27{,}000\ \textit{kWh/yr}$$

The annual cost savings can be estimated as:

$$\textit{Annual Cost Savings} = (27{,}000\ \textit{kWh/yr})(\$0.10/\textit{kWh})$$

$$\textit{Annual Cost Savings} = \$2{,}700/\textit{yr}$$

9.4.9.1 Chiller Water-Use Best Practices

The predominant impact chillers have on water use relates to proper function. An inefficient chiller will require longer hours of operation to satisfy the load. It is these additional hours that result in greater water use though evaporation at the cooling tower and any leaks in the system. Any inefficiency results in a less-than-optimal operation leading to increased resource use – water is one of those resources.

9.4.10 Chillers Checklist

Description	Comments	Maintenance Frequency			
		Daily	Weekly	Semi-Annually	Annually
Chiller use/sequencing	Turn off/sequence unnecessary chillers	X			
Overall visual inspection	Complete overall visual inspection to be sure all equipment is operating and safety systems are in place	X			
Check setpoints	Check all setpoints for proper setting and function	X			
Evaporator and condenser	Assess evaporator and condenser coil fouling as required		X		
Compressor motor temperature	Check temperature per manufacturer's specifications		X		

Chiller Checklist (contd)

Description	Comments	Maintenance Frequency			
		Daily	Weekly	Semi-Annually	Annually
Perform water quality test	Check water quality for proper chemical balance		X		
Leak testing	Conduct leak testing on all compressor fittings, oil pump joints and fittings, and relief valves		X		
Check all insulation	Check insulation for condition and appropriateness		X		
Control operation	Verify proper control function including: • Hot gas bypass • Liquid injection		X		
Check vane control settings	Check settings per manufacturer's specification			X	
Verify motor load limit control	Check settings per manufacturer's specification			X	
Verify load balance operation	Check settings per manufacturer's specification			X	
Check chilled water reset settings and function	Check settings per manufacturer's specification			X	
Check chiller lockout setpoint	Check settings per manufacturer's specification				X
Clean condenser tubes	Clean tubes at least annually as part of shutdown procedure				X
Eddy current test condenser tubes	As required, conduct eddy current test to assess tube wall thickness				X
Clean evaporator tubes	Clean tubes at least annually as part of shutdown procedure				X
Eddy current test evaporator tubes	As required, conduct eddy current test to assess tube wall thickness				X
Compressor motor and assembly	• Check all alignments to specification • Check all seals, provide lubrication where necessary				X
Compressor oil system	• Conduct analysis on oil and filter • Change as required • Check oil pump and seals • Check oil heater and thermostat • Check all strainers, valves, etc.				X
Electrical connections	Check all electrical connections/ terminals for contact and tightness				X
Water flows	Assess proper water flow in evaporator and condenser				X
Check refrigerant level and condition	Add refrigerant as required. Record amounts and address leakage issues.				X

9.4.11 Sample Chiller Operation Log

Job Name		Date					
Unit Tag							
Model #		Time					
Serial #							
Full Load Design	Operating Condition						
__________degF	Operating Code						
	Last Diagnostic						
	LCHW Setpoint						
	Current Limit Setpoint						
	Start #						
	Run Hours						
__________Volts	Volts – AB						
__________Hertz	Volts – AC						
	Volts – BC						
	Amps L1						
	Amps L2						
	Amps L3						
	Amps AVG						
__________RLA	% of RLA						
	Oil Sump Temperature						
	Oil Temperature to Bearings						
	Oil Level						
	Low Oil Pressure						
	High Oil Pressure						
	Net Oil Pressure						
	Operating Purge Pressure						
	Operating Purge Oil Level						
	Purge Starts						
	Purge Run Hours						
_____PSID_____gpm	CHW PSID						
__________degF	CHW Temperature in						
__________degF	CHW Temperature out						
__________degF	CHW Temperature Differential						
	CHW Makeup Water						
	Evaporator Temperature						
	Evaporator Pressure						
_____PSID_____gpm	CW PSI Differential						
__________degF	CW Temperature in						
__________degF	CW Temperature out						
___________degF	CW Temperature Differential						
	Condenser Temperature						
	Condenser Pressure						
	Cooling Tower Makeup Water						
	CHW Makeup Water						
	Operator Initials						

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9.5 Cooling Towers

9.5.1 Introduction

A cooling tower (Figure 9.5.1) is a specialized heat exchanger in which two fluids (air and water) are brought into direct contact with each other to affect the transfer of heat. In a “spray-filled” tower, this is accomplished by spraying a flowing mass of water into a rain-like pattern, through which an upward moving mass flow of cool air is induced by the action of a fan (Marley Cooling Technologies 2001a).

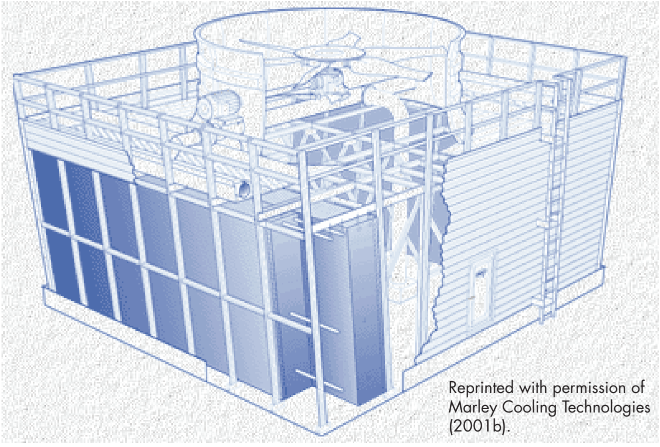

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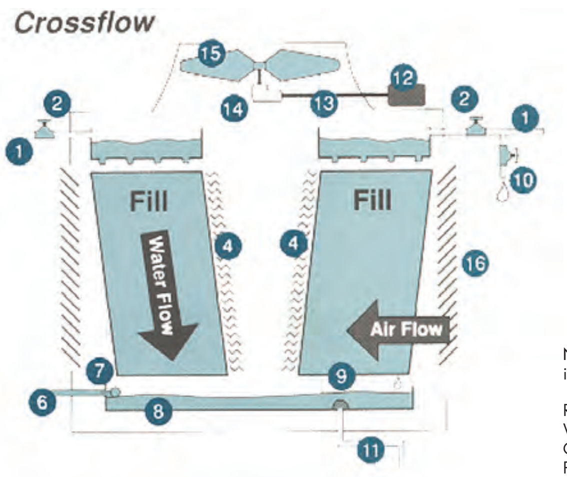
Figure 9.5.1. Cooling tower

9.5.2 Types of Cooling Towers

There are two basic types of cooling towers, direct or open and indirect or closed.

1. Direct or open cooling tower (Figure 9.5.2)

   This type of system exposes the cooling water directly to the atmosphere. The warm cooling is sprayed over a fill in the cooling tower to increase the contact area, and air is blown through the fill. The majority of heat removed from the cooling water is due to evaporation. The remaining cooled water drops into a collection basin and is recirculated to the chiller (WSUCEEP 2001).



1. Hot water from chiller
2. Flow control valve
3. Distribution pipes and nozzles
4. Draft eliminators
5. Centrifugal blower
6. Make-up water infeed
7. Float valve
8. Collection basin
9. Strainer
10. Bleed water
11. Cooled water to chiller
12. Fan drive
13. Drive shaft
14. Gear box
15. Propeller fan
16. Air intake louvers

Note: Items 3 and 5 not shown in Figure 9.5.2.

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Figure 9.5.2. Direct or open cooling tower

2. Indirect or closed cooling tower

   An indirect or closed cooling tower circulates the water through tubes located in the tower. In this type of tower, the cooling water does not come in contact with the outside air and represents a "closed" system.

9.5.3 Key Components

A cooling tower is a collection of systems that work together. Following is an overview of how these systems operate.

Hot water from a chilled water system is delivered to the top of the cooling tower by the condenser pump through distribution piping. The hot water is sprayed through nozzles onto the heat transfer media (fill) inside the cooling tower. Some towers feed the nozzles through pressurized piping; others use a water distribution basin and feed the nozzles through gravity.

A cold-water collection basin at the base of the tower gathers cool water after it has passed through the heat transfer media. The cool water is pumped back to the condenser to complete the cooling water loop.

Cooling towers use evaporation to release waste heat from a HVAC system. Hot water flowing from the condenser is slowed down and spread out in the heat transfer media (fill). A portion of the hot water is evaporated in the fill area, which cools the bulk water. Cooling tower fill is typically arranged in packs of thin corrugated plastic sheets or, alternately, as splash bars supported in a grid pattern.

Large volumes of air flowing through the heat transfer media help increase the rate of evaporation and cooling capacity of the tower. This airflow is generated by fans powered by electric motors. The cooling tower fan size and airflow rate are selected for the desired cooling at the design conditions of hot water, cold water, water flow rate, and wet bulb air temperature.

HVAC cooling tower fans may be propeller type or squirrel cage blowers, depending on the tower design. Small fans may be connected directly to the driving motor, but most designs require an intermediate speed reduction provided by a power belt or reduction gears. The fan and drive system operates in conjunction with a starter and control unit that provides start/stop and speed control.

As cooling air moves through the fill, small droplets of cooling water become entrained and can exit the cooling tower as carry-over or drift. Devices called drift eliminators are used to remove carry-over water droplets. Cooling tower drift becomes an annoyance when the droplets fall on people and surfaces downwind from the cooling tower. Efficient drift eliminators remove virtually all of the entrained cooling water droplets from the air stream (Suptic 1998).

9.5.4 Safety Issues

Warm water in the cooling system is a natural habitat for microorganisms. Chemical treatment is required to eliminate this biological growth. Several acceptable biocides are available from water treatment companies for this purpose. Cooling towers must be thoroughly cleaned on a periodic basis to minimize bacterial growth. Unclean cooling towers promote growth of potentially infectious bacteria, including Legionella Pneumophilia (Suptic 1998).

Legionella may be found in water droplets from cooling towers, which may become airborne and become a serious health hazard if inhaled by a human. The lung is a warm and moist environment, which presents perfect conditions for the growth of such a disease. Common symptoms on patients with legionnaires disease are cough, chills, and fever. In addition, muscle aches, headache, tiredness, loss of appetite, and, occasionally, diarrhea can also be present. Laboratory tests may show decreased function of the kidneys. Chest x-rays often show pneumonia.

9.5.5 Cost and Energy Efficiency

An improperly maintained cooling tower will produce warmer cooling water, resulting in higher condenser temperatures than a properly maintained cooling tower. This reduces the efficiency of the chiller, wastes energy, and increases cost. The chiller will consume 2.5% to 3.5% more energy for each degree increase in the condenser temperature.

For example, if a 100-ton chiller costs $20,000 in energy to operate each year, it will cost you an additional $500 to $700 per year for every degree increase in condenser temperature. Thus, for a 5°F to 10°F increase, you can expect to pay $2,500 to $7,000 a year in additional electricity costs. In addition, a poorly maintained cooling tower will have a shorter operating life, is more likely to need costly repairs, and is less reliable (WSUCEEP 2001).

9.5.6 Maintenance of Cooling Towers

Cooling tower maintenance must be an ongoing endeavor. Lapses in regular maintenance can result in system degradation, loss of efficiency, and potentially serious health issues.

General Requirements for Safe and Efficient Cooling Towers Provide:
(Suptic 1998)

1. Safe access around the cooling tower, including all points where inspection and maintenance activities occur.
2. Fall protection around inspection and maintenance surfaces, such as the top of the cooling tower.
3. Lockout of fan motor and circulating pumps during inspection and maintenance.
4. Protection of workers from exposure to biological and chemical hazards within the cooling water system.
5. Cooling tower location must prevent cooling tower discharge air from entering the fresh air intake ducts of any building.
6. When starting the tower, inspect and remove any accumulated debris.
7. Balance waterflow following the tower manufacturer's procedure to ensure even distribution of hot water to all areas of the fill. Poorly distributed water can lead to air bypass through the fill and loss of tower performance.
8. Follow your water treating company's recommendations regarding chemical addition during startup and continued operation of the cooling system. Galvanized steel cooling towers require special passivation procedures during the first weeks of operation to prevent "white rust."
9. Before starting the fan motor, check the tightness and alignment of drive belts, tightness of mechanical hold-down bolts, oil level in gear reducer drive systems, and alignment of couplings. Rotate the fan by hand and ensure that blades clear all points of the fan shroud.
10. The motor control system is designed to start and stop the fan to maintain return cold water temperature. The fan motor must start and stop no more frequently than four to five times per hour to prevent motor overheating.
11. Blowdown water rate from the cooling tower should be adjusted to maintain between two to four concentrations of dissolved solids.

9.5.7 Common Causes of Cooling Towers Poor Performance

- **Scale Deposits** – When water evaporates from the cooling tower, it leaves scale deposits on the surface of the fill from the minerals that were dissolved in the water. Scale build-up acts as a barrier to heat transfer from the water to the air. Excessive scale build-up is a sign of water treatment problems.
- **Clogged Spray Nozzles** – Algae and sediment that collect in the water basin as well as excessive solids that get into the cooling water can clog the spray nozzles. This causes uneven water distribution over the fill, resulting in uneven airflow through the fill and reduced heat transfer surface area. This problem is a sign of water treatment problems and clogged strainers.
- **Poor AirFlow** – Poor airflow through the tower reduces the amount of heat transfer from the water to the air. Poor airflow can be caused by debris at the inlets or outlets of the tower or in the fill. Other causes of poor airflow are loose fan and motor mountings, poor motor and fan alignment, poor gear box maintenance, improper fan pitch, damage to fan blades, or excessive vibration. Reduced airflow due to poor fan performance can ultimately lead to motor or fan failure.
- **Poor Pump Performance** – An indirect cooling tower uses a cooling tower pump. Proper water flow is important to achieve optimum heat transfer. Loose connections, failing bearings, cavitation, clogged strainers, excessive vibration, and non-design operating conditions result in reduced water flow, reduced efficiency, and premature equipment failure (WSUCEEP 2001).

9.5.8 Diagnostic Tools

- **Thermography** – An infrared thermometer or camera allows for an accurate, non-contact assessment of temperature. Applications for cooling towers include bearing and electrical contact assessments on motor and fan systems as well as hot spots on belt and other drive systems. More information on thermography can be found in Chapter 6.
- **Ultrasonic analyzer** – Electric motor and fan systems emit very distinct sound patterns around bearings and drives (direct or belt). In most cases, these sounds are not audible to the unaided ear, or are drown-out by other equipment noises. Using an ultrasonic detector, the analyst is able to isolate the frequency of sound being emitted by the bearing or drive. Changes in these ultrasonic wave emissions are indicative of changes in equipment condition-some of these changes can be a precursor to component degradation and failure. More information on ultrasonic analysis can be found in Chapter 6.

9.5.8.1 Cooling Tower Water-Use Best Practices

As discussed, cooling towers regulate temperature by dissipating heat from recirculating water used to cool chillers, air-conditioning equipment, or other process equipment. Heat is rejected from the tower primarily through evaporation. Therefore, by design, cooling towers consume significant amounts of water. The thermal efficiency and longevity of the cooling tower and equipment used to cool depend on the proper management of water recirculated through the tower (FEMP 2008).

Water leaves a cooling tower system in any one of four ways:

1. **Evaporation:** This is the primary function of the tower and is the method that transfers heat from the cooling tower system to the environment. The quantity of evaporation is not a subject for water efficiency efforts (although improving the energy efficiency of the systems you are cooling will reduce the evaporative load on your tower). Evaporative losses relate to the specifics of the system and environment. In rough terms, for every 10°F of water temperature drop across the tower, there is an evaporative loss of approximately 1 percent, equating, on average, to 2.5 to 4.0 gpm per 100 tons of capacity.
2. **Blowdown or Bleed-off**: When water evaporates from the tower leaves behind dissolved and suspended substances. If left unchecked, these chemicals will lead to basin water with increasing concentrations of total dissolved solids (TDS). If the concentration gets too high, the solids can come out of solution and cause scale to form within the system and/or the dissolved solids can lead to corrosion problems. Additional problems may arise by creating conditions conducive to biofouling. To mediate this problem, a certain amount of water is removed from the cooling tower – this water is referred to as blowdown or bleed off. As this water is being removed, the same quantity is being reintroduced and is called make up. Carefully monitoring and controlling the quantity of blowdown and make up provides the most significant opportunity to conserve water in cooling tower operations.
3. **Drift**: A comparatively small quantity of water may be carried from the tower not as vapor but as mist or small droplets. Drift loss is small compared to evaporation and blow-down, and is controlled with baffles and drift eliminators. While estimates of drift losses range well below 1% of tower flow rate, on larger towers these losses can add up.
4. **Basin Leaks/Overflows**: Properly operated towers should not have leaks or overflows.

In addition to carefully controlling tower operation, other water efficiency opportunities arise from using alternate sources of make-up water. Sometimes water from other equipment within a facility can be recycled and reused for cooling tower make-up with little or no pre-treatment, including the following:

- Air handler condensate (water that collects when warm, moist air passes over the cooling coils in air handler units). This reuse is particularly appropriate because the condensate has a low mineral content, and typically is generated in greatest quantities when cooling tower loads are the highest.
- Water used in a once through cooling system.
- Pretreated effluent from other processes, provided that any chemicals used are compatible with the cooling tower system.
- High-quality municipal wastewater effluent or recycled water (where available).

9.5.8.2 Operations and Maintenance Opportunities

- From an operational perspective, the blowdown losses represent the most significant water conservation opportunity. To maximize efficiency potential, calculate and understand your "cycles of concentration." Check the ratio of conductivity of blowdown and make-up water. Work with your cooling tower water treatment specialist to maximize the cycles of concentration. Many systems operate at 2 to 4 cycles of concentration, while 6 cycles or more may be possible. Increasing your cycles from 3 to 6 will reduce cooling tower make-up water by 20 percent, and cooling tower blowdown by 50 percent. The actual number of cycles you can carry will depend on your make-up water quality and cooling tower water treatment regimen. Depending on your make-up water, treatment programs may include corrosion and scaling inhibitors, along with biological fouling inhibitors.

- Install a conductivity controller to automatically control your blowdown. Working with your water treatment specialist, determine the maximum cycles of concentration you can safely achieve, and the resulting conductivity (typically measured as microSiemens per centimeter, uS/cm). A conductivity controller can continuously measure the conductivity of the cooling tower water and discharge water only when the conductivity set point is exceeded.

- Install flow meters on make-up and blowdown lines. Check the ratio of make-up flow to blowdown flow. Then check the ratio of conductivity of blowdown water and the make-up water (you can use a handheld conductivity meter if your tower is not equipped with permanent meters). These ratios should match your target cycles of concentration. If both ratios are not about the same, check the tower for leaks or other unauthorized draw-off. If you are not maintaining target cycles of concentration, check system components, including conductivity controller, make-up water fill valve, and blowdown valve.

- Read conductivity and flow meters regularly to quickly identify problems. Keep a log of make-up and blowdown quantities, conductivity, and cycles of concentration. Monitor trends to spot deterioration in performance.

- Consider using acid treatment such as sulfuric, hydrochloric, or ascorbic acid, where appropriate. When added to recirculating water, acid can improve the efficiency of a cooling system by controlling the scale buildup potential from mineral deposits. Acid treatment lowers the pH of the water, and is effective in converting a portion of the alkalinity (bicarbonate and carbonate), a primary constituent of scale formation, into more readily soluble forms. Make sure that workers are fully trained in the proper handling of acids. Also note that acid overdoses can severely damage a cooling system. The use a timer or continuous pH monitoring via instrumentation should be employed. Additionally, it is important to add acid at a point where the flow of water promotes rapid mixing and distribution. Be aware that lowering pH may mean you may have to add a corrosion inhibitor.

- Select your water treatment vendor with care. Tell vendors that water efficiency is a high priority and ask them to estimate the quantities and costs of treatment chemicals, volumes of blowdown water and the expected cycles of concentration ratio. Keep in mind that some vendors may be reluctant to improve water efficiency because it means the facility will purchase fewer chemicals. In some cases, saving on chemicals can outweigh the savings on water costs. Vendors should be selected based on "cost to treat 1,000 gallons make-up water" and highest "recommended system water cycle of concentration."

- Consider measuring the amount of water lost to evaporation. Some water utilities will provide a credit to the sewer charges for evaporative losses, measured as the difference between metered make-up water minus metered blowdown water.
- Consider a comprehensive air handler coil maintenance program. As coils become dirty or fouled, there is increased load on the chilled water system in order to maintain conditioned air set point temperatures. Increased load on the chilled water system not only has an associated increase in electrical consumption, it also increases the load on the evaporative cooling process which uses more water.

9.5.8.3 Retrofit Opportunities

- Install a sidestream filtration system that is composed of a rapid sand filter or high-efficiency cartridge filter to cleanse the water. These systems draw water from the sump, filter out sediments and return the filtered water to the tower, enabling the system to operate more efficiently with less water and chemicals. Sidestream filtration is particularly helpful if your system is subject to dusty atmospheric conditions. Sidestream filtration can turn a troublesome system into a more trouble-free system.
- Install a make-up water softening system when hardness (calcium and magnesium) is the limiting factor on your cycles of concentration. Water softening removes hardness using an ion exchange resin, and can allow you to operate at higher cycles of concentration.
- Install covers to block sunlight penetration. Reducing the amount of sunlight on tower surfaces can significantly reduce biological growth such as algae.
- Consider alternative water treatment options such as ozonation or ionization, to reduce water and chemical usage. Be careful to consider the life-cycle cost impact of such systems.
- Install automated chemical feed systems on large cooling tower systems (over 100 ton). The automated feed system should control blowdown/bleed-off by conductivity and then add chemicals based on make-up water flow. These systems minimize water and chemical use while optimizing control against scale, corrosion, and biological growth.

9.5.9 Cooling Towers Checklist

Description	Comments	Maintenance Frequency			
		Daily	Weekly	Monthly	Annually
Cooling tower use/ sequencing	Turn off/sequence unnecessary cooling towers	X			
Overall visual inspection	Complete overall visual inspection to be sure all equipment is operating and safety systems are in place	X			
Inspect for clogging	Make sure water is flowing in tower	X			
Fan motor condition	Check the condition of the fan motor through temperature or vibration analysis and compare to baseline values		X		
Clean suction screen	Physically clean screen of all debris		X		
Test water samples	Test for proper concentrations of dissolved solids, and chemistry. Adjust blowdown and chemicals as necessary.		X		
Operate make-up water	Operate switch manually to ensure proper float switch operation		X		
Vibration	Check for excessive vibration in motors, fans, and pumps		X		
Check tower structure	Check for loose fill, connections, leaks, etc.		X		
Check belts and pulleys	Adjust all belts and pulleys		X		
Check lubrication	Assure that all bearings are lubricated per the manufacture's recommendation			X	
Check motor supports and fan blades	Check for excessive wear and secure fastening			X	
Motor alignment	Aligning the motor coupling allows for efficient torque transfer			X	
Check drift eliminators, louvers, and fill	Look for proper positioning and scale build up			X	
Clean tower	Remove all dust, scale, and algae from tower basin, fill, and spray nozzles				X
Check bearings	Inspect bearings and drive belts for wear. Adjust, repair, or replace as necessary.				X
Motor condition	Checking the condition of the motor through temperature or vibration analysis assures long life				X

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9.6 Energy Management/Building Automation Systems

9.6.1 Introduction

The objective of an energy management/building automation system (also know as an energy management and control system [EMCS]) is to achieve an optimal level of control of occupant comfort while minimizing energy use. These control systems are the integrating component to fans, pumps, heating/cooling equipment, dampers, mixing boxes, and thermostats. Monitoring and optimizing temperature, pressure, humidity, and flow rates are key functions of modern building control systems.

9.6.2 System Types

At the crudest level of energy management and control is the manual operation of energy using devices; the toggling on and off of basic comfort and lighting systems based on need. The earliest forms of energy management involved simple time clock- and thermostat-based systems; indeed, many of these systems are still being used. Typically, these systems are wired directly to the end-use equipment and mostly function autonomously from other system components. Progressing with technology and the increasing economic availability of microprocessor-based systems, energy management has quickly moved to its current state of computer based, digitally controlled systems.

Direct digital control (DDC) systems function by measuring particular system variables (temperature, for instance), processing those variables (comparing a measured temperature to a desired setpoint), and then signaling a terminal device (air damper/mixing box) to respond. With the advent of DDC systems, terminal devices are now able to respond quicker and with more accuracy to a given input. This increased response is a function of the DDC system capability to control devices in a nonlinear fashion. Control that once relied on linear "hunting" to arrive at the desired setpoint now is accomplished through sophisticated algorithms making use of proportional and integral (PI) control strategies to arrive at the setpoint quicker and with more accuracy.

9.6.3 Key Components

The hardware making up modern control systems have three necessary elements: sensors, controllers, and the controlled devices.

- **Sensors** – There is an increasing variety and level of sophistication of sensors available for use with modern control systems. Some of the more common include: temperature, humidity, pressure, flow rate, and power. Sensors are now available that track indoor air quality, lighting level, and fire/smoke.
- **Controllers** – The function of the controller is to compare a signal received from the sensor to a desired setpoint, and then send out a corresponding signal to the controlled device for action. Controllers may be very simple such as a thermostat where the sensor and controller are usually co-located, to very sophisticated microprocessor based systems capable of powerful analysis routines.
- **Controlled devices** – The controlled device is the terminal device receiving the signal from the controller. Amongst others, typical controlled devices include: air dampers, mixing boxes, control valves, and in some cases, fans, pumps, and motors.

9.6.4 Safety Issues

The introduction of outdoor air is the primary means for dilution of potentially harmful contaminants. Because an EMCS has the capability to control ventilation rates and outdoor-air volumes, certain health and safety precautions need to be taken to ensure proper operation and air quality. Regular checks of contaminant levels, humidity levels, and proper system operation are recommended.

A modern EMCS is capable of other control functions including fire detection and fire suppression systems. As these systems take on other roles, roles that now include responsibilities for personal safety, their operations and maintenance must be given the highest priority.

9.6.5 Cost and Efficiency

Simply installing an EMCS does not guarantee that a building will save energy. Proper installation and commissioning are prerequisites for optimal operation and realizing potential savings. While it is beyond the scope of this guide to detail all the possible EMCS savings strategies, some of the more common functions are presented below.

- **Scheduling** – An EMCS has the ability to schedule the HVAC system for night setback, holiday/weekend schedules (with override control), optimal start/stop, and morning warm-up/cool-down functions.
- **Resets** – Controlling and resetting temperatures of supply air, mixed air, hot water, and chilled water optimize the overall systems for efficiency.
- **Economizers** – Controlling economizer functions with an EMCS helps to assure proper integration and function with other system components. Strategies include typical air-side functions (i.e., economizer use tied to inside setpoints and outside temperatures) and night-time ventilation (purge) operations.
- **Advanced functionality** – A more sophisticated EMCS has expended capabilities including chiller/boiler staging, variable speed drive control, zoned and occupancy-based lighting control, and electrical demand limiting.

9.6.6 Maintenance

The ability of an EMCS to efficiently control energy use in a building is a direct function of the data provided to the EMCS. The old adage ‘garbage in - garbage out’ could not hold more truth than in an EMCS making decisions based on a host of sensor inputs.

For a number of reasons, the calibration of sensors is an often overlooked activity. In many ways, sensors fall into the same category as steam traps: if it doesn’t ‘look’ broken - don’t fix it. Unfortunately, as with steam traps, sensors out of calibration can lead to enormous energy penalties. Furthermore, as with steam traps, these penalties can go undetected for years without a proactive maintenance program.

