Energy Auditing

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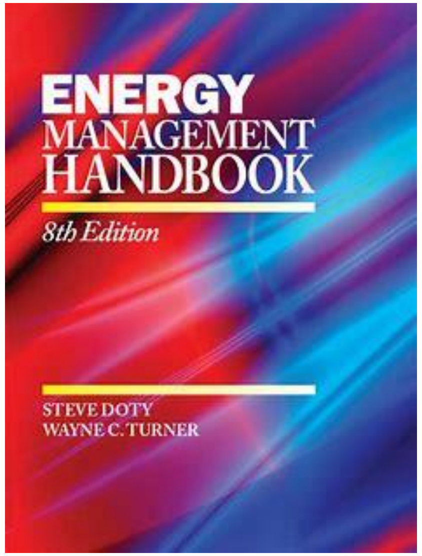
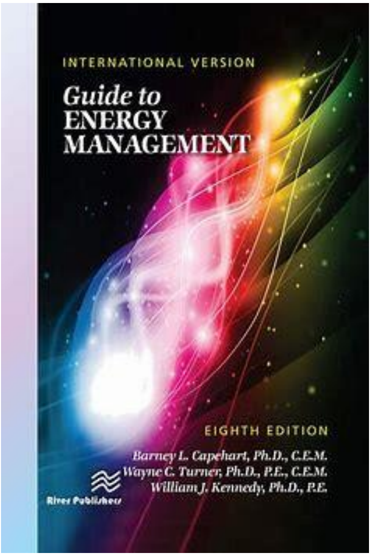
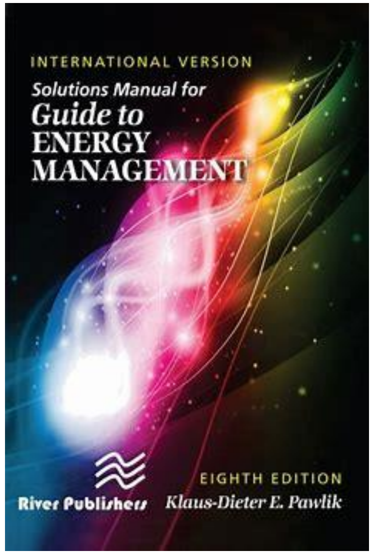
Contents

Useful references

- Energy Management Handbook, 8^{th} edition, 2013.
- Guide to Energy management, 8^{th} edition, international version, 2020.
- Solution manual for guide to energy management, 8^{th} edition, international version, 2020.







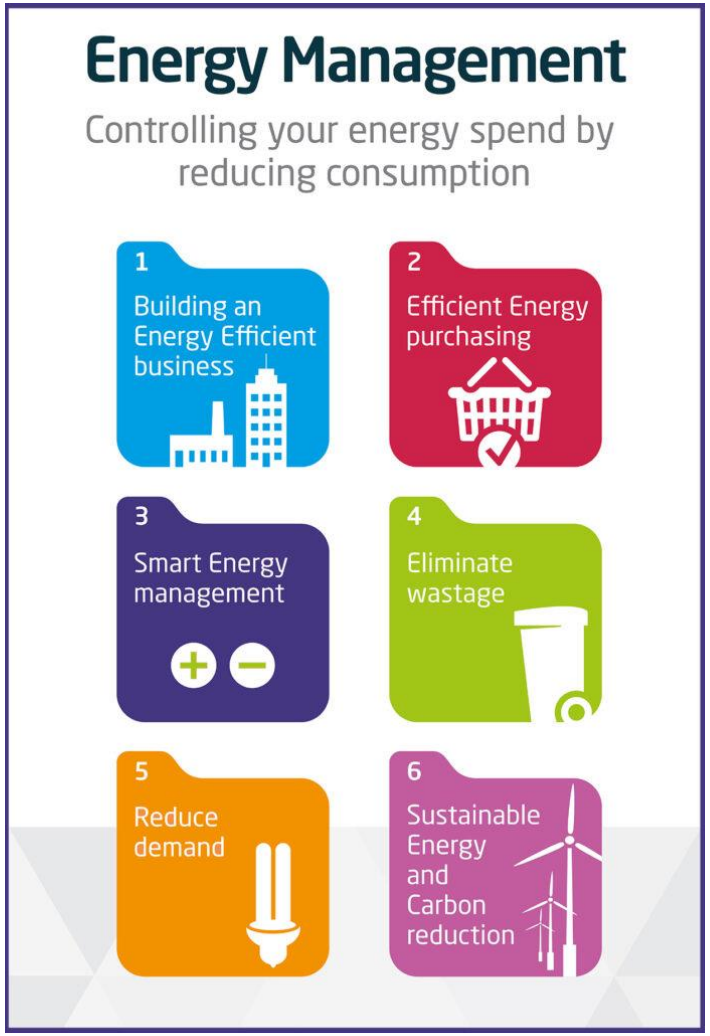
Skills development tips

- Understand the concepts.
- Practice too many calculations, **BACK OF THE ENVELOPE**!
- Keep aware about the state of the art **MARKET** available technologies.
- Develop your own excel sheets tools (recommended), or use suitable software packages (optional)

Part I:
Introduction to Energy Management

What is energy management?

- The efficient and effective use of energy to maximize profits (minimize costs) and enhance competitive positions.



Energy management sub-objectives

1) Improving energy efficiency and reducing energy use, thereby reducing costs.
2) Reduce greenhouse gas emissions and improve air quality.
3) Cultivating good communications on energy matters.
4) Developing and maintaining effective monitoring, reporting, and management strategies.
5) Finding new and better ways to increase returns from energy investments through research and development.
6) Developing interest in and dedication to the energy management program from all employees.
7) Reducing the impacts of curtailments, brownouts, or any interruption in energy supplies.

Energy management sub-objectives

Curtailments occur when a major supplier of an energy source is forced to reduce shipments or allocations (sometimes drastically) because of severe weather conditions and/or distribution problems.

The need for energy management on national and global levels

Economics

- Any new activity can be justified **ONLY** if it is cost effective.
- New buildings designed to be energy efficient often operate on 20% of the energy (with a corresponding 80% savings) normally required by existing buildings.

Reduce Cost of Imported Oil (in barrels):

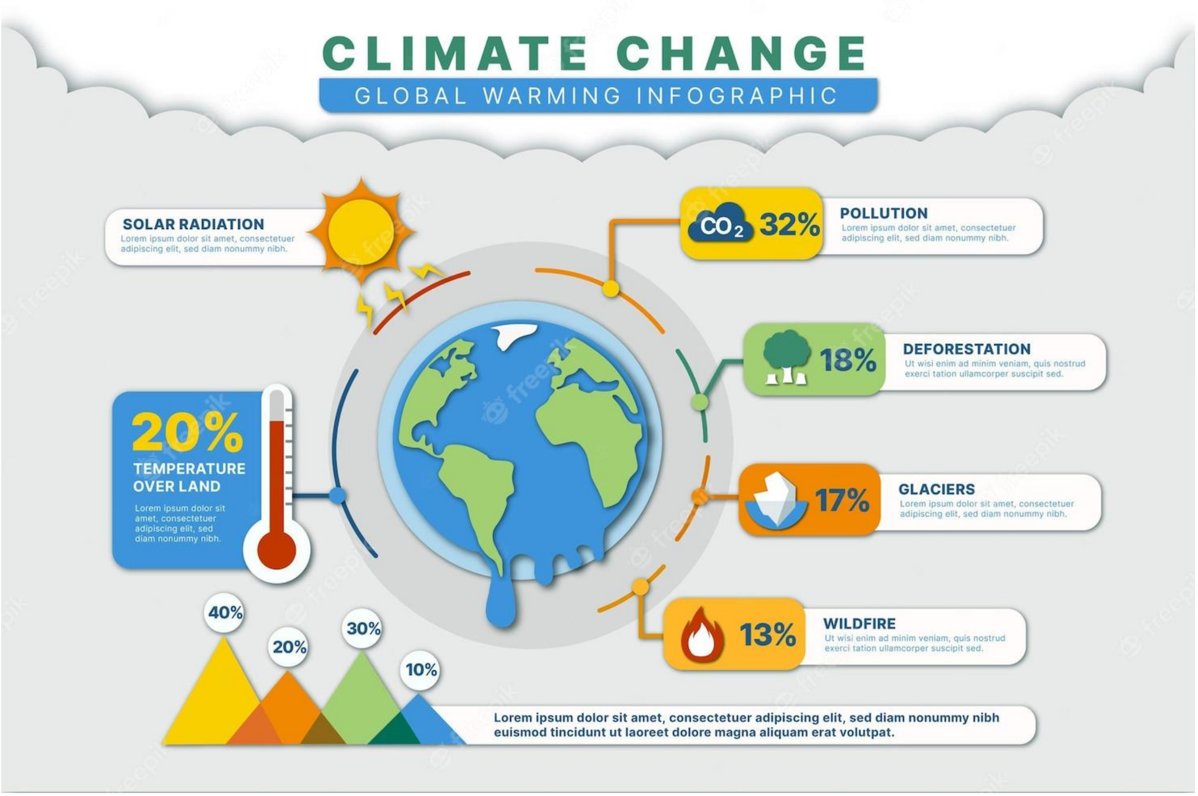
- Average world oil prices climbed dramatically since 1970.
- The average annual cost per barrel of oil in 1970 was USD1.80.
- In 1980 it had risen to USD36.83. The cost came down significantly in 1990 to USD23.73, and up only to USD28.50 in 2000.
- But by 2005, it had risen to USD54.52 per barrel.

Reduce Cost of Reliance on Imported Oil:

The need for energy management on national and global levels

Reduce environmental challenges

- Limiting global climate change
- Reducing ozone depletion
- Reducing acid rain
- Improving national and world security



Each of the possibilities discussed below has its own problems

- Coal
- Synfuels
- Solar-generated electricity
- Biomass energy
- Wind energy
- Fuel cells
- Alcohol production
- Fission
- Fusion

- **Saved energy can be used elsewhere**, so one energy source not mentioned in the preceding list is energy management. In fact, energy available from energy management activities has almost always proven to be the most economical source of “new” energy.

Energy manager MUST skills

- Energy terminology and units of measure.
- Informed about their national energy picture as well as the world energy picture.
- The historical use patterns as well as the current trends are important to an understanding of options available to many facilities.
- Energy modeling and calculations.
- State of the art technology.
- Measurements and verification.
- Economic analysis.
- **COMMUNCATION**.

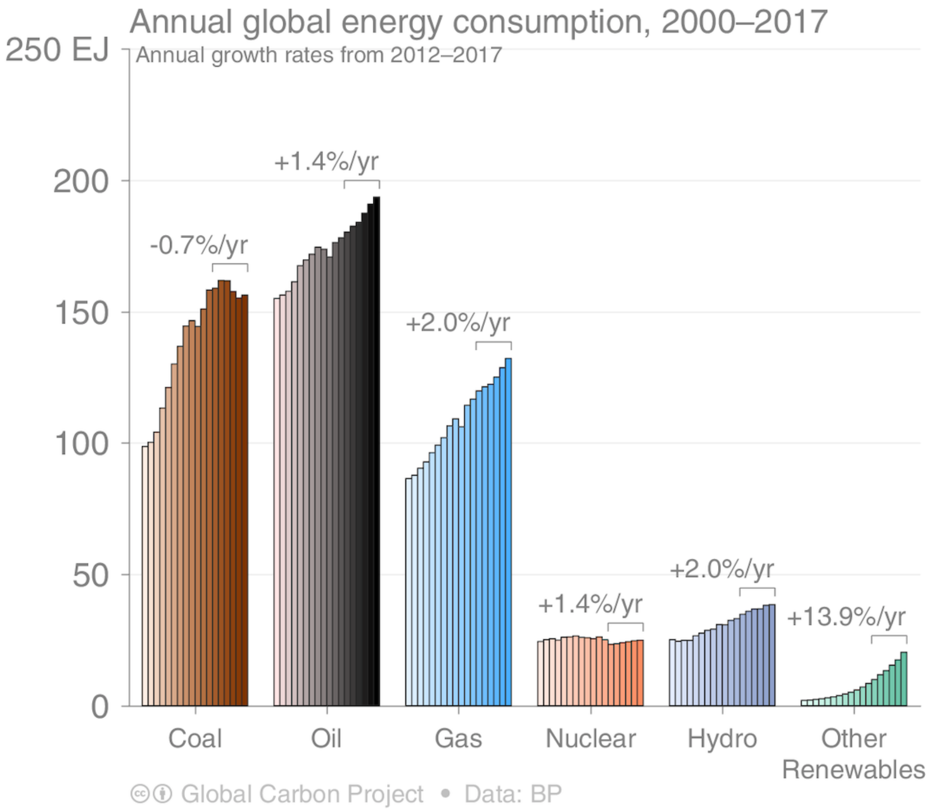
Energy Terminology, Units and Conversions

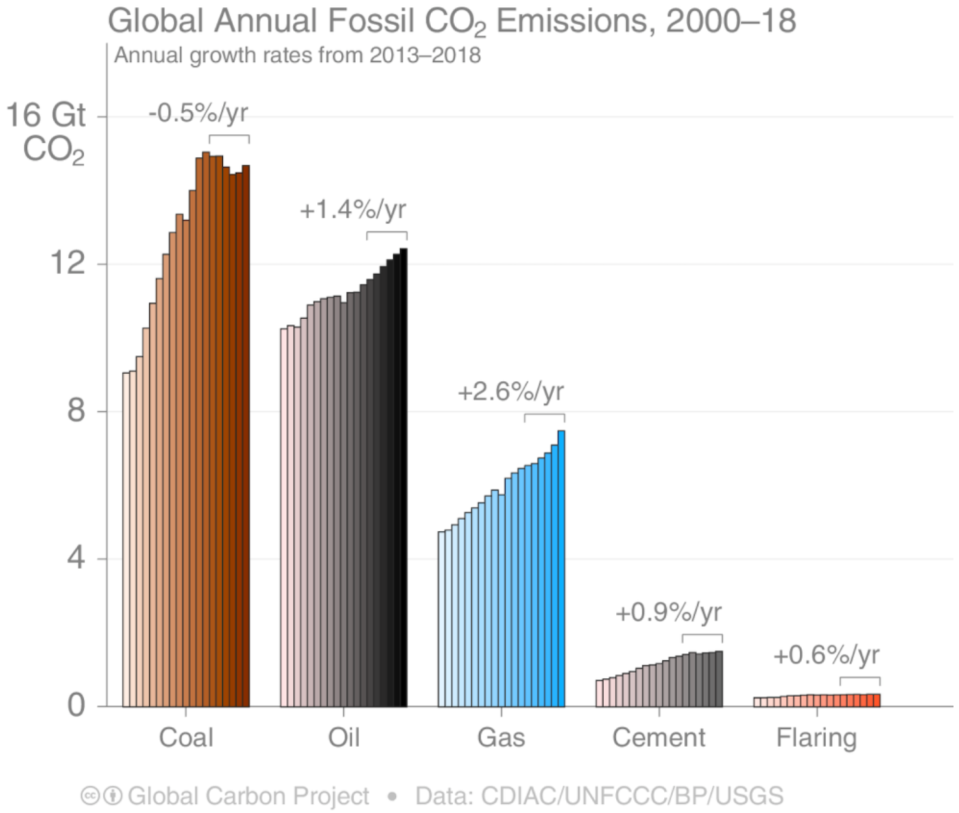
- Energy is the ability to do work, and the standard engineering measure for energy is the Joule, or J. **One J is one watt × second.**
- The energy content of most common fuels is well known. For example,
  - ✓One liter of gasoline contains about 35 MJ
  - ✓One cubic meter of natural gas contains about 37 MJ.
- **1kWh = 3600000J = 3600 kJ = 3.6MJ = 0.0036 GJ.**

Energy Units and Energy Content of Fuels

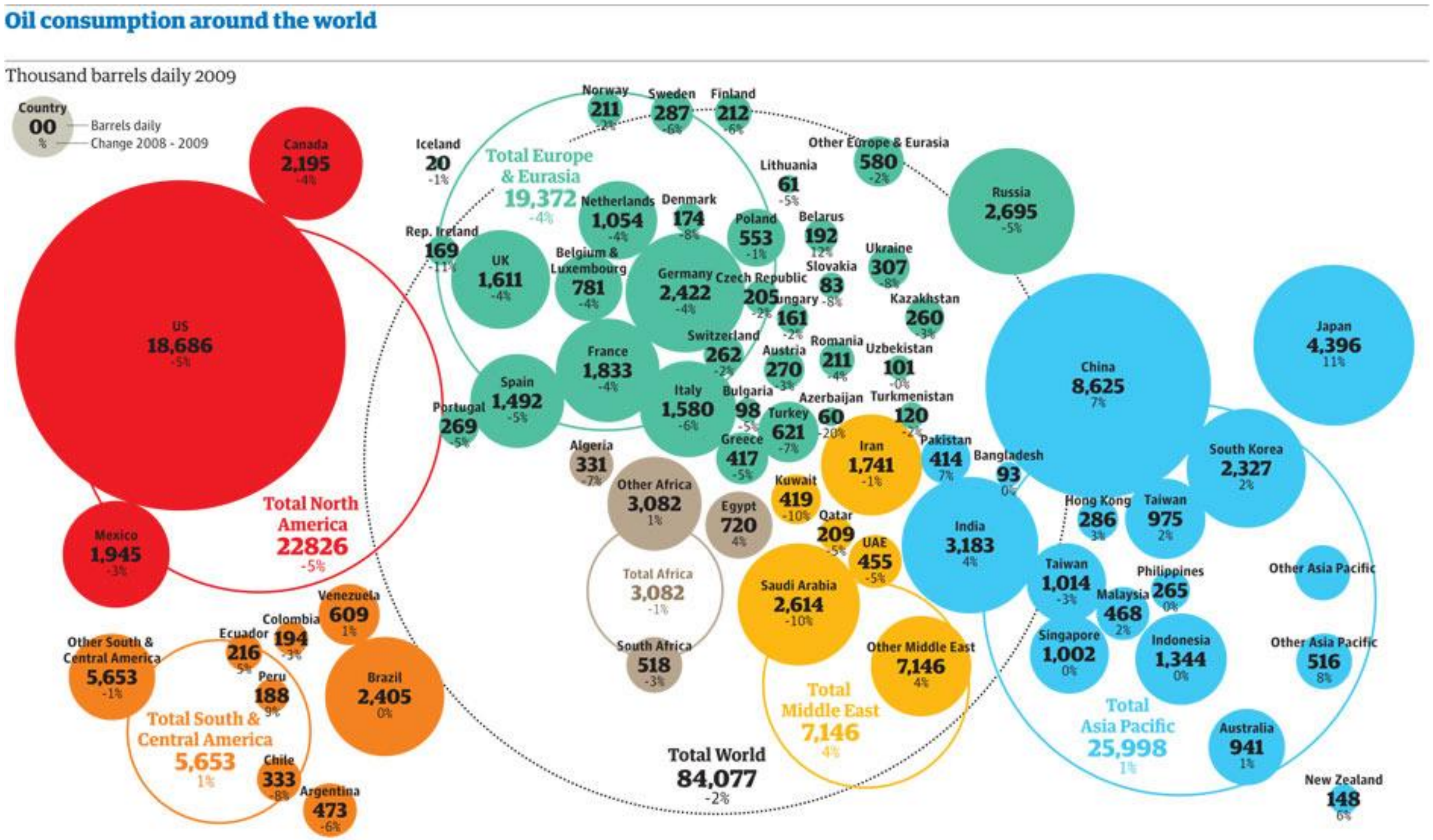
1 kWh	3.6 MJ
1 m^3 natural gas	37 MJ
1 kg #2 fuel oil	42 MJ
1 litre gasoline	35 MJ
1 m^3 #2 fuel oil	39 GJ
1 m^3 propane (LPG)	25.5 GJ
1 kg propane (LPG)	45.65 MJ
1 tonne hard coal	25 GJ
1 barrel crude oil	5.8 GJ
1 MJ	1000 kJ
1 GJ	10^6 kJ
1 MW	10^6 watts