The following is a list of sensors and actuators that will most need calibration (PECI 1997):

- Outside air temperature
- Mixed air temperature
- Return air temperature
- Discharge or supply air temperature
- Coil face discharge air temperatures
- Chilled water supply temperature
- Condenser entering water temperature
- Heating water supply temperature
- Wet bulb temperature or RH sensors
- Space temperature sensors
- Economizer and related dampers
- Cooling and heating coil valves
- Static pressure transmitters
- Air and water flow rates
- Terminal unit dampers and flows.

Sensor and actuator calibration should be an integral part of all maintenance programs.

Are You Calibrated?

Answer the following questions to determine if your system or equipment needs calibration (PECI 1997):

1. Are you sure your sensors and actuators were calibrated when originally installed?
2. Have your sensors or actuators been calibrated since?
3. Have temperature complaints come from areas that ought to be comfortable?
4. Are any systems performing erratically?
5. Are there areas or equipment that repeatedly have comfort or operational problems?

9.6.7 Diagnostic Equipment

- **Calibration** – All energy management systems rely on sensors for proper feedback to adjust to efficient conditions. The accuracy with which these conditions are reached is a direct function of the accuracy of the sensor providing the feedback. Proper and persistent calibration activities are a requirement for efficient conditions.

9.6.8 Relevant Operational/Energy Efficiency Measures

There are many operational/energy efficiency measures that could be presented for proper EMCS/BAS operation and control. The following section focuses on the most prevalent O&M recommendations having the greatest energy impacts at Federal facilities.

EMCS Measure #1: HVAC Scheduling, Temperature/Pressure Setpoints

Site energy/facility managers should have a goal of matching HVAC scheduling to the actual tenant schedules within all buildings. The building operators should closely monitor tenant schedules and adjust the HVAC schedules accordingly to meet changing schedules throughout the year.

The construction of the building, including the types of windows, insulation, and overall orientation, contributes to its ability to retain conditioned air. This coupled with the internal heating and cooling loads in the building will dictate when the HVAC system should be cycled during the day.

Direct Digital Control (DDC) Optimal Start/Stop

Most DDC systems have optimal start-stop programs with software algorithms that assess indoor and outdoor temperatures and, based on adaptive learning, the DDC system will activate the building's HVAC system at different times each day. This technology is one of the most energy-efficient HVAC control programs available and should be utilized whenever possible. Other DDC systems have the ability to program preset start-stop times for the building's HVAC system. In this case, the building operators should try to start the HVAC system as close to the tenants arrival as possible. The operators should also consider applying different start times based on average outdoor air temperatures versus times of extreme outdoor air temperatures.

DDC Holiday Scheduling

If the building has a DDC control system, it will typically come equipped with a holiday scheduling feature. Building operators should utilize this feature to turn off the building's HVAC system during unoccupied periods and holidays. In addition to unoccupied periods and holidays, many DoD facilities, such as barracks, training facilities, and mess halls, will go unoccupied for periods of time when troops are deployed, therefore they should have scheduling adjusted accordingly. It should be noted that if the building is located in a humid climate, the HVAC system should be put into standby mode and turned on to maintain the humidity limits and unoccupied setback temperatures within the facility.

Building operators should periodically review their DDC codes to make sure the HVAC schedules matches the tenant schedules as closely as possible. If the building operators have to implement overrides to handle extreme weather conditions or special occupancy circumstances, these overrides should be recorded and removed as soon as possible.

In buildings with electromechanical and pneumatic controls, the building operators should at a minimum apply a start-stop schedule based on historic data relating to the amount of time it takes to condition the building. In general, when the HVAC system is turned off, the building operators need to ensure that all of the HVAC fans and pumps are turned off. Although it might be necessary to continuously operate the building chillers and boilers, the building's fans and pumps can be turned off when the HVAC system is not operating.

Temperature and Pressure Setpoints

Temperature setpoints in buildings can typically be programmed using the proportional integral (PI) control loop. If the PI control loop is used, the site must ensure that the throttling range is not too small (DDC Online 2006b). The throttling range relates to the gap between the heating setpoint and cooling setpoint. The larger this gap is, the less energy the site will use to condition the interior air. Guidelines on indoor temperature setpoints for energy efficiency target the heating season setpoint at between 68°F - 72°F and the cooling season setpoint at between 72°F - 78°F. The optimal seasonal setpoint (balancing thermal comfort with energy efficiency) will be a function of type of activity taking place in the space and the ambient relative humidity.

While some facilities target 68°F heating and 78°F cooling setpoints, they are not operated at these temperatures because of occupant complaints. Regardless of the chosen setpoints, facility managers should strive to have the largest throttling range (or dead-band gap) between the two setpoints. This ensures that the HVAC system will not slightly overcool the building, causing the building to immediately go into heating mode, and then slightly overheat the building, causing it to go back into cooling mode. This type of constant cycling is inefficient, hard on equipment, and causes the building to constantly "hunt" for the right temperature.

As previously mentioned, the building operators should also implement a nighttime or unoccupied setback temperature. The unoccupied setback for heating should be 5°F to 10°F cooler than the occupied setpoint, and the unoccupied setback for cooling should be 5°F to 10°F warmer than the occupied setpoint. In humid climates, the underlying activator of the system should be the relative humidity ratios. As long as these ratios are met, the interior temperatures should be allowed to float over the preset unoccupied setpoints.

The temperature setpoint methodology is also valid for electromechanical and pneumatic controls. The only difference may be in the allowable control points – two are typical with electromechanical systems.

Pressure Setpoints

Based on energy and O&M audits of a variety of Federal facilities, many air-side static pressure setpoints fall in range of the 1.9" water column (w.c.) to 2.6" w.c. This is far higher than necessary where most variable air volume (VAV) systems are intended to operate in the 1" to 1.5" w.c. range (Lundstrom 2006). If this type of operation is encountered, the site should investigate the system to make sure the VAV fans are operating and controlling properly. These high static pressure readings can sometimes be caused by site staff looking to make a quick fix when one of the fans is not operating or controlling properly. This could also be caused by a failed static pressure sensor, failed inlet vane controls, slipping belts or breached ductwork. In any case, the building operator should determine the design air-side static pressure setpoint for the particular air-handling unit to ensure the current operation is as close to this value as possible. The operator should identify the location of the static pressure gauges – they should be installed about 2/3 of the way down the longest stretch of ductwork.

Setting and Setpoint: Questions to Ask

A key element of any effective HVAC O&M program is the proper setting and the persistence of all HVAC control parameters. Below is a set of questions site staff should be asking when assessing how settings and setpoints may have changed over time (PECI 1999).

- Have occupancy patterns or space layouts changed? Are HVAC and lighting still zoned to efficiently serve the spaces?
- Have temporary occupancy schedules been returned to original settings?
- Have altered equipment schedules or lockouts been returned to original settings?
- Is equipment short-cycling?
- Are time-clocks checked monthly to ensure proper operation?
- Are seasonally changed setpoints regularly examined to ensure proper adjustment?
- Have any changes in room furniture or equipment adversely affected thermostat function? (Check thermostat settings or other controls that occupants can access.)
- Are new tenants educated in the proper use and function of thermostats and lighting controls?

In DDC control systems, some HVAC operators encourage unoccupied pressure setpoint reductions to be implemented in conjunction with the unoccupied temperature setpoint changes. This offers greater energy savings in VAV systems by allowing for a larger dead-band temperature range and less air to be circulated through the building.

As staff perform certain maintenance tasks to prepare equipment for heating or cooling seasons, they should also review and adjust operational strategies seasonally.

EMCS Measure #2: HVAC Tune-Up and Maintenance

Some of the most important HVAC tune-up and maintenance activities a site should consider are related to the following: valves, filters, coil cleanings, sensor calibration, damper operation, belt system checks, system override correction, and air/water flow analysis.

Valves

Control valves in HVAC systems are used to control the amount of hot or chilled water that circulates through heating or cooling coils. While a necessary component, control valves are notorious for failing. Unfortunately, when a control valve failure occurs, it often goes unnoticed by site staff because it is difficult to assess visually. Common control valve problems/malfunctions include valves that have been manually overridden in the open position, valves stuck in a fixed position, valves that are leaking, and valves that are incorrectly wired – usually backwards.

One method of valve diagnosis starts with the DDC system. Through the DDC system, an operator will determine if a particular heating coil is hot (i.e., is being supplied with hot water). This will be evident through the system reported as a temperature at the coil. Next, the operator will make sure the zone served by this coil is actually calling for heat; this is represented in the system as a request for service. If the zone is not calling for heat, yet the coil is hot, the operator should examine the control valve for either leakage or manual override. This same procedure holds true for cooling coils.

Another method of valve diagnosis again makes use of the DDC system. In this scenario, the operator uses the system to fully close both the heating and cooling valves or he can manually override them. Once done, the operator then reviews the air temperatures on either side of the heating/cooling coils for which there should not be more than a 2°F to 4°F temperature difference between the two temperature sensors. If the temperature difference exceeds this range, the operator should consider either control valve or temperature sensor malfunction.

Sensor Calibration

The HVAC temperature, pressure, relative humidity and CO_2 sensors within a building have certain calibration limits that they operate within. The accuracy of a given sensor is primarily a function of the sensor type, with accuracy of all sensors usually degrading over time. Accordingly, as a general maintenance function, sensor assessment and calibration should be a routine function. Refer to manufacturer's data for the recommendations of assessment and calibration.

As with valves, damper operation can be verified using a DDC control system. Through this system, a facility manager can activate the damper to the fully open and then fully closed position while a colleague in the field verifies this function. If a particular damper is not actuating as it should, the linkages and actuator should be examined for proper connection and operation. During this process, field staff should also verify that all moving parts are properly lubricated and seals are in good shape.

Because economizers are dampers that interact with outside air, buildings where these are installed should receive special attention. In addition to the above procedure, economizer dampers should be checked at a higher frequency to ensure proper modulation, sealing, and sensor calibration. The temperature and/or humidity (i.e., enthalpy) sensor used to control the economizers should be part of a routine calibration schedule.

Belt-Driven System

Belt-driven systems are common in HVAC fan systems. Belt drives are common because they are simple and allow for driven equipment speed control, which is accomplished through the adjustment of pulley size. While belt-drive systems are generally considered to be efficient, certain belts are more efficient than others. Standard belt drives typically use V-belts that have a trapezoidal cross section, and operate by wedging themselves into the pulley. These V-belts have initial efficiencies on the order of 95% to 98%, which can degrade by as much as 5% over the life of the system, if the belts are not periodically re tensioned (DOE 2005b).

If the fans currently have standard V-belts, retrofit options for consideration include cogged-V-belts or synchronous belts and drives. In both cases, efficiency gains on the order of 2% to 5% are possible, depending on the existing belt and its condition. It should be noted that cogged-V-belts do not require a pulley change as part of the retrofit while the synchronous belt retrofit does.

System Overrides

System overrides that are programmed into the buildings DDC systems should be periodically checked. System overrides are sometimes necessary to handle extreme weather conditions, occupancy conditions, or special events. As these are programmed, a special note should be made of what was over-ridden, for what purpose, and when it can be reset. The site should implement a continuous override inspection program to look at all of the overrides that have been programmed into the DDC system and to make sure they are removed as soon as possible.

Simultaneous Heating and Cooling

In dry climates that do not have a need to simultaneously heat and cool the air to control the relative humidity, it is generally advised that the heating should be disabled whenever the cooling system is activated and vice versa. In pneumatic and electromechanical systems, the building operator may have to manually override the heating and cooling system to accomplish this.

With DDC systems installed in areas not requiring dehumidification the system should be programmed to lock out the hot-water pumps during high ambient conditions (e.g., outdoor air temperatures above 70°F) and lock out the chilled water pumps during low ambient conditions (e.g., outdoor air temperatures below 60°F to 55°F). This will ensure that only the necessary service is provided and eliminate the wasteful practice of unnecessary simultaneous heating and cooling.

Where simultaneous heating and cooling is required (e.g., in humid climatic regions) to remove the moisture from the conditioned air, and then to heat the air back up to the required setpoint temperatures, building operators should check for proper operation. As noted above, checks should be made to ensure temperature dead-band setting is far enough apart that it does not cause the HVAC system to continuously "hunt."

9.6.9 Case Studies

Benefit of O&M Controls Assessments (PECI 1999)

A 250,000 square-foot office building in downtown Nashville, Tennessee, was renovated in 1993. The renovation included installing a DDC energy management control system to control the variable air volume (VAV) HVAC system and lighting and a variable frequency drive (VFD) for the chilled water system. The building was not commissioned as part of the renovation. An O&M assessment was performed 3 years later because the building was experiencing problems and energy bills seemed higher then expected. As a result of the assessment, a total of 32 O&M related problems including a major indoor air quality (IAQ) deficiency were identified. It was also determined that the majority of these problems had been present since the renovation. Annual energy savings from the recommended O&M improvements and repairs are estimated at $9,300. The simple payback for both the assessment and implementation is under 7 months.

GSA/FEMP Pre-Cooling Strategy at the Philadelphia Custom House (FEMP 2007)

FEMP performed a study of prospective load management and demand response approaches for the General Services Administration's (GSA) Philadelphia Custom House in early 2005 (Figure 9.6.1). GSA adopted the key recommendation and, through a few targeted operational changes and almost no capital cost, saved nearly $70,000 in demand payments in 2005-2006 and more than $100,000 (almost 15 percent of the facility's annual electricity bill) in 2006-2007.


Figure 9.6.1. General Services Administration's Custom House, Philadelphia, PA

GSA pays more than $28 per kilowatt (kW)—two to three times the national norm—in demand charges for the 570,000 square foot Custom House, and is also subject to a demand "ratchet" such that 80 percent of its summer peak power draw (i.e., its highest single 30-minute interval reading between June and September) becomes its minimum billed demand for each of the next eight months (October through May).

Since the Custom House generally experiences a summer peak of about 2,000 kW, this means that GSA is obligated to pay for at least 1,600 kW during these off-peak months. However, the facility is a conventional Federal office building with a low load factor, and barely reaches peaks of 1,000 kW from December to March. At more than $28 per kW, the Custom House regularly pays its utility (PECO Energy) over $15,000 per month during those four months (as well as additional sums in the "shoulder" months of October, November, April, and May) for power it does not even draw.

With this in mind, GSA requested that FEMP conduct a study on the potential to cost-effectively reduce its peak demand. The central component of FEMP's recommendation was a "precooling" strategy where GSA would turn on its chilled water plant very early in the morning (as opposed to the usual 6 A.M.) on hot summer days. In addition, FEMP recommended that the chilled water valves in the building's roughly one thousand perimeter induction units be tripped to a "fail-open" position during these early morning hours so that the facility would actually be somewhat over-cooled. The idea was to utilize the circa 1934 building's substantial mass as a thermal storage medium, which could then absorb heat and provide cool-temperature radiation throughout the day, mitigating the customary afternoon power peak.

GSA adopted this strategy, and working with their operations and maintenance contractor developed a multi-part plan to reduce the building's peak through early morning pre-cooling and afternoon "demand-limiting." The key elements are:

- If the outside air exceeds 70°F at 2 A.M., one of the facility's two 650-ton chillers is turned on and programmed to produce 42°F chilled water;
- All induction unit chilled water valves are set to a full-open position during the early morning;
- At 9 A.M., the chilled water temperature is raised to 46°F and induction unit control reverts to the tenants (the units have no re-heat coils but the unit controls can be set towards "warmer" to reduce or eliminate the flow of chilled water through them);
- If demand reaches 1,500 kW and is still rising by 12 noon, the chilled water temperature is raised again, to 48°F;
- Only one of the two 650-ton chillers is allowed to operate at any given time.

In the beginning of summer 2005, the team executed the strategy manually, using control system overrides for chiller operation and bleeding the air out of the pneumatic lines to open the induction unit valves. Once the team gained confidence in this strategy, the building's controls contractor was called in to help automate it within the energy management control system (installed in 2003 as part of a Super Energy Savings Performance Contract).

As a result, the operations team was able to keep the facility's peak demand down to 1,766 kW over the summer (defined by the PECO tariff as June though September), as opposed to the 2,050 kW or higher that would likely have been reached. GSA benefited directly from the reduced demand in the summer, saving an estimated $26,000 (see Table 9.6.1) in those four months alone.

Table 9.6.1. Custom House demand reduction and savings 2005-2006

Month	Expected Peak (kW)*	Actual Peak (kW)*	Billed Peak (kW)**	Peak Reduction (kW)	kW Value
June 2005	1,900	1,766	1,766	134	$3,410
July 2005	2,050	1,692	1,692	358	$9,109
August 2005	2,050	1,692	1,697	353	$8,982
September 2005	1,900	1,711	1,711	189	$4,809
October 2005	1,640	1,640	1,604	36	$916
November 2005	1,640	1,448	1,448	192	$4,885
December 2005	1,640	1,015	1,413	227	$5,776
January 2006	1,640	992	1,413	227	$6,134
February 2006	1,640	961	1,413	227	$6,134
March 2006	1,640	953	1,413	227	$6,134
April 2006	1,640	1,393	1,413	227	$6,134
May 2006	1,850	1,646	1,646	204	$5,512
Total Savings					**$67,934**

* June - Sept. 05 and May 06 figures are projected, without pre-cooling; October through April numbers represent 80% of projected summer peak maximum (see orange-shaded cells)

** Dec. 05 - April 06 figures represent 80% of actual summer peak maximum (see green-shaded cells).

GSA reaped even greater savings from the reduced ratchet charges during the winter months. The ratchet clause set the minimum demand charge for the October through May bills at 1,413 kW (80 percent of the 1,766 kW summer peak). While the previous four summers' average peak was 2,080 kW, FEMP conservatively estimated that 2,050 kW would have been 2005's peak draw (this is a conservative estimate because the summer of 2005 was an unusually hot one in the mid-Atlantic). Since 80 percent of 2,050 is 1,640, this figure was used to estimate the ratchet savings – i.e., to represent what the billed peak would have been without the pre-cooling. The 227 kW reduction (1640 – 1413) translated to more than $30,000 in savings for the five months of December through April; additional ratchet relief in October, November, and May made for a total (including the $26,000 in direct summer months' savings) of roughly $68,000.

In sum, the Custom House's pre-cooling thermal storage experiment has been an enormous success. The GSA avoided almost $70,000 in demand charges during the first year (2005-6). GSA concluded at a "lessons learned" meeting that the GSA should "declare summer 2005's usage was only 0.5 percent higher, despite the fact that it had 4.3 percent more cooling degree days." Moreover, a regression plotting the four previous summers' kWh consumption against the number of cooling degree days in each revealed that summer 2005's actual consumption was 2 percent less than what the model predicted. The facility's summer 2006 usage fell a remarkable 7.5 percent below the regression's prediction.

9.6.10 Building Controls Checklist

Description	Comments	Maintenance Frequency			
		Daily	Weekly	Semi-Annually	Annually
Overall visual inspection	Complete overall visual inspection to be sure all equipment is operating and safety systems are in place	X			
Verify control schedules	Verify in control software that schedules are accurate for season, occupancy, etc.	X			
Verify setpoints	Verify in control software that setpoints are accurate for season, occupancy, etc.	X			
Time clocks	Reset after every power outage	X			
Check all gauges	Check all gauges to make sure readings are as expected		X		
Control tubing (pneumatic system)	Check all control tubing for leaks		X		
Check outside air volumes	Calculated the amount of outside air introduced and compare to requirements		X		
Check setpoints	Check setpoints and review rational for setting		X		
Check schedules	Check schedules and review rational for setting		X		
Check deadbands	Assure that all deadbands are accurate and the only simultaneous heating and cooling is by design		X		
Check sensors	Conduct thorough check of all sensors – temperature, pressure, humidity, flow, etc. – for expected values			X	
Time clocks	Check for accuracy and clean			X	
Calibrate sensors	Calibrate all sensors: temperature, pressure, humidity, flow, etc.				X

9.6.11 References

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9.7 Air Handling Systems

9.7.1 Introduction

The components of most air handling systems include fans, ductwork, damper assemblies, heating and cooling coils (or elements), and associated sensors.

9.7.2 Types of Air Handling Systems

Most air handling systems fall into two broad categories, constant-volume (CV) and variable-air-volume (VAV). The following descriptions provide an overview of generic system types commonly found in larger commercial and institutional buildings (Better Bricks 2008).

Constant Air Volume. Constant air volume systems provide a constant airflow rate to the zone. The control variable is the temperature of the air supplied to the zone. These systems can be configured for single-zone or multi-zone systems and may be configured as a single duct or two duct (dual duct) system.

Variable Air Volume. VAV systems provide comfort by changing the volume of air delivered to a zone based on temperature needs and controlled by static pressure measured in the duct system. Most VAV systems are single duct systems and provide cooling and ventilation – when necessary, air is heated often at the terminal unit.

9.7.3 Key Components

- **Fans** – This topic will be addressed in Section 9.8
- **Coils** – Coils provide the mechanism for heat transfer between the air stream and the heat-exchange fluid (usually water, steam or refrigerant). These coils are made of tubes that carry the fluid and are surrounded by rows of thin fins designed to increase the heat-transfer surface area. For maximum heat transfer, it is imperative to keep these coils clean and free of obstructions.
- **Filters** – With the goal of efficient heat transfer and good air quality, filters are used to prevent particulate matter or other contaminants from entering (or re-circulating) though an air handling system. Filters are classified by ASHRAE Standard 52.2 and rated by their Minimum Efficiency Reporting Value (MERV). By design, the airflow through a filter bank should be as uniform across the entire filter surface area and, depending on the filter type and design, in the range of 400 to 600 feet per minute (fpm). Filters are a required maintenance item and should be changed based on system use and contaminant loading.
- **Dampers** – To control and direct the flow of air through the system, dampers are installed at the inlet, the outlet, or internal to the air handling system. There are a variety of damper types and configurations. Dampers are a notorious source of energy waste via leakage, malfunction, or being disabled. Due to their typical location and challenges associated with proper assessment, damper assemblies are often not addressed in standard maintenance practices.
- **Ducts** – The ducts found in most commercial facilities are usually made of galvanized steel and are insulated to reduce heat transfer and prevent condensation. Duct connections from section to section, or at the terminal apparatus, need to be done according local code requirements and should be checked annually for integrity.

9.7.4 Cost and Energy Efficiency

Many air handling system efficiency measures relate to how the system is controlled and are covered in Section 9.6 Energy Management and Building Automation Systems. Additional measures for consideration are presented below.

- **Filters** – Air filters play a critical role in maintaining indoor air quality and protecting the downstream components of the system from dirt that reduces equipment efficiency. In the worse case, dirty filters can result in supply air bypassing the filter and depositing dirt on the heating/cooling coils rather than on the filter. This results in dirty coils, poor heat transfer, and general inefficiency. In addition to the efficiency penalty, cleaning a dirty coil is far more difficult and labor intensive than replacing filters (DOE 2005).

  As a rule, sites should routinely change filters based on either the pressure drop across the filter, calendar scheduling, or visual inspection. Scheduled intervals should be between 1 and 6 months, depending on the dirt loading from indoor and outdoor air. Measuring the pressure drop across the filter is the most reliable way to assess filter condition. In facilities with regular and predictable dirt loading, measuring the pressure drop across the filter can be used to establish the proper filter-changing interval; thereafter, filter changes can be routinely scheduled. Refer to manufacturer's data for the recommendations of pressure drop across specific filters.

- **Coil Cleaning** – Hot water and chilled water coils in HVAC systems tend to accumulate dirt and debris, similarly to HVAC filters. As dirt and debris accumulates, it inhibits the heat transferred from the working fluid to the air stream, thus reducing the efficiency of the HVAC system. Much like HVAC filters, the scheduled intervals between cleanings is a function of the dirt loading across the coil and is primarily a function of how much dirt is in the ambient air and what has bypassed the filter. Based on the site's periodic inspections, the given facility should develop appropriate cleaning schedules for all of the hot water and chilled water coils. Figure 9.7.1 presents a cooling coil in great need of maintenance.

- **Damper Operation** – There are a number of potential faults HVAC dampers may be subject to. These include dampers stuck open or closed, dampers manually positioned (i.e., mechanically fixed in a position using wire, boards, etc.), dampers with missing vanes, or dampers operating with poor seals. Figure 9.7.2 shows one all too common solution to a damper issue – something not recommended by this guide's authors.

9.7.5 Maintenance

Proper maintenance for air handling systems includes scheduled filter replacement, coil cleaning, duct integrity evaluation, damper cleanliness and function.

9.7.5.1 Diagnostic Tools

The combination of a facility's building automation system and occupant interaction can be very diagnostic of an air handling systems function. Repeated cold/warm complaint calls, validated through the BAS sensor readings, can be indicative of a poorly performing system in need of maintenance.

Figure 9.7.1. Cooling coil requiring cleaning

Figure 9.7.2. Damper quick fix – not recommended

9.7.5.2 Case Study

Retro-Commissioning of Air-Handling System at the Ronald V. Dellums Federal Building (QuEST 2004)

During a Building Tune-Up (BTU) Program audit at the Ronald V. Dellums Federal Building in Oakland, program engineers identified several simple ways to improve energy efficiency in its air handling systems yielding more than $65,000 in annual savings.

The 1.1 million square foot office building was the focus of a thorough retro-commissioning (R-Cx) audit provided as part of the Oakland Energy Partnership (OEP) Program. The audit team found that energy costs could be cut by improving placement of key air stream sensors, addressing air damper problems, and reducing pressure setpoints.

An Efficient Building Can Reduce Costs Even More.

Although the building was completed in 1994 and has an energy use intensity of 54 kBtu/sqft-yr, well below the average 70 kBtu/sqft-yr for typical office buildings in Oakland, the tune-up team managed to find numerous cost-effective savings measures.

One of the findings of the program was that poor sensor locations in the air handlers have been wasting over $27,000 per year. By simply moving sensors to locations that are more representative of the air stream of interest, the existing control algorithms work as they were originally intended.

In another case, air was flowing through the ducts in the reverse direction of the intended design. Functional testing showed that under certain conditions, air from one hot deck supply fan was flowing up the common supply shaft and back feeding through the other fan. The R-Cx team recommended controlling both 5th floor & penthouse fans in unison to prevent this problem. Expert analysis required to identify this problem was paid for by the BTU program and building owners paid relatively little to implement the measures.

The investigation phase of the project included analysis of trended data logs and extensive functional testing of the HVAC equipment. A total of 12 operational deficiencies were observed in the air handling systems. The problems with the greatest potential for energy savings were thoroughly analyzed and corrective measures were recommended. The project team also made specific recommendations on how to improve the operation and comfort of the facility on other non-energy related issues.

Improvements Save Energy and Increase Comfort.

Identification, documentation and implementation of non-energy measures can often improve occupant comfort, reduce operator workload and generally improve the operation of the facility. Examples of such measures at the Ronald V. Dellums Federal Building included:

- Cleaning and calibrating airflow-monitoring stations on supply and return fans. This corrective measure allowed proper tracking of the return fans speed, which helped maintain the proper pressurization within the building.
- Adding an "auto-zero" calibration feature to the VAV box control programs. This ensured that each occupant received the correct airflow in the work area.
- Adjusting the valve actuators and positioners serving the chilled water coils to reduce hunting and increase coil capacity.