Global energy statistics knowledge

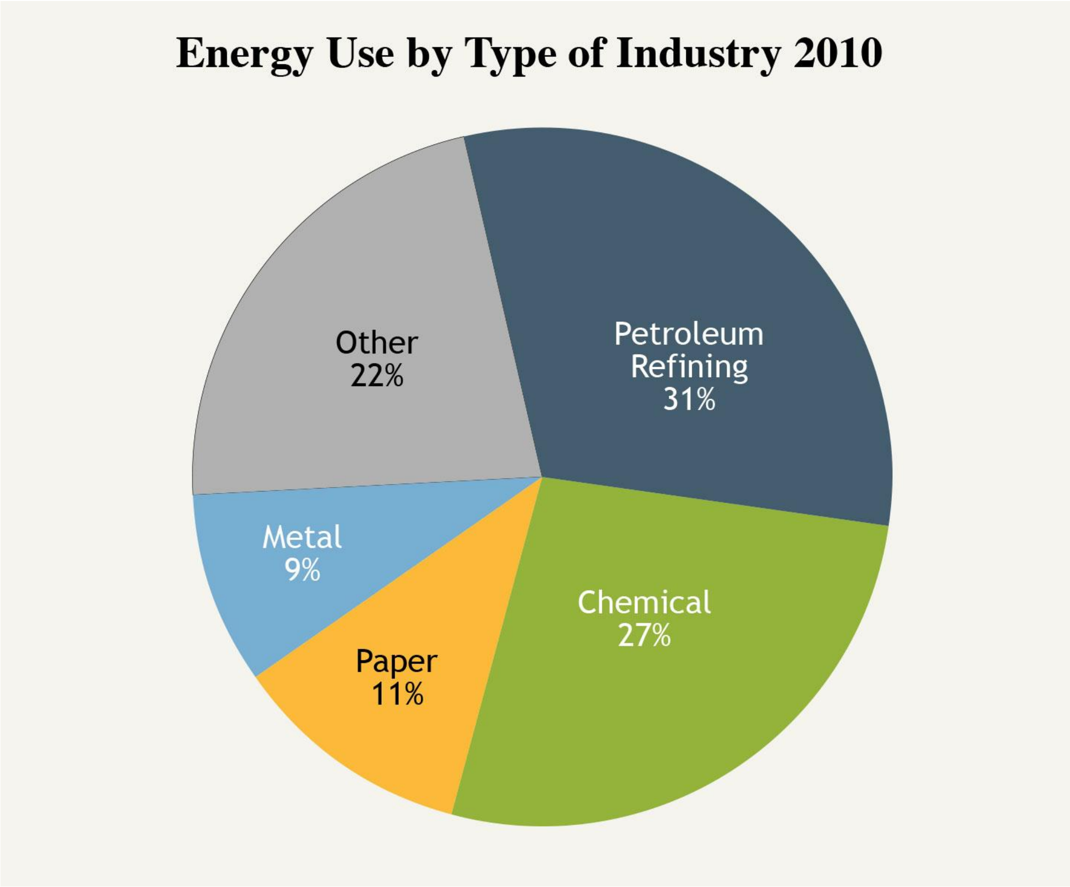




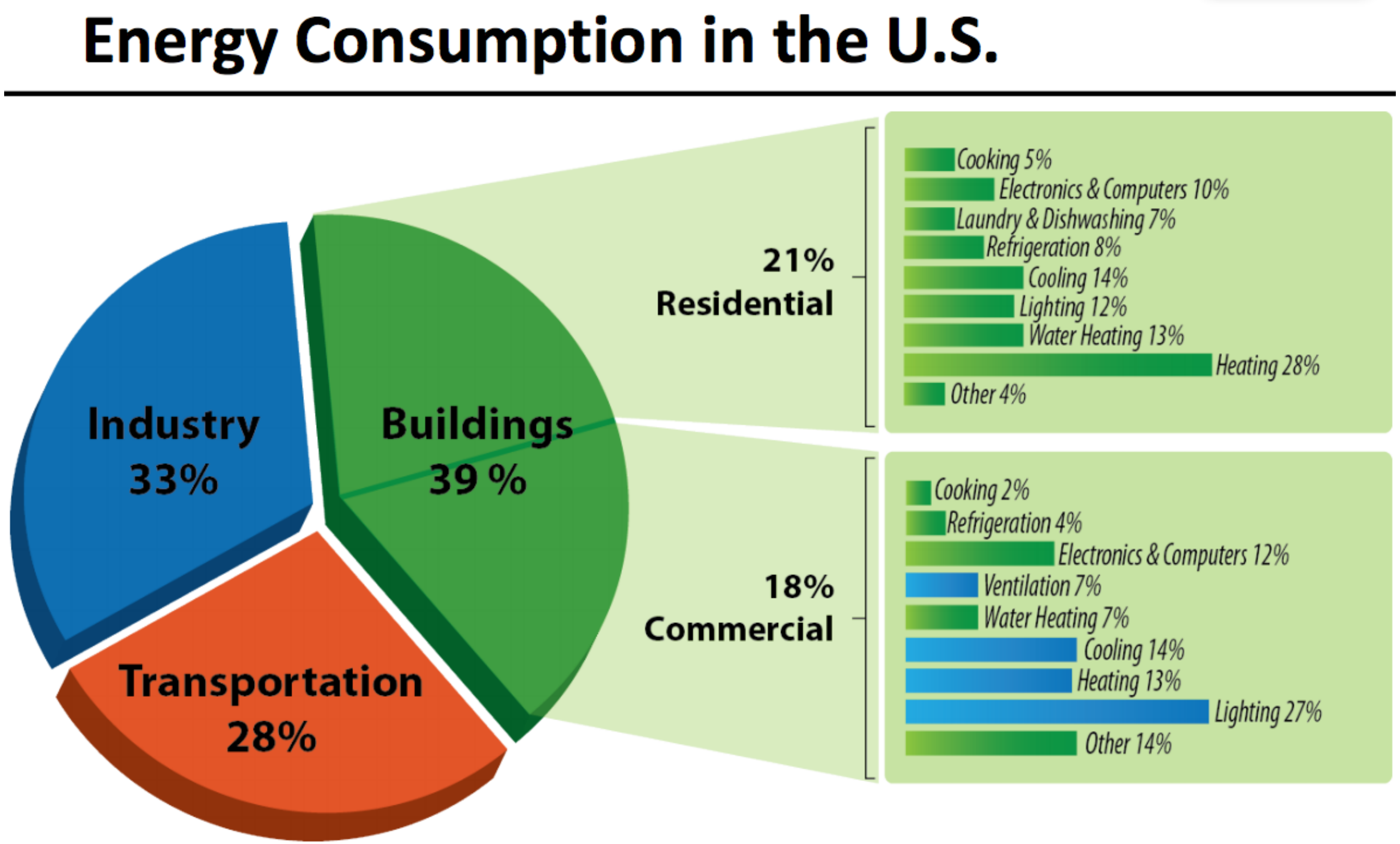
Global energy statistics knowledge



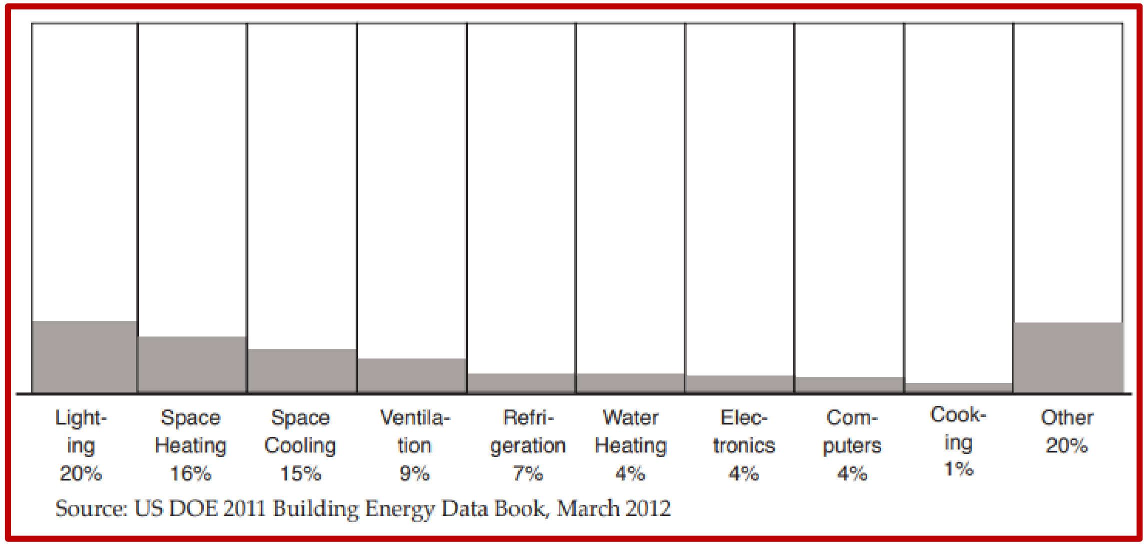
Global energy statistics knowledge

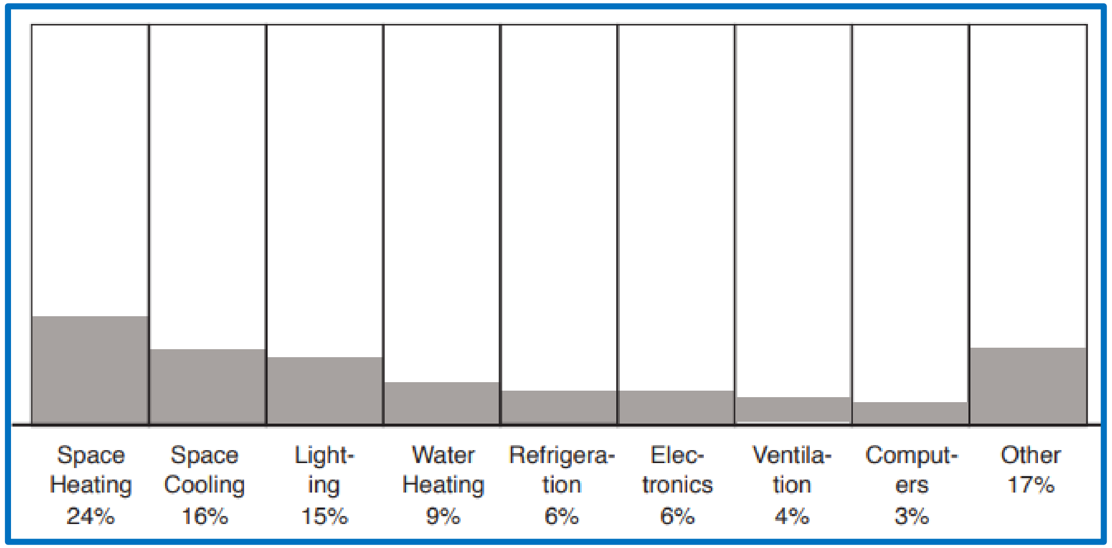


Global energy statistics knowledge



Energy Use in Commercial Businesses in the US

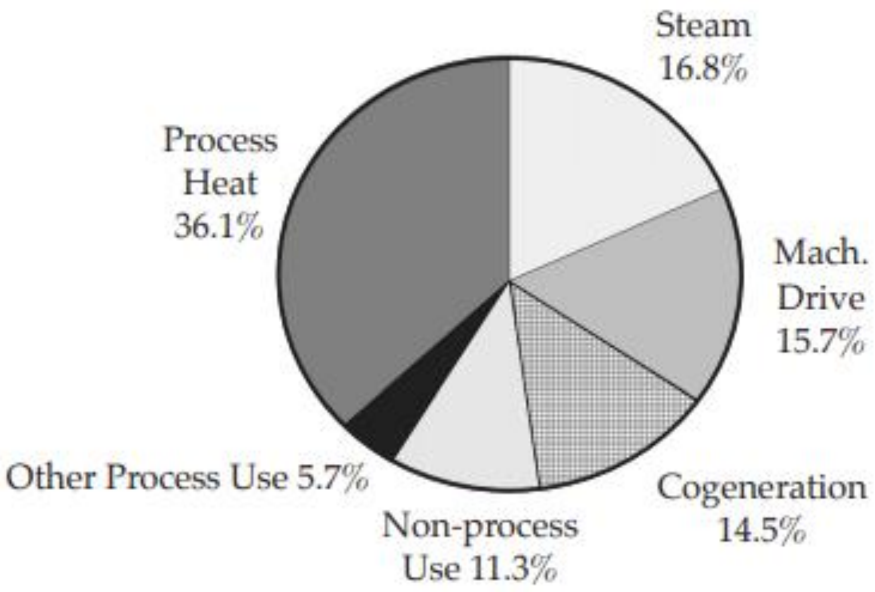




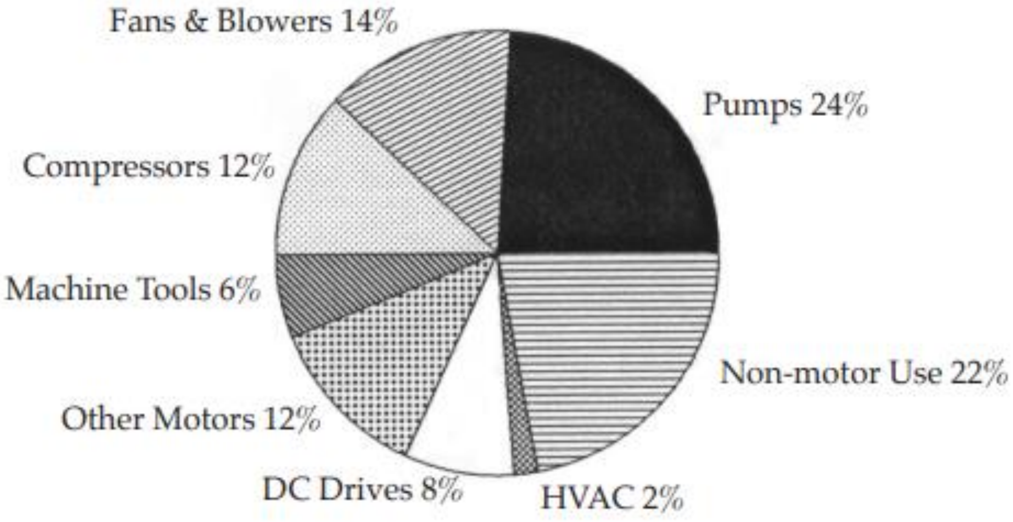
U S Commercial Energy Use

U S DOE 2011

Energy Use in Industry in the US

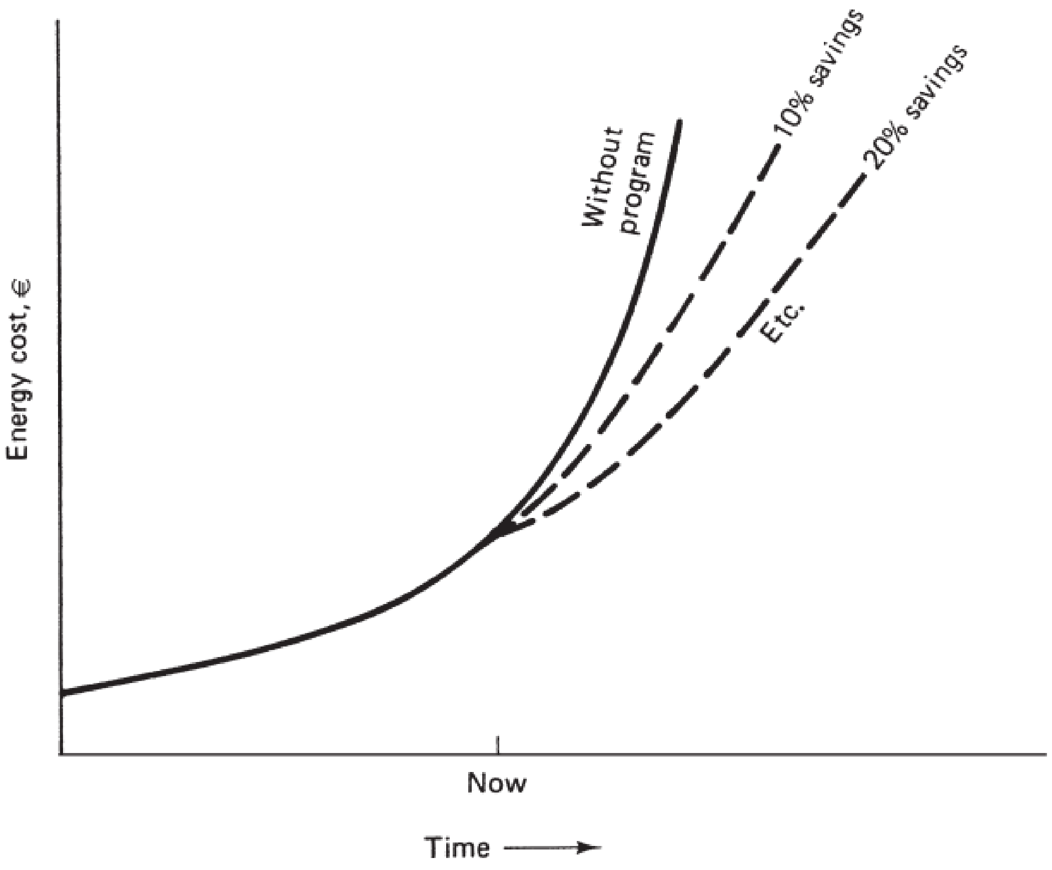


U S Industrial energy use 2002



U S Industrial electricity use

Designing an energy management program



Typical Energy Savings	
Low cost, no cost changes	5-10%
Dedicated programs (3 years or so)	25-35%
Long-range goal	40-50%