9.7.6 Air Handling System Checklists (Better Bricks 2008)

Description	Comments	Maintenance Frequency			
		Daily	Weekly	Monthly	Annually
Overall visual inspection	Complete overall visual inspection to be sure all equipment is operating and safety systems are in place	X			
Filters	Check filter condition according to system type and manufacturer's recommendations			X	
System integrity	Inspect for leakage due to major connections and access doors not being properly closed.			X	
Dampers	Inspect damper actuator and linkage for proper operation by cycling fully opened to fully closed.			X	
Filter assemblies	Inspect filter rack for integrity. Inspect local pressure differential gauge, tubing, and pilot tubes for condition				X
Coils	Inspect coil fins for physical damage, and comb out any bent fins. Clean coils if significant dirt is present and hampering coil performance				X

9.7.7 References

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9.8 Fans

9.8.1 Introduction

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) defines a fan as an "air pump that creates a pressure difference and causes airflow. The impeller does the work on the air, imparting to it both static and kinetic energy, varying proportion depending on the fan type" (ASHRAE 1992).

9.8.2 Types of Fans (Bodman and Shelton 1995)

The two general types of fans are axial-flow and centrifugal. With axial-flow fans, the air passes through the fan parallel to the drive shaft. With centrifugal fans, the air makes a right angle turn from the fan inlet to outlet.

9.8.2.1 Axial Fan

Axial-flow fans can be subdivided based on construction and performance characteristics.

- **Propeller fan** – The basic design of propeller fans enhances maintenance to remove dust and dirt accumulations. The fan normally consists of a "flat" frame or housing for mounting, a propeller-shaped blade, and a drive motor. It may be direct drive (Figure 9.8.1) with the wheel mounted on the motor shaft or belt driven (Figure 9.8.2) with the wheel mounted on its own shaft and bearings.

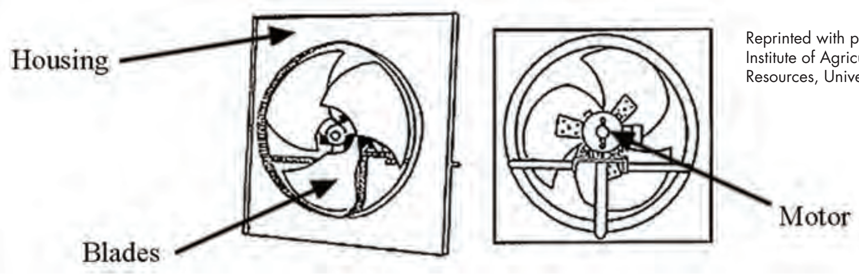

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Figure 9.8.1. Propeller direct-drive fan (front and rear view).

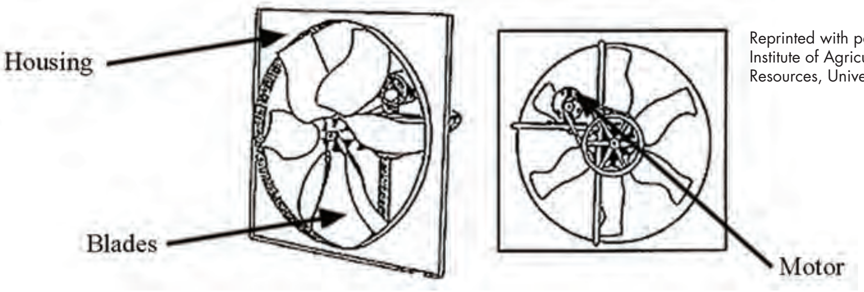

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Figure 9.8.2. Propeller belt-drive fan (front and rear view).

- **Tube-axial fans** – A tube-axial fan (Figure 9.8.3) consists of a tube-shaped housing, a propeller-shaped blade, and a drive motor. Vane-axial fans (Figure 9.8.4) are a variation of tube-axial fans, and are similar in design and application. The major difference is that air straightening vanes are added either in front of or behind the blades. This results in a slightly more efficient fan, capable of somewhat greater static pressures and airflow rates.

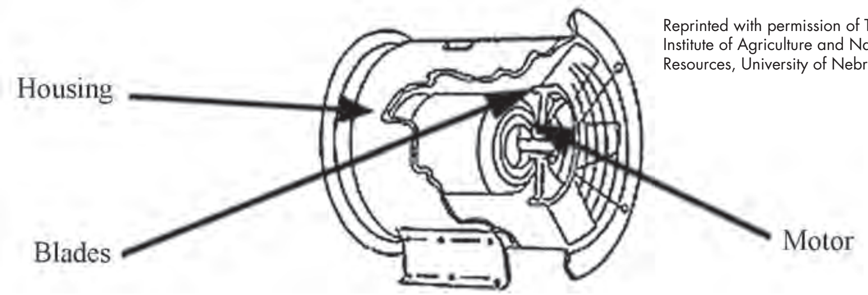

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Figure 9.8.3. Tube-axial fan

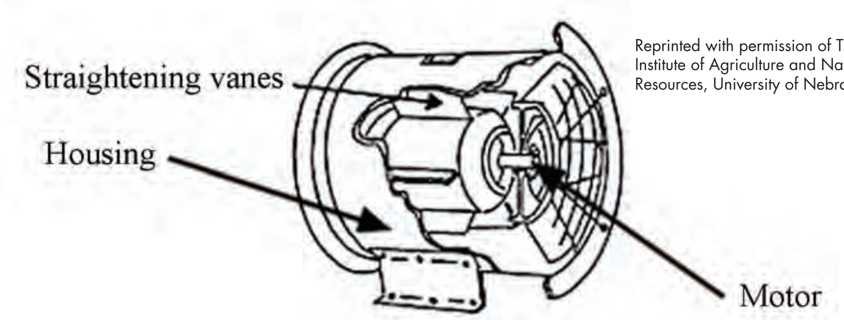

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Figure 9.8.4. Vane axial fan

9.8.2.2 Centrifugal Fans

Often called "squirrel cage" fans, centrifugal fans have an entirely different design (Figure 9.8.5). These fans operate on the principle of "throwing" air away from the blade tips. The blades can be forward curved, straight, or backward curved. Centrifugal fans with backward curved blades are generally more efficient than the other blade configurations. This design is most often used for aeration applications where high airflow rates and high static pressures are required. Centrifugal fans with forward curved blades have somewhat lower static pressure capabilities but tend to be quieter than the other blade designs. Furnace fans typically use a forward curved blade. An advantage of the straight blade design is that with proper design it can be used to handle dirty air or convey materials. Centrifugal fans are generally less expensive than axial fans and simpler in construction, but generally do not achieve the same efficiency.

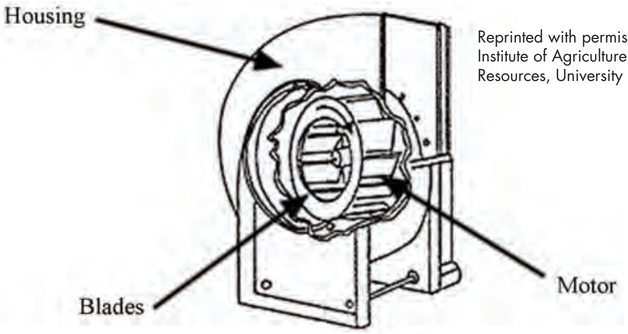

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Figure 9.8.5. Centrifugal fan

9.8.3 Key Components

- **Impeller or rotor** – A series of radial blades are attached to a hub. The assembly of the hub and blades is called impeller or rotor. As the impeller rotates, it creates a pressure difference and causes airflow.
- **Motor** – Drives the blades so they turn. It may be direct drive with the wheel mounted on the motor shaft or belt driven with the wheel mounted on its own shaft and bearings. It is important to note that fans may also be driven by other sources of motive power such as an internal combustion engine, or steam or gas turbine.
- **Housing** – Encloses and protects the motor and impeller.

9.8.4 Safety Issues

Continuously moving fresh air through a confined space is the most effective means of controlling pollutant levels and ensuring good air quality. Ventilation dilutes and displaces air contaminants, assures that an adequate oxygen supply is maintained during entry, and exhausts contaminants created by entry activities such as welding, oxygen-fuel cutting, or abrasive blasting (North Carolina State University 2001).

9.8.5 Cost and Energy Efficiency

In certain situations, fans can provide an effective alternative to costly air conditioning. Fans cool people by circulating or ventilating air. Circulating air speeds up the evaporation of perspiration from the skin so we feel cooler. Ventilating replaces hot, stuffy, indoor air with cooler, fresh, outdoor air. Research shows moving air with a fan has the same affect on personal comfort as lowering the temperature by over 5°F. This happens because air movement created by the fan speeds up the rate at which our body loses heat, so we feel cooler. Opening and closing windows or doors helps the fan move indoor air outside and outdoor air inside, increasing the efficiency of the fan. When it is hot outside, close windows and doors to the outside. In the morning or evening, when outdoor air is cooler, place the fan in front of a window or door and open windows on the opposite side of the room. This draws cooler air through the living area (EPCOR 2001).

In many applications, fan control represents a significant opportunity for increased efficiency and reduced cost. A simple and low-cost means of flow control relies on dampers, either before or after the fan. Dampers add resistance to accomplish reduced flow, while increasing pressure. This increased pressure results in increased energy use for the flow level required. Alternatives to damper flow control methods include physical reductions in fan speed though the use of belts and pulleys or variable speed controllers.

9.8.6 Maintenance of Fans

Typically, fans provide years of trouble-free operation with relatively minimal maintenance. However, this high reliability can lead to a false sense of security resulting in maintenance neglect and eventual failure. Due to their prominence within HVAC and other process systems (without the fan operating, the system shuts down), fans need to remain high on the maintenance activity list.

Most fan maintenance activities center on cleaning housings and fan blades, lubricating and checking seals, adjusting belts, checking bearings and structural members, and tracking vibration.

9.8.7 Diagnostic Tools

- **Ultrasonic analyzer** – Air moving systems emit very distinct sound patterns around bearings and fan blades. In most cases, these sounds are not audible to the unaided ear or are drown-out by other equipment noises. Using an ultrasonic detector, the analyst is able to isolate the frequency of sound being emitted by the bearing or blades. Changes in these ultrasonic wave emissions are indicative of changes in equipment condition-some of these changes can be a precursor to component degradation and failure. More information on ultrasonic analysis can be found in Chapter 6.
- **Vibration analyzer** – Within air moving systems, there are many moving parts, most in rotational motion. These parts generate a distinct pattern and level of vibration. Using a vibration analyzer and signature analysis software, the analyst can discern the vibration amplitude of the point on the equipment being monitored. This amplitude is then compared with trended readings. Changes in these readings are indicative of changes in equipment condition. More information on vibration analysis can be found in Chapter 6.

9.8.8 Available Software Tools

Fan System Assessment Tool (FSAT)

Description: Experience has shown that greater energy savings can be achieved through system optimization than through component optimization. The DOE Fan System Assessment Tool (FSAT) helps users quantify energy consumption and energy savings opportunities in industrial fan systems. By reducing the engineering time associated with analyzing fan systems it now becomes easier to understand the economic and energy significance of changes in both system equipment and operating practices.

FSAT helps users quantify the difference between rated performance and installed performance due to such things as:

- High duct velocity
- Discharge dampers locked in position
- Obstructed inlets
- Incorrectly sized fans
- Poor duct geometry
- Degraded impellers.

FSAT is simple and quick to use, and requires only basic information about fans and the motors that drive them. With FSAT, users can calculate the amount of energy used by a fan system; determine system efficiency; and quantify the savings potential of an upgraded system. The tool also provides a prescreening filter to identify fan systems that are likely to offer optimization opportunities based on the system's control, production and maintenance, and effect.

FSAT estimates the work done by the fan system and compares that to the estimated energy input into the system. Using generic typical performance characteristics for fans and motors, indications of potential savings (in energy and dollars) are developed.

Availability: To download the Fan System Assessment Tool and learn more about DOE Qualified Specialists and training opportunities, visit the Industrial Technology Program Web site: www.eere.energy.gov/industry/bestpractices.

9.8.9 Relevant Operational/Energy Efficiency Measures

There are a number of operational/energy efficiency measures that could be presented for proper fan operation and control. This section focuses on the most prevalent O&M recommendations having the greatest energy impacts at Federal facilities and includes (DOE 2003, UNEP 2006):

Oversized Fans: A common problem in many facilities is the purchase of oversized fans for their service requirements. These oversized fans will not operate at the most efficient point and in extreme cases these fans may operate in an unstable manner because of the point of operation on the fan airflow pressure curve. Oversized fans generate excess flow energy, resulting in high airflow noise and increased stress on the fan and the system. Consequently, oversized fans not only cost more to purchase and to operate, they create avoidable system performance problems. Possible solutions include, amongst other replacing the fan, replacing the motor, or introducing a variable speed drive motor.

Fan System Operational-Efficiency Considerations
(UNEP 2006)

- Use smooth, well-rounded air inlet cones for fan air intake
- Avoid poor flow distribution at the fan inlet
- Minimize fan inlet and outlet obstructions
- Clean screens, filters and fan blades regularly
- Minimize fan speed
- Use low slip or flat belts for power transmission
- Check belt tension regularly
- Use variable speed drives for large variable fan loads
- Use energy-efficient motors for continuous or near continuous operation
- Eliminate leaks in ductwork
- Minimize bends in ductwork
- Turn fans and blowers off when not needed
- Reduce the fan speed by pulley diameter modifications in case of oversized motors
- Adopt inlet guide vanes in place of discharge damper control
- Reduce transmission losses by using energy-efficient flat belts or cogged raw-edged V-belts instead of conventional V-belt systems
- Ensure proper alignment between drive and driven system
- Ensure proper power supply quality to the motor drive
- Regularly check for vibration trend to predict any incipient failures like bearing damage, misalignments, unbalance, foundation looseness.

System Resistance: The fan operates at a point where the system resistance curve and the fan curve intersects. The system resistance has a major role in determining the performance and efficiency of a fan. The system resistance also changes depending on the process. For example, the formation of the coatings/erosion of the lining in the ducts, changes the system resistance marginally. In some cases, the change of equipment, or duct modifications, drastically shift the operating point, resulting in lower efficiency. In such cases, to maintain the efficiency as before, the fan has to be changed. Hence, the system resistance has to be periodically checked, more so when modifications are introduced and action taken accordingly, for efficient operation of the fan.

Fan Maintenance: Regular maintenance of fans is important to maintain their performance levels. Maintenance activities include:

- Periodic inspection of all system components
- Bearing lubrication and replacement
- Belt tightening and replacement
- Motor repair or replacement
- Fan cleaning

Fan Control: Normally, an installed fan operates at a constant speed. But some situations may require a speed change; for example, more airflow may be needed from the fan when a new run of duct is added, or less airflow may be needed if the fan is oversized. There are several ways to reduce or control the airflow of fans. These are summarized in Table 9.8.1.

Table 9.8.1. Fan-flow control comparison (adapted from DOE 2003)

Type of Fan Flow Control	Advantages	Disadvantages
Pulley change: reduces the motor/drive pulley size	Permanent speed decrease Real energy reduction	Fan must be able to handle capacity change Fan must be driven by V-belt system or motor
Dampers: reduce the amount of flow and increases the upstream pressure, which reduces fan output	• Inexpensive • Easy to install	• Provide a limited amount of adjustment • Reduce the flow but not the energy consumption • Higher operating and maintenance costs
Inlet guide vanes: create swirls in the fan direction thereby lessening the angle between incoming air and fan blades, and thus lowering fan load, pressure and airflow	• Improve fan efficiency because both fan load and delivered airflow are reduced • Cost-effective at airflows between 80-100% of full flow	• Less efficient at airflows lower than 80% of full flow
Variable Speed Drive (VSD): reducing the speed of motor of the fan to meet reduced flow requirements • Mechanical VSDs: hydraulic clutches, fluid couplings, and adjustable belts and pulleys • Electrical VSDs: eddy current clutches, wound rotor motor controllers, and variable frequency drives (VFDs: change motor's rotational speed by adjusting electrical frequency of power supplied)	• Most improved and efficient flow control • Allow fan speed adjustments over a continuous range For VFDs specifically: • Effective and easy flow control • Improve fan operating efficiency over a wide range of operating conditions • Can be retrofitted to existing motor's compactness • No fouling problems • Reduce energy losses and costs by lowering overall system flow	Mechanical VSDs can have fouling problems • Investment costs can be a barrier

9.8.10 Case Studies

Blower for an Industrial Application

The operation of a centrifugal fan by damper control is energy inefficient because part of the energy supplied to the fan is lost across damper. The damper control has to be minimized by suitably optimizing the capacity of the fan to suit the requirement. One of the best methods to optimize the capacity of the fan is by reducing the rpm of the fan and operate the blower with more damper opening.

Previous Status. An air blower was operated with 30% damper opening. The blower was belt-driven. The pressure required for the process was 0.0853 psi. The pressure rise of the blower was 0.1423 psi and the pressure drop across the damper was 0.0569 psi. This indicates an excess capacity/ static head available in the blower.

Energy Saving Project. The rpm of the blower was reduced by 20% by suitably changing the pulley. After the reduction in rpm, the damper was operated with 60% to 70% opening.

The replacement of the pulley was taken up during a non-working day. No difficulties were encountered on implementation of the project.

Financial Analysis. The reduction in rpm of the blower and minimizing the damper control resulted in reduction of power consumption by 1.2 kW. The implementation of this project resulted in an annual savings of approximately $720. The investment made was approximately $210, which was paid back in under 4 months (Confederation of Indian Industry 2001).

9.8.11 Fans Checklist

Description	Comments	Maintenance Frequency			
		Daily	Weekly	Monthly	Annually
System use/ sequencing	Turn off/sequence unnecessary equipment	X			
Overall visual inspection	Complete overall visual inspection to be sure all equipment is operating and safety systems are in place	X			
Observe belts	Verify proper belt tension and alignment			X	
Inspect pulley wheels	Clean and lubricate where required			X	
Inspect dampers	Confirm proper and complete closure control; outside air dampers should be airtight when closed			X	
Observe actuator/ linkage control	Verify operation, clean, lubricate, adjust as needed			X	
Check fan blades	Validate proper rotation and clean when necessary			X	
Filters	Check for gaps, replace when dirty – monthly			X	
Check for air quality anomalies	Inspect for moisture/growth on walls, ceilings, carpets, and in/outside of ductwork. Check for musty smells and listen to complaints.			X	
Check wiring	Verify all electrical connections are tight				X
Inspect ductwork	Check and refasten loose connections, repair all leaks				X
Coils	Confirm that filters have been kept clean, as necessary				X
Insulation	Inspect, repair, replace all compromised duct insulation				X

9.8.12 References

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9.9 Pumps

9.9.1 Introduction

Keeping pumps operating successfully for long periods of time requires careful pump design selection, proper installation, careful operation, the ability to observe changes in performance over time, and in the event of a failure, the capacity to thoroughly investigate the cause of the failure and take measures to prevent the problem from recurring. Pumps that are properly sized and dynamically balanced, that sit on stable foundations with good shaft alignment and with proper lubrication, that operators start, run, and stop carefully, and that maintenance personnel observe for the appearance of unhealthy trends which could begin acting on and causing damage to, usually never experience a catastrophic failure (Piotrowski 2001).

9.9.2 Types of Pumps

The family of pumps comprehends a large number of types based on application and capabilities.

The two major groups of pumps are dynamic and positive displacement.

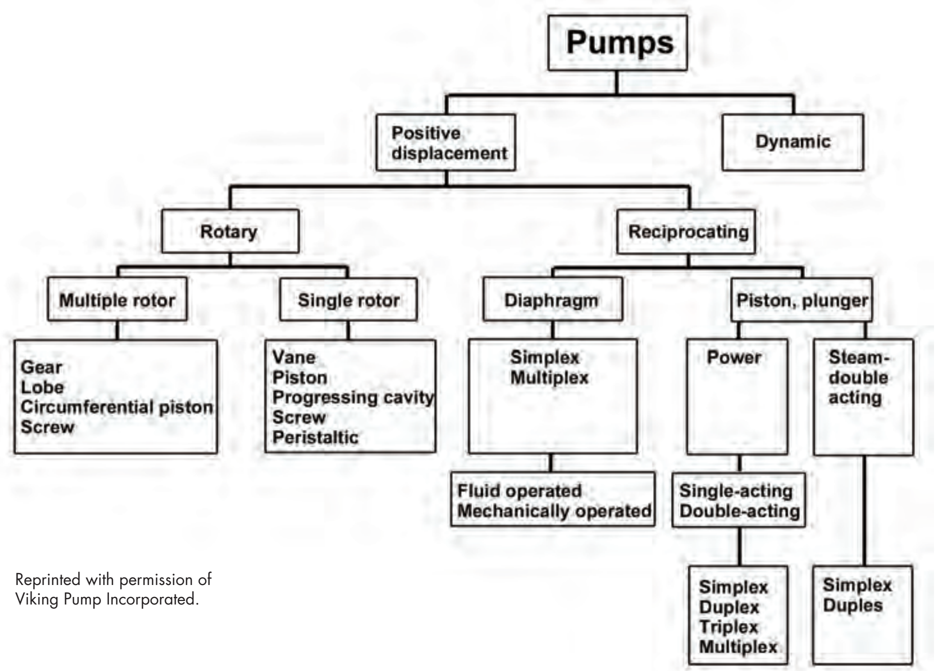

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Figure 9.9.1. Technology tree for pumps.

9.9.2.1 Dynamic Pump (Centrifugal Pump) (Pump World 2001a)

Centrifugal pumps are classified into three general categories:

- **Radial flow** – a centrifugal pump in which the pressure is developed wholly by centrifugal force.
- **Mixed flow** – a centrifugal pump in which the pressure is developed partly by centrifugal force and partly by the lift of the vanes of the impeller on the liquid.
- **Axial flow** – a centrifugal pump in which the pressure is developed by the propelling or lifting action of the vanes of the impeller on the liquid.

9.9.2.2 Positive Displacement Pump (Pump World 2001c)

A positive displacement pump (Figure 9.9.2) has an expanding cavity on the suction side of the pump and a decreasing cavity on the discharge side. Liquid is allowed to flow into the pump as the cavity on the suction side expands and the liquid is forced out of the discharge as the cavity collapses. This principle applies to all types of positive displacement pumps whether the pump is a rotary lobe, gear within a gear, piston, diaphragm, screw, progressing cavity, etc.

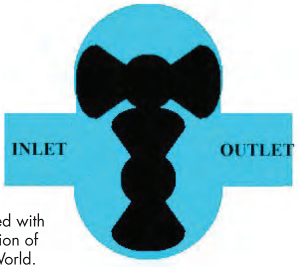

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Figure 9.9.2. Rotary lobe pump

A positive displacement pump, unlike a centrifugal pump, will produce the same flow at a given rpm no matter what the discharge pressure is. A positive displacement pump cannot be operated against a closed valve on the discharge side of the pump, i.e., it does not have a shut-off head like a centrifugal pump does. If a positive displacement pump is allowed to operate against a closed discharge valve, it will continue to produce flow which will increase the pressure in the discharge line until either the line bursts or the pump is severely damaged or both (Pump World 2001d).

For purposes of this guide, positive displacement pumps (Figure 9.9.3) are classified into two general categories and then subdivided into four categories each:

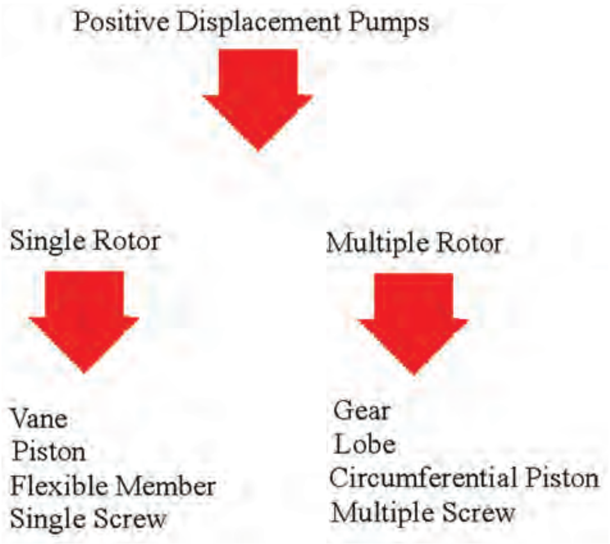

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Figure 9.9.3. Positive displacement pumps.

9.9.3 Key Components

9.9.3.1 Centrifugal Pump (Pump World 2001b)

The two main components of a centrifugal pump (Figure 9.9.4) are the impeller and the volute.

The impeller produces liquid velocity and the volute forces the liquid to discharge from the pump converting velocity to pressure. This is accomplished by offsetting the impeller in the volute and by maintaining a close clearance between the impeller and the volute at the cut-water. Please note the impeller rotation. A centrifugal pump impeller slings the liquid out of the volute.

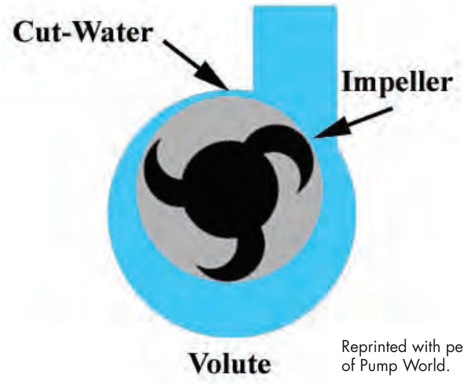

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Figure 9.9.4. Centrifugal pump.

9.9.3.2 Positive Displacement Pumps

- Single Rotor (Pump World 2001d)
  - ***Vane*** – The vane(s) may be blades, buckets, rollers, or slippers that cooperate with a dam to draw fluid into and out of the pump chamber.
  - ***Piston*** – Fluid is drawn in and out of the pump chamber by a piston(s) reciprocating within a cylinder(s) and operating port valves.
  - ***Flexible Member*** – Pumping and sealing depends on the elasticity of a flexible member(s) that may be a tube, vane, or a liner.
  - ***Single Screw*** – Fluid is carried between rotor screw threads as they mesh with internal threads on the stator.
- Multiple Rotor (Pump World 2001d)
  - ***Gear*** – Fluid is carried between gear teeth and is expelled by the meshing of the gears that cooperate to provide continuous sealing between the pump inlet and outlet.
  - ***Lobe*** – Fluid is carried between rotor lobes that cooperate to provide continuous sealing between the pump inlet and outlet.
  - ***Circumferential Piston*** – Fluid is carried in spaces between piston surfaces not requiring contacts between rotor surfaces.
  - ***Multiple Screw*** – Fluid is carried between rotor screw threads as they mesh.

- Relief Valves (Pump World 2001e)

  Note: *A relief valve (Figure 9.9.5) on the discharge side of a positive displacement pump is an absolute must for safety!*

  - ***Internal Relief Valve*** – Pump manufacturers normally have an option to supply an internal relief valve. These relief valves will temporarily relieve the pressure on the discharge side of a pump operating against a closed valve. They are normally not full ported, i.e., cannot bypass all the flow produced by the pump. These internal relief valves should be used for pump protection against a temporary closing of a valve.
  - ***External Relief Valve*** – An external relief valve (RV) installed in the discharge line with a return line back to the supply tank is highly recommended to provide complete protection against an unexpected over pressure situation.

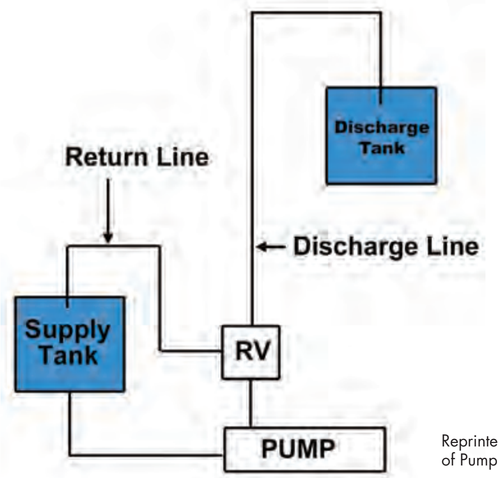

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Figure 9.9.5. Schematic of pump and relief valve.