Designing an Energy Management Program

- **Success factors:**

1. **Management commitment**
2. **Energy Management Coordinator/Energy Manager**
3. **Backup Talent**
4. **Records and Cost Allocation**
5. **Reporting and Monitoring**
6. **Financing resources**
7. **Training**

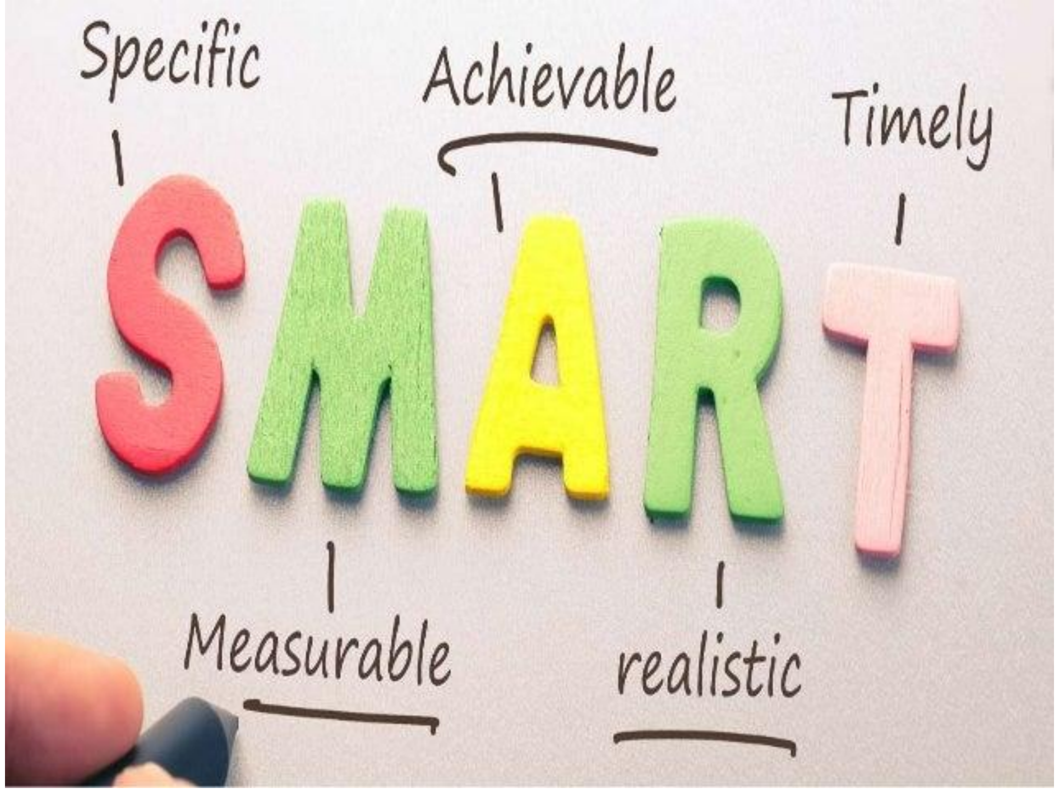
Early Project/Opportunity Selection

- An early failure can also be harmful, if not disastrous, to the program. Thus, energy management coordinator should be astute.
- **It should has a rapid payback, a high probability of success, and few negative consequences.**

- Examples:
  1. Repairing steam leaks. Even a small leak can be very expensive over a year and quite uncomfortable for employees working in the area.
  2. Insulating steam, hot water, and other heated fluid lines and tanks. Heat loss through an uninsulated steam line can be quite large, and the surrounding air may be heated unnecessarily.
  3. Install high efficiency motors. This saves dramatically on the electrical utility cost in many cases, and has no negative employee consequences. However, the employees should be told about the savings since motor efficiency improvement has no physically discernible effect, unlike the lighting example above.

Establishing objectives for an Energy Management Program

- **<u>Goals need to be set</u>**, and these goals should be **tough but achievable, measurable, and specific**. They must also include a **<u>deadline for accomplishment</u>**.



Establishing objectives for an Energy Management Program

- **The following list provides some examples of such goals:**

✓ Total energy per unit of production will drop by 10 percent the first year and an additional 5 percent the second.

✓ Within 2 years all energy consumers of 5 GJ per hour (GJ/h) or larger will be separately metered for monitoring purposes.

✓ Each plant in the division will have an active energy management program by the end of the first year.

✓ All plants will have contingency plans for gas curtailments of varying duration by the end of the first year.

✓ All boilers of 50,000 kg/hour or larger will be examined for waste heat recovery potential the first year. Total energy per unit of production will drop by 10 percent the first year and an additional 5 percent the second.

Performance Measures

- **Energy Utilization Index (EUI)**

This is a statement of the number of kJs of energy used annually per square meter of conditioned space.

$$EUI = \frac{Total\ energy\ consumed\ in\ MJ's}{total\ conditioned\ space\ in\ m^2}$$

- **Energy Cost Index (ECI)**

This is a statement of the cost of energy used annually per square meter of conditioned space.

$$ECI = \frac{Total\ energy\ consumed\ in\ \$}{total\ conditioned\ space\ in\ m^2}$$

Performance Measures Examples

EX 1. **Consider a building with 10,000 square meters of floor space. It uses 2.0 million kWh and 6800 GJ of natural gas in one year. Find the Energy Utilization Index (EUI) for this facility.**

Performance Measures Examples

EX 2. Consider the building in Example 1.1. The annual cost for electric energy is €153,200 and the annual cost for natural gas is €52,500. Find ECI for this facility.

Energy Monitoring, Targeting and Reporting (MT&R)

- **Energy Monitoring** is the regular collection and analysis of information on energy use.

➢ **<u>Its purpose is</u>**

1. to establish a basis of management control,
2. to determine when and why energy consumption is deviating from an established pattern
3. to provide a basis for taking management action where necessary.

- **Targeting** is the identification of levels of energy consumption towards which it is desirable, as a management objective, to work.

- **Reporting** closes the loop, by putting the management information generated in a form that enables ongoing control of energy use, the achievement of reduction targets, and the verification of savings.

Energy Monitoring, Targeting and Reporting (MT&R)

- <u>**MT&R is a powerful management technique for**</u>

✓ Analyzing the historical energy performance of industrial, commercial, and institutional facilities

✓ Setting energy reduction targets

✓ Controlling current energy performance

✓ Projecting future energy budgets

- **MT&R benefits:**

1. Improved budgeting and forecasting
2. Improved product/service costing
3. Tracking and verification of energy efficiency retrofits
4. Opportunities for improved operation and maintenance practices.

Energy Monitoring, Targeting and Reporting (MT&R)

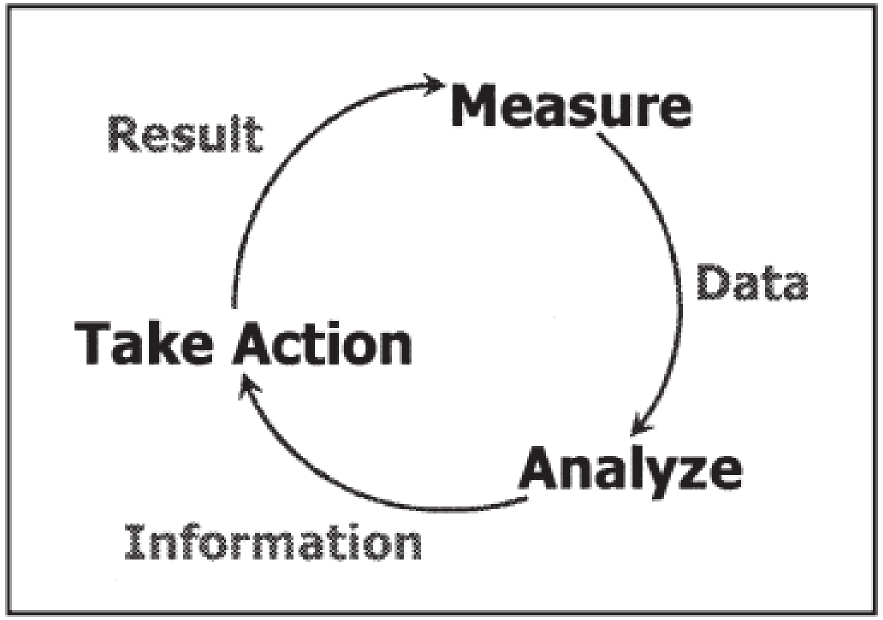
The key steps in an effective MT&R process are:

- ✓ Measurement of energy consumption over time
- ✓ Measurement of the independent variables that influence energy consumption (weather, production, occupancy) over corresponding time intervals
- ✓ Development of a relationship (the energy performance model) between energy and the independent variables
- ✓ Historical analysis of energy performance using CUSUM, and application of the CUSUM trend into the future
- ✓ Definition of reduction targets
- ✓ Frequent comparison of actual consumption to targets Result/Measure
- ✓ Reporting of consumption and target variances
- ✓ Taking action to address variances and ensure targets are met.

MT&R and Continuous Improvement

- As a general rule, however, monitoring comes before target setting because without monitoring you cannot know precisely where you are starting from or decide if a target has been achieved.

- MT&R is consistent with other **continuous improvement techniques** applied in organizations, and should be viewed as an ongoing, cyclical process as:



The Measure-analyze-action cycle

Part II:
Energy Audit Process

What is Energy Audit?

The energy audit examines the ways energy is currently used in that facility and identifies some alternatives for reducing energy costs.

The goals of the audit are:

- to clearly identify the types and costs of energy use.
- to understand how that energy is being used—and possibly wasted.
- to identify and analyze alternatives such as improved operational techniques and/or new equipment that could substantially reduce energy costs.
- to perform an economic analysis on those alternatives and determine which ones are cost-effective for the business or industry involved.

Energy Audit Phases

- Phase I - preparing for the audit visit
- Phase II - performing the facility survey
- Phase III - implementing the audit recommendations

Phase I - preparing for the energy audit visit

i. Gathering Preliminary Data on the Facility, which includes:

- ✓ Analysis bills (Electricity, fuel if any)
- ✓ Geographic Location/Degree Days/Weather Data
- ✓ Facility layout
- ✓ Operating hours
- ✓ Equipment list

ii. Tools for the audit

- ✓ Power analyzer
- ✓ Combustion analyze/ flue gas analyzer
- ✓ Thermal camera
- ✓ Multi-meter
- ✓ Ultrasonic leaks detector
- ✓ Airflow measurement devices
- ✓ Blower door attachment
- ✓ Smoke generator
- ✓ Safety equipment

Phase I - preparing for the energy audit visit

iii. Safety considerations

Wearing safety clothes such as a helmet, protective vest, and gloves is a **must**.

Safety Checklist

Electrical:
- Avoid working on live circuits, if possible.
- Securely lock circuits and switches in the off position before working on a piece of equipment.
- Always keep one hand in your pocket while making measurements on live circuits to help prevent accidental electrical shocks.

Respiratory:
- When necessary, wear a full face respirator mask with adequate filtration particle size.
- Use activated carbon cartridges in the mask when working around low concentrations of noxious gases. Change the cartridges on a regular basis.
- Use a self-contained breathing apparatus for work in toxic environments.

Hearing:
- Use foam insert plugs while working around loud machinery to reduce sound levels by nearly 30 decibels.

Phase II – Facility inspection

i. Introductory Meeting

ii. Audit interviews

iii. Initial Walk-through Tour

iv. Gathering detailed data, which includes:

- ✓ The building envelope
- ✓ The steam boiler and steam distribution system.
- ✓ The heating, ventilation, and air conditioning system (HVAC)
- ✓ The electrical supply system
- ✓ Lights, windows, and reflective surfaces
- ✓ The hot water distribution system
- ✓ Air compressors and the air distribution system.
- ✓ Motors
- ✓ Manufacturing processes

Samples of gathering detailed data

Area	Type of lighting (e.g., HPS)	Watts per fixture	Number of fixtures	Total kW	Operating hours	Operating days	kWh/month
Interior							
____	______	______	______	______	______	______	______
____	______	______	______	______	______	______	______
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Exterior							
____	______	______	______	______	______	______	______
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Data collection form for lighting system

System: Envelope

Component	Location	Maintenance condition	Est. air gap (total)
Door	North side	Poor	0.2 m^2
	South	OK	0.05 m^2
	Gymnasium	Good	None
Windows	North	Some broken	2.2 m^2
	East	OK	None
Roof	Main building	No insulation	

Data collection form for building envelope

Phase II – Facility inspection

v. Preliminary identification of energy management opportunities

vi. The energy audit report

vii. The energy action plan

Energy Audit Report Format

Executive Summary
  A brief summary of the recommendations and cost savings

Table of Contents

Introduction
  Purpose of the energy audit
  Need for a continuing energy cost control program

Facility Description
  Product or service, and materials flow
  Size, construction, facility layout, and hours of operation
  Equipment list, with specifications

Energy Bill Analysis
  Utility rate structures
  Tables and graphs of energy consumptions and costs
  Discussion of energy costs and energy bills

Energy Management Opportunities
  Listing of potential EMOs
  Cost and savings analysis
  Economic evaluation

Energy Action Plan
  Recommended EMOs and an implementation schedule
  Designation of an energy monitor and ongoing program

Conclusion
  Additional comments not otherwise covered

Phase III – Implementing the audit recommendations

i. The Energy Action Team

Funding for the changes and employee support are two additional critical ingredients for success. These can best be obtained with the help of a committee, preferably called something like the energy action team. The specific tasks of this committee are:

- ✓ Set goals
- ✓ Implementing recommendations
- ✓ Monitoring results

Energy audit tools

Power analyzer

Infrared thermal camera

Current data logger

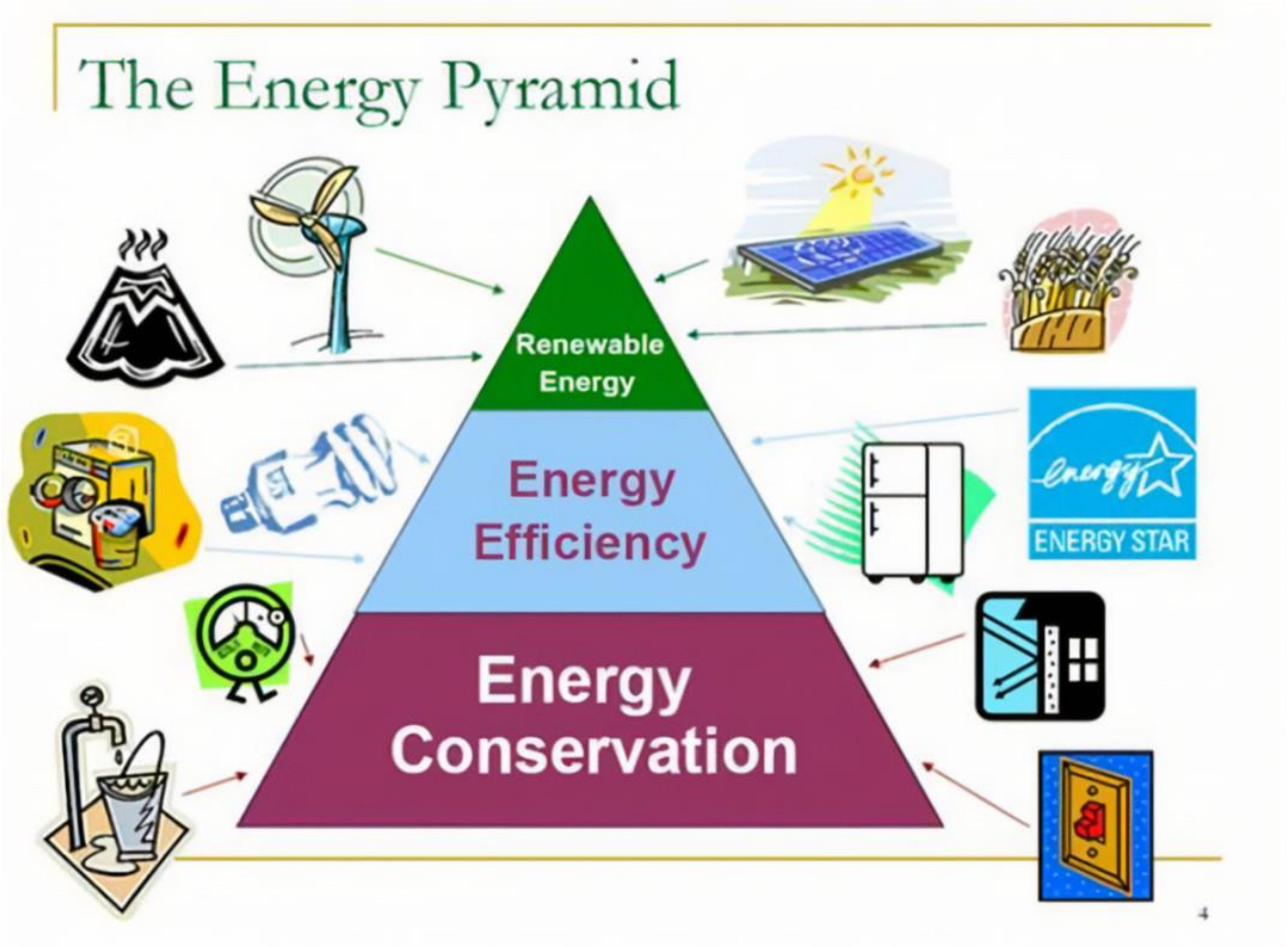
Combustion analyzer

Ultrasonic leak detector

Multimeter

Lux meter

The whole integrated approach



Summary

In this chapter, we have explained the mechanics of performing and implementing the energy audit as well as the reasoning behind the energy audit process.

- The energy audit process should be a dynamic feedback loop.
- The process starts with the analysis of past data. Then each energy system is examined for savings potential.
- Recommendations for energy cost saving actions are made and an energy action committee is formed.
- Attractive energy cost savings projects are implemented.
- Monitoring program which necessarily leads back to the first step of analysis, thus renewing the cycle.

Part III:
Understanding Energy Bills

Introduction

The impact of an increase in energy costs can be easily seen by examining the rate schedules for the various fuel sources, yet few managers take the time to peruse and understand their utility's billing procedures.

Why? The reasons seem to be the following:

- Rate schedules are sometimes very complicated.
- Energy is too often treated as an overhead item rather than a direct cost item.

Introduction

- Utility costs, includes: Physical plant, transmission lines, substations, distribution systems, meters, administrative, energy, and profit.
- Utility regulations.
- Customer classes and basic rate schedules
    i. Residential rate schedules
    ii. General service rate schedules
    iii. Small industries rate schedules
    iv. Large industries rate schedules

Customer classes and basic rate schedules

- An electric utility must serve several classes of customers. These classes vary in complexity of energy use, amount of consumption, and priority of need. The typical customer class categories are **residential, commercial and industrial**.
- The most common components of rate schedules are described below, but not all of these components are included in the rate schedule for every customer class:
    1. Administrative/Customer Charge:
    2. Energy Charge
    3. Fuel Cost Adjustment
    4. Demand Charge
    5. Demand Ratchet
    6. Power Factor

Customer classes and basic rate schedules

Customer Class	Comments	Consumption (kWh)	Demand (kW)	Power factor (kVAR)
1. Residential	Small user but large numbers of them	√		
2. Commercial	Small to moderate user; relatively large numbers	√		
3. Small industrial	Small to moderate user; fewer customers	√	√	
4. Large commercial and industrial	Large user with low priority; typically, only a few customers in this class, but they consume a large percentage of the electricity produced.	√	√	√

Generalized breakdown of electric rate schedule components

Residential Rate Schedules

A typical residential bill includes an **administrative/customer charge**, an **energy charge** which is large enough to cover both the actual energy charge and an implicit demand charge, and a **fuel adjustment charge.**

- Standard residential rate schedule

Customer charge:	€8.00/month
Energy Charge:	All kWh @ €0.06972/kWh
Fuel adjustment:	(A formula is provided by the utility to calculate the fuel adjustment charge each month. It is rather complex and will not be covered here.)

Residential Rate Schedules

- Low-use residential rate schedule

This schedule, which is an attempt to meet the needs of those on fixed incomes, is used for customers whose monthly consumption never exceeds 500 kWh. In addition, it cannot exceed 400 kWh more than twice a year.

Customer charge:	€5.45/month
Energy Charge:	€0.05865/kWh (Cannot exceed 400 kWh per month in more than two months per year)
Fuel adjustment:	(A formula is provided for calculating this charge.)

Residential Rate Schedules

- Seasonal use rate schedule

The season of use is a factor in the rate structure. This utility has chosen to reduce its residential peaking problem by charging more for electricity consumed in the summer months when the highest peaks occur.

Customer charge:	€6.50/month
Energy Charge:	On-peak season (June through October)
	All kWh @ €0.07728/kWh
	Off-peak season (November through May)
	First 600 kWh € 0.07728/kWh
	All additional kWh @ €0.03898/kWh
Fuel adjustment:	(Calculated by a formula provided by the utility.)

Residential Rate Schedules

- Residential rate schedules to control peak uses
  1. Time-of-day or time-of-use pricing
  2. Peak shaving

Customer charge:	€16.00/month
Energy charge:	
On-peak energy	€0.10857/kWh
Off-peak energy	€0.0580/kWh
On-peak hours:	
November through March:	
Monday through Friday	6:00 a.m. to 10:00 a.m. 6:00 p.m. to 10:00 p.m.
April through October:	
Monday through Friday	12:00 noon to 9:00 p.m.
Off-peak hours:	All other hours

Sample time-of-day electric rate

Customer charge: €9.00/month

Energy charge: First 1000 kWh @ €0.0825/kWh
Over 1000 kWh @ €0.0930/kWh

Load management credit per month: Credit will be applied to the bill of all customers with load management switches who use 500 kWh or more per month as follows:

Electric water heater controlled January-December	€4.00
Electric central heating controlled October-March for 5 to 7.5 minutes of each 25-minute period	€3.00
Electric central air conditioner controlled April-September for 5 to 7.5 minutes of each 25-minute period	€3.00
Electric central heating controlled October-March for 12.5 minutes of each 25-minute period	€8.00
Electric central air conditioner controlled April-September for 5 to 7.5 minutes of each 25-minute period	€8.00

Sample load management rate for residential service

Industrial Rate Schedule

- Voltage level
- Demand billing
- Power factor (Cosine Phi)
- To understand the power factor, you must understand electric currents. The current required by induction motors, transformers, fluorescent lights, induction heating furnaces, resistance welders, etc., is made up of three types of current:
    1. Power-producing current (working current or current producing real power).
    2. Magnetizing current (wattless or reactive current). This is the current which is required to produce the magnetic flux necessary for the operation of induction devices.
    3. Total current (current producing apparent power or total power). This is the current that is read on an ammeter in the circuit. It is made up of the vector sum of the magnetizing current and the power-producing current.

Industrial Rate Schedule

- **Demand level effect**

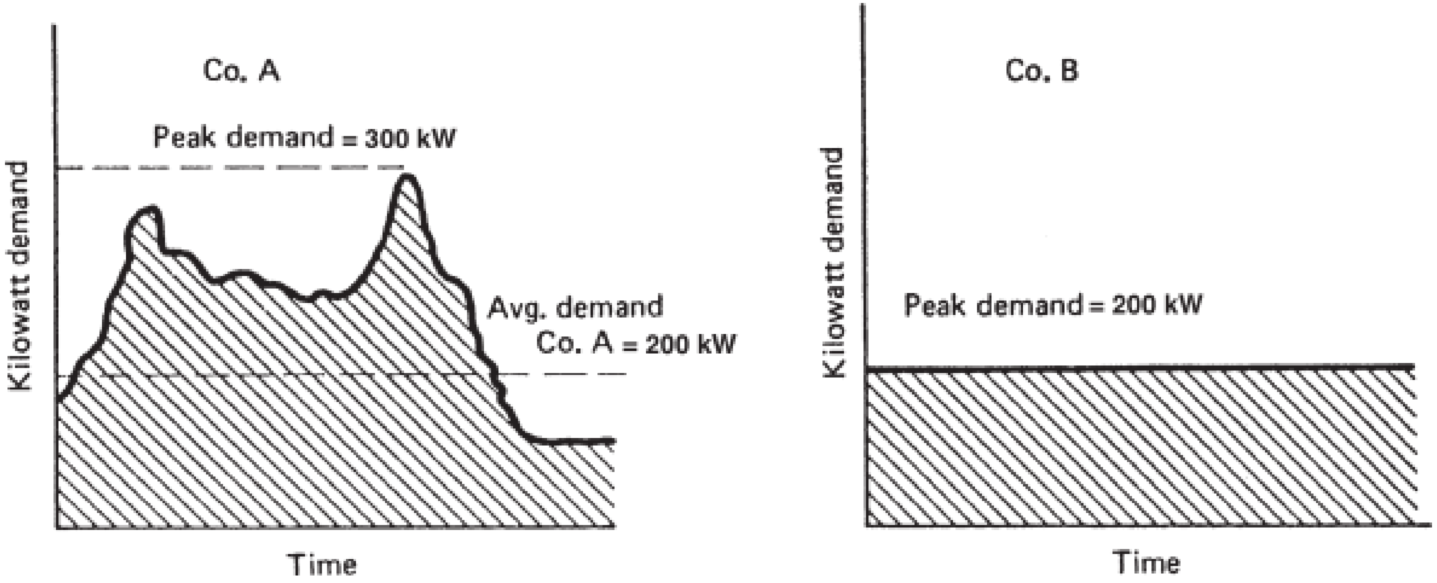
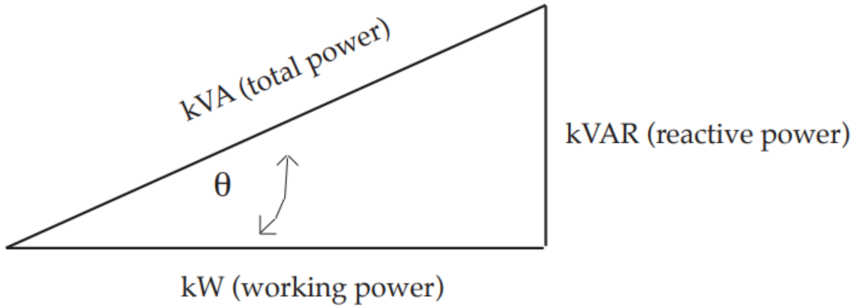


Figure 3-8 Demand profiles for two hypothetical industrial firms.

Industrial Rate Schedule

- **Power factor**



Lagging Power Factor

θ = phase angle = measure of net amount of inductive reactance in circuit

$\cos\theta$ = PF = ratio of *real power* to *apparent power*

$$kVA = \frac{kW}{\cos\theta} = \frac{kW}{PF} = \sqrt{(kW)^2 + (kVAR)^2} \qquad PF = \frac{kW}{kVA}$$

$$Billed\ Demand = Actual\ Metered\ Demand \times \frac{Base\ Power\ Factor}{Actual\ Power\ Factor}$$

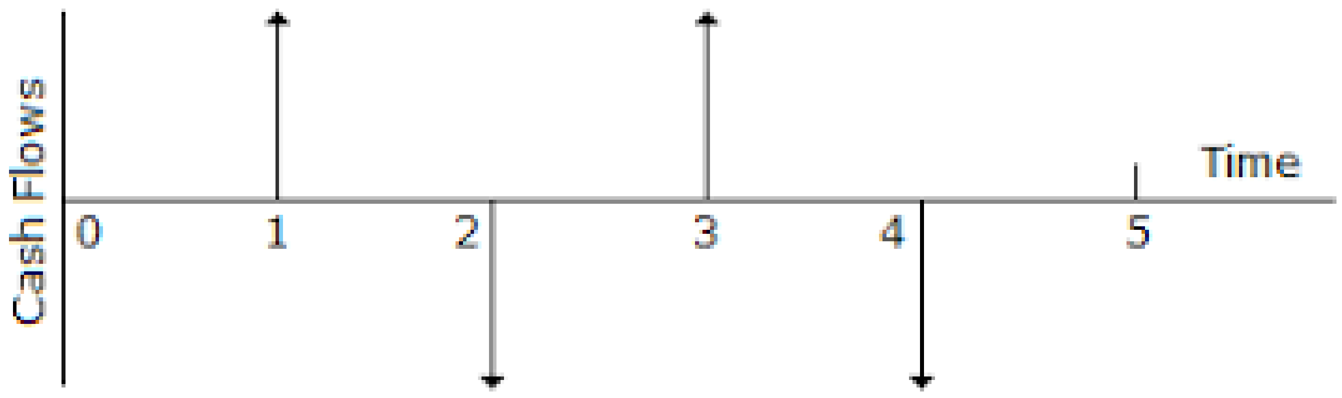
Part IV: Economic Analysis & Life Cycle Costing

Introduction

- Organizations incur various types of costs. These are generally classified into two broad categories: expenses, and capital investments.
- Expenses are the routine, ongoing costs that are necessary for conducting business or operations.
- Capital investments have four important characteristics.
  1. First, they are relatively large, depending on the size of the organization.
  2. Second, the benefits of a capital investment are returned over the lifetime of the investment, which is typically several years.
  3. Third, capital investments are relatively irreversible. After the initial investment has been made, altering the project significantly, or terminating the project, has substantial (usually negative) implications.
  4. Fourth, capital investments can have significant tax implications, depending on the choice of financing methods.

Cash flow diagram

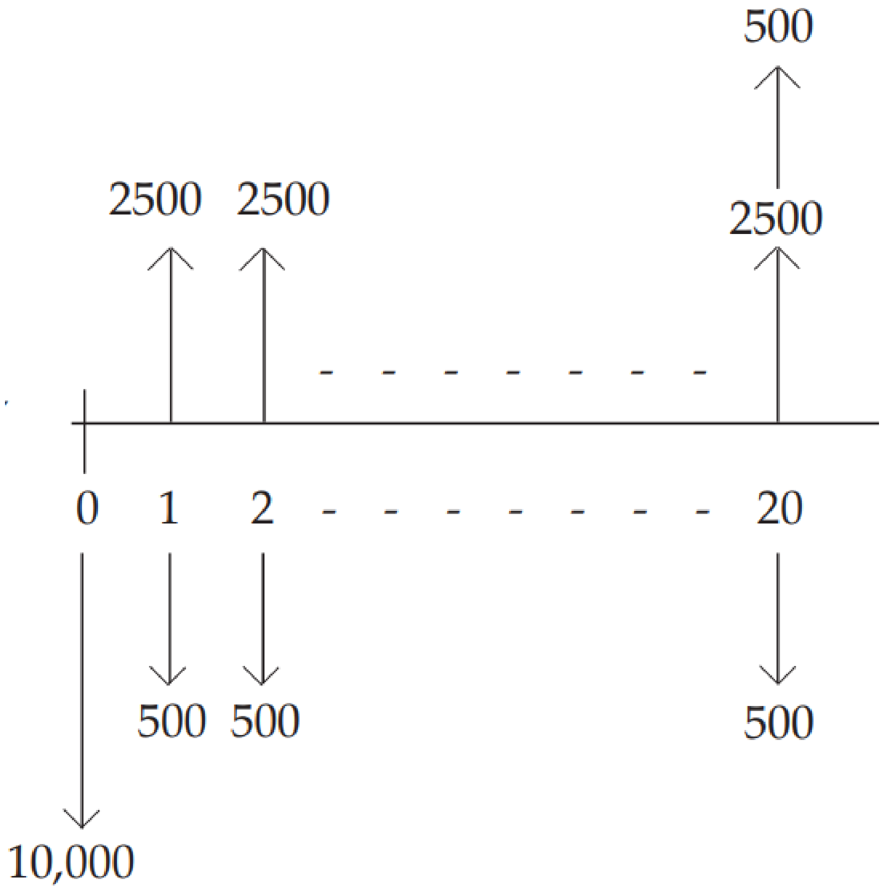
- A cash flow diagram is a pictorial display of the **costs** and **revenues** associated with a project.
- An interest rate or discount rate can also be shown.
- Costs are represented by arrows pointing down, while revenues are represented by arrows pointing up. The time periods for the costs dictate the horizontal scale for the diagram.
- Although some costs occur at different points in time, most of the time, an end-of-year approach is sufficient.



Example

A cash flow diagram to look at the costs and benefits of purchasing a heat pump. The costs/benefits associated with the heat pump are:

- The heat pump costs €10,000 initially
- The heat pump saves €2,500 per year in energy costs for 20 years
- The maintenance costs are €500 per year for 20 years
- The estimated salvage value is €500 at the end of 20 years.



Economic performance indicators

- The most energy related common indicators are:
  1. Simple payback period.
  2. Present worth.
  3. Life cycle costing.
  4. Internal rate of return.
  5. Cost to benefit ratio, also called Saving to investment ratio.
  6. Levelized cost of electricity also called levelized cost of energy.

SIMPLE PAYBACK PERIOD COST ANALYSIS

- Its called also payback period PBP
- It determines the number of years required to recover an initial investment through project returns. Its formula:

$$SPP = (\text{Initial cost})/(\text{Annual savings})$$

Advantages:

1. Its simplicity, and it is easily understood by workers and management. It does provide a rough measure of the worth of a project.
2. The methodology does not consider the time value of money
3. The methodology does not consider any of the costs or benefits of the investment following the payback period

Example

The heat pump discussed above has an initial cost of €10,000, an energy savings of €2,500 per year, and a maintenance cost of €500 per year. Thus, the net annual savings is €2,000. Therefore, its SPP would be:

Economic analysis using time value of money

- The Mathematics of Interest and Discounting

Two factors affect the calculation of interest: the amount and the timing of the cash flows. The basic formula for calculating interest is:

$$F_n = P + I_n$$

Where, F_n = a future cash flow of money at the end of the nth year

P = a present cash flow of money

I = the interest accumulated over n years

n = the number of years between P and F

Discounted Cash Flow

- Single sum, future worth
- To determine how to convert a single sum of money from a present amount to a future amount.
- This is similar to asking the question "If I borrow €5,000 at 10% interest for five years, how much will I owe at the end of the five years?"
- In this problem, the present amount, P, and the interest rate are known. The unknown is the future amount, F. The formula for finding F is:

$$F = P(1 + I)^n$$

It is known as the single sum, future worth factor, or the single payment, future worth factor. The term is also known as the factor **(F/Pi,n)**, which is read: **find F, given P, at i% for n periods** (years in our case).

Discounted Cash Flow

- Single sum, present worth

The formula for finding the present worth of a single sum is found by solving for P. Thus, the single sum, present worth formula, or single payment, present worth formula, is:

$$P = F(1 + I)^{-n}$$

The term (1 + i)–n is called the present worth factor, (P/Fi,n), which is read: find P, given F, at i% for n periods (years).

Interest rate

- Its called: **interest rate**, **discount rate**, or **Minimum Attractive Rate of Return (MARR).**

- It is a company-specific or organization-specific value. It must be supplied by the company, or corporate, accounting department, and is usually the value the company uses for evaluating investments.

- The magnitude of the discount rate depends on the source of capital which will be used to finance the project. If money must be borrowed (debt capital), the discount rate is likely to be higher than if company funds (equity capital) are to be used.

- Simple interest rate Vs compound interest rate.

Internal Rate of Return

- The Internal Rate of Return or IRR of the project (IRR)is defined to be that value of the interest rate or discount rate that makes the present worth of the costs of a project equal to the present worth of the benefits of the project.

- Many private organizations prefer the IRR method since it produces a rate of return to compare to their MARR that they have already established, where:
  - If the computed IRR is **greater** than the MARR for an organization, the project is **cost effective**.
  - If the IRR **equals** the MARR, the investment's **benefits or savings just equal its costs**.
  - If IRR is **less** than the MARR, the investment is **uneconomic**.

Life cycle costing

- LCC is the total cost of purchase and operation over its entire service life of a project or a piece of equipment .
- This total cost includes the **costs of acquisition**, **operation including energy costs**, **maintenance and disposal**. (Most of these costs occur at some future time beyond the purchase date, and must be analyzed using the time value of money)
- The Simple Payback Period is not a life cycle cost analysis method.
- Some organizations still make purchase decisions based on lowest initial costs and do not consider the operating and maintenance costs at all.
- Use of LCC can lead to more rational purchase decisions, and can often lead businesses to higher profits.

Example

- An energy efficient air compressor is proposed by a vendor. The compressor will cost $30,000 to install, and $1,000 per year for maintenance over its 10 years estimated life. Energy costs will be $6,000 per year. In comparison, a standard air compressor will cost $25,000 to install, and $500 per year for maintenance. Its energy will cost $10,000 per year. If the company uses 10% MARR in their analysis, which compressor should they choose? Use SPP, PW, IRR, LCC, and SiR.

Example

- A factory wants to install 100 kWp PV system on their available roof area. If the system costs $1,000 per kWp, and it will generate about 1,650 kWh/kWp/year. The feed in tariff equals to 0.1 $/kWh, factory MARR is 10% per year, and the system estimated life equals to 25 years.
- Calculate SPP, PW, IRR, SiR, LCC, and LCOE.