9.9.4 Safety Issues (Pompe Spec Incorporated 2001)

Some important safety tips related to maintenance actions for pumps:

- Safety apparel
  - Insulated work gloves when handling hot bearings or using bearing heater.
  - Heavy work gloves when handling parts with sharp edges, especially impellers.
  - Safety glasses (with side shields) for eye protection, especially in machine shop area.
  - Steel-toed shoes for foot protection when handling parts, heavy tools, etc.
- Safe operating procedures
  - Coupling guards: Never operate a pump without coupling guard properly installed.
  - Flanged connections:
    - Never force piping to make connection with pump.
    - Insure proper size, material, and number of fasteners are installed.
    - Beware of corroded fasteners.

  - When operating pump:
    - Do not operate below minimum rated flow, or with suction/discharge valves closed.
    - Do not open vent or drain valves, or remove plugs while system is pressurized.

- Maintenance safety
  - Always lock out power.
  - Ensure pump is isolated from system and pressure is relieved before any disassembly of pump, removal of plugs, or disconnecting piping.
  - Pump and components are heavy. Failure to properly lift and support equipment could result in serious injury.
  - Observe proper decontamination procedures. Know and follow company safety regulations.
  - Never apply heat to remove impeller.

9.9.5 Cost and Energy Efficiency

Pumps frequently are asked to operate far off their best efficiency point, or are perched atop unstable base-plates, or are run under moderate to severe misalignment conditions, or, having been lubricated at the factory, are not given another drop of lubricant until the bearings seize and vibrate to the point where bolts come loose. When the unit finally stops pumping, new parts are thrown on the machine and the deterioration process starts all over again, with no conjecture as to why the failure occurred.

Proper maintenance is vital to achieving top pump efficiency expected life. Additionally, because pumps are a vital part of many HVAC and process applications, their efficiency directly affects the efficiency of other system components. For example, an improperly sized pump can impact critical flow rates to equipment whose efficiency is based on these flow rates–a chiller is a good example of this.

The following are measures that can improve pump efficiency: (OIT 1995)

- Shut down unnecessary pumps.
- Restore internal clearances if performance has changed.
- Trim or change impellers if head is larger than necessary.
- Control by throttle instead of running wide-open or bypassing flow.
- Replace oversized pumps.
- Use multiple pumps instead of one large one.
- Use a small booster pump.
- Change the speed of a pump for the most efficient match of horsepower requirements with output.

9.9.6 Maintenance of Pumps

(General Services Administration 1995)

The importance of pumps to the daily operation of buildings and processes necessitates a proactive maintenance program. Most pump maintenance activities center on checking packing and mechanical seals for leakage, performing preventive/predictive maintenance activities on bearings, assuring proper alignment, and validating proper motor condition and function.

The heart beats an average of 75 times per minute, or about 4,500 times per hour. While the body is resting, the heart pumps 2.5 ounces of blood per beat. This amount does not seem like much, but it sums up to almost 5 liters of blood pumped per minute by the heart, or about 7,200 liters per day. The amount of blood delivered by the heart can vary depending upon the body's need. During periods of great activity, such as exercising, the body demands higher amounts of blood, rich in oxygen and nutrients, increasing the heart's output by nearly five times.

Large Horsepower (25 horsepower and above) Pump Efficiency Survey

(OIT 1995)

Actions are given in decreasing potential for efficiency improvement:

1. Excessive pump maintenance – this is often associated with one of the following:
   - Oversized pumps that are heavily throttled.
   - Pumps in cavitation.
   - Badly worn pumps.
   - Pumps that are misapplied for the present operation.
2. Any pump system with large flow or pressure variations. When normal flows or pressures are less than 75% of their maximum, energy is probably being wasted from excessive throttling, large bypass flows, or operation of unneeded pumps.
3. Bypassed flow, either from a control system or deadhead protection orifices, is wasted energy.
4. Throttled control valves. The pressure drop across a control valve represents wasted energy, that is proportional to the pressure drop and flow.
5. Fixed throttle operation. Pumps throttled at a constant head and flow indicate excess capacity.
6. Noisy pumps or valves. A noisy pump generally indicates cavitation from heavy throttling or excess flow. Noisy control valves or bypass valves usually mean a higher pressure drop with a corresponding high energy loss.
7. A multiple pump system. Energy is commonly lost from bypassing excess capacity, running unneeded pumps, maintaining excess pressure, or having as large flow increment between pumps.
8. Changes from design conditions. Changes in plant operating conditions (expansions, shutdowns, etc.) can cause pumps that were previously well applied to operate at reduced efficiency.
9. A low-flow, high-pressure user. Such users may require operation of the entire system at high pressure.
10. Pumps with known overcapacity. Overcapacity wastes energy because more flow is pumped at a higher pressure than required.

9.9.7 Diagnostic Tools

- **Thermography** – An infrared thermometer or camera allows for an accurate, non-contact assessment of temperature. Applications for pumps include assessments on bearing assemblies at the impeller housing and motor system connections. More information on thermography can be found in Chapter 6.
- **Ultrasonic analyzer** – Fluid pumping systems emit very distinct sound patterns around bearings and impellers. In most cases, these sounds are not audible to the unaided ear, or are drown-out by other equipment noises. Using an ultrasonic detector, the analyst is able to isolate the frequency of sound being emitted by the bearing or impeller. Changes in these ultrasonic wave emissions are indicative of changes in equipment condition-some of these changes can be a precursor to component degradation and failure. More information on ultrasonic analysis can be found in Chapter 6.
- **Vibration analyzer** – Within a fluid pump, there are many moving parts; some in rotational motion and some in linear motion. In either case, these parts generate a distinct pattern and level of vibration. Using a vibration analyzer and signature analysis software, the analyst can discern the vibration amplitude of the point on the equipment being monitored. This amplitude is then compared with trended readings. Changes in these readings are indicative of changes in equipment condition. More information on vibration analysis can be found in Chapter 6.

9.9.8 Available Software Tools

Pumping System Assessment Tool (PSAT)

Description: The Pumping System Assessment Tool (PSAT) software uses data that is typically available or easily obtained in the field (e.g., pump head, flow rate, and motor power) to estimate potential energy and dollar savings in industrial pump systems. The software, developed by the DOE Industrial Technologies Program (ITP), is available at no cost for evaluating industrial pump systems.

Use the PSAT prescreening filter to identify areas that are likely to offer the greatest savings. Look for symptoms associated with inefficient energy consumption:

- Throttle-valve control for the system
- Cavitation noise or damage in the system
- Continuous pump operation to support a batch process
- Constant number of parallel pumps supporting a process with changing demands
- Bypass or recirculation line normally open
- High system maintenance
- Systems that have undergone change in function.

PSAT assesses current pump system operating efficiency by comparing field measurements of the power delivered to the motor with the fluid work (flow and head) required by the application. It estimates a system's achievable efficiency based on pump efficiencies (from Hydraulic Institute standards) and performance characteristics of pumps and motors (based on the MotorMaster+ database, see Section 9.10.8). Subsequent comparison of the actual and achievable efficiencies distinguishes systems with lower levels of opportunity from those that warrant additional engineering analysis.

Availability: To download the PSAT and learn more about DOE Qualified Specialists and training opportunities, visit the Industrial Technology Program Web site: **www1.eere.energy.gov/industry/bestpractices**.

9.9.9 Relevant Operational/Energy Efficiency Measures

There are a number of operational/energy efficiency measures that could be presented for proper pump operation and control. This section focuses on the most prevalent O&M recommendations having the greatest energy impacts at Federal facilities and includes (DOE 2001, DOE 2004, BEE 2004):

- Pump Selection
- Controlling the flow rate by speed variation
- Eliminating flow control valve
- Eliminating by-pass control
- Impeller trimming

Pump Selection

In selecting a pump, facility managers try to match the system curve supplied by the user with a pump curve that satisfies these needs as closely as possible. The pump operating point is the point where the pump curve and the system resistance curve intersect. However, it is impossible for one operating point to meet all desired operating conditions. For example, when the discharge valve is throttled to control flow, the system resistance curve shifts so does the operating point – this to a less-than efficient point of operation.

The efficiency of a pump is affected when the selected pump is oversized. This is because flow of oversized pumps must be controlled with different methods, such as a throttle valve or a by-pass line. These devices provide additional resistance by increasing the friction. As a result the system curve shifts and intersects the pump curve at a different point, a point of lower efficiency. In other words, the pump efficiency is reduced because the output flow is reduced but power consumption is not. Inefficiencies of oversized pumps can be overcome by, for example, the installation of variable speed drives, two-speed drives, operating the pump at a lower rpm, or installing a smaller impeller or trimmed impeller (BEE 2004).

Controlling flow rate by speed variation

A centrifugal pump's rotating impeller generates head. The impeller's peripheral velocity is directly related to shaft rotational speed. Therefore varying the rotational speed has a direct effect on the performance of the pump. The pump performance parameters (flow rate, head, power) will change with varying rotating speeds. To safely control a pump at different speeds it is therefore important to understand the relationships between the two. The equations that explain these relationships are known as the "Affinity Laws" these are:

- Flow rate (Q) is directly proportional to the rotating speed
- Head (H) is proportional to the square of the rotating speed
- Power (P) is proportional to the cube of the rotating speed

As can be seen from the above laws, doubling the rotating speed of the centrifugal pump will increase the power consumption by 8 times. Conversely a small reduction in speed will result in a very large reduction in power consumption. This forms the basis for energy conservation in centrifugal pumps with varying flow requirements. It is relevant to note that flow control by speed regulation is always more efficient than by a control valve. This is because valves reduce the flow, but not the energy consumed by pumps. In addition to energy savings, other benefits could include:

- Increased bearing life – this is because bearings carry the hydraulic forces on the impeller (created by the pressure profile inside the pump casing), which are reduced approximately with the square of speed. For a pump, bearing life is proportional to the seventh power of speed.
- Vibration and noise are reduced and seal life is increased, provided that the duty point remains within the allowable operating range.

Using variable speed drive (VSD)

Controlling the pump speed is the most efficient way to control the flow, because when the pump's speed is reduced, the power consumption is also reduced. The most commonly used method to reduce pump speed is Variable Speed Drive (VSD). VSDs allow pump speed adjustments over a continuous range, avoiding the need to jump from speed to speed as with multiple-speed pumps. VSDs control pump speeds use two types of systems:

- Mechanical VSDs include hydraulic clutches, fluid couplings, and adjustable belts and pulleys.
- Electrical VSDs include eddy current clutches, wound-rotor motor controllers, and variable frequency drives (VFDs). VFDs are the most popular and adjust the electrical frequency of the power supplied to a motor to change the motor's rotational speed.

For many systems, VFDs offer a means to improve the pump operating efficiency under different operating conditions. When a VFD reduced the RPM of a pump, the head/flow and power curves move down and to the left, and the efficiency curve also shifts to the left. The major advantages of VSD application in addition to energy saving are (DOE, 2004):

- Improved process control because VSDs can correct small variations in flow more quickly.
- Improved system reliability because wear of pumps, bearings and seals is reduced.
- Reduction of capital & maintenance cost because control valves, by-pass lines, and conventional starters are no longer needed.
- Soft starter capability: VSDs allow the motor the motor to have a lower startup current.

Eliminating flow control valve

Another method to control the flow by closing or opening the discharge valve (this is also known as "throttling" the valves). While this method reduces the flow, it does not reduce the power consumed, as the total head (static head) increases. This method increases vibration and corrosion and thereby increases maintenance costs of pumps and potentially reduces their lifetimes. VSDs are always a better solution from an energy efficiency perspective.

Eliminating by-pass control

The flow can also be reduced by installing a by-pass control system, in which the discharge of the pump is divided into two flows going into two separate pipelines. One of the pipelines delivers the fluid to the delivery point, while the second pipeline returns the fluid to the source. In other words, part of the fluid is pumped around for no reason, and thus is energy inefficient. Because of this inefficiency, this option should therefore be avoided.

Impeller trimming

Changing the impeller diameter gives a proportional change in the impeller's peripheral velocity. Similar to the affinity laws, the following equations apply to the impeller diameter:

- Flow rate (Q) is proportional to the diameter
- Head (H) is proportional to the square of the diameter
- Power (P) is proportional to the cube of the diameter

Changing the impeller diameter is an energy efficient way to control the pump flow rate. However, for this option, the following should be considered:

- This option cannot be used where varying flow patterns exist.
- The impeller should not be trimmed more than 25% of the original impeller size, otherwise it leads to vibration due to cavitation and therefore decrease the pump efficiency.
- The balance of the pump has to been maintained, i.e. the impeller trimming should be the same on all sides.

Changing the impeller itself is a better option than trimming the impeller, but is also more expensive and sometimes the next smaller impeller is too small.

9.9.9.1 Pump System Water-Use Best Practices

The predominant impact pumps have on water use relates to proper function and no leakage. A pump operating at too high of a pressure can lead to leak formation and/or leakage increase. As part of the daily maintenance activity, pressure verification and leakage survey should be completed and documented.

9.9.10 Case Study (DOE 2001)

Pump Optimization for Sewage Pumping Station

The town of Trumbull, CT was looking for a way to increase the operating performance of one of its ten sewage-pumping stations. The station consisted of two identical sewage-handling pumps (each with a 40-hp direct drive motor) vertically mounted below ground, handling 340,000 gallons of raw sewage per day. The system used one pump to handle the entire flow under normal operation, and used the second pump only in extreme conditions (heavy rainfall). To meet normal loads, each pump rarely operated more than 5 minutes at a time. The control system required two continuously running compressors. A constant pump speed of 1,320 rpm was obtained using a wound rotor and variable resistance circuit motor control system. The pumping system experienced frequent breakdowns, occasional flooding, and sewage spills.

After a thorough systems analysis, engineers installed an additional 10-hp pump with direct on-line motor starters and a passive level control system with float switches, replacing the old active control system. The new pump handles the same volume as the original 40-hp pumps during normal periods, but runs for longer periods of time. The lower outflow rate reduces friction and shock losses in the piping system, which lowers the required head pressure (and thus, the energy consumption).

In addition, the existing pump speed control was eliminated and the motors were wired for direct on-line start. Without the speed control, the motors powering the existing pumps run at 1,750 rpm instead of 1,320 rpm, so their impellers were trimmed to a smaller diameter. The existing pumps are still used for the infrequent peak flows that the new smaller pump cannot handle. Energy consumption was further reduced through the elimination of the two compressors for the active control system and the two circulating pumps for the old motor control system. The installed cost of all the added measures was $11,000.

Results. In addition to the annual 17,650 kWh of electricity savings from modifying the pump unit, significant energy savings also resulted from changes made to other energy use sources in the station (Figure 9.9.6). Annual energy consumption of the active level control (7,300 kWh/year) and the cooling water pumps (1,750 kWh/year) was entirely eliminated. In all, over 26,000 kWh is being saved annually, a reduction of almost 38%, resulting in $2,200 in annual energy savings.

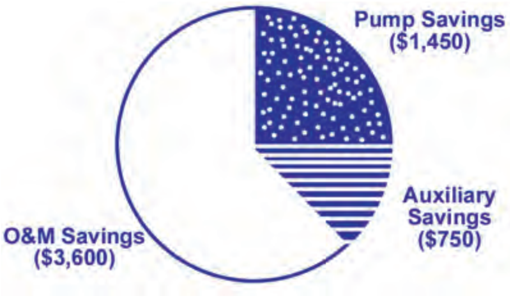

Figure 9.9.6. Pump system energy use and savings.

This project also produced maintenance savings of $3,600. Maintenance staff no longer needs to replace two mechanical seals each year. Other benefits of the project savings include extended equipment life due to reduced starting and stopping of the equipment, increased system capacity, and decreased noise. Most of the same measures can be utilized at the town's other pumping stations, as well.

The total annual savings from the project, due to lower energy costs as well as reduced maintenance and supplies, is $5,800 (Figure 9.9.7), which is roughly half of the total retrofit cost of $11,000.

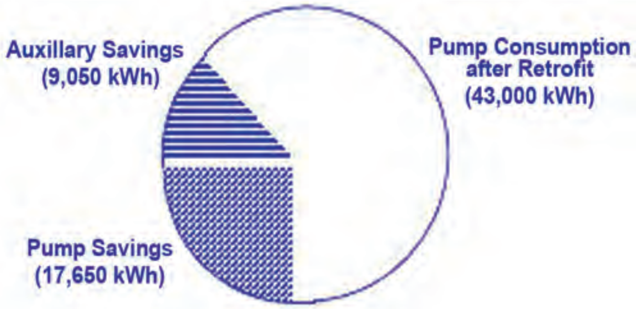

Figure 9.9.7. Retrofit cost savings ($5,800 annually).

Lessons Learned. Several key conclusions from Trumbull's experience are relevant for virtually any pumping systems project:

- Proper pump selection and careful attention to equipment operating schedules can yield substantial energy savings.
- In systems with static head, stepping of pump sizes for variable flow rate applications can decrease energy consumption.
- A "systems" approach can identify energy and cost savings opportunities beyond the pumps themselves.

9.9.11 Pumps Checklist

Description	Comments	Maintenance Frequency			
		Daily	Weekly	Monthly	Annually
Pump use/sequencing	Turn off/sequence unnecessary pumps	X			
Overall visual inspection	Complete overall visual inspection to be sure all equipment is operating and safety systems are in place	X			
Check lubrication	Assure that all bearings are lubricated per the manufacture's recommendation			X	
Check packing	Check packing for wear and repack as necessary. Consider replacing packing with mechanical seals.			X	
Motor/pump alignment	Aligning the pump/motor coupling allows for efficient torque transfer to the pump			X	
Check mountings	Check and secure all pump mountings			X	
Check bearings	Inspect bearings and drive belts for wear. Adjust, repair, or replace as necessary.				X
Motor condition	Checking the condition of the motor through temperature or vibration analysis assures long life				X

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9.10 Motors

9.10.1 Introduction

Motor systems consume about 70% of all the electric energy used in the manufacturing sector of the United States. To date, most public and private programs to improve motor system energy efficiency have focused on the motor component. This is primarily due to the complexity associated with motor-driven equipment and the system as a whole. The electric motor itself, however, is only the core component of a much broader system of electrical and mechanical equipment that provides a service (e.g., refrigeration, compression, or fluid movement).

Numerous studies have shown that opportunities for efficiency improvement and performance optimization are actually much greater in the other components of the system-the controller, the mechanical system coupling, the driven equipment, and the interaction with the process operation. Despite these significant system-level opportunities, most efficiency improvement activities or programs have focused on the motor component or other individual components (Nadel et al. 2001).

9.10.2 Types of Motors

9.10.2.1 DC Motors (Naves 2001a)

Direct-current (DC) motors (Figure 9.10.1) are often used in variable speed applications. The DC motor can be designed to run at any speed within the limits imposed by centrifugal forces and commutation considerations. Many machine tools also use DC motors because of the ease with which speed can be adjusted.

All DC motors, other than the relatively small brushless types, use a commutator assembly on the rotor. This requires periodic maintenance and is partly responsible for the added cost of a DC motor when compared to an alternate-current (AC) squirrel-cage induction motor of the same power. The speed adjustment flexibility often justifies the extra cost (Apogee Interactive 2001a).

9.10.2.2 AC Motors

(Naves 2001b)

As in the DC motor case, an AC motor (Figure 9.10.2) has a current passed through the coil, generating a torque on the coil. The design of an AC motor is considerably more involved than the design of a DC motor. The magnetic field is produced by an electromagnet powered by the same AC voltage as the motor coil. The coils that produce the magnetic field are traditionally called the "field coils" while the coils and the solid core that rotates is called the "armature."

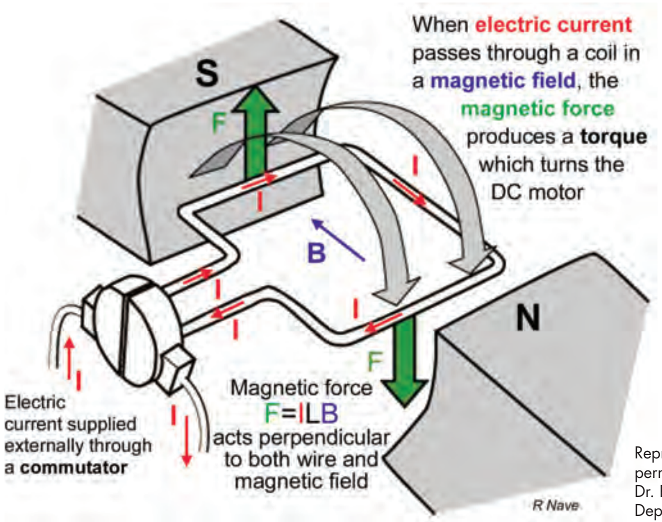

Figure 9.10.1. DC motor.

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- Induction motor (VPISU 2001) – The induction motor is a three-phase AC motor and is the most widely used machine. Its characteristic features are:
  - Simple and rugged construction.
  - Low cost and minimum maintenance.
  - High reliability and sufficiently high efficiency.
  - Needs no extra starting motor and need not be synchronized.

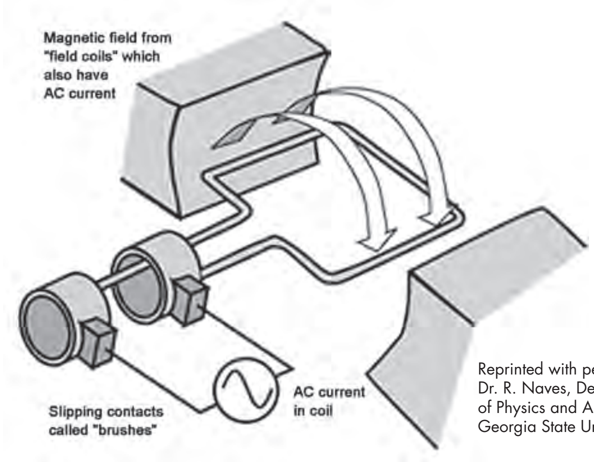

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Figure 9.10.2. AC motor

An induction motor operates on the principle of induction. The rotor receives power due to induction from stator rather than direct conduction of electrical power. When a three-phase voltage is applied to the stator winding, a rotating magnetic field of constant magnitude is produced. This rotating field is produced by the contributions of space-displaced phase windings carrying appropriate time displaced currents. The rotating field induces an electromotive force (emf).

- Synchronous motor (Apogee Interactive 2001b) – The most obvious characteristic of a synchronous motor is its strict synchronism with the power line frequency. The reason the industrial user is likely to prefer a synchronous motor is its higher efficiency and the opportunity for the user to adjust the motor's power factor.

  A specially designed motor controller performs these operations in the proper sequence and at the proper times during the starting process.

9.10.3 Key Components

9.10.3.1 DC Motor (The World Book Encyclopedia 1986)

- **Field pole** – The purpose of this component is to create a steady magnetic field in the motor. For the case of a small DC motor (Figure 9.10.3), a permanent magnet, field magnet, composes the field structure. However, for larger or more complex motors, one or more electromagnets, which receive electricity from an outside power source, is/are the field structure.

- **Armature** – When current goes through the armature, it becomes an electromagnet. The armature, cylindrical in shape, is linked to a drive shaft in order to drive the load. For the case of a small DC motor, the armature rotates in the magnetic field established by the poles, until the north and south poles of the magnets change location with respect to the armature. Once this happens, the current is reversed to switch the south and north poles of the armature.

- **Commutator** – This component is found mainly in DC motors. Its purpose is to overturn the direction of the electric current in the armature. The commutator also aids in the transmission of current between the armature and the power source.

9.10.3.2 AC Motor

- Rotor
    - Induction motor (VPISU 2001) – Two types of rotors are used in induction motors: squirrel-cage rotor and wound rotor. (Figure 9.10.4)

      A squirrel-cage rotor consists of thick conducting bars embedded in parallel slots. These bars are short-circuited at both ends by means of short-circuiting rings. A wound rotor has three-phase, double-layer, distributed winding. It is wound for as many poles as the stator. The three phases are wired internally and the other ends are connected to slip-rings mounted on a shaft with brushes resting on them.

    - Synchronous motor – The main difference between the synchronous motor and the induction motor is that the rotor of the synchronous motor travels at the same speed as the rotating magnetic field. This is possible because the magnetic field of the rotor is no longer induced. The rotor either has permanent magnets or DC-excited currents, which are forced to lock into a certain position when confronted with another magnetic field.

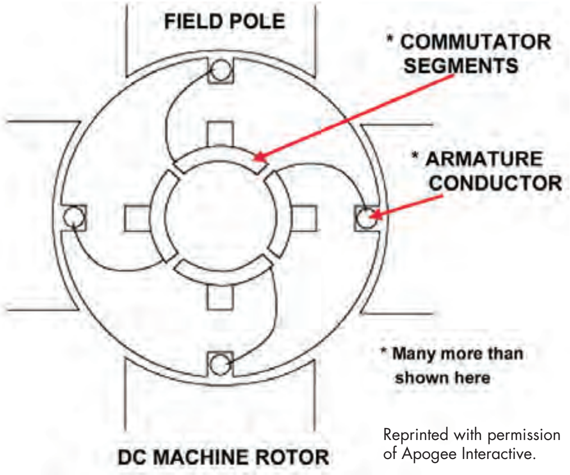

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Figure 9.10.3. Parts of a direct current motor

- **Stator** (VPISU 2001)
    - Induction motor – The stator is made up of a number of stampings with slots to carry three-phase windings. It is wound for a definite number of poles. The windings are geometrically spaced 120 degrees apart.
    - Synchronous motor – The stator produces a rotating magnetic field that is proportional to the frequency supplied.

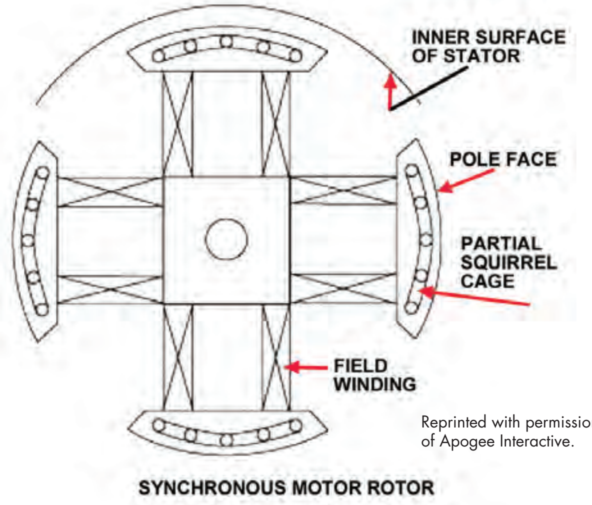

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Figure 9.10.4. Parts of an alternating current motor

9.10.4 Safety Issues (Operators and Consulting Services Incorporated 2001)

Electric motors are a major driving force in many industries. Their compact size and versatile application potentials make them a necessity. Motors are chosen many times because of the low vibration characteristics in driving equipment because of the potential extended life of the driven equipment. The higher rpm and small size of a motor will also make it a perfect fit for many applications.