Effect of inflation

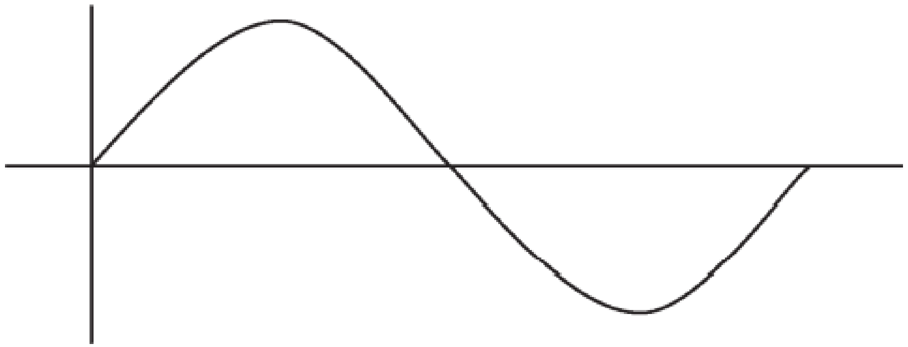
- Inflation is the term for the loss in purchasing power of a euro over time, and should be accounted for in any life cycle analysis

- The mathematical relationship between market interest rate, the inflation rate, and the real interest rate is

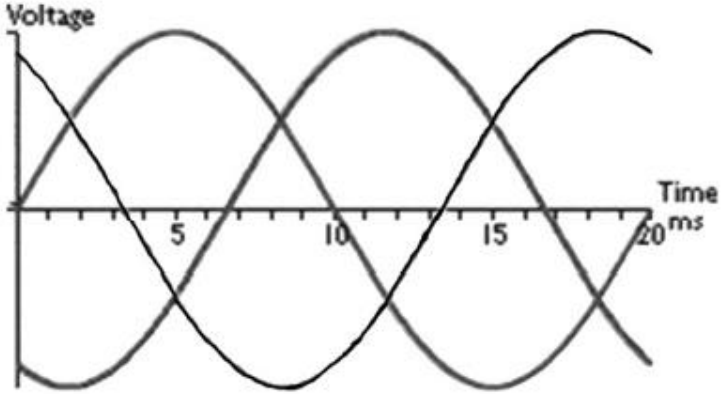
$$i\%_{\text{with inflation}} = i\% + f\% + (i*f)\%$$

Part V:
Electric Distribution Systems

Quick Review

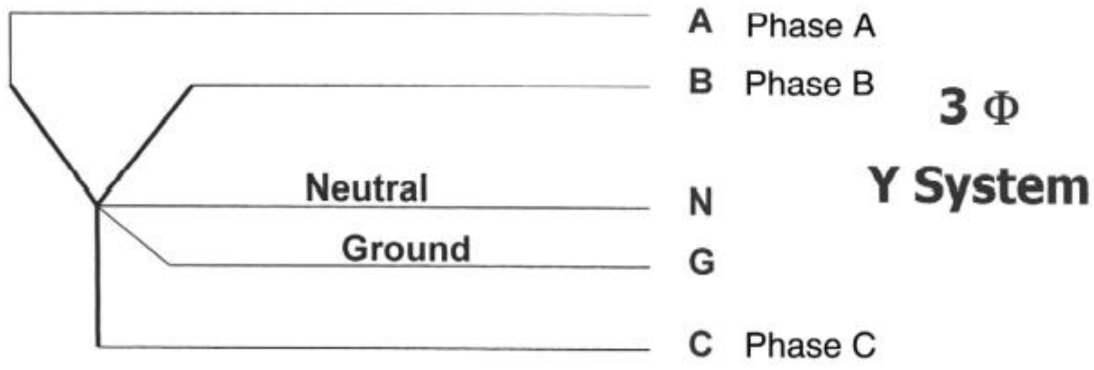


Single phase electric voltage



Three phase electric voltage

Typical Three-phase, 380-Volt Facility Electrical Distribution System



$V_{L\text{-}L}$ = 380 V = $V_{A\text{–}B}$, $V_{B\text{–}C}$, $V_{A\text{–}C}$

$V_{L\text{-}N}$ = 380/√3 = 220 V = $V_{A\text{–}N}$, $V_{B\text{–}N}$, $V_{C\text{–}N}$

I_N = 0 in a balanced 3Φ system

Most large facilities are upgrading internal distribution to 380 V

Figure 5-3 380-volt, five-wire, three-phase wye system

Introduction

- **Ohm's Law**

For DC circuits, or for AC circuits with only resistors, we have the following relationship.

$$V = I \times R \text{ or Volts} = \text{Amps} \times \text{Ohms}$$

$$\text{Or } I = V / R \text{ or } R = V / I$$

- **Example 1**: A 100 ohm resistor is connected to a source of 220 volts. What is the current through the resistor?

Introduction

- Electrical power for DC and pure resistive AC loads

$$\text{Watts} = \text{Volts x Amps, or}$$
$$P = V \times I$$

- **Example 2**: How much power is the resistor dissipating (i.e. converting to heat) if single phase 2.2A, 220V heater is on?

Introduction

- Ohm's law for power for DC and pure resistive AC loads

$$P = VI = I \times R \times I = I^2R$$

- **Example 3**: Repeat previous example using the above formula.

Electrical Formulas

These are the Basic Electrical Formulas.
Related to Ohm's Law.
Variables used in these formulas are as follows;

- V = Voltage in Volts
- I = Current in Amperes
- R= Resistance in Ohms
- Power = In Watts

Voltage Formulas

$V=I \times R$, $V=P/I$, $V=\sqrt{P \times R}$

Current Formulas

$I = V/R$, $I=P/V$, $I=\sqrt{P/R}$

Resistance Formulas

$R=V/I$, $R=P/V^2$, $R=P/I^2$

Power Formulas

$P=V \times I$, $P=V^2/R$, $P=I^2 \times R$

Following are several additional formulas, which are useful for calculating Current, Horsepower, kW, and kVA for both Single Phase & Three Phase AC Current.

- HP= Horsepower
- EFE = EfficiencyFactor (Use 0.9 when not mentioned)
- PF=Power Factor (Use 0.8 when not mentioned)

AC = Alternating Current

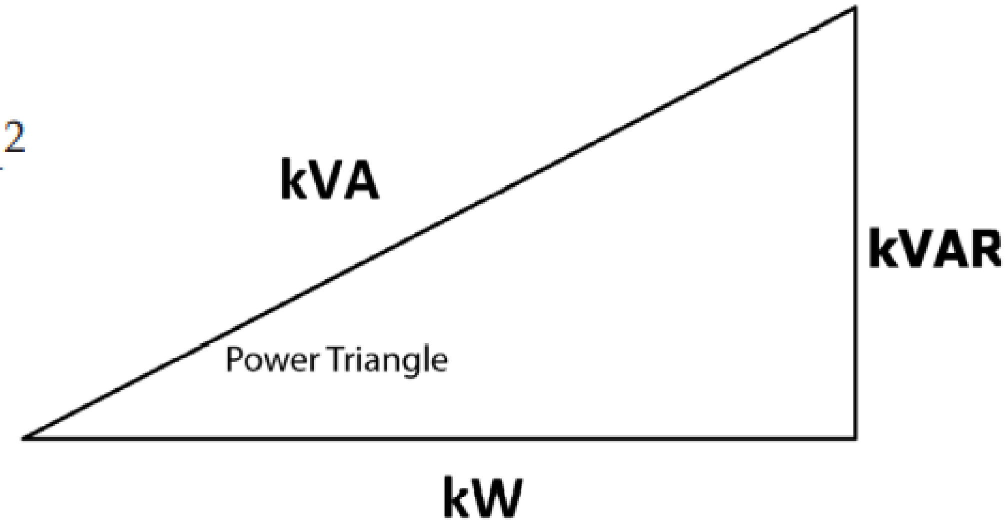
To Find:	Single-Phase	Three Phase
Current, when Motor Hp is known	$\frac{HP \times 746}{V \times EFE \times PF}$	$\frac{HP \times 746}{V \times EFE \times PF \times 1.73}$
Ampers, when kW is knon	$\frac{kW \times 1000}{V \times PF}$	$\frac{kW \times 1000}{V \times PF \times 1.73}$
Current, when kVA is Known	$\frac{kVA \times 1000}{V}$	$\frac{kVA \times 1000}{V \times 1.73}$
kilowatts (kW)	$\frac{V \times I \times PF}{1000}$	$\frac{V \times I \times PF \times 1.73}{1000}$
kW input, when Motor HP is Known	$\frac{HP \times 0.746}{EFE}$	$\frac{HP \times 0.746}{EFE}$
kilovolt-Amperes (kVA)	$\frac{V \times I}{1000}$	$\frac{V \times I \times 1.73}{1000}$
Horsepower (HP)	$\frac{V \times I \times EFE \times PF}{746}$	$\frac{V \times I \times EFE \times PF \times 1.73}{746}$

POWER IN GENERAL AC CIRCUITS AND SYSTEMS

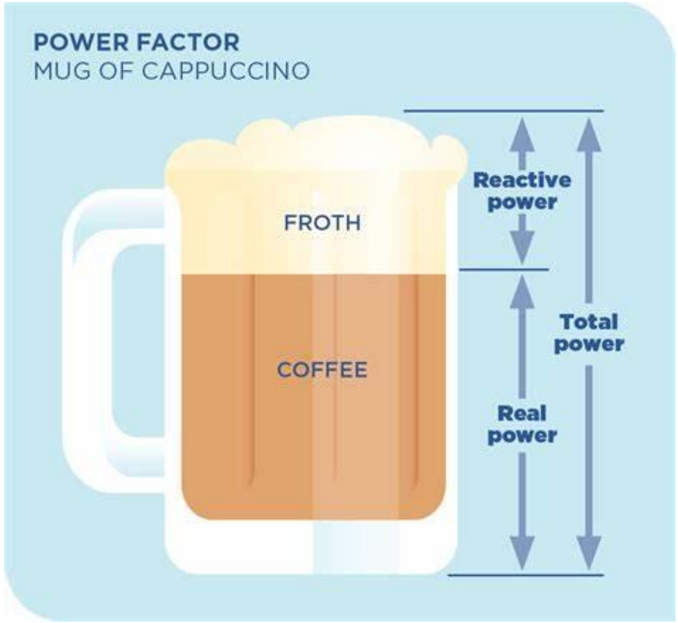
- In AC power systems, pure resistive loads such as incandescent lights, resistance space heaters, resistance water heaters and electric ovens all have power factors (Cos Phi) of 1.0 or 100%.

$$kW^2 + kVAR^2 = kVA^2$$

$$PF = kW / kVA = \text{Cos Phi}$$

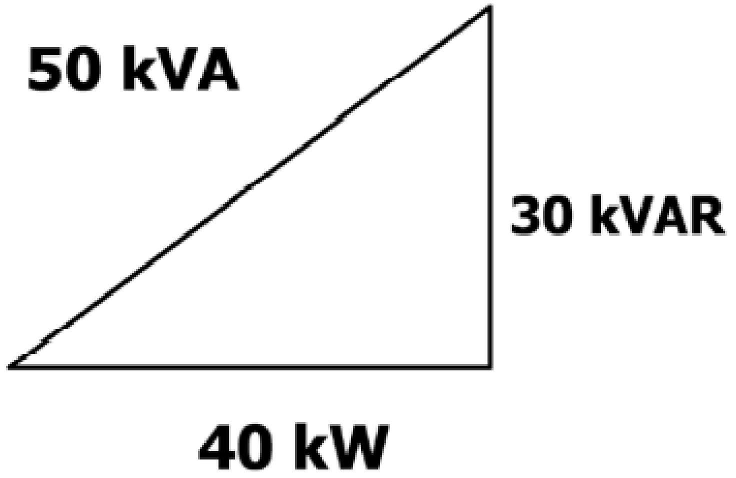


Power Triangle



POWER IN GENERAL AC CIRCUITS AND SYSTEMS

- **Example 4**: An AC induction motor has the following power triangle. Verify the relationship between kW, kVAR and kVA. What is the power factor of the motor?



Power Triangle for example 4

Power in single phase AC systems

- Most residential and small commercial buildings only have single phase AC 100/127 or 220-240-volt power available.
- Devices like full house air conditioners, electric hot water heaters, and electric clothes dryers are almost always operated on 220-240 volts AC, single phase.
- For single phase AC systems, electric power equation is:
  - P = V x I x PF (Cos Phi)
  - Where P = real power in watts, V = voltage in volts, I = current in amperes, and PF = power factor or Cos Phi.

Power in single phase AC systems

- **Example 5**: Find the real power drawn by a 240-volt AC, single phase electric **resistance** water heater, if it is drawing 20 amps of current.

Power in single phase AC systems

- Almost all electric motors over 1 HP, as well as all large pieces of electrical equipment in a facility, run on three-phase AC power.
- The equation for the power drawn by a general three-phase load is:
  - $P = \sqrt{3} \times V \times I \times PF$ (or Cos Phi) watts where $\sqrt{3} = 1.732$

Power in single phase AC systems

- **Example 6**: A three-phase, 380-volt electric motor draws 100 amperes, and has a power factor, Cos Phi of 87%. How much real power is the motor using?

Reactive power and PF (cos Pi) in AC systems

- Reactive power comes primarily as a result of magnetizing power to operate devices like AC induction motors, lighting ballasts, transformers, and induction heaters.
- The reactive power itself does not do real work, but it allows real work to occur in these devices.

POWER FACTOR OR Cos Phi CORRECTION CAPACITORS

- For induction motors and other AC inductive equipment, the most cost effective way to provide reactive power is to provide capacitors for the motor or equipment, instead of having to buy the reactive power from the electric utility.
- Reasonable cost capacitors can usually be put on the motors or equipment to increase their power factors to about 90%.
- The next table shows how to find the number of kVAR of capacitors needed to improve the power factor, or Cos Phi, of a given electrical power load in kW in a building or a facility.

kVAR needed = Real power x Table Factor

Original Power Factor	Desired Power Factor																			
	0.81	0.82	0.83	0.84	0.85	0.86	0.87	0.88	0.89	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1.00
0.51	.962	.989	1.015	1.041	1.067	1.094	1.120	1.147	1.175	1.203	1.231	1.261	1.292	1.324	1.358	1.395	1.436	1.484	1.544	1.687
0.52	.919	.945	.971	.997	1.023	1.050	1.076	1.103	1.131	1.159	1.187	1.217	1.248	1.280	1.314	1.351	1.392	1.440	1.500	1.643
0.53	.876	.902	.928	.954	.980	1.007	1.033	1.060	1.088	1.116	1.144	1.174	1.205	1.237	1.271	1.308	1.349	1.397	1.457	1.600
0.54	.835	.861	.887	.913	.939	.966	.992	1.019	1.047	1.075	1.103	1.133	1.164	1.196	1.230	1.267	1.308	1.356	1.416	1559
0.55	.795	.821	.847	.873	.899	.926	.952	.979	1.007	1.035	1.063	1.093	1.124	1.156	1.190	1.227	1.268	1.316	1.377	1.519
0.56	.756	.782	.808	.834	.860	.887	.913	.940	.968	.996	1.024	1.054	1.085	1.117	1.151	1.188	1.229	1.277	1.338	1.480
0.57	.718	.744	.770	.796	.822	.849	.875	.902	.930	.958	.986	1.016	1.047	1.079	1.113	1.150	1.191	1.239	1.300	1.442
0.58	.681	.707	.733	.759	.785	.812	.838	.865	.893	.921	.949	.979	1.010	1.042	1.076	1.113	1.154	1.202	1.263	1.405
0.59	.645	.671	.697	.723	.749	.776	.802	.829	.857	.885	.913	.943	.974	1.006	1.040	1.077	1.118	1.166	1.226	1.368
0.60	.609	.635	.661	.687	.713	.740	.766	.793	.821	.849	.877	.907	.938	.970	1.004	1.041	1.082	1.130	1.192	1.334
0.61	.575	.601	.627	.653	.679	.706	.732	.759	.787	.815	.843	.873	.904	.936	.970	1.007	1.048	1.096	1.157	1.299
0.62	.542	.568	.594	.620	.646	.673	.699	.726	.754	.782	.810	.840	.871	.903	.937	.974	1.015	1.063	1.123	1.265
0.63	.509	.535	.561	.587	.613	.640	.666	.693	.721	.749	.777	.807	.838	.870	.904	.941	.982	1.030	1.091	1.233
0.64	.474	.503	.529	.555	.581	.608	.634	.661	.689	.717	.745	.775	.806	.838	.872	.909	.950	.998	1.068	1.200
0.65	.445	.471	.497	.523	.549	.576	.602	.629	.657	.685	.713	.743	.774	.806	.840	.877	.918	.966	1.027	1.169
0.66	.414	.440	.466	.492	.518	.545	.571	.598	.626	.654	.682	.712	.743	.775	.809	.846	.887	.935	.996	1.138
0.67	.384	.410	.436	.462	.488	.515	.541	.568	.596	.624	.652	.682	.713	.745	.779	.816	.857	.905	.966	1.108
0.68	.354	.380	.406	.432	.458	.485	.511	.538	.566	.594	.622	.652	.683	.715	.749	.786	.827	.875	.937	1.079
0.69	.325	.351	.377	.403	.429	.456	.482	.509	.537	.565	.593	.623	.654	.686	.720	.757	.798	.846	.907	1.049
0.70	.296	.322	.348	.374	.400	.427	.453	.480	.508	.536	.564	.594	.625	.657	.691	.728	.769	.817	.878	1.020
0.71	.268	.294	.320	.346	.372	.399	.425	.452	.480	.508	.536	.566	.597	.629	.663	.700	.741	.789	.850	.992
0.72	.240	.266	.292	.318	.344	.371	.397	.424	.452	.480	.508	.538	.569	.601	.635	.672	.713	.761	.821	.963
0.73	.212	.238	.264	.290	.316	.343	.369	.396	.424	.452	.480	.510	.541	.573	.607	.644	.685	.733	.794	.936
0.74	.185	.211	.237	.263	.289	.316	.342	.369	.397	.425	.453	.483	.514	.546	.580	.617	.658	.706	.767	.909
0.75	.158	.184	.210	.236	.262	.289	.315	.342	.370	.398	.426	.456	.487	.519	.553	.590	.631	.679	.740	.882

Original Power Factor	Desired Power Factor																			
	0.81	0.82	0.83	0.84	0.85	0.86	0.87	0.88	0.89	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1.00
0.76	.131	.157	.183	.209	.235	.262	.288	.315	.343	.371	.399	.429	.460	.492	.526	.563	.604	.652	.713	.855
0.77	.105	.131	.157	.183	.209	.236	.262	.289	.317	.345	.373	.403	.434	.466	.500	.537	.578	.626	.687	.829
0.78	.078	.104	.130	.156	.182	.209	.235	.262	.290	.318	.346	.376	.407	.439	.473	.510	.551	.599	.661	.803
0.79	.052	.078	.104	.130	.156	.183	.209	.236	.264	.292	.320	.350	.381	.413	.447	.484	.525	.573	.634	.776
0.80	.026	.052	.078	.104	.130	.157	.183	.210	.238	.266	.294	.324	.355	.387	.421	.458	.499	.547	.608	.750
0.81	.000	.026	.052	.078	.104	.131	.157	.184	.212	.240	.268	.298	.329	.361	.395	.432	.473	.521	.582	.724
0.82		.000	.026	.052	.078	.105	.131	.158	.186	.214	.242	.272	.303	.335	.369	.406	.447	.495	.556	.698
0.83			.000	.026	.052	.079	.105	.132	.160	.188	.216	.246	.277	.309	.343	.380	.421	.469	.530	.672
0.84				.000	.026	.053	.079	.106	.134	.162	.190	.220	.251	.283	.317	.354	.395	.443	.504	.645
0.85					.000	.027	.053	.080	.108	.136	.164	.194	.225	.257	.291	.328	.369	.417	.478	.620
0.86						.000	.026	.053	.081	.109	.137	.167	.198	.230	.264	.301	.342	.390	.451	.593
0.87							.000	.027	.055	.083	.111	.141	.172	.204	.238	.275	.316	.364	.425	.567
0.88								.000	.028	.056	.084	.114	.145	.177	.211	.248	.289	.337	.398	.540
0.89									.000	.028	.056	.086	.117	.149	.183	.220	.261	.309	.370	.512
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0.91											.000	.030	.061	.093	.127	.164	.205	.253	.314	.456
0.92												.000	.031	.063	.097	.134	.175	.223	.284	.426
0.93													.000	.032	.066	.103	.144	.192	.253	.395
0.94														.000	.034	.071	.112	.160	.221	.363
0.95															.000	.037	.079	.126	.187	.328

POWER FACTOR OR Cos Phi CORRECTION CAPACITORS

- **Example 7**

A facility has a power factor, or Cos Phi, of 72%, and a real power load of 800 kW. How many kVAR of capacitance is needed to add to the facility load to have a new power factor, or Cos Phi, of 92%?

THE FACILITY MONTHLY ELECTRIC LOAD FACTOR

- A performance measure for electrical energy use in a building or facility that has an electric rate structure that has both an energy cost (kWh) and demand cost (kW) is called the **facility monthly electric load factor (FMELF).**
- The facility **monthly** electric load factor, FMELF, can be calculated for other periods of time like hourly, daily, weekly, **seasonably**, or **yearly**.
- The monthly period is usually selected for convenience, since every facility gets a monthly electric bill, but the daily and seasonal Factory Load Factors (FLF's) can give us a lot of information about how our facility uses electrical energy in response to varying conditions.

THE FACILITY MONTHLY ELECTRIC LOAD FACTOR

- The general formula and concept of the FMELF is as follows:

FMELF = Monthly kWh/(Monthly peak kW x Hours of the month)

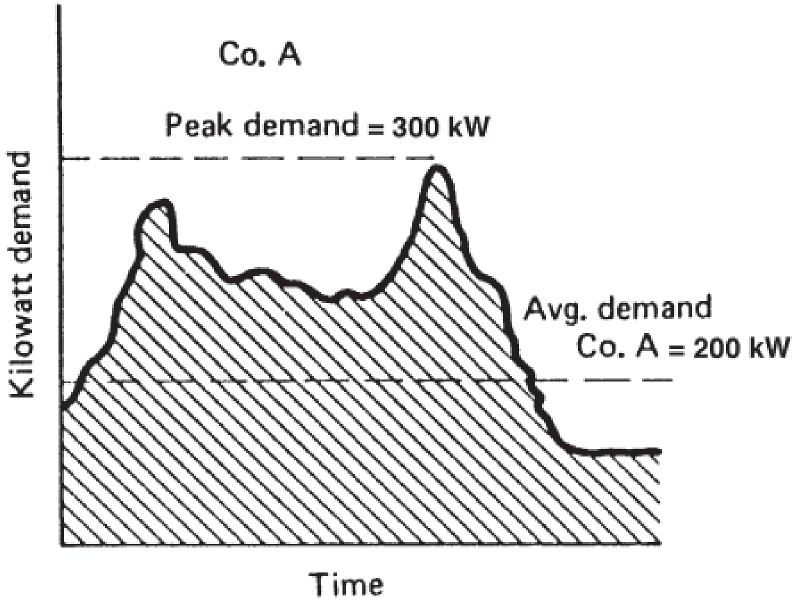
- **Example 8**:

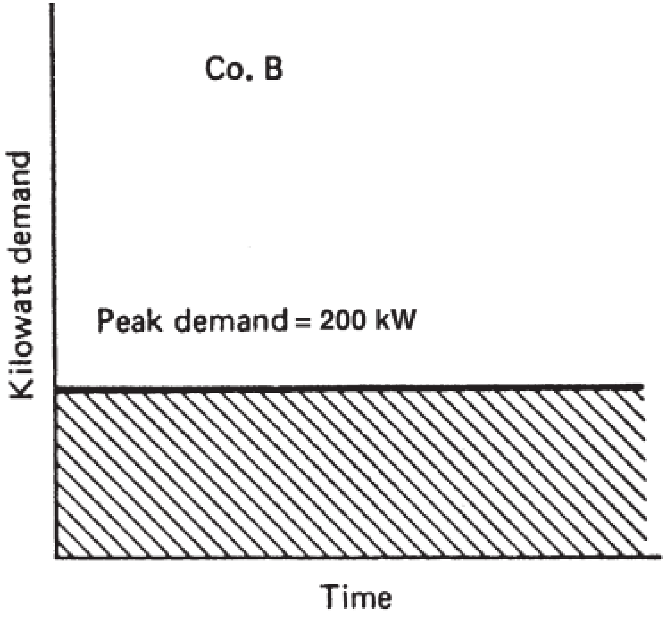
A facility receives a monthly utility bill that shows an energy use of 100,000 kilowatt-hours, a maximum demand, or maximum kW, of 250 kW, and a billing period of 30 days. Find the facility load factor for this 30-day period.

- **Note**: The lower the FMELF, the higher average cost per kWh for the month.

THE FACILITY MONTHLY ELECTRIC LOAD FACTOR

- **Example 9**: Consider the following two electrical load patterns for a two facilities with a thirty-day billing cycle. Energy consumption equals 144,000 kWh. Electric rate structure is €6.50 per kW per month for the demand charge, and pays €0.08 per kilowatt-hour for the energy charge. Calculate the average energy charge and FMELF for both.





Part VI:
Heating, Ventilating, and Air Conditioning (HVAC)

Introduction

- The HVAC system is responsible for a significant portion of the energy use and energy cost in most residential and commercial buildings.
- A number of manufacturing plants are fully heated and air conditioned.
- **Improving the operation of the HVAC system provides many opportunities to save energy and reduce costs, where:**
  1. Many facilities have HVAC systems that were designed and installed during periods of low energy costs; these are often relatively expensive to operate because energy efficiency was not a consideration in the initial selection of the system.
  2. Many HVAC systems are designed to meet extreme load conditions of very hot or very cold weather.

What is the HVAC and its purpose?

HVAC system for a facility is the system of motors, ducts, fans, controls, and heat exchange units which delivers heated or cooled air to various parts of the facility.

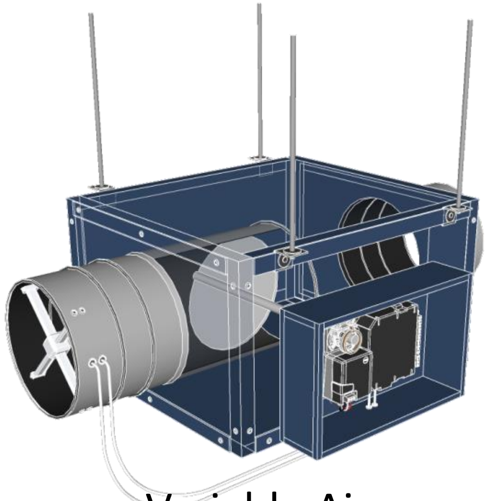
- **The purpose of the HVAC system is**

1. Add or remove heat and moisture and remove undesirable air components from the facility in order to maintain the desired environmental conditions for people, products or equipment.
2. Provide acceptable indoor air quality is a critical function of the HVAC system, and air movement to remove odors, dust, pollen, etc. is necessary for comfort and health.
3. Air-condition an area to protect Products or to meet unusual requirements such as those in a laboratory or a clean room.

HVAC system components

1. Grilles.
2. Heat exchangers.
3. Ductwork.
4. Motors and fans.
5. Controls (dampers, sensors, actuators, and communication links).

HVAC System Types



Variable Air Volume (VAV) system

Fan Coil System

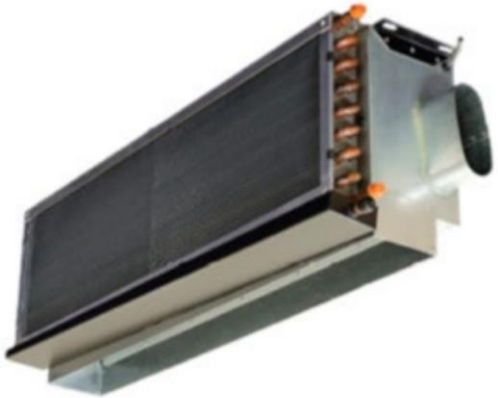
Unit ventilator system

HVAC System Types

Water unit

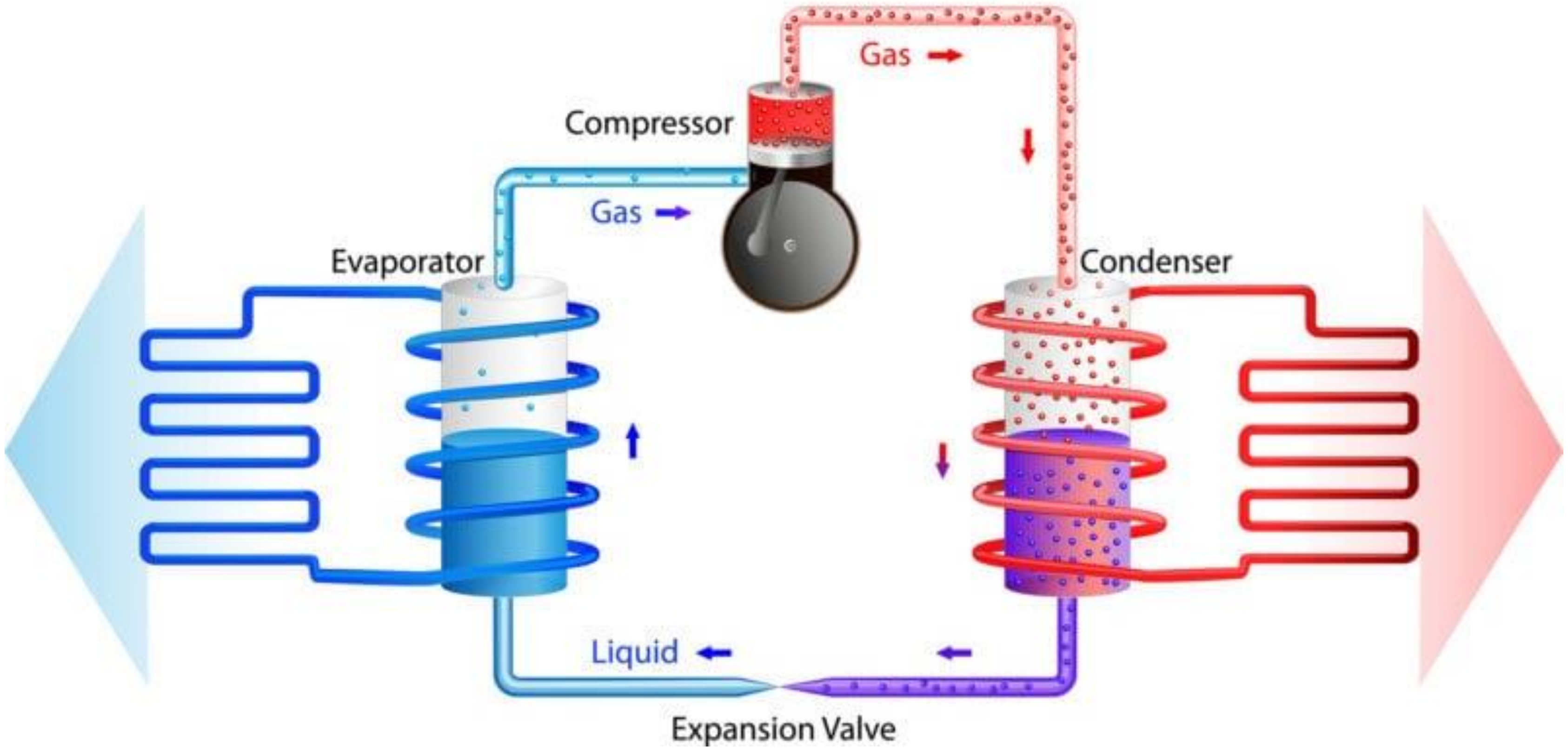
Steam unit

Heat pump unit



Induction unit

How Does a Heat pump system work?



Production of hot and cold fluid for HVAC system

- **Hot Fluids**
- Hot air, hot water and steam are produced using **furnaces or boilers** which are **called primary conversion units.**
- These furnaces and boilers can burn a **fossil fuel such as natural gas, oil or coal, or use electricity** to provide the **primary heat**.
- **Primary heat** transferred into air or water.
- Direct production of hot air/water is accomplished by a furnace which takes the heat of combustion of fossil fuels or electric resistance heat, and transfers it to moving air/water.
- This hot air/water then distributed by ductwork/pipes or by direct supply from the furnace to areas where it is needed.
- A boiler might also be used to add more heat to the water to produce steam which is then distributed to its area of need.

Production of hot and cold fluid for HVAC system

- **Cold Fluids**

- Cold air, cold water and other cold fluids such as (glycol) are produced by **refrigeration units or by chillers**, which are the primary conversion units.

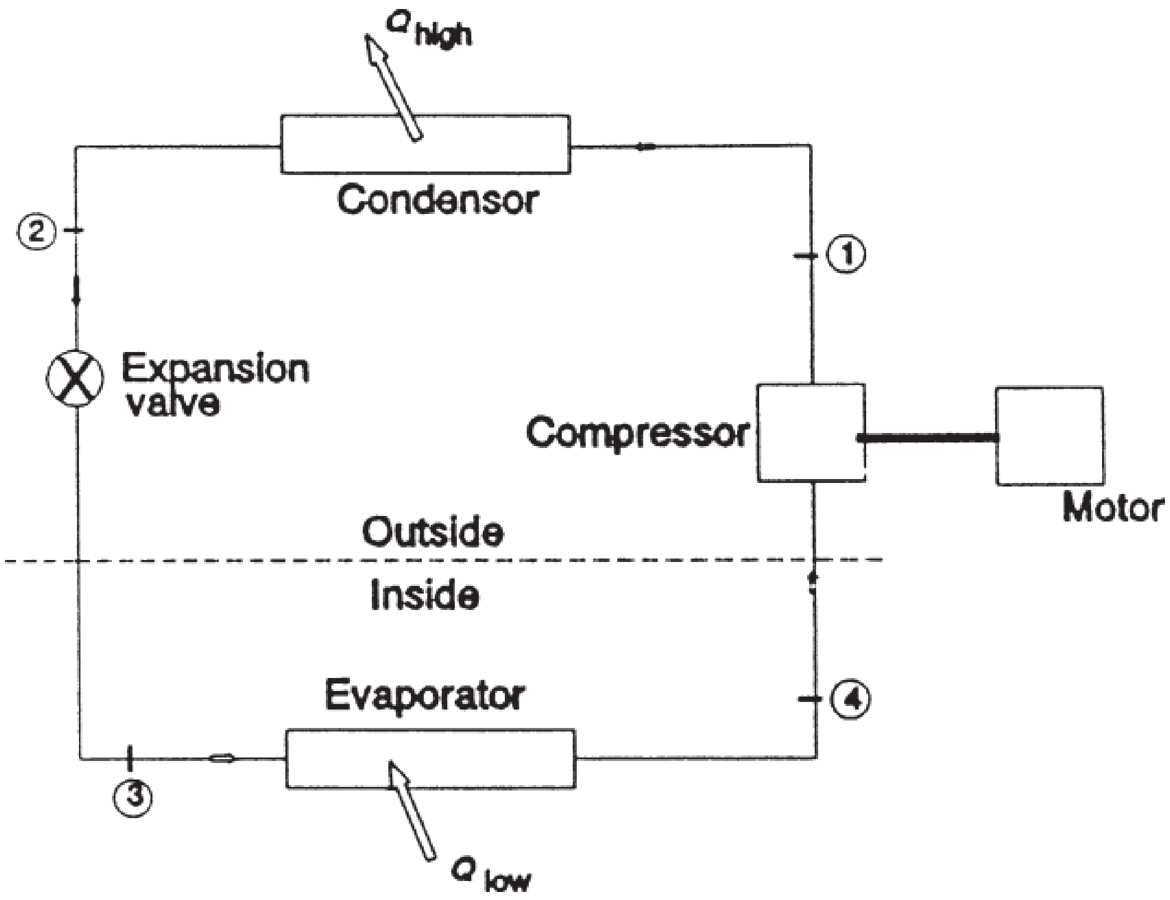
- **Refrigeration units or chillers** commonly use either a vapor-compression cycle or an absorption cycle to provide the primary source of cooling which is then used to cool air, water or other fluids

- Cold air/water then distributed to areas in which they are needed.