Motors can be purchased for varying application areas such as for operating in a potentially gaseous or explosive area. When purchasing a motor, be sure to check the classification of the area, you may have a motor that does not meet the classification it is presently in! For example, a relatively new line of motors is being manufactured with special external coatings that resist the elements. These were developed because of the chemical plant setting in which highly corrosive atmospheres were deteriorating steel housings. They are, for the most part, the same motors but have an epoxy or equivalent coating.

9.10.5 Cost and Energy Efficiency (DOE 2001)

An electric motor performs efficiently only when it is maintained and used properly. Electric motor efficiencies vary with motor load; the efficiency of a constant speed motor decreases as motor load decreases. Below are some general guidelines for efficient operations of electric motors.

- Turn off unneeded motors – Locate motors that operate needlessly, even for a portion of the time they are on and turn them off. For example, there may be multiple HVAC circulation pumps operating when demand falls, cooling tower fans operating when target temperatures are met, ceiling fans on in unoccupied spaces, exhaust fans operating after ventilation needs are met, and escalators operating after closing.

- Reduce motor system usage – The efficiency of mechanical systems affects the run-time of motors. For example, reducing solar load on a building will reduce the amount of time the air handler motors would need to operate.

- Sizing motors is important – Do not assume an existing motor is properly sized for its load, especially when replacing motors. Many motors operate most efficiently at 75% to 85% of full load rating. Under-sizing or over-sizing reduces efficiency. For large motors, facility managers may want to seek professional help in determining the proper sizes and actual loadings of existing motors. There are several ways to estimate actual motor loading: the kilowatt technique, the amperage ratio technique, and the less reliable slip technique. All three are supported in the MotorMaster+ software.

- Replacement of motors versus rewinding – Instead of rewinding small motors, consider replacement with an energy-efficient version. For larger motors, if motor rewinding offers the lowest life-cycle cost, select a rewind facility with high quality standards to ensure that motor efficiency is not adversely affected. For sizes of 10 hp or less, new motors are generally cheaper than rewinding. Most standard efficiency motors under 100 hp will be cost-effective to scrap when they fail, provided they have sufficient run-time and are replaced with energy-efficient models.

9.10.6 Maintenance of Motors

Electric motors fail for a variety of reasons. Certain components of motors degrade with time and operating stress. Electrical insulation weakens over time with exposure to voltage unbalance, over and under-voltage, voltage disturbances, and temperature. Contact between moving surfaces causes wear. Wear is affected by dirt, moisture, and corrosive fumes and is greatly accelerated when lubricant is misapplied, becomes overheated or contaminated, or is not replaced at regular intervals. When any components are degraded beyond the point of economical repair, the motor's economic life is ended.

Strategies to Reduce Motor System Usage

- Reduce loads on HVAC systems.
  - Improve building shell.
  - Manage restorations better.
  - Improve HVAC conditions.
  - Check refrigerant charge.
- Reduce refrigeration loads.
  - Improve insulation.
  - Add strip curtains on doors.
  - Calibrate control setpoints.
  - Check refrigerant charge.
- Check ventilation systems for excessive air.
  - Re-sheave fan if air is excessive.
  - Downsize motors, if possible.
- Improve compressed air systems.
  - Locate and repair compressed air leaks.
  - Check air tool fittings for physical damage.
  - Turn off air to tools when not in use.
- Repair duct leaks.

The best safeguard against thermal damage is avoiding conditions that contribute to overheating. These include dirt, under and over-voltage, voltage unbalance, harmonics, high ambient temperature, poor ventilation, and overload operation (even within the service factor). Bearing failures account for nearly one-half of all motor failures. If not detected in time, the failing bearing can cause overheating and damage insulation, or can fail catastrophically and do irreparable mechanical damage to the motor.

Preventative and predictive maintenance programs for motors are effective practices in manufacturing plants. These maintenance procedures involve a sequence of steps plant personnel use to prolong motor life or foresee a motor failure. The technicians use a series of diagnostics such as motor temperature and motor vibration as key pieces of information in learning about the motors. One way a technician can use these diagnostics is to compare the vibration signature found in the motor with the failure mode to determine the cause of the failure. Often failures occur well before the expected design life span of the motor and studies have shown that mechanical failures are the prime cause of premature electrical failures. Preventative maintenance takes steps to improve motor performance and to extend its life. Common preventative tasks include routine lubrication, allowing adequate ventilation, and ensuring the motor is not undergoing any type of unbalanced voltage situation.

The goal of predictive maintenance programs is to reduce maintenance costs by detecting problems early, which allows for better maintenance planning and less unexpected failures. Predictive maintenance programs for motors observe the temperatures, vibrations, and other data to determine a time for an overhaul or replacement of the motor (Barnish et al. 2001).

Consult each motor's instructions for maintenance guidelines. Motors are not all the same. Be careful not to think that what is good for one is good for all. For example, some motors require a periodic greasing of the bearings and some do not (Operators and Consulting Services Incorporated 2001).

General Requirements for Safe and Efficiency Motor Operation

(DOE 2001)

1. Motors, properly selected and installed, are capable of operating for many years with a reasonably small amount of maintenance.
2. Before servicing a motor and motor-operated equipment, disconnect the power supply from motors and accessories. Use safe working practices during servicing of the equipment.
3. Clean motor surfaces and ventilation openings periodically, preferably with a vacuum cleaner. Heavy accumulations of dust and lint will result in overheating and premature motor failure.
4. Facility managers should inventory all motors in their facilities, beginning with the largest and those with the longest run-times. This inventory enables facility managers to make informed choices about replacement either before or after motor failure. Field testing motors prior to failure enables the facility manager to properly size replacements to match the actual driven load. The software mentioned below can help with this inventory.

9.10.7 Diagnostic Equipment

- **Thermography** – An infrared thermometer or camera allows for an accurate, non-contact assessment of temperature. Applications for motors include bearing and electrical contact assessments on motor systems and motor control centers. More information on thermography can be found in Chapter 6.
- **Ultrasonic analyzer** – Electric motor systems emit very distinct sound patterns around bearings. In most cases, these sounds are not audible to the unaided ear or are drown-out by other equipment noises. Using an ultrasonic detector, the analyst is able to isolate the frequency of sound being emitted by the bearing. Changes in these ultrasonic wave emissions are indicative of changes in equipment condition-some of these changes can be a precursor to component degradation and failure. More information on ultrasonic analysis can be found in Chapter 6.
- **Vibration analyzer** – The rotational motion within electric motors generates distinct patterns and levels of vibration. Using a vibration analyzer and signature analysis software, the analyst can discern the vibration amplitude of the point on the motor being monitored. This amplitude is then compared with trended readings. Changes in these readings are indicative of changes in equipment condition. More information on vibration analysis can be found in Chapter 6.
- **Other motor analysis** – Motor faults or conditions including winding short-circuits, open coils, improper torque settings, as well as many mechanical problems can be diagnosed using a variety of motor analysis techniques. These techniques are usually very specialized to specific motor types and expected faults. More information on motor analysis techniques can be found in Chapter 6.

9.10.8 Available Software Tools

MotorMaster+ Version 4.0 for Motor Replace/Rewind Decisions

Description: Developed by the DOE Industrial Technologies Program, this software tool handles everything from calculating the simple payback on a single motor purchase to comprehensive, integrated motor system management.

MotorMaster+ allows users to create or import an inventory of in-plant operating and spare motors. Motor load, efficiency at the load point, annual energy use, and annual operating costs can be determined after taking field measurements. The software quickly identifies inefficient or oversized facility motors and computes the savings that can be achieved by replacing older, standard efficiency motors with premium efficiency models. The software runs on local or wide-area networks for access by multiple users.

Some of MotorMaster+ features include:

- Expanded list of more than 17,000 motors from 14 manufacturers, including National Electrical Manufacturers Association (NEMA) Premium® efficiency medium-voltage (>600 volt) motors.
- Improved predictive maintenance testing—facilitates rapid data entry, sorting by condition, and rewind/replace recommendations.
- Technical data to help optimize drive systems, such as data on motor part-load efficiency and power factor; full-load speed; and locked-rotor, breakdown, and full-load torque.
- Motor purchasing information, including list prices, warranty periods, catalog numbers, motor weights, and manufacturer addresses.
- Capability to calculate energy savings, dollar savings, simple payback, cash flows, and the after-taxes rate of return-on-investment for energy programs—taking into account such variables as load factor, motor efficiency, purchase price, energy costs, hours of operation, and utility rebates.

Availability: To download the MotorMaster+ and learn more about DOE Qualified Specialists and training opportunities, visit the Industrial Technology Program Web site: **www1.eere.energy.gov/industry/bestpractices**.

9.10.9 Relevant Operational/Energy Efficient Measures

There are a number of operational/energy efficiency measures that could be presented for proper motor operation and control. This section focuses on the most prevalent O&M recommendations having the greatest energy impacts at Federal facilities and includes (DOE 2003, UNEP 2006):

Replace standard motors with energy efficient motors. High efficiency motors have been designed specifically to increase operating efficiency compared to standard motors. Design improvements focus on reducing intrinsic motor losses and include the use of lower-loss silicon steel, a longer core (to increase active material), thicker wires (to reduce resistance), thinner laminations, smaller air gap between stator and rotor, copper instead of aluminum bars in the rotor, superior bearings and a smaller fan, etc.

Energy efficient motors cover a wide range of ratings and the full load and efficiencies are 3% to 7% higher compared with standard motors.. As a result of the modifications to improve performance, the costs of energy efficient motors are higher than those of standard motors. The higher cost will often be paid back rapidly through reduced operating costs, particularly in new applications or end-of-life motor replacements. But replacing existing motors that have not reached the end of their useful life with energy efficient motors may not always be financially feasible, and therefore it is recommended to only replace these with energy efficiency motors when they fail.

Sizing to variable load. Industrial motors frequently operate under varying load conditions due to process requirements. A common practice in this situation is to select a motor based on the highest anticipated load. But this makes the motor more expensive as the motor would operate at full capacity for short periods only, and it carries the risk of motor under-loading.

An alternative is to select the motor rating based on the load duration curve of a particular application. This means that the selected motor rating is slightly lower than the highest anticipated load and would occasionally overload for a short period of time. This is possible as manufacturers design motors with a service factor (usually 15% above the rated load) to ensure that running motors above the rated load once in a while will not cause significant damage.

The biggest risk is overheating of the motor, which adversely affects the motor life and efficiency and increases operating costs. A criteria in selecting the motor rating is therefore that the weighted average temperature rise over the actual operating cycle should not be greater than the temperature rise under continuous full-load operation (100%). Overheating can occur with:

- Extreme load changes, such as frequent starts / stops, or high initial loads
- Frequent and/or long periods of overloading
- Limited ability for the motor to cool down, for example at high altitudes, in hot environments or when motors are enclosed or dirty

Improving power quality. Motor performance is affected considerably by the quality of input power, which is determined by the actual volts and frequency compared to rated values. Fluctuation in voltage and frequency much larger than the accepted values has detrimental impacts on motor performance.

Voltage unbalance can be even more detrimental to motor performance and occurs when the voltages in the three phases of a three-phase motor are not equal. This is usually caused by the supply different voltages to each of the three phases. It can also result from the use of different cable sizes in the distribution system.

The voltage of each phase in a three-phase system should be of equal magnitude, symmetrical, and separated by 120°. Phase balance should be within 1% to avoid de-rating of the motor and voiding of manufacturers' warranties. Several factors can affect voltage balance: single-phase loads on any one phase, different cable sizing, or faulty circuits. An unbalanced system increases distribution system losses and reduces motor efficiency.

Voltage unbalance can be minimized by:

- Balancing any single phase loads equally among all the three phases
- Segregating any single phase loads which disturb the load balance and feed them from a separate line/transformer

Improving maintenance. Most motor cores are manufactured from silicon steel or de-carbonized cold-rolled steel, the electrical properties of which do not change measurably with age. However, poor maintenance can cause deterioration in motor efficiency over time and lead to unreliable operation. For example, improper lubrication can cause increased friction in both the motor and associated drive transmission equipment. Resistance losses in the motor, which rise with temperature, would increase.

Ambient conditions can also have a detrimental effect on motor performance. For example, extreme temperatures, high dust loading, corrosive atmosphere, and humidity can impair insulation properties; mechanical stresses due to load cycling can lead to misalignment.

Appropriate maintenance is needed to maintain motor performance. A checklist of good maintenance practices would include:

- Inspect motors regularly for wear in bearings and housings (to reduce frictional losses) and for dirt/dust in motor ventilating ducts (to ensure proper heat dissipation.
- Check load conditions to ensure that the motor is not over or under loaded. A change in motor load from the last test indicates a change in the driven load, the cause of which should be understood
- Lubricate appropriately. Manufacturers generally give recommendations for how and when to lubricate their motors. Inadequate lubrication can cause problems, as noted above. Over-lubrication can also create problems, e.g. excess oil or grease from the motor bearings can enter the motor and saturate the motor insulation, causing premature failure or creating a fire risk
- Check periodically for proper alignment of the motor and the driven equipment. Improper alignment can cause shafts and bearings to wear quickly, resulting in damage to both the motor and the driven equipment
- Ensure that supply wiring and terminal box are properly sized and installed. Inspect regularly the connections at the motor and starter to be sure that they are clean and tight
- Provide adequate ventilation and keep motor cooling ducts clean to help dissipate heat to reduce excessive losses. The life of the insulation in the motor would also be longer: for every 10°C increase in motor operating temperature over the recommended peak, the time before rewinding would be needed is estimated to be halved.

Multi-speed motors. Motors can be wound such that two speeds, in the ratio of 2:1, can be obtained. Motors can also be wound with two separate windings, each giving two operating speeds and thus a total of four speeds. Multi-speed motors can be designed for applications involving constant torque, variable torque, or for constant output power. Multi-speed motors are suitable for applications that require limited speed control (two or four fixed speeds instead of continuously variable speed). These motors tend to be very economical as their efficiency is lower compared to single-speed motors.

Variable speed drives (VSDs). VSDs are also called adjustable speed drives and can change the speed of a motor and are available in a range from several kW to 750 kW. They are designed to operate standard induction motors and can therefore be easily installed in an existing system.

When loads vary, VSDs or two-speed motors can often reduce electrical energy consumption in centrifugal pumping and fan applications by 50% or more. The basic drive consists of the inverter itself which converts the 60 Hz incoming power to a variable frequency and variable voltage. The variable frequency will control the motor speed.

9.10.10 Electric Motors Checklist

Description	Comments	Maintenance Frequency			
		Daily	Weekly	Monthly	Annually
Motor use/ sequencing	Turn off/sequence unnecessary motors	X			
Overall visual inspection	Complete overall visual inspection to be sure all equipment is operating and safety systems are in place	X			
Motor condition	Check the condition of the motor through temperature or vibration analysis and compare to baseline values		X		
Check lubrication	Assure that all bearings are lubricated per the manufacture's recommendation			X	
Check packing	Check packing for wear and repack as necessary. Consider replacing packing with mechanical seals.			X	
Motor alignment	Aligning the motor coupling allows for efficient torque transfer to the pump			X	
Check mountings	Check and secure all motor mountings			X	
Check terminal tightness	Tighten connection terminals as necessary			X	
Cleaning	Remove dust and dirt from motor to facilitate cooling			X	
Check bearings	Inspect bearings and drive belts for wear. Adjust, repair, or replace as necessary.				X
Motor condition	Checking the condition of the motor through temperature or vibration analysis assures long life				X
Check for balanced three-phase power	Unbalanced power can shorten the motor life through excessive heat build up				X
Check for over-voltage or under-voltage conditions	Over- or under-voltage situations can shorten the motor life through excessive heat build up				X

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9.11 Air Compressors

9.11.1 Introduction

Compressed air, along with gas, electricity, and water, is essential to most modern industrial and commercial operations. It runs tools and machinery, provides power for material handling systems, and ensures clean, breathable air in contaminated environments. It is used by virtually every industrial segment from aircraft and automobiles to dairies, fish farming, and textiles.

The Compressed Air Challenge™

The Compressed Air Challenge™ is a national collaborative formed in October 1997 to assemble state-of-the-art information on compressed air system design, performance, and assessment procedures.

Available from: **http://www.knowpressure.org**.

A plant's expense for its compressed air is often thought of only in terms of the cost of the equipment. Energy costs, however, represent as much as 70% of the total expense in producing compressed air. As electricity rates escalate across the nation and the cost of maintenance and repair increases, selecting the most efficient and reliable compressor becomes critical (Kaeser Compressors 2001a).

9.11.2 Types of Air Compressors (Dyer and Maples 1992)

The two general types of air compressors are positive displacement and centrifugal.

9.11.2.1 Positive Displacement

- **Rotary screw compressor** – The main element of the rotary screw compressor (Figure 9.11.1) is made up of two close clearance helical-lobe rotors that turn in synchronous mesh. As the rotors revolve, the gas is forced into a decreasing inter-lobe cavity until it reaches the discharge port. In lubricated units, the male rotor drives the female and oil is injected into the cylinder serving as a lubricant, coolant, and as an oil seal to reduce back slippage. On non-lubricated types, timing gears are used to drive the rotors and multistaging is necessary to prevent gas temperatures from going too high.

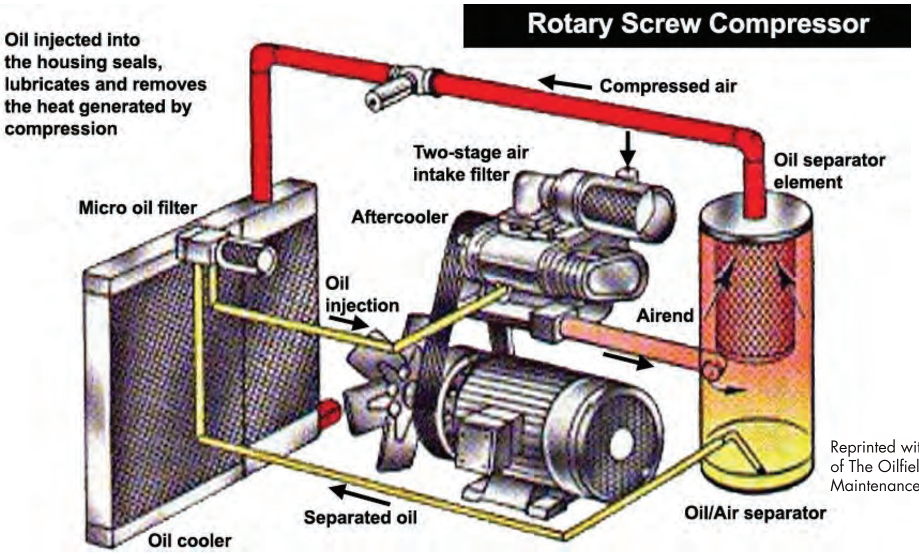

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Figure 9.11.1. Rotary screw compressor

- **Reciprocating compressor** – A reciprocating compressor (Figure 9.11.2) is made up of a cylinder and a piston. Compression is accomplished by the change in volume as the piston moves toward the "top" end of the cylinder. This compression may be oil-lubricated or, in some cases, it may require little or no lubrication (oil-free) in the cylinder.

The cylinder in the reciprocating machines may be air cooled or water cooled. Water cooling is used on the larger units. This cooling action is very important to increase compressor life and to keep maintenance and repairs low.

Multiple stage compressors have a minimum of two pistons. The first compresses the gas to an intermediate pressure. Intercooling of the gas before entering the second stage usually follows the first stage compression. Two stage units allow for more efficient and cooler operating compressors, which increases compressor life.

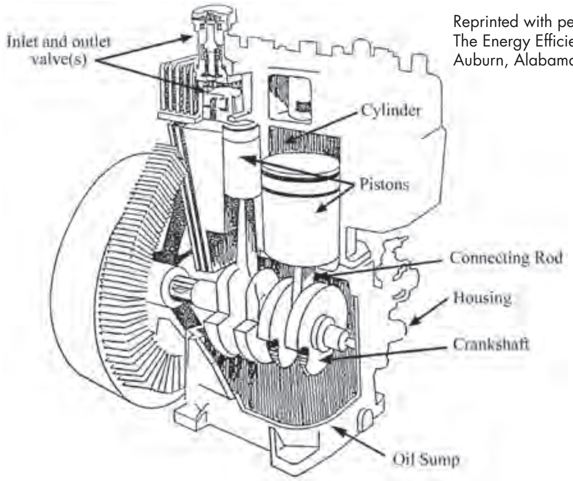

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Figure 9.11.2. Typical single acting two-stage compressor

9.11.2.2 Centrifugal Compressor

The compression action is accomplished when the gas enters the center of rotation and is accelerated as it flows in an outward direction. This gas velocity is then transferred into a pressure rise. Part of the pressure rise occurs in the rotor and part in a stationary element called the diffuser. The rotating element can have either forward curved blades, radial blades, or backward blades.

The centrifugal compressor will usually have more than one stage of compression with intercooling between each stage. One of the drawbacks of this machine is its inability to deliver part-load flow at overall efficiencies as high as other types of compressors. Many people consider the centrifugal machine a base-load machine.

9.11.3 Key Components (Dyer and Maples 1992)

- Positive Displacement Air Compressor
    - Cylinder – Chamber where the compression process takes place by the change in its volume as the piston moves up and down.
    - Piston – Component located inside the cylinder directly responsible for the compression of air.
    - Crankshaft – Converts rotational motion generated by the motor to unidirectional motion for the piston.
    - Connecting rod – Connects the crankshaft with the piston.
    - Inlet and exhaust valves – Control the amount of air going in and out of the cylinder.

- Rotary Screw Compressor
  - Helical-lobe rotors – The main elements of this type of compressor where two close clearance helical-lobe rotors turn in synchronous mesh. As the rotors revolve, the gas is forced into a decreasing "inter-lobe cavity until it reaches the discharge port (Figure 9.11.3).
- Centrifugal Compressor
  - Rotating Impeller – Imparts velocity to the air, which is converted to pressure.

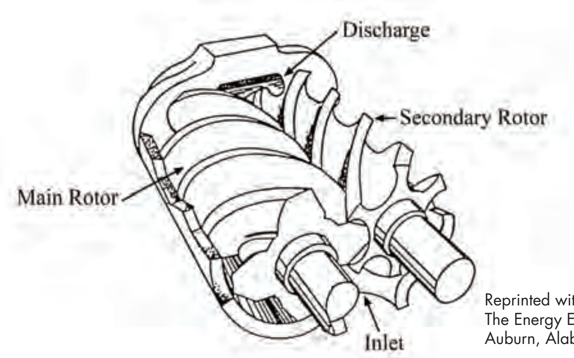

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Figure 9.11.3. Helical-lobe rotors

9.11.4 Safety Issues (UFEHS 2001)

9.11.4.1 General Safety Requirements for Compressed Air

All components of compressed air systems should be inspected regularly by qualified and trained employees. Maintenance superintendents should check with state and/or insurance companies to determine if they require their own inspection of this equipment. Operators need to be aware of the following:

- Air receivers – The maximum allowable working pressures of air receivers should never be exceeded except when being tested. Only hydrostatically tested and approved tanks shall be used as air receivers.
  - Each air receiver shall be equipped with at least one pressure gauge and an ASME safety valve of the proper design.
  - A safety (spring loaded) release valve shall be installed to prevent the receiver from exceeding the maximum allowable working pressure.
- Air distribution lines
  - Air lines should be made of high quality materials, fitted with secure connections.
  - Hoses should be checked to make sure they are properly connected to pipe outlets before use.
  - Air lines should be inspected frequently for defects and any defective equipment repaired or replaced immediately.
  - Compressed air lines should be identified as to maximum working pressures (psi) by tagging or marking pipeline outlets.

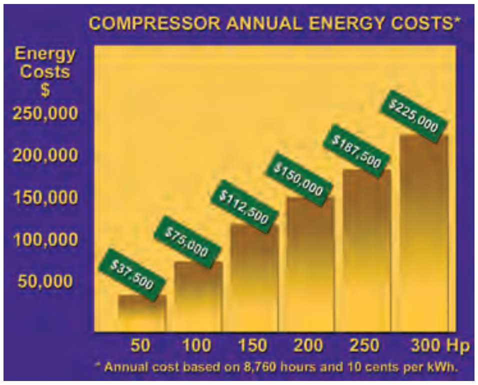
- Pressure regulation devices
    - Valves, gauges, and other regulating devices should be installed on compressor equipment in such a way that cannot be made inoperative.
    - Air tank safety valves should be set no less than 15 psi or 10% (whichever is greater) above the operating pressure of the compressor but never higher than the maximum allowable working pressure of the air receiver.
- Air compressor operation
    - Air compressor equipment should be operated only by authorized and trained personnel.
    - The air intake should be from a clean, outside, fresh air source. Screens or filters can be used to clean the air.
    - Air compressors should never be operated at speeds faster than the manufacturers recommendation.
    - Moving parts, such as compressor flywheels, pulleys, and belts that could be hazardous should be effectively guarded.

9.11.5 Cost and Energy Efficiency (Kaeser Compressors 2001b)

It takes 7 to 8 hp of electricity to produce 1 hp worth of air force. Yet, this high-energy cost quite often is overlooked. Depending on plant location and local power costs, the annual cost of electrical power can be equal to-or as much as two times greater than-the initial cost of the air compressor. Over a 10-year operating period, a 100-hp compressed air system that you bought for $40,000 will accumulate up to $800,000 in electrical power costs. Following a few simple steps can significantly reduce energy costs by as much as 35%.

9.11.5.1 Identify the Electrical Cost of Compressed Air

To judge the magnitude of the opportunities that exist to save electrical power costs in your compressed air system, it is important to identify the electrical cost of compressed air. The chart below shows the relationship between compressor hp and energy cost. In addition, consider the following:



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- Direct cost of pressure – Every 10 psig increase of pressure in a plant system requires about 5% more power to produce. For example: A 520 cubic-feet-per-minute (cfm) compressor, delivering air at 110 pounds per-square-inch-gage (psig), requires about 100 horsepower (hp). However, at 100 psig, only 95 hp is required. Potential power cost savings (at 10 cents per kWh; 8,760 hr/year) is $3,750/year.
- Indirect cost of pressure – System pressure affects air consumption on the use or demand side. The air system will automatically use more air at higher pressures. If there is no resulting increase in productivity, air is wasted. Increased air consumption

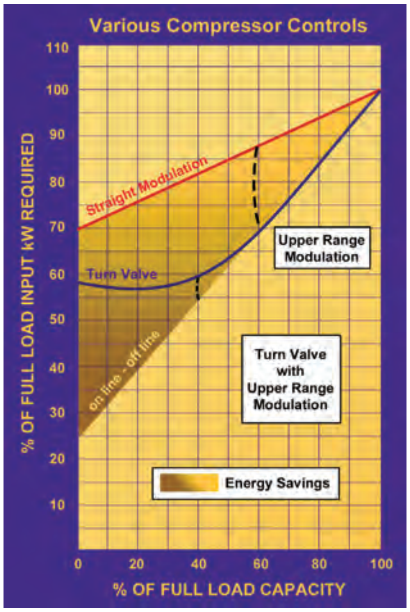
caused by higher than needed pressure is called *artificial demand*. A system using 520 cfm at 110 psig inlet pressure will consume only 400 cfm at 80 psig. The potential power cost savings (520 cfm - 400 cfm = 120 cfm, resulting in 24 hp, at 10 cents/kWh; 8,760 hr/year) is $18,000/year. Note: Also remember that the leakage rate is significantly reduced at lower pressures, further reducing power costs.

- The cost of wasted air volume – Each cubic feet per meter of air volume wasted can be translated into extra compressor horsepower and is an identifiable cost. As shown by Chart 1, if this waste is recovered, the result will be $750/hp per year in lower energy costs.
- Select the most efficient demand side – The magnitude of the above is solely dependent on the ability of the compressor control to translate reduced airflow into lower electrical power consumption.