Production of hot and cold fluid for HVAC system

- **Cold Fluids**

  The basic vapor-compression cycle

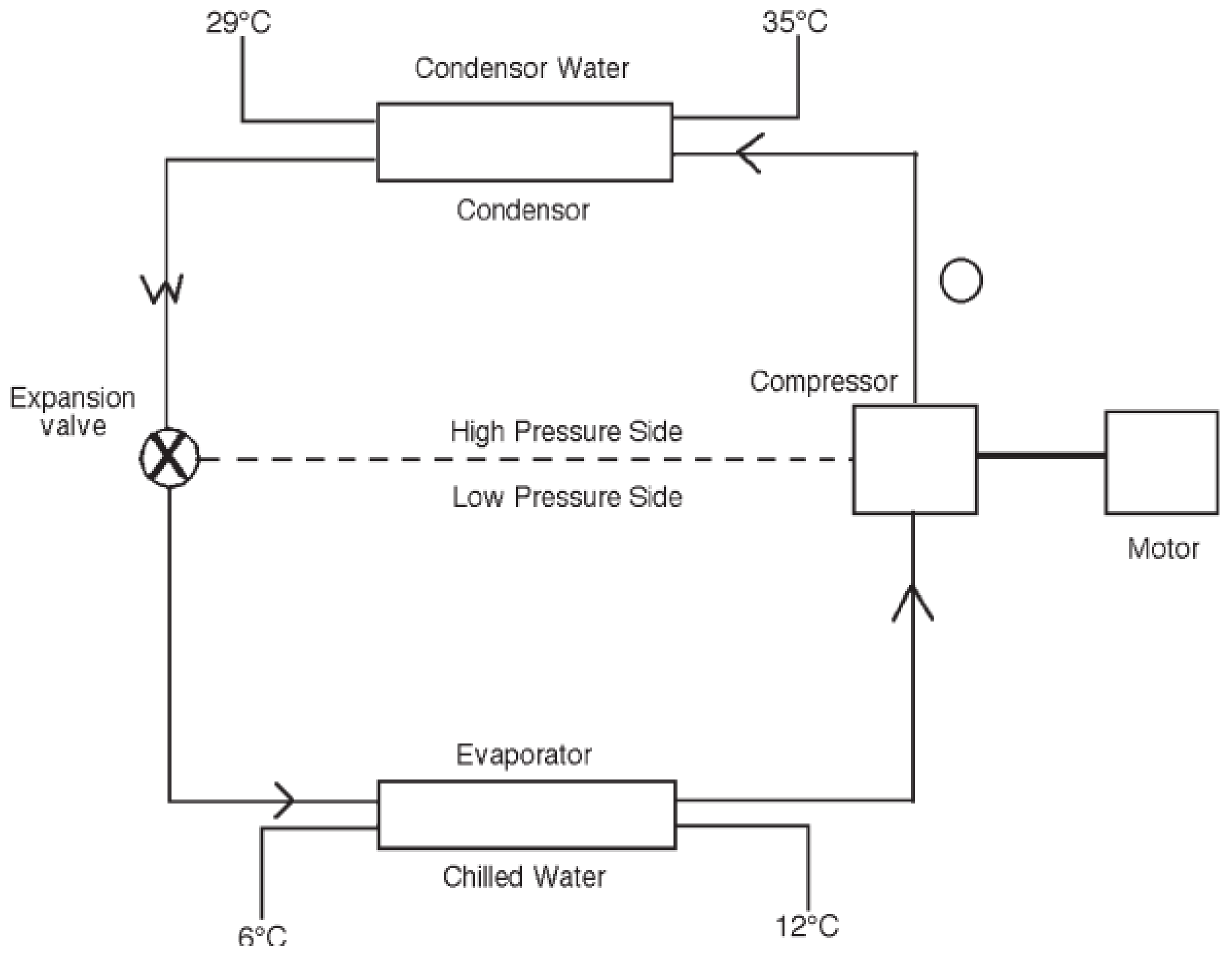


Production of hot and cold fluid for HVAC system

- **Cold Fluids**

  Diagram of a typical chiller

- A typical chiller provides cold water or some cold fluid such as glycol which is supplied to areas where secondary units such as fan-coil units are used to provide the cooling that is needed.
- The majority of chillers use either the vapor-compression cycle or the absorption cycle as the basic cooling mechanism.



Power and Energy

- For air-conditioning systems, the most common terms for heat removal capacity of the HVAC system are the kW, which is a heat removal rate of 3.6 MJ/h

1 kW = 3.6 MJ/h

- Since this is a rate of flow of energy (MJ/h), it is a measure of power, not energy. The unit of energy in the HVAC system is kWh, which is equal to 3.6 MJ.

One kWh = 3.6 MJ

- **Example:**

large room in a commercial office building has a heat production rate of 600 MJ per hour from lights, equipment, people and heat flow from the outside. How many kW of air-conditioning is required to remove this heat?

HVAC system performance measures

- **Energy Efficiency Ratio (EER):** it is the kJ of heat removal by the AC system per Wh of electric input,

$$EER = \frac{MJ}{Wh}$$

- **Coefficient of Performance COP:** it is the kJ/h of heat removal for the AC system/kJ/h of energy used by the AC unit ,

$$COP = \frac{kW\ of\ heat\ removal}{kW\ of\ electric\ input}$$

EER = COP x 3.6 MJ/kWh

HVAC loads

- One of the easiest ways to reduce costs in HVAC systems is to reduce the amount of energy that must be added to or extracted from an area.

- Two **major strategies** for accomplishing this are available:
  (1) Reducing the heating or cooling load;
  (2) Changing the targeted temperature range.

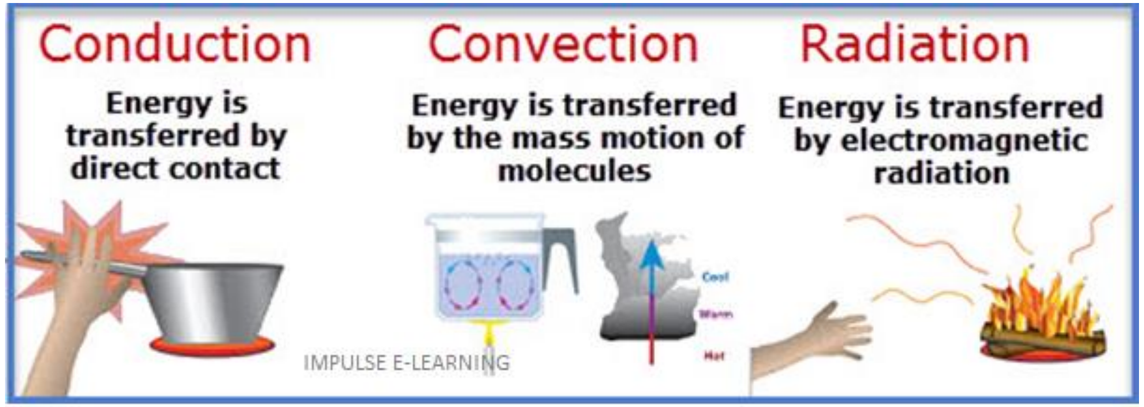
- The heating and cooling loads in a building occur because of:
  1. Heat given off by people;
  2. Heat conducted through the building envelope (walls, roofs, floors, and windows) to or from the environment around the building by either conduction and/or radiation;
  3. Waste heat given off by processes and machinery within the building;
  4. Heat given off by lighting;
  5. Heat or cooling lost to ventilation or infiltration air.

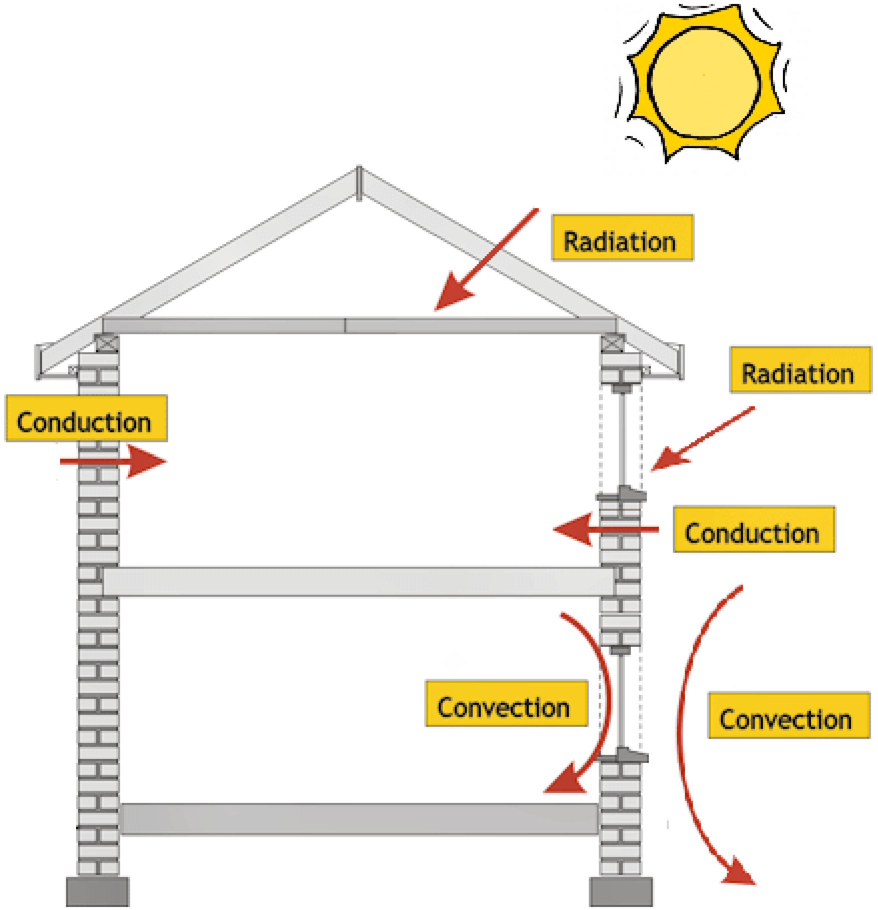
Heating and cooling load: people

- People give off heat, and the amount they give off **depends on** **the type of work they are doing**, **the temperature of their surroundings**, **and whether they are men or women**.

Activity	Total heat gain for male adults (W)
Seated at rest	115
Seated, writing	130
Seated, typing	140
Standing, light work or slow walking	160
Light bench work	235
Normal walking, light machine work	295
Heavy work	440
Heavy machine work, lifting	470

Heat transfer modes





Heating and Cooling Load: Conduction

- In addition to inside heating caused by radiation of solar energy absorbed by inside materials, the sun heat combines with the outside temperatures to create heating due to conduction through the walls and the roof.

- Several observations can be made that are relevant to **energy management**:

  1. The amount of heat gain or loss through a wall depends on the thermal conductance (U value).
  2. Adding insulation to walls or roofs can significantly reduce the unwanted heat gain or loss.
  3. The construction of the wall and roof is also an important factor, with the material used to build the structure having a potential thermal storage effect that can be utilized.

Heating and Cooling Load: Conduction

$$R = \frac{x}{k}$$

$$R_{total} = R_1 + R_2 + \cdots + R_n$$

$$U_{OA} = \frac{1}{R_{total}}$$

$$Q = U_{OA}\, A\, \Delta T$$

$$Q = U_{OA}\, A \left(\frac{DD}{year}\right)\left(\frac{24\text{hr}}{\text{day}}\right) = \frac{\text{Wh}}{\text{year}}$$

- Where,
- x is the layer thickness.
- k is the thermal conductivity.
- A is the area of the wall.
- U_{OA} is the thermal conductance of the wall [W / m^2 ^{o}C].
- Q is the heat flow through the wall (in Wh/year), and the temperature difference ΔT is replaced by the number of heating or cooling degree days, HDD or CDD.

Heating and Cooling Load: Conduction

Example

A wall has an area of 100 m^2 and has a thermal conductance of 1.4 W/m^2 °C. If there are 3000 degree days in the heating season, what is the total amount of heat lost through the wall?

Heating and Cooling Load: Equipment

- The energy consumption in kJ per hour from computers, ovens, industrial processes such as solder pots that use much heat, and many other types of equipment can either be read directly from nameplates or can be approximated from gas or electricity usage where,

$$1 \text{ kWh} = 3600 \text{ kJ of heat}$$

- Decreasing or rescheduling the equipment operation using electricity or gas at a given time has a twofold effect:
  1. the actual energy used at that time is decreased.
  2. the heat introduced into the space is also reduced. If this heat must be removed by cooling, the cooling load is thus reduced by turning off this equipment.
- The amount of heat given off by a motor can also be determined from its nameplate rating in kW if there is one,

$$\text{kWh/h} = \text{kW} \times \text{use factor (fraction of time that the motor is in use)}$$

- or by the calculation involving the nameplate voltage, current and power factor

$$\text{kWh/h} = \text{voltage} \times \text{current} \times \text{power factor} \times \text{use factor (for a single-phase motor)}$$

$$\text{kJ/h} = \text{voltage} \times \text{current per phase} \times (\text{power factor}) \times 1.732 \times 3.6 \times \text{use factor (for a three-phase motor)}$$

Heating and Cooling Load: Lighting

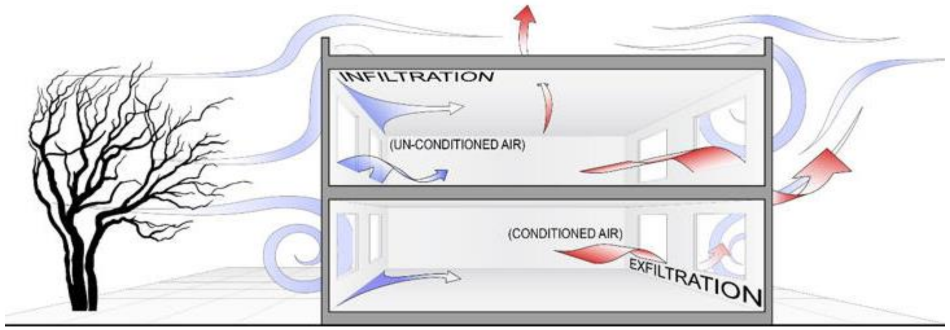
- Heat generated from lighting is another example in which all of the energy used is generally converted to heat in the immediate space.
- Incandescent lamps convert about 2-3% of the energy they use into visible light. The remaining 97% is immediately converted to heat which enters the surrounding space.
- Fluorescent lights are more efficient, and they convert around 10% of their input energy into visible light.
- To calculate the amount of heat that is added to a space from lighting, remember that each kWh of electricity is equivalent to 3600 kJ. Thus the heat produced each hour is found by

$$\text{kJ/h} = (3600\ \text{kJ/kWh}) \times (\text{kWh consumed per hour})$$

- Replacing lamps with more efficient lamps, cleaning the luminaries, and painting adjacent surfaces are ways of reducing the amount of lighting energy.

Heating and Cooling Load: Infiltration

- Air infiltration can occur through the envelope at many places.
- This part of the heating or cooling load can be reduced by:
    1. weather stripping
    2. caulking cracks
    3. tightening windows
    4. installing loading dock shelters
    5. replacing broken windows
- It can also prove worthwhile to prevent airflow from conditioned areas of a plant to unconditioned areas (or vice versa) by installing airflow barriers indoors such as a plastic curtain.



Notes

- Outside air ventilation for commercial buildings is required by most developed countries.
- The purpose is to make sure the air in commercial buildings is safe enough for the people inside the buildings. However, there is no real international ventilation standard that applies to most of these countries.
- There is an ASHRAE International Standard, and there is also a European Union International Standard, but these are quite different.

Thermal and Environmental Conditions for HVAC Systems

1. **Temperature**

Two kinds of temperatures. One is what we call dry bulb (DB) temperature (which is just a fancy name for the reading we take from an ordinary Mercury bulb thermometer or regular temperature sensor). The other, the wet bulb temperature (WB). The wet bulb reading will always be lower than the dry bulb reading.

2. **Relative Humidity**

RH is the percent weight of water vapor that air is currently holding compared to the weight of water vapor it could potentially hold at its present temperature. Thus, RH is always less than or equal to 100%.

- When the RH is 100%, the air is saturated (it cannot hold any more water vapor at its present temperature).
- The warm air holds more water vapor than cold air. Thus, if some cold air has a relative humidity of 80%, and we simply heat it up, it will have a new RH less than 80%.

Thermal and Environmental Conditions for HVAC Systems

- Relative humidity in facilities is controlled by adding water vapor to the air or removing water vapor from the air as needed;
  1. Adding water vapor to air is called humidification.
  2. Removing water vapor from air is called dehumidification.

- Energy is necessary to humidify or dehumidify air. For humidification, heat must be added to water so it will vaporize and mix with the air.
- For dehumidification, heat must be removed from moist air so that water vapor will condense and drain away from the air.

Thermal and Environmental Conditions for HVAC Systems

Ex1. One kilogram (kg) of air at 25 degrees Celsius, has a RH of 20%, and contains three grams of water vapor. When this air is heated to 30 degrees C with no change in water vapor, what will its RH be if the 30-degree C air could hold a maximum of 27 grams of water vapor?

Ex2. Is it possible for relative humidity to go as high as 150 percent?

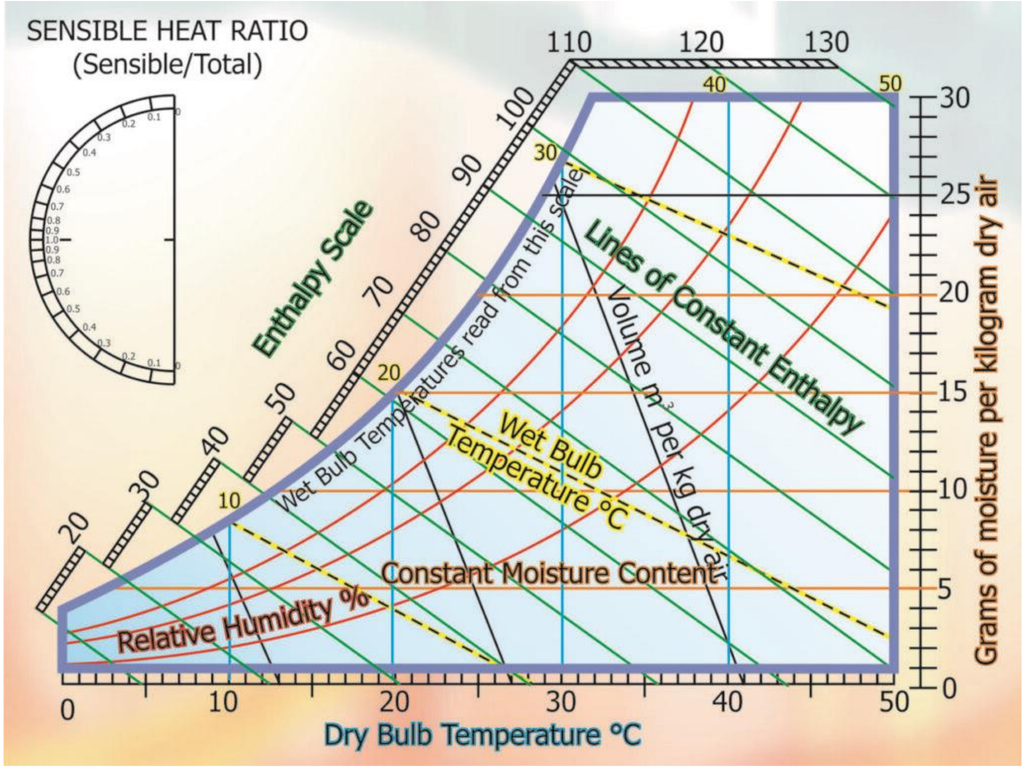
Sensible and Latent heat

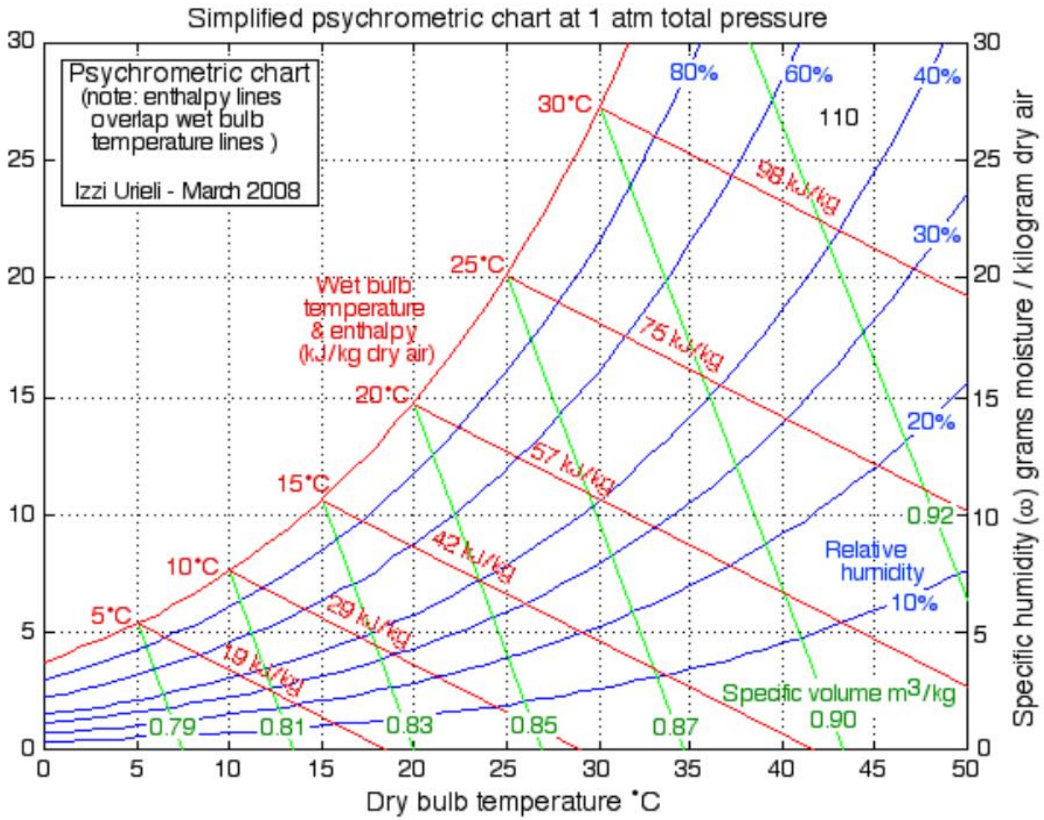
- A substance, like air or water, can have one of three states (phases): **solid, liquid or vapor (gas)**. For example, when water is heated and changes to steam, that change from liquid to vapor is a state change.
- **Sensible heat** is the heat associated with a **temperature change** of a substance, with no associated phase or state change.
- **Latent heat** is the heat associated with a **state or phase change** at a constant temperature.
- **For air**, the only way latent heat is involved is when we humidify or dehumidify the air.
- **Humidification:** adding water vapor to the air (spraying steam or water drops into an air duct or air stream)
- **Dehumidification:** remove water vapor from the air (blowing the air over a very cold cooling coil in an air-conditioning system or air handling unit and condensing the water vapor so that it can be drained to the outside)