The chart below shows the relationship between the full load power required for a compressor at various air demands and common control types. It becomes apparent that the on line-off line control (dual control) is superior to other controls in translating savings in air consumption into real power savings. Looking at our example of reducing air consumption from 520 cfm to 400 cfm (77%), the compressor operating on dual control requires 83% of full load power. That is 12% less energy than when operated on modulation control. If the air consumption drops to 50%, the difference (dual versus modulation) in energy consumption is increased even further, to 24%.

General Notes on Air Compressors (OIT 1995)

- Screw air compressors use 40% to 100% of rated power unloaded.
- Reciprocating air compressors are more efficient, but also more expensive.
- About 90% of energy becomes heat.
- Rule of thumb: roughly 20 hp per 100 cfm at 100 psi.
- Use low-pressure blowers versus compressed air whenever possible.
- Second, third, weekend shifts may have low compressed air needs that could be served by a smaller compressor.
- Outside air is cooler, denser, easier to compress than warm inside air.
- Friction can be reduced by using synthetic lubricants.
- Older compressors are driven by older less efficient motors.



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9.11.5.2 Waste Heat Recovered from Compressors can be Used for Heating (Kaeser Compressors 2001c)

The heat generated by air compressors can be used effectively within a plant for space heating and/or process water heating. Considerable energy savings result in short payback periods.

- Process heating – Heated water is available from units equipped with water-cooled oil coolers and after-coolers. Generally, these units can effectively discharge the water at temperatures between 130°F and 160°F.
- Space heating – Is essentially accomplished by ducting the heated cooling air from the compressor package to an area that requires heating. If ductwork is used, be careful not to exceed the manufacturer's maximum back-pressure allowance.

When space heating is used in the winter, arrangements should be made in the ductwork to return some of the heated air to the compressor room in order to maintain a 60°F room temperature. This ensures that the air discharged is at comfortable levels.

9.11.5.3 Use of Flow Controllers

Most compressed air systems operate at artificially high pressures to compensate for flow fluctuations and downstream pressure drops caused by lack of "real" storage and improperly designed piping systems. Even if additional compressor capacity is available, the time delay caused by bringing the necessary compressor(s) on-line would cause unacceptable pressure drop.

Operating at these artificially high pressures requires up to 25% more compressor capacity than actually needed. This 25% in wasted operating cost can be eliminated by reduced leakage and elimination of artificial demand.

A flow controller separates the supply side (compressors, dryers, and filters) from the demand side (distribution system). It creates "real" storage within the receiver tank(s) by accumulating compressed air without delivering it downstream. The air pressure only increases upstream of the air receiver, while the flow controller delivers the needed flow downstream at a constant, lower system pressure. This reduces the actual flow demand by virtually eliminating artificial demand and substantially reducing leakage.

9.11.5.4 Importance of Maintenance to Energy Savings

- Leaks are expensive. Statistics show that the average system wastes between 25% and 35% to leaks. In a compressed air system of 1,000 cfm, 30% leaks equals 300 cfm. That translates into savings of 60 hp or $45,000 annually.
- A formalized program of leak monitoring and repair is essential to control costs. As a start, monitor all the flow needed during off periods.
- Equip maintenance personnel with proper leak detection equipment and train them on how to use it. Establish a routine for regular leak inspections. Involve both maintenance and production personnel.
- Establish accountability of air usage as part of the production expense. Use flow controllers and sequencers to reduce system pressure and compressed air consumption.
- A well-maintained compressor not only serves you better with less downtime and repairs, but will save you electrical power costs too.

9.11.5.5 Leak Evaluation Procedure

Leaks can be a significant source of wasted energy in an industrial compressed air system, sometimes wasting 20 to 30% of a compressor's output. A typical plant that has not been well maintained will likely have a leak rate equal to 20 percent of total compressed air production capacity. On the other hand, proactive leak detection and repair can reduce leaks to less than 10 percent of compressor output (DOE 1998, UNEP 2006).

In addition to being a source of wasted energy, leaks can also contribute to other operating losses. Leaks cause a drop in system pressure, which can make air tools function less efficiently, adversely affecting production. In addition, by forcing the equipment to run longer, leaks shorten the life of almost all system equipment (including the compressor package itself). Increased running time can also lead to additional maintenance requirements and increased unscheduled downtime. Finally, leaks can lead to adding unnecessary compressor capacity.

While leakage can come from any part of the system, the most common problem areas are:

- Couplings, hoses, tubes, and fittings
- Pressure regulators
- Open condensate traps and shut-off valves
- Pipe joints, disconnects, and thread sealants.

Leakage rates are a function of the supply pressure and increase with higher system pressures.

For compressors that have start/stop or load/unload controls, there is an easy way to estimate the amount of leakage in the system. This method involves starting the compressor when there are no demands on the system (when all the air-operated, end-use equipment is turned off). A number of measurements are taken to determine the average time it takes to load and unload the compressor. The compressor will load and unload because the air leaks will cause the compressor to cycle on and off as the pressure drops from air escaping through the leaks. Total leakage (percentage) can be calculated as follows (DOE 1998):

Leakage Percentage (%) = $\{(T \times 100)/(T + t)\}$

where: T = on-loading time in minutes

t = off-loading time in minutes

Leakage will be expressed in terms of the percentage of compressor capacity lost. The percentage lost to leakage should be less than 10 percent in a well-maintained system. Poorly maintained systems can have losses as high as 20 to 30 percent of air capacity and power.

9.11.6 Maintenance of Air Compressors (Oil Machinery Maintenance Online 2001)

Maintenance of your compressed air system is of great importance and is often left undone or half done. Neglect of an air system will ultimately "poison" the entire downstream air system and cause problems. Clean dry air supplies start at the air compressor package. The small amount of time you spend maintaining the system is well worth the trouble.

9.11.6.1 General Requirements for a Safe and Efficient Air Compressor

- Always turn power off before servicing.
- Compressor oil and oil cleanliness:
  - Change the oil according to manufacturer's recommendations.
  - Use a high-quality oil and keep the level where it's supposed to be.
  - Sample the oil every month.

- Condensate control
  - Drain fluid traps regularly or automatically.
  - Drain receiving tanks regularly or automatically.
  - Service air-drying systems according to manufacturer's recommendations.

Common Causes of Air Compressor Poor Performance (Kaeser Compressors 2001d)

Problem	Probable Cause	Remedial Action
Low pressure at point of use	Leaks in distribution piping	Check lines, connections, and valves for leaks; clean or replace filter elements
	Clogged filter elements	Clean heat exchanger
	Fouled dryer heat exchanger	
	Low pressure at compressor discharge	
Low pressure at compressor discharge	For systems with modulating load controls, improper adjustment of air capacity control	Follow manufacturer's recommendation for adjustment of control
	Worn or broken valves	Check valves and repair or replace as required
	Improper air pressure switch setting	Follow manufacturer's recommendations for setting air pressure switch
Water in lines	Failed condensate traps	Clean, repair, or replace the trap
	Failed or undersized compressed air dryer	Repair or replace dryer
Liquid oil in air lines	Faulty air/oil separation	Check air/oil separation system; change separator element
Dirt, rust, or scale in air lines	In the absence of liquid water,normal aging of the air lines	Install filters at point of use
Excessive service to load/hour ratio	System idling too much	For multiple compressor systems, consider sequencing controls to minimize compressor idle time; adjust idle time according to manufacturer's recommendations
	Improper pressure switch setting	Readjust according to manufacturer's recommendations
Elevated compressor temperature	Restricted airflow	Clean cooler exterior and check inlet filter mats
	Restricted water flow	Check water flow, pressure, and quality; clean heat exchanger as needed
	Low oil level	Check compressor oil level; add oil as required
	Restricted oil flow	Remove restriction; replace parts as required
	Excessive ambient temperatures	Improper ventilation to compressor; check with manufacturer to determine maximum operating temperature

- Keep air inlet filters clean.
- Keep motor belts tight.
- Minimize system leaks.

9.11.7 Diagnostic Tools

- **Ultrasonic analyzer** – Compressed gas systems emit very distinct sound patterns around leakage areas. In most cases, these sounds are not audible to the unaided ear or are drown-out by other equipment noises. Using an ultrasonic detector, the analyst is able to isolate the frequency of sound being emitted by the air or gas leak. The ultrasonic detector represents an accurate and cost-effective means to locate leaks in air/gas systems. More information on ultrasonic analysis can be found in Chapter 6.
- **Vibration analyzer** – Within a compressor, there are many moving parts; some in rotational motion and some in linear motion. In either case, these parts generate a distinct pattern and level of vibration. Using a vibration analyzer and signature analysis software, the analyst can discern the vibration amplitude of the point on the equipment being monitored. This amplitude is then compared with trended readings. Changes in these readings are indicative of changes in equipment condition. More information on vibration analysis can be found in Chapter 6.

9.11.8 Available Software Tools

AIRMaster+ Improves Compressed Air System Performance Software

Description: AIRMaster+, developed by the DOE Industrial Technologies Program (ITP), provides a systematic approach for assessing the supply-side performance of compressed air systems. Using plant-specific data, the software effectively evaluates supply-side operational costs for various equipment configurations and system profiles. It provides useful estimates of the potential savings to be gained from selected energy-efficiency measures and calculates the associated simple payback periods.

AIRMaster+ includes a database of generic or industry-standard compressors and creates an inventory specific to your actual, in-plant air compressors. Based on user-provided data, the software simulates existing and modified compressed air system operations. It can model part-load system operations for an unlimited number of rotary screw, reciprocating, and centrifugal air compressors operating simultaneously with independent control strategies and schedules.

Powerful software features facilitate development of 24-hour metered airflow or power data load profiles for each compressor; calculation of life-cycle costs; input of seasonal electric energy and demand charges; and tracking of maintenance histories for systems and components.

AIRMaster+ also includes LogTool, companion software that serves as a data importation and analysis aid. The tool helps users import data that is exported from different types of data loggers; select logger data channels and modify their properties (e.g., name, type, units, etc.); view data values for one or more logger channels; display trend plots with one or two Y axes; display scatter plots; and display day type plots in the format that is needed for AIRMaster+.

Availability: To download AIRMaster+ and learn more about DOE Qualified Specialists and training opportunities, visit the Industrial Technology Program Web site: **www.eere.energy.gov/industry/bestpractices.**

9.11.9 Relevant Operational/Energy Efficiency Measures

There are many operational/energy efficiency measures that could be presented for proper compressed air operation and control. The following section focuses on the most prevalent O&M recommendations having the greatest energy impacts at Federal facilities. These recommendations are also some of the most easily implemented for boiler operators and O&M contractors.

Compressed Air Measure: Cost Evaluation of Compressed Air Leakage

Table 9.11.4 below can be used to approximate the flow rate in cfm of compressed air leaks as a function of orifice size and line pressure (DOE 2000).

Table 9.11.4. Steam trap discharge rate

Leakage Rates for Different Supply Pressures and Approximate Orifice Sizes (cfm)						
Pressure (psig)	Orifice Diameter (in.)					
	1/64	1/32	1/16	1/8	¼	3/8
70	0.29	1.16	4.66	18.62	74.40	167.80
80	0.32	1.26	5.24	20.76	83.10	187.20
90	0.36	1.46	5.72	23.10	92.00	206.60
100	0.40	1.55	6.31	25.22	100.90	227.00
125	0.48	1.94	7.66	30.65	122.20	275.50
For well-rounded orifices, multiply the values by 0.97, and for sharp-edged orifices, multiply the values by 0.61 (DOE 2000).						

Estimated Annual Energy Savings. The annual energy savings, which could be realized by fixing a compressed air leak, can be estimated as follows:

$$Annual\ Energy\ Savings = N \times LR \times EU \times H \times C$$

where

N = number of leaks, no units

LR = leakage rate, cfm (from the table above)

EU = compressor energy use, kW/cfm

H = annual hours of operation, hours

C = orifice edge coefficient, no units

Estimated Annual Cost Savings. The annual cost savings, which could be realized by fixing a compressed air leak, can be estimated as follows:

$$Annual\ Cost\ Savings = Annual\ Energy\ Savings \times ER$$

where ER = average annual electricity rate, $/kWh

It should be noted that this cost savings calculation doesn't account for an electric peak demand reduction. If the facility has a peak demand charge, and the compressor operates everyday with an operational schedule that is coincident with the facility's peak demand, then this estimate slightly underestimates the cost savings.

Compressed Air Leaks Energy Savings and Economics

Example Synopsis

A compressed air system audit reveals 5 air leaks, all with an estimated orifice diameter of 1/16 of an inch. The leaks are located in a line pressurized to 100 psig. The energy use of the compressor is 18 kW/100 cfm, and is operated 8,760 hrs per year. The electrical rate is approximately $0.10 per kWh. (Assumed sharp edged orifice, multiplier equals 0.61)

The annual energy savings can be estimated as:

$$\mathit{Annual\ Energy\ Savings} = 5 \times 6.31 \times 0.18 \times 0.61 \times 8{,}670$$

$$\mathit{Annual\ Energy\ Savings} = 30{,}346.30\ kWh/yr$$

The annual cost savings can be estimated as:

$$\mathit{Annual\ Energy\ Savings} = (30{,}346.30\ kWh/yr)(\$0.10/kWh)$$

$$\mathit{Annual\ Energy\ Savings} = \$3{,}034/yr$$

Compressed Air Systems Rules of Thumb (EPA 2003)

- **Compressed Air Rule 1**. Efficiency improvements can reduce *compressed air system* energy use by 20% to 50%.
- **Compressed Air Rule 2**. Efficiency improvements to compressed air systems can save approximately one-half percent of a *facility's* total energy use.
- **Compressed Air Rule 3**. Repairing air leaks can reduce *compressed air system* energy use by 30% or more.
- **Compressed Air Rule 4**. Repairing air leaks can reduce a *facility's* total energy use by about one-half percent, with an average simple payback of 3 months.
- **Compressed Air Rule 5**. It takes approximately 2.5 to 5.0 kWh to compress 1,000 ft^3 of air to 100 psi. Each psi reduction in compressed air loss from the distribution system (at 100 psi), reduces a compressor's energy use by more than one-half percent.

In the absence of calculating the cost of a compressed air leak, Table 9.11.5 can be used as a rough cost estimate for compressed air leakage cost (DOE 2003)

Table 9.11.5. Compressed air leaks – cost per year assuming $0.05/kWh

Size (in.)	Cost Per Year ($/yr)
1/16	$523
1/8	$2,095
1/4	$8,382

9.11.9.1 Air Compressor Water-Use Best Practices

In some instances larger air compressors will be water cooled using the practice of “single-pass” or “once-through cooling.” Single-pass or once through cooling systems provide an opportunity for significant water savings. In these systems, water is circulated only once through the compressor and then is disposed of to drain. To remove the same heat load, single-pass systems use 40 times more water than a cooling tower operated at 5 cycles of concentration. To maximize water savings, single-pass cooling equipment should be either modified to recirculate water or if possible, should be eliminated altogether. Possible options to minimize water usage include (FEMP 2008):

- Eliminate single pass cooling by modifying equipment to operate on a closed loop that recirculates the water instead of discharging it.
- If modification of equipment to a closed loop system is not feasible, add an automatic control to shut off the entire system during unoccupied night or weekend hours. This option should only be considered where shutdown would have no adverse impact on indoor air quality.
- Installation of a chiller or cooling tower is also an economical alternative. Excess cooling capacity may already exist within the building that can be utilized.
- Find another use for the single-pass effluent, in boiler make-up supply or landscape irrigation, and implement. Note some equipment effluent may be contaminated such as degreasers and hydraulic equipment. This effluent must not be used in boilers.

9.11.10 Case Study

Air Compressor Leakage (OIT 1995)

The cost of compressed air leaks is the energy cost to compress the volume of the lost air from atmospheric pressure to the compressor operating pressure. The amount of lost air depends on the line pressure, the compressed air temperature and the point of the leak, the air temperature at the compressor inlet, and the estimated area of the leak.

A study of a 75-hp compressor that operates 8,520 hours per year was shown to have a leakage rate of 24%. The majority of these leaks were due to open, unused lines. The compressor, a single-stage screw type, provides compressed air at 115 psi, is 91.5% efficient, and operates with electricity costing $14.05 per million Btu.

The study identified eight major leaks ranging in size from 1/16 to 1/8 inches in diameter. The calculated total annual cost of these leaks was $5,730.

Correcting the leaks in this system involved the following:

- Replacement of couplings and/r hoses.
- Replacement of seals around filters.
- Repairing breaks in compressed-air lines.

The total cost of the repairs was $460. Thus, the cost savings of $5,730 would pay for the implementation cost of $460 in about a month.

9.11.11 Air Compressors Checklist

Description	Comments	Maintenance Frequency			
		Daily	Weekly	Monthly	Annually
Compressor use/ sequencing	Turn off/sequence unnecessary compressors	X			
Overall visual inspection	Complete overall visual inspection to be sure all equipment is operating and safety systems are in place	X			
Leakage assessment	Look for and report any system leakages	X			
Compressor operation	Monitor operation for run time and temperature variance from trended norms	X			
Dryers	Dryers should be observed for proper function	X			
Compressor ventilation	Make sure proper ventilation is available for compressor and inlet	X			
Compressor lubricant	Note level, color, and pressure. Compare with trended values.	X			
Condensate drain	Drain condensate from tank, legs, and/or traps	X			
Operating temperature	Verify operating temperature is per manufacturer specification	X			
Pressure relief valves	Verify all pressure relief valves are functioning properly		X		
Check belt tension	Check belt tension and alignment for proper settings		X		
Intake filter pads	Clean or replace intake filter pads as necessary		X		
Air-consuming device check	All air-consuming devices need to be inspected on a regular basis for leakage. Leakage typically occurs in: • Worn/cracked/frayed hoses • Sticking air valves • Cylinder packing		X		
Drain traps	Clean out debris and check operation		X		
Motor bearings	Lubricate motor bearings to manufacturer's specification			X	

Chiller Checklist (contd)

Description	Comments	Maintenance Frequency			
		Daily	Weekly	Monthly	Annually
System oil	Depending on use and compressor size, develop periodic oil sampling to monitor moisture, particulate levels, and other contamination. Replace oil as required.			X	
Couplings	Inspect all couplings for proper function and alignment				X
Shaft seals	Check all seals for leakage or wear				X
Air line filters	Replace particulate and lubricant removal elements when pressure drop exceeds 2-3 psid				X
Check mountings	Check and secure all compressor mountings				X

9.11.12 References

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9.12 Lighting

9.12.1 Introduction

Recent studies reveal that over 20% of the nation's electricity consumption is related to various types of lighting products and systems. Advanced energy saving technologies are readily available to reduce both the connected load and energy consumption, but are only effective if they are properly installed, calibrated, and maintained. Improvements in lighting efficiencies are so rapid that it can be cost-effective to implement upgrades, retrofits or redesigns to lighting systems that are only 5 to 10 years old. In addition to everyday maintenance and operation of lighting systems, this section discusses the important issues of commissioning and regular reevaluation of system components with a view toward upgrades.

9.12.2 Systems and Components

A lighting system consists of light sources, the ballasts or other devices that regulate the power that drives electric lights, the luminaire housing with components that hold the sources and direct and shield the light, and lighting controls that manipulate the time or intensity of lighting systems.

9.12.2.1 Light Sources

Natural light sources include the sun and daylight (light from the sky). The electric light sources most common to Federal buildings include incandescent/halogen, fluorescent, high intensity discharge, and light emitting diodes. Characteristics common to light sources include their output, efficiency, life, color, and distribution.

A. **Daylight/Sunlight** – Daylight is an acceptable and desirable light source for building interiors. It uses the light from the sky, or occasionally sunlight reflected off building surfaces. Direct sunlight should generally be shielded, preferably before it hits the windows to reduce glare and thermal gains. In particular, direct sun penetration should be kept out of work environments. Interior window blinds are almost always needed to control sky glare and sun penetration, even when overhangs or light shelves exist.

B. **Electrical Lamps** – The lamp is the source of electric light, the device that converts electric power into visible light. Selecting the lamp types is at the heart of a high-quality lighting plan, and central to visual performance, energy conservation, and the appearance of a space. Various light sources have different characteristics, but the basic performance principles include the following:

- Lumen output – the amount of light emitted by a lamp
- Efficacy – the efficiency of lamps in producing light, measured in lumens of light per watt of energy
- Rated lamp life – expected lamp life typically reported in hours
- Lamp lumen depreciation – the loss of light output over time, usually reported as a percentage
- Color temperature (CCT) and color rendering (CRI) – a numerical value related to the appearance of the light and the objects illuminated

Fluorescent lamps generate their light by using electricity to excite a conductive vapor of mercury and an inert gas. The resultant ultraviolet light strikes a phosphor coating on the inside of the tube, causing it to glow. The elements used in the phosphor coating control the lamp's color.

***T12* lamps** – Linear fluorescent lamps with a 1-1/2 inch diameter (12/8 of an inch). They are now considered obsolete for most new applications. These were the standard fluorescent lamps until T8 lamps came on the market in the 1980s.

Fluorescent lamp advantages, disadvantages, and appropriate uses

Advantages:

- Very high efficacy – T8/T5 lamps are 80 to 98 lumens per watt
- Flexible source with a wide range of colors, (75 to 98 CRI), sizes, and shapes
- Very long lamp life: 20,000 to 30,000 hours
- Cool operation
- Low diffused surface brightness

Disadvantages:

- Require a compatible ballast
- Dimming requires a more expensive ballast
- Temperatures can affect start-up, lumen output, and lamp life
- Not a point source if narrow beam distribution is required

Appropriate Uses:

- Fluorescent and compact fluorescent lamps are appropriate for most of the applications that Federal facilities managers encounter in their buildings

***T8* lamps** – Linear fluorescent lamps with a 1 inch diameter (8/8 of an inch). These are the workhorse of the commercial lighting industry and have become the standard for offices and general applications. Since they are 22% more efficient than T12s, it is generally always cost-effective to retrofit or replace fixtures that use T12 lamps in existing applications even before the existing T12 lamps burn out. The rare exception might be individual fixtures that are rarely used. However, it will be more efficient to replace or upgrade these at the same time to avoid costly individual replacements at a later date. T8 lamps use the same socket as T12, but not the same ballast. There is a wide range of T8 design options and good color rendition. The most commonly used T8 lamp is 4-feet-long and 32-watts (F32T8).

High performance or premium T8 lamps – High performance T8s are marketed under the tradenames Ultra (GE), Advantage (Philips), or Super T8 (Sylvania). These T8 lamps provide higher efficacy, higher maintained lumens, and are available in extended life versions with a 20% increase in lamp life. The improved performance is achieved in different ways by different products. Some products have reduced wattages (28 to 30 watts) while achieving the same lumen output as a standard T8. Others have increased lumen output (3,100 lumens) without increasing the wattage. The increased lumen output results in a brighter lamp and potentially more glare. This can be prevented by using the lower wattage version, or by coupling a 3,100 lumen lamp with a reduced output ballast (.77 BF). Premium T8s have a higher initial cost, but the increased energy efficiency and life make them the recommended light source for most commercial fluorescent installations including Federal projects.

***T5* lamps** – Linear fluorescent lamps with a diameter of 5/8 of an inch. These cannot replace T8 lamps because they have different characteristics and different lengths (metric), socket configurations and ballasts. T5s are smaller lamps than T8s, but have similar efficacy (lumens per watts). Their smaller diameter allows for shallower fixtures and greater reflector control, but also increases the brightness, limiting their use to heavily shielded or indirect fixtures.

***T5HO* (high output)** – T5 lamps with approximately the same maintained lumens as two standard T8 lamps but less efficient, with about 7% to 10% fewer lumens per watt. This development allows the designer to potentially reduce the number of fixtures, lamps, and ballasts in an application, making it less expensive to maintain. However, the intense brightness of T5HOs limits their use to primarily indirect luminaires to avoid glare. Also, using one-lamp rather than two-lamp luminaires eliminates the potential for two-level switching. Analysis is required to demonstrate the benefits of using T5HO lamps to offset their lower efficacy and higher cost.

Compact fluorescent lamps (CFLs) – Fluorescent lamps with a single base and bent-tube construction. Originally designed for the retrofitting of standard incandescents, the first CFLs had a screw-type base. While screw base lamps are still available, commercial applications typically use lamps with a 4-pin base. This prevents the future replacement of a screw-based CFL with a much less efficient incandescent lamp. CFL lamps have a wide range of sizes and attractive colors, and can be used in most Federal applications that formerly used incandescent.

High Intensity Discharge (HID) lamps also use a gas-filled tube to generate light, but use an arc current and vaporized metals at relatively high temperatures and pressures. There are two main types in current use – metal halide (MH) and high-pressure sodium (HPS) – and their characteristics are determined by the gas. MH provides a white light with a CRI of 65-95, while HPS emits a yellowish light with a CRI of 22 to 65. Historically, HID lamps were relegated to outdoor or service areas, but advances in color, configurations, and efficacy have made them more attractive for commercial and interior use.

CFL advantages and disadvantages

Advantages:

- Good substitution for most incandescent lamps
- High efficacy – 56 to 71 lumens per watt.
- Flexible source with a wide range of sizes and shapes, and good color rendering (82 CRI)
- Long lamp life: 10,000 to 12,000 hours
- Cool operation
- Diffused surface brightness

Disadvantages:

- Require a compatible ballast
- Dimming requires a more expensive ballast
- Temperatures can affect start-up, lumen output, and lamp life
- Not a point source if narrow beam distribution is required

Electrodeless lamps (also called induction lamps) most commonly use radio frequency to ionize mercury vapor at low-pressures, resulting in exciting the phosphors inside the envelope to create a glow, similar to fluorescent technology. The three major lamp manufacturers each produce a distinctive lamp design, the small reflector “Genura” lamp by GE, the globe-shaped “QL” by Philips, and the high-output donut-shaped “Icetron” by Sylvania.

Incandescent/Halogen lamps generate their light by heating a tungsten filament until it glows, in the presence of an inert gas such as argon or nitrogen. A halogen lamp is a form of incandescent lamp that introduces traces of halogen gas and a quartz envelope to burn hotter and prolong the filament life. Consequently, they are whiter (3000K rather than 2700K) and are slightly more energy efficient than standard incandescents. Halogen should be used in lieu of standard incandescent, and low voltage should be considered for the tighter, more focused beam. However, whenever possible, the use of more efficient CFL or ceramic metal halide sources should be explored. Since incandescent/halogen lamp types are very inefficient (roughly five times less efficient than fluorescent), they should be used sparingly, or the project will not meet the energy code. See the suggested uses below.

Light Emitting Diodes (LEDs) are made of an advanced semi-conductor material that emits visible light when current passes through it. Different conductor materials are used, each emitting a distinctive wavelength of light. LEDs come in red, amber, blue, green, and a cool white. LEDs are beginning to see extensive use in a variety of applications including street/parking lot lighting, supermarket refrigerated display case lighting, and other display lighting applications.

9.12.2.2 Ballasts, Transformers, and Power Packs

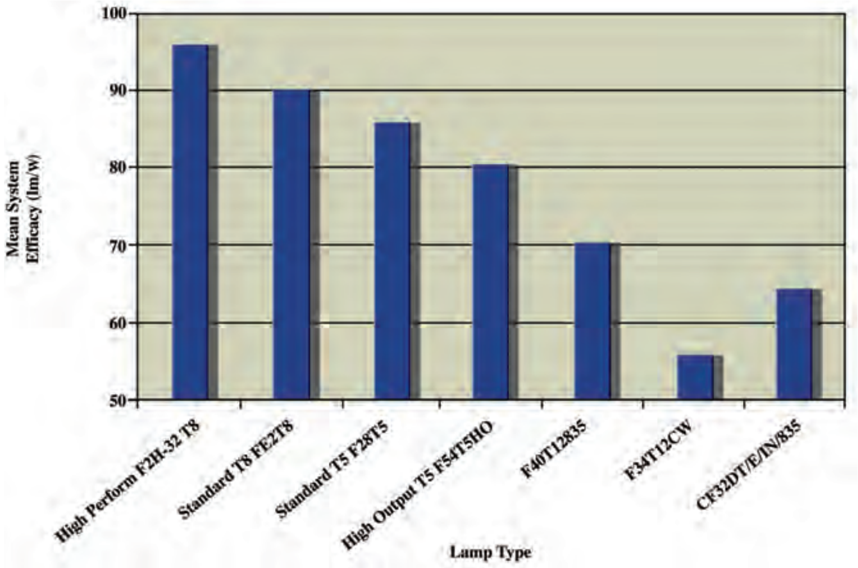


Figure 9.12.1. Fluorescent lamp/ballast efficacy

Electrical devices are needed to provide the necessary high starting voltage, and then limit and regulate the current to the lamp during operations. All gas discharge lamps, like fluorescent and high intensity discharge (HID), require ballasts (incandescent lamps do not). Ballasts typically are designed to efficiently operate a specific lamp type, so lamps and ballasts are chosen together. The final ballast product selection is usually done by the fixture manufacturer, in response to the lighting designer’s minimum performance requirements. In specifying or evaluating ballasts, the basic performance criteria to consider include the following:

- Ballast Factor (BF) – proportion of potential light output. Not a measure of efficiency.
- Lamp-Ballast System Efficacy – Mean lumens of lamps divided by input wattage of ballast. Best measure to evaluate system efficiency.

- Power Factor (PF) – Not lower than 0.90
- Total Harmonic Distortion (THD) – Not higher than 20%
- Minimum Starting Temperature – appropriate for application
- Voltage requirements – matching supply voltage, or multi-voltage taps
- Maximum distance between lamp and remotely located ballast – check with manufacturer.

9.12.2.3 Luminaire Housing

A luminaire is the entire lighting assembly that includes a light source, a ballast to control the power, and a housing with components necessary for light distribution and shielding of the source.

Aspects of the luminaire housing related to building operations and maintenance include:

- Sturdy construction, not easily moved or damaged or vandalized.
- Materials that maintain their initial characteristics, like reflectance or shininess (specularity) or cleanliness.
- Features that make installation, wiring, and leveling easy.
- Features that make maintenance easy, like hinges, fasteners, self-tapping screws, safety chains, no rough edges, easy access to ballasts and wiring, ease of cleaning.

Luminaires are most often classified by the light source and the distribution of the light. Once the most appropriate distribution is selected for a particular application, then luminaires within that classification can be compared for glare control, efficiency, and overall performance.

- Direct 90% to 100% downlight
- Semi-direct 60% to 90% downlight, 10% to 40% uplight
- General diffuse 40% to 60% up and downlight
- Semi-indirect 60% to 90% uplight, 10% to 40% downlight
- Indirect 90% to 100% uplight

Cleaning classification – The recommended cleaning schedules for luminaires depends on the openness of the fixture design, the distribution characteristics mentioned above, and the dirtiness of the environment.

These conditions are components of the "luminaire dirt depreciation" (LDD) factor (see recoverable light losses, Section 9.12.4.1). The capacity for a luminaire to retain dirt or dust falls into two categories:

- Open/Unventilated – Luminaires that are open on the bottom, with or without louvers or baffles, and a housing that has no top ventilation apertures that would provide a steady path for air to move through the fixture.
- All Other – Luminaires that do not meet the description above, such as bare lamps, strip fixtures, enclosed or lensed fixtures, or any fixtures with top openings for ventilation.

9.12.2.4 Lighting Control Devices

There is seldom just one way to accomplish the desired control of lighting, and a variety of equipment is available to the lighting designer. (Minimum lighting controls are required by code – see Energy Codes, Section 9.12.4.4.) A comprehensive strategy uses several of these control devices in concert, responding to project-specific usage patterns:

- Manual controls
    - Switches and switching patterns
    - Manual dimmers
- Automatic controls
    - Occupancy sensors
    - Daylight sensors
    - Pre-set controls
    - Time controls
    - Centralized control management

Manual Controls – Manual controls allow the users to select the lighting levels best suited to their immediate needs. Task lights located in workstations should have manual controls. Spaces with variable activities, such as training rooms, multi-purpose rooms, or conference centers, generally require manual controls to enable the users to tailor the light for each different activity. Allowing the users to select a "pre-set" lighting scene will generally reduce consumption. With manual controls, occupancy satisfaction is achieved, but the reduction in energy use is unpredictable since it requires individuals to turn off their lights. For effective use, the controls need to be intuitive and labeled. Note that even with manual controls, the energy standard still requires automatic shutoff when spaces are not occupied.

Switches. Switching strategies can be used in combinations to offer multiple levels of illumination, and multiple mixes of available light sources. In its simplest application, open work areas can have several zones of luminaires, so partially occupied rooms do not need to burn all the lights. Three-way switches are typically used in multi-entry and multi-zoned rooms to facilitate people moving from zone to zone. Automatic switches, (or Sentry-type switches that reset to the off position) are appropriate for use with manual-on/automatic-off occupancy sensors. Another strategy is bi-level switching – two (or more) light levels within a space can be attained with multi-lamp luminaires, factory pre-wired for easy connection to separate switches, which allows one lamp in each fixture to be turned off, effectively "dimming" the lights. When several light sources – e.g., overhead luminaries, wall washers, down lights – are present, each type should be switched separately.

Manual dimmers. Manual dimming is most useful to respond to specific user needs – dimming the conference room lights for AV presentations, raising the light level for the cleaning crew, changing the mood in a cultural space. Manual dimmers can be wall box sliders or hand-held remote controls. Both incandescent and fluorescent light sources are dimmable, and both use less energy when dimmed, although the energy saved is not always proportional to the decrease in light. Incandescent lamps can be readily dimmed, but fluorescent need specialized electronic dimming ballasts.

Automatic Controls – Automatic controls provide benefits in user comfort and energy conservation. Automatic controls can deliver reliable energy savings without occupant participation, and when well designed, without their notice. In addition, they can make adjustments to light levels throughout the day, or in response to specific needs. For safety reasons, lighting controls should be specified to default to full-on when control equipment fails. Recommissioning is valuable for determining that all the controls operate and save energy as intended.

Automatic controls advantages, disadvantages, and appropriate uses

Advantages:

- Sufficient energy conservation possible
- Energy savings are more predictable
- Allows a comprehensive daylighting strategy
- Subtle changes in light levels can be accomplished without occupant participation
- Flexible for accommodating changes in use or occupancy over the moderate/long-term

Disadvantages:

- Controls must be very reliable and predictable for user acceptance
- May require expertise and/or training of maintenance personnel
- Commissioning is required and adjustments may be necessary when layouts change
- Moderate to high initial cost ($0.20/ft^2 for scheduling, higher for daylighting)

Appropriate Uses:

- Dimming of electric lighting to support a daylighting strategy
- Rooms with periods of no occupancy during the day (for occupancy sensors) or have regular operating hours (time clocks)
- Support spaces and outdoor areas with predictable needs

Occupancy Sensors. Occupancy sensors turn off the lights when they detect that no occupants are present. The occupancy sensor includes a motion sensor, a control unit, and a relay for switching the lights. The sensor and control unit are connected to the luminaire by low voltage wiring, with a transformer stepping down the current. There are three commonly used types of occupancy sensors, defined by how they detect motion: ultrasonic, passive infrared and dual-technology.

Figure 9.12.2. Wall-box occupancy sensor uses hidden internal dip-switches to set manual-on, auto-off.

- *Ultrasonic sensors* (US) utilize a quartz crystal that emits high frequency ultrasonic waves throughout the room. Shifts to the frequency of the wave (called Doppler effect) indicate that there is motion/occupancy in the space. US cover the area in a continuous manner, and there are no blind spots in the coverage, e.g., a desk behind a partition. While this makes them effective at detecting occupancy, it also makes them more vulnerable to "false-on" readings caused by traffic in adjacent corridors and air currents. Therefore, they can be most effectively used in combination with manual-on switches (see below), particularly in daylighted spaces. Manual-on prevents false-ons and saves energy by avoiding unnecessary automatic activation when daylight or spill-light is sufficient for the activity.

HID lamp advantages, disadvantages, and appropriate uses

Advantages:

- High lumen output – up to 1,000 wattage lamps available
- Medium to high efficacy – MH: 51 to 85 lumens per watt; HPS: 60 to 115 lumens per watt
- Long lamp life – MH: 10,000 to 20,000 hours; HPS: 10,000 to 24,000+ hours
- Insensitivity to ambient temperatures
- 50% and 100% bi-level switching ballasts available

Disadvantages:

- Lamps have a warm-up period before reaching full output/color
- If power is interrupted, lamps must cool off before restriking (hence unreliable dimming and unacceptability for emergency lighting). Some HPS lamps are available with instant restrike.
- Inappropriate for many control strategies like daylight harvesting, occupancy sensors, or frequent switching.

Appropriate Uses:

- Metal halide lamps come in a wide range of shapes and colors, and are suitable for most lighting applications where continuous operation is required. "Ceramic" metal halide technology provides colors in the 80 to 98 CRI range with a warm color temperature of 3000K.
- Metal halide PAR and small tubular lamps provide an energy-efficient substitute for many types incandescent/halogen reflector and tubular lamps
- High-pressure sodium (HPS) lamps are most often used in roadway and other outdoor applications. Lamp life is very long (30,000+ hours), but the CRI is low (about 22 to 30). Improved whiter HPS lamps are available with a CRI of 65, but as color improves, efficacy and life are significantly reduced.
- Not a point source if narrow beam distribution is required

Electrodeless lamp advantages, disadvantages, and appropriate uses

Advantages:

- Very long life (100,000 hours) due to lack of electrodes to deteriorate
- Good maintained lumen output over life
- Low to high light output available (1,100 to 12,000 lumens per lamp)
- Medium to high efficacy (40 to 60 lumens/watt)

Disadvantages:

- Not interchangeable with other lamps and ballasts. No competition.
- Only one manufacturer per lamp style (donut, reflector, globe)
- Limited to diffuse distribution
- Limited wattages and lumen output for each style
- Requires magnetic core, which has shorter life than the lamp

Appropriate Uses:

- Locations where maintenance is expensive or difficult
- Replacement reflector lamp for incandescent floodlight in high ceilings
- Locations where high lumen output and diffuse distribution is desirable (indirect kiosks in high ceilings)
- More information is available from the manufacturers and the Advanced Lighting Guidelines.

Incandescent/Halogen lamp advantages, disadvantages, and appropriate uses

Advantages:

- Excellent color rendering and a warm appearance
- Can be focused for use in reflector lamps
- Compact size
- No ballast required
- Easily dimmed
- Minimal ultra-violet emissions for conservation of light sensitive materials

Disadvantages:

- Low efficacy – Halogen is the best at 13 to 21 lumens per watt.
- Shorter lamp life than alternatives – Halogen is the best at 3,000 to 6,000 hours
- Lamp can get very hot
- Low voltage transformers may be required for halogen lights
- Point source is glary if not shielded.

Appropriate Uses:

- Historic settings when CFL lamps cannot be used
- Applications in which color rendering is extremely important (art work, limited retail)
- Displays where the narrowest beam control is necessary

LED Lamp advantages, disadvantages, and appropriate uses

Advantages:

- Impact resistant
- Operate best at cooler temperatures so good for outdoor applications
- Small size
- Low to medium efficacy, depending on the color. Red is highest, followed by amber, green, white, and blue. A more efficient white light can be created by combining red, green, and blue LEDs. White LEDs are currently about 30 lumens per watt, but efficacies are expected to increase steadily.
- Monochromatic color for exit signs, signals, and special effects
- Effective for rapid or frequent switching applications

Disadvantages:

- Rapid lumen depreciation: White LEDs may last 12,000 hours or longer, but “useful life” is only 6,000 hours, the point at which point light output has reduced 50%.
- Monochromatic color
- Heat buildup
- Cost
- White LEDs are still bluish and provide low lumens per watt, similar to incandescent. Both conditions are expected to improve rapidly over the next 15 years.

Appropriate Uses:

- Currently used primarily in exit signage, traffic signaling, and certain special effects
- Excellent for projecting words or an image – as in walk/don’t walk signs or exit signs. FEMP recommends them for these uses.
- LED sources may have the greatest potential for technical improvements and new applications in the next 15 years.

- *Passive infrared sensors* (PIR) respond to the infrared heat energy of occupants, detecting motion at the "human" wavelength. They operate on a line-of-sight basis and do not detect occupants behind partitions or around corners. They also are less likely to detect motion as the distance increases. Therefore, they are useful when a room is small or it is desirable to control only a portion of a space. PIR are more susceptible to false-off readings than false-ons, so tend to be more annoying to occupants than ultrasonic sensors.
- *Dual-technology sensors* combine two technologies to prevent both false-offs and false-ons. The most common one uses both ultrasonic and passive infrared sensing to detect occupancy. The sensor usually requires that both US and PIR sense occupancy before turning on. The lights will remain on as long as either technology detects someone. High quality occupancy sensors use the dual technology, since it is more reliable than each of the separate technologies used independently. Dual-technology sensors cost more than sensors using either US or PIR alone.

Other occupancy sensor features to consider include:

- Mounting location – Ceiling, high-wall or corner, or wall box. Room size and layout are the major determinants. Ceiling-mounted sensors are the most versatile because their view is less obstructed. Wall box sensors take the place of the room's wall switch, and they are economical and easy to retrofit. Wall box sensors are appropriate for small, unobstructed spaces.
- On-Off settings – Occupancy sensors can automatically turn on (auto-on) and then automatically turn off (auto-off). Or, they can require the user to turn them on (manual-on) and then automatically turn off. Manual-on sensors save more energy because the lights do not turn on when the user does not need them. Auto-on sensors are useful in applications where the users are not familiar with the layout and switch locations, or where finding a switch would be inconvenient.
- Sensitivity – Most sensors can be adjusted for the desired degree of activity that will trigger a sensor response. The time-delay (i.e., the time elapsed between the moment a sensor stops sensing an occupant and the time it turns off) can also be selected. The setting can range from 30 seconds to 30 minutes, and the choice becomes a balance between energy conservation, user tolerance, and lamp life. We suggest no less than 15 minutes if controlling instant start ballasts.
- Multiple level control – Occupancy sensors are effective for multiple level switching in spaces where full off is not acceptable, but occupancy is not continuous. By using a two- or three-level ballast, or multi-lamp fixtures with lamps wired separately, the lowest level may be allowed to operate at most hours, but when occupancy is sensed, the light level increases. This is a useful energy saving strategy in areas where safety or security requires some light at all times, such as certain enclosed stairs, security corridors, restrooms, etc. Of the two strategies, multi-level ballasts have the advantage of keeping the lamp warm, reducing early burn-outs caused by frequent switching.

Daylight Controls. Daylight controls are photoelectric devices that turn off or dim the lights in response to the natural illumination available. Depending on the availability of daylight, the hours of operation and the space function, photoelectrically-controlled lighting can save 10% to 60% of a building's lighting energy. This can translate into even more savings since daylight availability coincides with the hours of the day when peak demand charges apply.

Smooth and continuous dimming is the preferred strategy for automated daylighting controls in offices or other work areas, since it is not distracting to the workers. The photosensor adjusts the light level based on the amount of natural light sensed by sending a signal to the dimming ballast. The less

Figure 9.12.3. Photosensor and fluorescent dimming ballast for continuous daylight dimming.

expensive dimming ballasts with minimum settings of 20% of full output are appropriate for daylight dimming (EPRI 1997). The two strategies, "closed-loop" and "open loop," are based on photosensor locations, and the correct sensor location is essential. In a "closed loop" system, the sensor is located above a horizontal surface to detect the light reflecting off that surface from both electric and daylight sources. Since the sensor is reading reflected light, the reflective characteristics of the surface should remain constant. Consequently, sensors are located over a circulation area, rather than a workstation where the reflectivity of the worker's clothes or desktop contents might change. In an "open-loop" system, the sensor is located near the window in such a way to only detect daylight. In both systems, the sensor must not pick up the direct illumination from the electric lights. Sensors can control more than one dimming ballast but the luminaires being controlled must all have a similar orientation to the natural light. For example, trees in front of several windows define a separate lighting "zone." Time-delay settings are used to slow down the response to rapid changes in natural lighting conditions, providing more steady lighting.

Switching the lights off when sufficient natural lighting is present is a less expensive strategy, but not as acceptable to the occupants. This approach is most commonly found in outdoor applications – controlling parking lot lighting for example. In buildings, a stepped approach to daylight switching is sometimes employed, in which only some lamps are switched off in multi-lamp luminaires. Alternately, daylight switching is used in rooms where continuous occupancy is not common, such as corridors, cafeterias, atria, or copy rooms.

Pre-set Controls. Switching, dimming, or a combination of the two functions can be automatically preprogrammed so that the user can select an appropriate lighting environment ("scene") at the touch of a button. Each scene uses a different combination of the luminaires in the room (sometimes dimmed) to provide the most appropriate light for one of several planned activities in that room. A "pre-set controller" and wiring plan organizes this. For example, the occupant of a conference room could select one pre-set scene from a five-button "scene selector" wall-mounted in the room, labeled "Conference," "Presentation," "Slide Viewing," "Cleaning," and "Off." This allows multiple lighting systems to be installed to meet the varying needs of separate activities, but prevents them from all being used at full intensity for every activity. A pre-set scene should be included for the cleaning crew, which should use the most energy-efficient lights that will allow them to do their work.

Time Controls. Time clocks are devices that can be programmed to turn lights on or off at designated times. These are a useful alternative to photoelectric sensors in applications with very predictable usage, such as in parking lots. Simple timers are another option, turning the lights on for a specified period of time, although there are limited applications where this is appropriate, e.g., library stacks. A time-controlled "sweep" strategy is sometimes effective. After normal hours of occupancy, most of the lighting is turned off (swept off), but if any occupants remain, they can override the command in just their space. Override controls can be wall switches located within the space or be activated by telephone or computer. These systems typically flash the lights prior to turnoff, to give any remaining occupants ample time to take action. There is usually more than one sweep operation scheduled after hours until all lights are turned off.

Centralized Control Management. Automated Building Management Systems (BMS) are becoming more common in medium- and large-sized facilities to control HVAC, electrical, water, and fire systems. Incorporating lighting controls is a natural step in efficient management, and centralized lighting control systems are available that can interface with building maintenance systems while providing data on lighting operation. However, in some cases, centralized systems are not appropriate for some functions, such as managing the dimming controls. The technological advance that may change this is DALI (digital addressable lighting interface), a communication protocol that allows an entire lighting system to be managed with computer software. This is promising for situations that require sophisticated control and flexibility for lighting reconfiguration. The DALI system is being designed based on an international standard so that various system components are compatible.

9.12.3 Safety Issues

In dealing with lighting equipment, the greatest concern is electrical shock, followed by injury from falls from high mounting locations, ladders and lifts, and handling of hazardous waste.

9.12.3.1 Electrical and Equipment Safety

- All electrical equipment should be properly grounded, including luminaires, ballasts, starters, capacitors and controls, and be in accordance with the National Electric Code® (NEC®).

Figure 9.12.4. Repair and rewiring must be done by a licensed electrician.

- Although maintenance personnel may handle routine maintenance such as changing lamps or cleaning luminaires, all trouble-shooting and repair must be handled by licensed electricians. All personnel must be properly trained and equipped.
- All maintenance personnel shall be provided with and instructed in the use of proper tools and equipment such as protective hand tools, fall protection such as safety belts or harnesses, hard hats, goggles, gloves, and testing tools.
- All maintenance of lighting equipment must follow the lockout/tagout standard in OSHA 1910.147 - *The Control of Hazardous Energy*. This standard applies to the control of energy during servicing and/or maintenance of machines and equipment. Employers must utilize procedures "for affixing appropriate lockout devices or tagout devices to energy isolating devices, and to otherwise disable machines or equipment to prevent unexpected energization, start-up or release of stored energy. The employer must be able to demonstrate that the tag-out device provides an equivalent level of safety to the lock-out device in that particular situation." Consult the OSHA website for the U.S. Department of Labor at **www.osha.gov**.
- Special precautions should be taken near high voltages and lighting components such as HID capacitors that may retain their electric change after the system has been de-energized. See OHSA.
- All forms of lifts, scaffolds, and ladders must meet OSHA standards for construction and use. Portable scaffolds, telescoping scaffolds, and personnel lifts are typically safer than ladders, by providing a firmer footing and space for tools, replacement items, and cleaning materials. Ladders used for lighting maintenance should not be made from materials that conduct electricity, such as aluminum. Stilts are sometimes used for maintenance of low ceilings or low-mounted luminaires.

9.12.3.2 Hazardous Materials Handling

- Breakage of mercury-containing lamps – Mercury vapor is most hazardous when lamps are operable. When a fluorescent or metal halide lamp containing mercury gas is broken, the following safety procedure is recommended. Clear the areas for 10 minutes; turn off AC so that mercury vapor does not spread; flush the area with fresh air: use an N95 respirator mask and goggles and gloves to sweep the particles into a glass jar. Double wrap in a paper bag. Dispose of as hazardous waste. Clean area and clothes. Discard gloves.

- Hazardous waste lamps are classified by the U.S. Environmental Protection Agency (EPA) as those failing the EPA Toxicity Characteristic Leaching Procedure (TCLP) for landfills, and include fluorescent, high pressure sodium, metal halide, mercury vapor, and neon lamps (if they contain mercury). The EPA revised their rules about mercury-containing lamps in 2000, allowing the following three options:

    - Mercury-containing lamps must pass the TCLP test

    - Must be treated as hazardous waste in storage, handling, collection, and transportation

    - Must be managed under the universal waste rule (40 CFR 273), i.e., recycled.

- The universal waste rule allows for disposal of hazardous lamps in small quantities. However, since the Federal government disposes of such high volumes of waste, this practice should not be followed. Recycling costs about $0.35 to $1.50 per 4-foot lamp depending on quantity and adjunct services. See **www.lamprecycle.org** for lamp disposal regulations and lists of recyclers. Hazardous waste landfill costs are about $0.25 to $0.50 per 4-foot lamp, not counting storage, collection, and transportation fees – costs that are generally more expensive than for recycling. Different states, (e.g., CA, CT, FL, ME, MI, PA, RI, VT) have more stringent regulations and do not even allow low-mercury lamps (i.e., lamps passing the TCLP test) in landfills.

- Magnetic ballasts with PCBs in the capacitors can still be found in older installations, even though they were banned from being manufactured or distributed after 1978. All ballasts produced after that date are clearly labeled “No PCBs.” PCBs are classified by the EPA as a hazardous waste under the Toxic Substances Control Act of 1976 (TSCA) section of their regulations, which requires disposal of the capacitor in a Federally-approved incinerator. Ballasts that are not leaking can be recycled. Whether or not the ballast is leaking fluid, the building manager should use a qualified disposal contractor who is aware of all PCB-related hazards.

- The building manager and the waste or recycling contractor must keep proper documentation and chain of possession records. Auditing the contractor and reviewing the contractor’s closure plan (for transition of materials if the contractor goes out of business) is recommended prior to signing a contract and every few years afterwards.

9.12.4 Energy Efficiency, Savings, and Cost

Ways to maintain performance and improve system efficiency through planned maintenance, response to complaints, retrofit, and redesign are described in this section.

9.12.4.1 Planned versus Reactive Maintenance

Lighting systems are intentionally overdesigned to account for losses in light output that will occur over time. Thus, the initial light levels are higher than needed, in order to ensure that the maintained light levels do not fall below design recommendations over time. The determination of overdesign depends on light loss factors (LLF) that include assumptions for cleaning and relamping fixtures at regular intervals, that is, a program of planned lighting maintenance.

$$\text{Luminaires required} = \frac{\text{Lighted area } \times \text{ desired maintained illuminance}}{\text{Initial lamp lumens } \times \text{ luminaire utilization efficiency } \times \text{ LLF}}$$

Planned maintenance can improve the LLF, reducing the number of luminaires required. Reactive maintenance, i.e., replacing lamps or ballasts when they fail, will not keep illumination at the desired levels. Following a planned maintenance program is essential to the success of any lighting system.

A planned maintenance program can reduce the degree of overdesign, resulting in significant reductions in first cost of equipment and in energy consumption. It can also improve safety, security, and the visual appearance of the spaces.

A proactive, planned maintenance program includes the following:

- Cleaning of lamps, luminaries, and room surfaces at regular intervals
- Group relamping on a scheduled basis of all luminaires in an area, with spot relamping in between. One cleaning can be performed in conjunction with relamping
- Inspection and repair of lighting equipment at regular intervals
- Inspection and re-calibration of lighting controls at regular intervals
- Re-evaluation of lighting system and potential upgrades. An upgrade may replace a group relamping cycle.

Recoverable light loss factors (LLF) are those that can be fully or partially returned to initial performance by proper maintenance. They include the following:

- ***Lamp Burnouts (LBO)***. “Rated Lamp Life” is provided by the manufacturer and represents the point in time when 50% of a group of lamps have burned out under controlled testing with lamps switched on 12-hour intervals. These are useful in determining exactly when group relamping interval is most economical (typically at about 70% to 80% of rated lamp life for fluorescent, see Figure 9.12.5). Extended life fluorescent lamps are available with 20% to 50% longer rated life. Frequent switching of fluorescent lamps (more than five on-off cycles per day) may greatly reduce lamp life, unless the cathodes are protected by a “programmed -start” ballast.

- ***Lamp Lumen Depreciation (LLD)***. Lamp lumen depreciation presents the decrease in light output of a lamp over time. Lamp catalogues provide both “initial lumens” and “mean lumens,” the former measured after 100 hours, and the latter occurring at 40% of the rated lamp life. New, high performance T8 lamps retain more of their lumen output than other sources (about 92%), while HPS retains only about 70% and metal halide about 65%. Mercury Vapor and LEDs have the greatest fall off in light output, so although they have longer rated lives, it makes more sense to consider replacing them before the end of their “useful” life.
- ***Luminaire Dirt Depreciation (LDD)***. Dirt and dust that settles on lamps and luminaire not only reduce the output but can also change the distribution of a luminaire (Levin 2002). The LDD factor used in lighting calculations depends on
  - The type of luminaire (open but unventilated, and all others)
  - The cleanliness of the environment
  - The anticipated cleaning schedule
  - See the IESNA RP-36-03 cleaning curves and equations to determine the best cleaning schedule. In a clean environment, some enclosed and ventilated luminaires can be cleaned every 24 to 30 months, resulting in less than 10% light loss (i.e., a LDD of 0.9). An open luminaire without ventilation would have to be cleaned every 12 months to keep the light loss at the same level. In a “dirty” environment, luminaires require cleaning every 6 months to a year to keep light losses above 20% (i.e., a LDD of 0.8).
- ***Room Surface Dirt Depreciation (RSDD)***. The reflective characteristics of the interior finishes can have a large impact on the efficiency of the lighting system and the quality and comfort of the light provided. Light levels can be better maintained by regular cleaning of the work surfaces. In existing facilities, light output, comfort, and lighting quality can be improved by repainting the walls a lighter color.

Non-recoverable light loss factors include:

- Ballast losses (the difference between rated lamp wattage and the actual input wattage)
- Supply voltage variations
- Ambient temperature of luminaire and surrounds
- Luminaire surface deterioration – Permanent deterioration of luminaire surfaces can be minimized by the wise specification of finishes for luminaire interiors and reflectors.

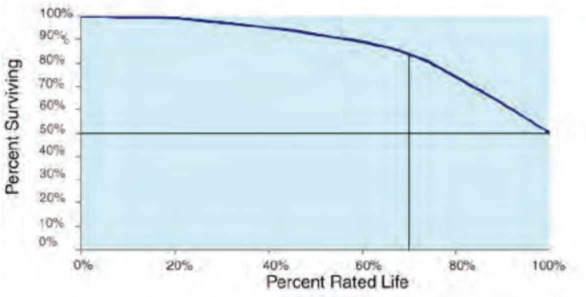


Figure 9.12.5. Fluorescent lamp mortality curve

9.12.4.2 Response to Complaints

Perhaps the greatest cause of lighting energy waste is controls that do not reduce energy consumption because they have failed or are improperly calibrated, or lighting controls that have been over-ridden or disabled rather than calibrated correctly. For example, an employee complains that the daylight dimming is too abrupt, or results in light levels that are too low. Rather than investigating the problem and fixing it, or providing the employee with an additional task light, either the staff cuts the control wires so the lights will not dim, or sets the sensor settings so high that the lights will not dim, or the employee puts tape over the light sensor so that the lights will not dim. While it is possible that a control system has been poorly designed and can never be calibrated well enough to satisfy the occupants, every effort should be made to work with the control manufacturer and the system designer to achieve the proper balance between energy savings and user acceptance. The easy way out of disabling the offending system can have a vast impact on the energy savings, and may even impact on cooling loads that were designed on the basis of reduced lighting consumption.

9.12.4.3 Retrofit versus Redesign

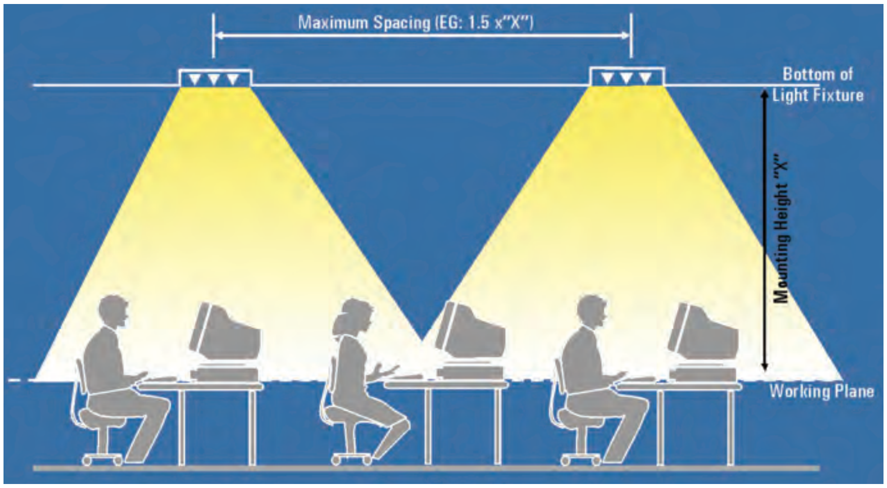
Retrofit is typically described as replacement of components (lamps, ballasts, reflectors, lenses, even luminaires) in the same housing or location as the original lighting equipment. Redesign is typically described as new luminaires in some new locations. On the surface, retrofit may appear to be the cheapest and easiest path, but in fact is not always the most cost-effective strategy. Retrofit may not be the best solution if:

- Existing lighting quality is poor
- Existing light levels are too low or contrast between bright and dark areas is too high
- Existing lighting does not light walls or work partitions
- Existing luminaire locations produce illumination that is not uniform
- Existing luminaire spacing is too wide and/or partial height partitions obstruct the light.
- Luminaire spacing or locations are inappropriate for current or proposed use or furniture layouts
- Existing room surfaces or furniture are dark in color
- Retrofit options will narrow the distribution of light or lessen the light levels on vertical surfaces.

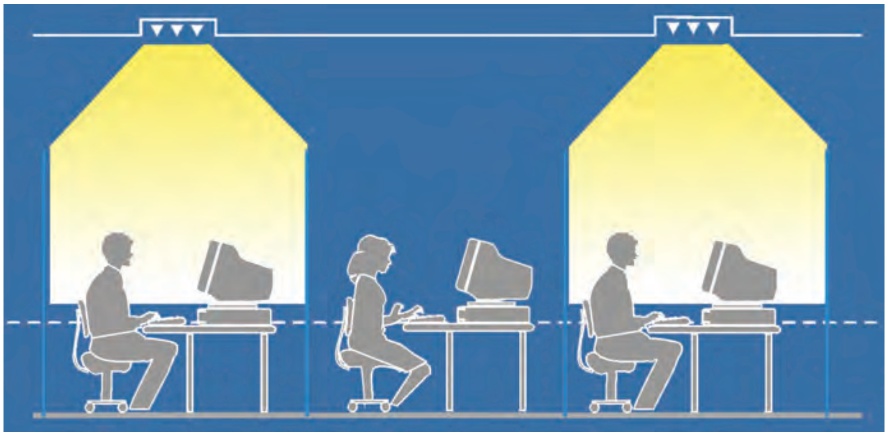
If "retrofit" still seems like the best option, consult the *IESNA Guidelines for Upgrading Lighting Systems in Commercial and Institutional Spaces* (LEM-3-07), available at **www.iesna.org**.

Otherwise, consider redesigning the lighting layouts and reconsidering the types of luminaires if any of the existing conditions make the space unsuitable for retrofit. The trend of improvements in lighting technologies can create cost-effective opportunities for upgrading the lighting in Federal facilities, even if they have been upgraded in the last 5 to 10 years. For example, high performance T8 lamps and ballasts could save 10% to 15% over standard T8s installed only 8 years ago.

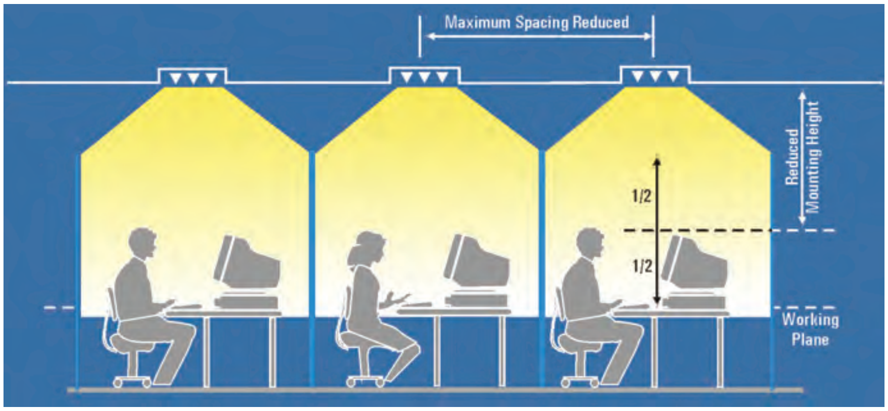
- At the very least, higher performance lamps should be considered for the next scheduled group relamping.
- Upgrade lamps (and ballasts) instead of group relamping



Uniform light distribution following maximum spacing criterion.



Spacing criterion does not account for partial height partitions.



Adjusted spacing criterion and mounting height to accommodate partitions.

Figure 9.12.6. Lighting uniformity and fixture spacing criteria.

When considering a retrofit or redesign, it is important to keep in mind the importance of the quality of the lighting in a space. Lighting quality is just as important, and oftentimes more so than quantity of illumination. The IESNA Handbook, Ninth Edition, Chapter 10, contains lighting design guides for a wide range of space functions. These outline the most important qualitative needs, as well as the recommended light levels for each function.

- Uniformity – There should not be a wide range of differences between the highest and lowest brightness in the space. The existence of partial height furniture partitions may significantly reduce uniformity, requiring a closer spacing or wider distribution of luminaires. Avoid harsh shadows or patterns (see Figure 9.12.6).
- Spacing Criterion – Manufacturers provide the maximum spacing between luminaires that will maintain acceptable uniformity. However, this "spacing criterion" assumes that a room is unobstructed. If a room has partial height furniture partitions, tall files, or other obstructions, the spacing criterion should be reduced by a factor of 0.75 to 0.85.
- Lighting Walls and Ceilings – The perception of occupants that the lighting is too bright, comfortable, or too dim is based more on the brightness of the room surfaces and vertical partitions than that of the task or desktop. A lighting system should be designed to distribute light to the walls and ceilings as well as the task. A light colored room can increase light levels as much as 20% over a dark colored room. Cleaning the wall surfaces improves efficiency, especially in a "dirty" environment, but repainting a wall with a lighter color will show much greater improvement.
- Glare – Excessive contrasts in light cause glare. It most often occurs when a bright light source (including windows) interfere with the viewing of less bright objects. Existing conditions of glare can be mitigated, or glare prevented in retrofits, by some of the following recommendations:
    - Shield the lamp from view with baffles, louvers, lenses, or diffusing overlays. Use only semi-specular or white painted louvers and reflectors.
    - Increase the reflectances of room surfaces by using lighter colored paints and fabrics in a matte or eggshell finish.
    - Use low output (high-efficiency) lamps in the field of view. T5HO lamps are very bright and best used in indirect applications.
    - Decrease the contrast between fixtures and ceilings by adding uplight or selecting luminaires with an uplight component.
- Color – For almost any task, color discrimination aids visibility. Light sources are typically described by their "correlated color temperature (CCT)" and their color rendering index (CRI). For most workplaces, use fluorescent lamps in the 80 to 85 CRI range, and metal halide lamps at 80 and higher. For most workspaces, CCT between 3500 and 4100 are acceptable. For reference, 3000 Kelvin CCT is warm, 3500 K is neutral, and 4100 K and higher become increasingly cool in appearance. Sunlight is in the 4000 to 6000K range, and daylight is in the 5000 to 10,000 K range.

9.12.4.4 Energy Codes

The current energy code applicable to all Federal buildings is 10 CFR 434 ("Energy Code for New Federal Commercial and Multi-Family High Rise Residential Buildings"). This code is similar in requirements to the ANSI/ASHRAE/IESNA 90.1-2001 standard for commercial buildings (ANSI/ASHRAE/IESNA 2001). It is expected to be upgraded to reference the current standard, which has limits on connected load up to 30% more stringent. This will have a big impact on major renovations in Federal facilities. The lighting portion of the energy code has three components – determination of a whole project interior lighting power allowance, determination of an exterior power allowance, and mandatory requirements for lighting controls and exterior lamp efficiencies.

9.12.5 Maintenance Procedures

9.12.5.1 Commissioning

"Commissioning" is defined as the entire process of quality assurance of a lighting system that begins with proper design and specifications, and concludes with calibration, fine tuning, aiming, documentation, monitoring, and verification and that the system operates and saves energy as intended, and is acceptable to the occupants. Even if a lighting system was carefully commissioned prior to occupancy, certain components of it should be recommissioned at intervals ranging from 2 to 5 years to ensure that it is operating as intended. In addition, as tasks or occupants change within the building, lighting controls and even some light levels may need adjustment. The specific lighting related recommendations below pertain equally to commissioning or recommissioning – to the initial design, or to any retrofit, upgrade, or redesign of the lighting system.

Lighting Efficiency Considerations
(UNEP 2006)

- Reduce excessive illumination levels to standard levels using switching, delamping, etc. (Know the electrical effects before doing delamping.)
- Aggressively control lighting with clock timers, delay timers, photocells, and/or occupancy sensors.
- Install efficient alternatives to incandescent lighting, mercury vapor lighting, etc. Efficiency (lumens/watt) of various technologies range from best to worst approximately as follows: low pressure sodium, high pressure sodium, metal halide, fluorescent, mercury vapor, incandescent.
- Select ballasts and lamps carefully with high power factor and long-term efficiency in mind obsolete fluorescent systems to Compact fluorescents and electronic ballasts.
- Consider lowering the fixtures to enable using less of them.
- Consider day lighting, skylights.
- Consider painting the walls a lighter color and using less lighting fixtures or lower wattages.
- Use task lighting and reduce background illumination.
- Re-evaluate exterior lighting strategy, type,and control. Control it aggressively.
- Change exit signs from incandescent to LED.

- A commissioning plan contains the following elements: design intent, design features, calibration levels, methods of verification, documentation requirements, schedules, and checklists.
- Establish schedules for relamping, cleaning, recalibration, and reevaluation of the lighting system.
- Intervals for recommissioning should be based on the type of equipment. See lighting controls below.

- Specify that the ballasts and lighting controls be factory pre-set to the greatest extent possible. This shall not remove the responsibility from the contractor for field calibration if it is needed. Specify calibration levels to the extent they can be known prior to installation.
- Aiming – Some lighting equipment is sensitive to orientation, such as spotlight, wall washers, and occupancy sensors. A "pre-aiming diagram" can be specified or requested prior to installation, so that the contractor can make reasonable adjustments to the equipment during the initial installation.
- Calibration – If calibration settings were not specified initially, the facility manager should contact the manufacturer of control equipment directly for assistance.
- Ensure that the commissioning is complete PRIOR to building occupancy. Even a few days of an improperly calibrated control device can turn occupants against the system, resulting in huge energy waste.

9.12.5.2 Common Causes of Poor Performance

Some maintenance items such as swirling lamps or inoperable ballasts are obviously in need of immediate attention and repair (see troubleshooting below).

Of more serious concern are systems that are improperly calibrated or not being maintained on a planned basis resulting in energy waste and/or poor lighting quality. These hidden factors include:

- Dirt accumulation on luminaires or room surfaces that has significantly reduced light output.
- Older lamps that have not burned out but output fewer lumens than the system design assumptions.
- Lamps that are still operating, but have passed their "useful" life, such as metal halides and LEDs.
- Dimming or stepped ballasts that are miswired or failed by defaulting to full output.
- Controls that were never properly calibrated or have fallen out of correct calibration.
- Controls or power packs that have failed and defaulted to continuous on.
- Motion sensors or light sensors that have been disabled by the occupants.
- Controls that have been overridden or disabled (rather than recalibrated) by the building staff in response to complaints.

9.12.5.3 Cleaning

The intent of cleaning lamps, luminaries, and room surfaces is to return them to their original condition recovering any interim losses in light output. It is important to use the proper cleaning compounds and strategies, so that luminaire surfaces are not damaged. Different surfaces require different cleaning compounds. In lieu of manufacturer's instructions, the following represents some guidance.

- Never clean lamps that are operational or still hot.
- Use very mild soaps and cleaners, followed by a clean rinse on most surfaces. Silver films require the mildest 0.5 % solution and a soft damp cloth. Avoid strong alkaline cleaners or abrasives cleaners.
- Glass cleaners may be used on porcelain or glass but the latter requires an additional clear rinse.
- To avoid static charge on plastics, use anti-static cleaning compounds. Do not dry-wipe plastic after a rinse, as this will create an electrostatic charge. Drip-drying creates streaks. Vacuuming is the best method for drying plastics.

9.12.5.4 Lamp and Ballast Troubleshooting

The most common problems associated with lamps and ballasts are:

- Lamps will not light or start erratically or slowly.
- Premature failure or lamp life shorter than expected.
- Deposits, discoloration, dark spots, or streaks of the lamps.
- Blinking, swirling, fluttering, spiraling, unexpected dimming.
- Light output or color degradation sooner that expected.
- Blistering/bulging on the bulb.
- Lamp cycling on and off.
- Ballast noise.

The Illuminating Engineering Society of North America (IESNA) and the interNational Association of Lighting Management Companies (NALMCO) have developed a joint publication titled *Recommended Practice for Planned Indoor Lighting Maintenance* (IESNA/NALMCO RP-36-03). It contains troubleshooting guidance for incandescent, fluorescent, and HID lamps and ballasts. This material is excerpted from troubleshooting guides originally published in *Illuminations*, a NALMCO publication. It is available electronically or as a publication at **www.iesna.org**.

9.12.5.5 Lighting Controls Calibration and Troubleshooting

Calibration

Evaluate lighting controls annually to determine if they are in need of recalibration see Figure 9.12.7. Seek advice from manufacturers of controls. Document all settings and dates of recalibration. Seek the optimum balance between energy savings and occupant satisfaction. For some strategies, like daylighting controls, calibrations strategies vary widely by manufacturer.

Control Type	Calibration(a)	Notes
Occupancy sensors ceiling-mounted	Time delay: 15 minutes Sensitivity: Medium high	1,2
Wall-box occupancy sensors	Manual-on Auto-off Time delay: 15 minutes Sensitivity: Medium	1,3
Daylight dimming	High illuminance before dimming begins Time delay: 5 minutes Fade rate: 1 minute Sensitivity: See manufacturer	4
Daylight switching	Time delay: 10 minutes Dead band: 15 footcandles Sensitivity: See manufacturer	5
Manual dimming	High end trim at 95% (incandescent only)	6
Automatic dimming	Time delay Fade rate	7
Pre-set dimming	Time delay Fade rate	7
Automatic timers Astronomical time clocks	On and off times, differ for weekends, holidays. Multiple settings depend on space function and occupancy. Daylight savings	8

a) Start with these settings and adjust upward and downward as required. (1) Time delays shorter than 15 minutes are likely to shorten lamp life unless programmed ballasts are installed. (2) Wire ceiling sensors to an automatic or Sentry-type switch for manual on operation. (3) Ensure that occupancy sensors can be set to manual "on" without over-riding the automatic off functionality. (4) Set the illuminance level 20% to 30% higher than the designed light level for the electric lighting. Thus, if 30 footcandles of electric light is provided, lamps should not start to dim until the daylight and electric light together provide 36 to 39 footcandles on the desktop. (5) Photosensor controlled switching or multi-level switching (sometimes called stepped dimming) is seldom acceptable to occupants in full time work environments. Set a wide "dead-band" of at least 15 footcandles to prevent cycling. (6) Slightly reducing the maximum light output of an incandescent lamp extends lamp life. It is not recommended for halogen lamps and is not effective with fluorescent sources. (7) Settings will depend on specific application. Time delays and fade rates are not recommended for pre-sets that are controlled by the occupants (rather than part of an automated program or AV sequence) because if the occupants do not see an immediate response, they often repeatedly turn lights on and off or try other pre-sets. (8) More energy is saved by tailoring the timeclocks more closely to the specific spaces being controlled and by providing more discrete schedules, i.e., one for Saturday and one for Sunday, rather than the same for the weekend.

Figure 9.12.7. Calibrations for controls

Troubleshooting

Occupancy sensors turn lights "on" when they are not needed. Is the sensor responding to movement in the corridor outside the office, currents from the air diffusers, or it is causing the lights to burn even when daylight is sufficient or preferred. Ultrasonic sensors are more prone to false on, but less prone to false offs, because they are more sensitive to subtle movement like occupants typing or writing.

- Start with adjusting (reducing) the sensitivity setting slightly, reducing the sensors sensitivity to motion, without creating a problem with false offs.
- If the occupants are agreeable, setting the sensor to manual "on" operation (if it is connected to, or integral with, a local switch) is the most energy efficient and increases lamp life.
- Mask the sensor so that it does not "see" motion outside the room.

Figure 9.12.8. Ceiling occupancy sensor.

Occupancy sensors turn lights "off" when occupants are still in the space.

- Check to confirm that sensor is not in test mode.
- Increase the sensitivity setting.
- Increase the time delay, but not longer than 30 minutes.
- Consider replacing infrared sensor with more sensitive ultrasonic sensors.
- Evaluate the number and distribution of the existing sensors and verify if the coverage is sufficient. (Partial height partitions and other vertical obstructions must be taken into consideration.)

Daylighting controls dim the lights too much.

- Verify light levels. If they meet design criteria, the problem may be one of window glare or excessive contrast. Verify that blinds are adequate to control glare. Diffuse shades may be too bright when sun hits them.
- Maximize the "fade rate." Dimming should be smooth and continuous and not perceptible to the occupants. Verify with manufacturer that product has a "continuous" dimming response, not a "threshold" dimming response. The latter is appropriate for spaces like warehouses, but not for offices or spaces with stationary workers.
- Increase time delay to 10 minutes so that lights do not respond to sudden changes like cloud movements near the sun, or people walking under the photosensor.
- Verify that the photocell is properly located over a space that does not change from day to day, like the carpet of aisles between cubicles or an unadorned wall. A photocell over a desktop will respond to the objects on a desk or the occupants clothing, and may dim lights more on days that the occupant wears a white shirt.
- Re-calibrate the photosensor at night and again during hours of daylight. Follow manufacturer's procedure.

Fluorescent lamps flicker when dimming ballasts are at the lowest end of the dimming range.

- Consult the ballast manufacturer and verify wiring is correct.
- Replace the ballasts.
- If the problem is extensive or attributable to the signal sent by the photosensor, increase the lowest setting, but not higher than 30%.

9.12.5.6 Diagnostic Tools

Unlike many HVAC systems and components, lighting equipment and systems tend to be fairly stable once installed and commissioned. Diagnostics is, therefore, generally applicable only periodically or when building needs change. However, when initiating any O&M program or assessment of building energy "health," it is important and can be very profitable to evaluate lighting conditions and equipment.

Generally, the diagnostics of lighting systems involves the evaluation of the basic characteristics of lighting:

- Quality and quantity of light.
- Equipment types and efficiency, condition, and cleanliness.
- Control condition/settings.
- Energy usage.

For some of these characteristics, visual inspection and physical testing is appropriate and requires no special tools. For others some basic tools can be helpful.

Illuminance (light) meter – Illuminance meters are often referred to as a "light meters" which is a generic term that also includes the meters used by photographers (which is not what is needed for building lighting). Illuminance meters come in many styles at a range of costs. Most will do an adequate job of evaluating basic light levels in building spaces. Light levels should be taken at the spaces where the specific tasks are to be performed such as desktops for office work, hallway floors for egress, etc.

Light levels will change over time as lamps age. However, with modern equipment this is a relatively slight effect and is not typically considered a metric used to make changes to equipment or replace lamps. The most important measurement of light levels is an evaluation when systems are initially installed, equipment changes are made, or an O&M program is initiated. Light levels that are higher than necessary to provide appropriate lighting or higher than designed are an opportunity for energy savings as light level and kWh usage are directly related.

The required light levels (illuminance) for building areas will depend on the expected tasks. The widely accepted and referenced quality and illuminance recommendations are developed by the Illuminating Engineering Society of North America (IESNA), and can be found in Chapter 10 of the IESNA Handbook, Ninth Edition. The building tenants or other regulatory organizations may also have specific requirements for the activities to be performed in the building.

Energy/lighting/occupancy loggers – Measurements of individual lighting fixtures or panels can provide specific lighting power information that if tracked over time can help identify controls savings opportunities. However, the equipment to support these continuous measurements can be expensive to install and maintain. Less costly options that provide similar useful results are individual lighting loggers than can measure lighting on/off schedules for long periods of time with the capability to download the data to any computer for analysis. This kind of data can identify areas where lighting is left on after hours. Similar occupancy based loggers can specifically identify lighting that remains on when spaces are unoccupied. This information can be used to identify overlit spaces as well as good applications for occupancy sensor controls. These loggers are available from a variety of sources. These can be found on the world-wide web or in the report, *Portable Data Loggers Diagnostic Tools for Energy-Efficient Building Operations* (PECI 1999).

Flicker checker – For hard-to-reach areas (high ceilings), it is often difficult to determine the type of lighting installed (electronic, magnetic ballast). There is a simple tool available to help determine the characteristics of ballast type (and therefore often lamp type) installed. A common version of this tool is a "flicker checker" used to determine electronic versus electromagnetic ballasts available from Sylvania (1-800-544-4828). It operates like a simple toy top and will indicate whether the operating ballast above is a 60 Hz type or electronic high frequency type. Typically the 60 Hz type will be operating T12 technology lamps. The high frequency may be operating T12 or T8 technology.

Solar data – When considering the application of daylighting into building spaces, it is important to understand the potential of the building space and the capability of the sun in your area to provide adequate daylight. This involves evaluating the tasks in the space, characterizing the configuration of the space including size and shape of windows or skylights, and assessment of the solar availability in your location. Solar availability data is maintained by the National Oceanographic and Atmospheric Association (NOAA) at **www.noaa.gov**. Available data includes number of hours of sunshine, number of clear, overcast, and partially cloudy days in a number of cities across the United States based on weather charts. Exterior illumination of sun and daylight can be found for any U.S. latitude through the IESNA daylight availability publication or the ASHRAE handbook. Sun angles can be determined by the Pilkington LOF Sun Angle Calculator, available from **www.sbse.org/resources/sac/**.

9.12.5.7 Economics

Operations and maintenance activities and equipment represent real costs to a facility and must be evaluated like any other proposed action.

Some potential actions can be evaluated using simple methods to provide appropriate cost-effectiveness analysis such as the replacement of incandescent exit signs with reduced-wattage LED signs. The cost of energy saved is easy to calculate based on the wattage difference, 24-hour operation, and local utility rates. The cost of the new exit sign divided by the cost savings provides a simple measure of the time required to pay off the new sign with energy savings (payback period). This is often all that is needed to determine whether the replacement is a good idea.

In other cases, more complicated analysis is required. Large cost items such as more advanced control systems may require longer term investment spanning many years. These types of investment decisions will often require more comprehensive cost analysis that involves more parameters to determine their cost-effectiveness. These often include:

- Installation costs
- Equipment life
- Replacement equipment cost
- Replacement labor
- Interest rate
- Fuel cost
- Fuel escalation rates.

With more advanced resulting analysis metrics such as:

- Return on investment
- Life-cycle cost.

Software tools are available from many sources to perform this type of analysis. The Federally supported Building Life Cycle Cost (BLCC5) tool for advanced economic analysis is one such tool that is available from the USDOE at **www.eere.energy.gov/femp/information/download_blcc.cfm**.

9.12.6 Lighting Checklist

Description	Comments	Maintenance Frequency
Visual inspection	Inspect fixtures to identify inoperable or faulty lamps or ballasts. Burned-out lamps may damage ballasts if not replaced.	Weekly to monthly
Visual inspection	Inspect fixtures and controls to identify excessive dirt, degraded lenses, inoperable or ineffective controls.	Semi-annually
Clean lamps and fixtures	Lamps and fixture reflective surfaces should be cleaned periodically for maximum efficient delivery of light to the space	6 to 30 months, depending on space and luminaire type
Clean walls and ceilings	Clean surfaces allow maximum distribution of light within the space	1 to 3 years, depending on dirtiness of environment
Replace degraded lenses or louvers	Replace yellowed, stained, or broken lenses or louvers	As identified
Repaint walls and replace ceilings	Lighter colored surfaces will increase light distribution efficiency within the space	As identified or at tenant change
Replace burned out lamps	For larger facilities consider group relamping	As needed or on group schedule
Evaluate lamps and ballasts for potential upgrade	Rapid change in technology may result in significant savings through relamping or simple retrofit.	Every five years or on group relamping schedule
Survey lighting use/illumination levels	Measure light levels compared to tasks needs in typical spaces. Identify areas for reduction or increase in illuminance	Initially and at task/tenant change
Survey for daylighting capability	Identify areas where daylighting controls could be used	One-time analysis or at tenant change
Survey for local controls capability	Identify areas where local automatic controls could be used	Initially and at tasks/tenant change

9.12.7 References

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