Sensible and Latent heat

- **For water**, the only way latent heat is involved is if we heat water to a high enough temperature that it converts it to steam; or if we cool water to a low enough temperature that it freezes to a solid (ice).
- The **total heat** of air or water, including both sensible heat and latent heat is called **enthalpy** [kJ/kg of air or water].
- The actual numerical values of enthalpy required to heat or cool air sensibly, or to add or remove latent heat, are found from a graph. **The graph for air is called the Psychrometric chart**.
- It takes about 2256 kJ of heat to evaporate one kg of liquid water into the air; and it takes about 2256 kJ of heat removed from moist air to condense one kg of water out of the air.

Psychrometric chart





Sensible heating and cooling loads with air and water

- A typical heating calculation that we might need to do is to find how many sensible kJ/h of heat flow do we need;

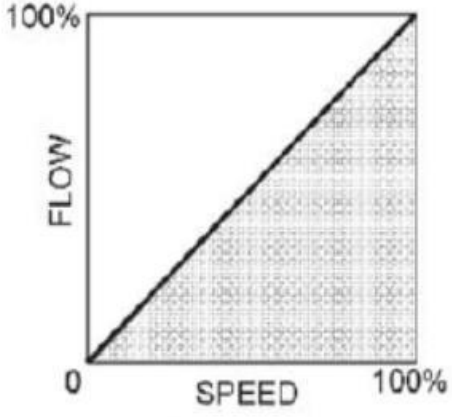
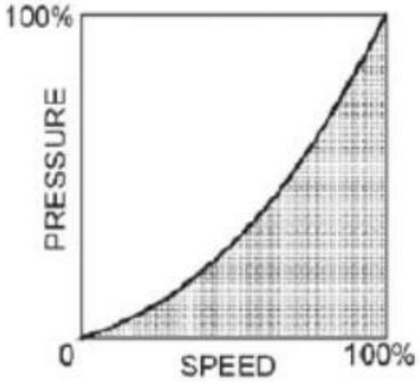
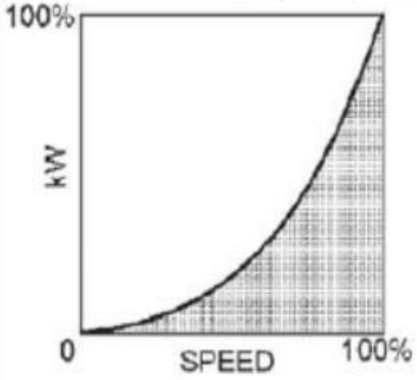
$$\dot{Q} = \dot{m}\, C_p\, \Delta T$$

- The above equation can be used for both sensible air and water heating/cooling.
- The density of air is 1.204 kg/m^3 of air. The Cp of standard air, which is 1.006 kJ per kg . °C
- The density of water is 1000 kg/m^3 . The Cp of liquid water, which is 4.2 kJ per kg . °C

Basic operating rules for energy saving

- **Rule 1.** Heat to the lowest temperature possible, and cool to the highest temperature possible.
- **Rule 2.** Avoid heating or cooling when heating or cooling is not needed.
- **Rule 3.** Learn how your control system is supposed to work and then maintain it properly.
- **Rule 4.** To insure that the minimum required amount of ventilation air is being used, adjust the ventilation system by altering the control system settings or by changing pulleys on fans or their drive motors or by using variable speed drives. One very useful relationship is
- **Rule 5.** If you do not need heating, cooling or ventilation, turn off the HVAC system.

Fan Laws

Flow α Speed	Pressure α (Speed)^2	Power α (Speed)^3
		
$\frac{Q_1}{Q_2} = \frac{N_1}{N_2}$	$\frac{SP_1}{SP_2} = \left(\frac{N_1}{N_2}\right)^2$	$\frac{kW_1}{kW_2} = \left(\frac{N_1}{N_2}\right)^3$
Varying the RPM by 10% decreases or increases air delivery by 10%.	***Reducing the RPM by 10% decreases the static pressure by 19% and an increase in RPM by 10% increases the static pressure by 21%***	***Reducing the RPM by 10% decreases the power requirement by 27% and an increase in RPM by 10% increases the power requirement by 33%***

Where Q – flow, SP – Static Pressure, kW – Power and N – speed (RPM)

Basic Operating Rules

Example 1

ACE Industries presently has a 5-kW ventilating fan that draws warm air from a production area. The motor recently failed and they think it can replaced with a smaller motor. They have determined that they can reduce the amount of ventilation air by one third. What size motor is needed now?

Notes:

- kW The power savings achieved by a reduction of some kW's is given by Power saved (kW) = (kW's reduced)/EFF, Where EFF is the motor efficiency, usually between .70 and .90.
- This expression can only be used if the old and new motors have the same efficiencies.

Basic Operating Rules

Example 2

What is the electrical load reduction for the smaller fan motor in the previous example if the 5-kW motor had an efficiency of 84%? The new 1.5-kW motor has an efficiency of 85.2%. ?

Inspecting the HVAC System

Inspecting HVAC component areas is necessary. Since the most common systems are those in which air is the working fluid, the rest of this discussion will be confined to air-cooled systems.

- **Heat transfer surfaces**

The surface where a hot or cold fluid gives up or receives heat from air that is passing around it. These heat transfer surfaces must be examined periodically and be maintained to continue to work properly. The points to be inspected are the fluid flow lines and the heat transfer surfaces.

- **Air transportation system**

The main components of this system are the ductwork, dampers, and filters and the fans, blowers, and associated motors.

1. **Ducts** can leak air through untapped seams, or they can be crushed by adjacent piping.
2. The **dampers** and filters should be clean and should close.
3. Return air **grilles** should also be inspected to see whether they need to be cleaned.
4. **Fans and blowers** should be operational, and the **belts** should be aligned correctly that the fan pulley and the motor pulley are in a straight line.

Inspecting the HVAC System

- **The control system**

The HVAC control system detects pressures or temperatures and compares these with preset values. Depending on the result, the control system sends electrical or pneumatic signals to open or close dampers, open or close valves, and turn furnaces, chillers, and blower motors on or off.

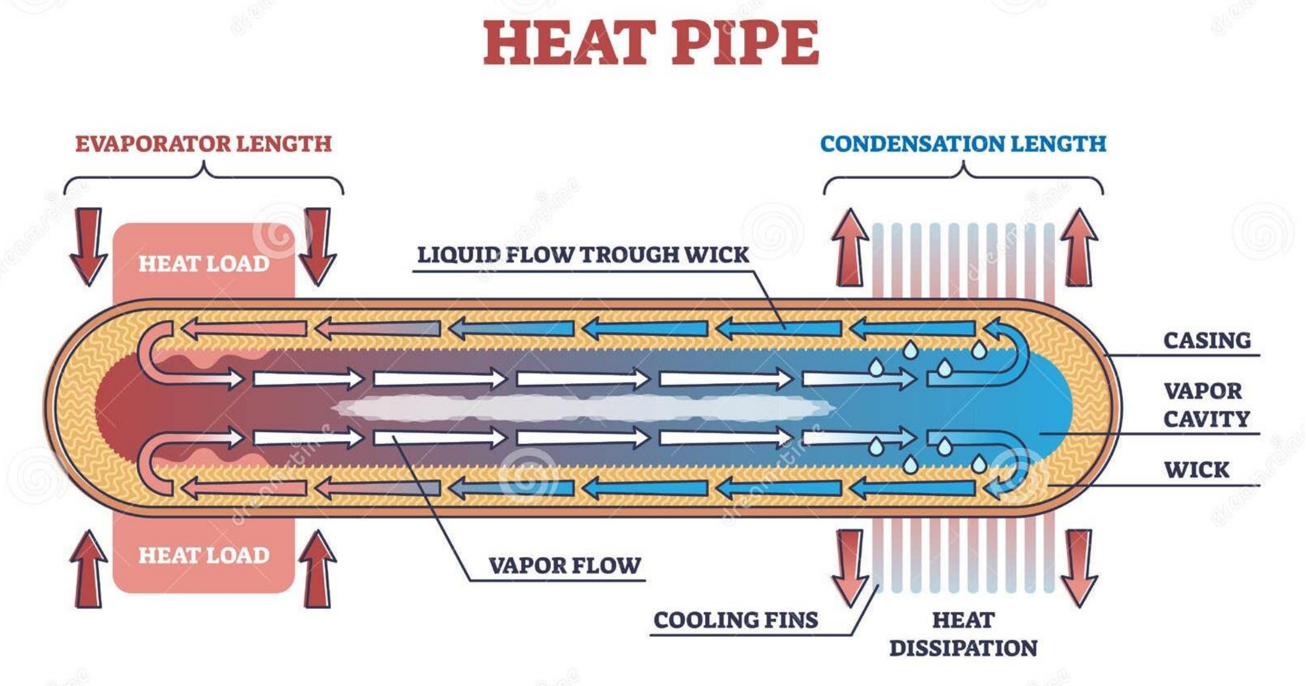
1. A reliable **industrial thermometer** can be used to calibrate each thermostat thermometer.
2. **Gauges** should be checked to see whether they are connected and whether they are reading within the correct operating ranges.
3. The **compressor** that supplies compressed air to the control system should be inspected to see that it is working properly and not leaking oil or water into the control system.
4. An **air dryer** is almost always a necessity on the air supply system to keep the controls working properly.

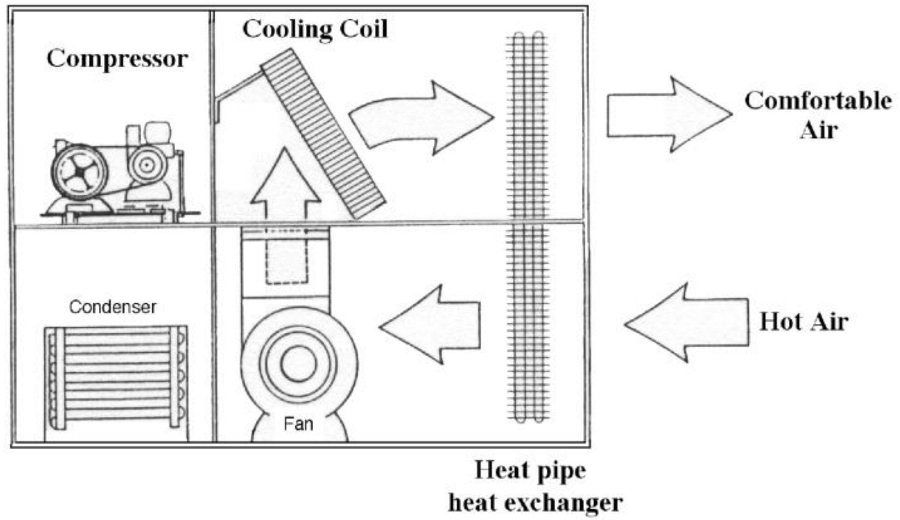
Heat pipes

- Removing humidity is the chief energy cost of air conditioning. Therefore, in areas where the humidity is high, the air must be cooled much lower than the desired temperature in order to remove the moisture and then heated back to the desired temperature. **This means that;**
  1. Energy is required to overcool the air
  2. Additional energy to reheat the air
  3. Equipment must be oversized in order to overcool the air which increases the power demand

- The older, energy-inefficient air-conditioners were designed with very cold cooling coils.
- Newer and high-efficiency models are often designed with warmer coils which is called "Heat pipes"

Heat pipes


HEAT PIPE
EVAPORATOR LENGTH
CONDENSATION LENGTH
HEAT LOAD
LIQUID FLOW TROUGH WICK
CASING
VAPOR
CAVITY
WICK
HEAT LOAD
VAPOR FLOW
COOLING FINS
HEAT
DISSIPATION


Compressor
Cooling Coil
Comfortable
Air
Condenser
Hot Air
Fan
Heat pipe
heat exchanger

Heat pipes

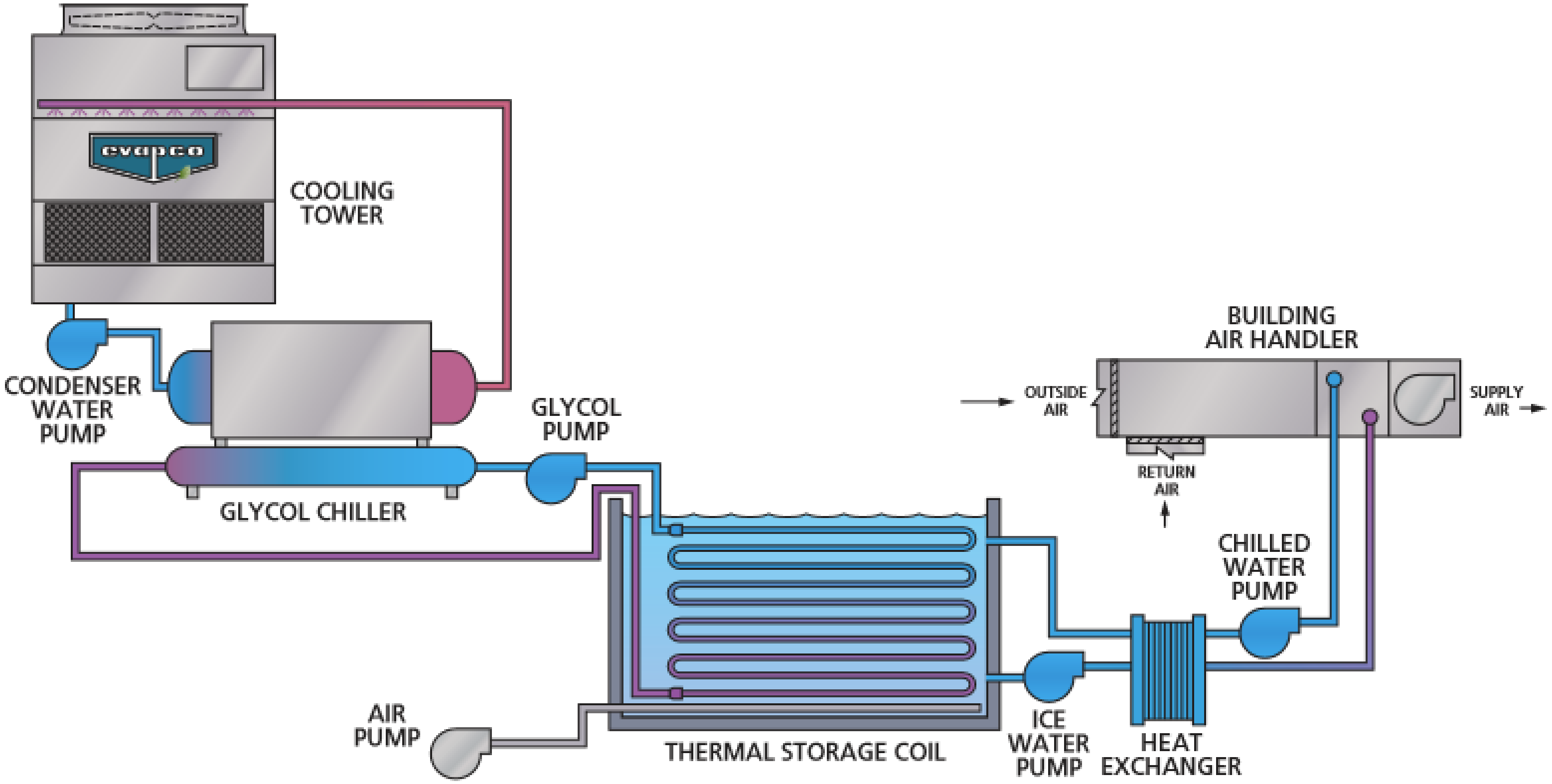
Applications/usages

1. Areas where the humidity is high
2. Well known in commercial sector
3. Areas which need large amounts of outside air for ventilation. (It allows the addition of up to 20% fresh air without increasing the size of the system).
4. Industries which require a low humidity level or humidity control include (electronic component production, assembly and storage; film drying, processing and storage; drug, chemical and paper manufacturing and storage; printing; candy and chocolate processing and storage)
5. Hospital operating rooms, libraries, grocery stores, telephone exchanges and relay stations, clean rooms, underground silos, and places with indoor swimming pool or spa facilities.

Thermal storage

- Thermal energy storage offers one of the most promising technologies for effective electrical peak load management in buildings and other facilities.
- A thermal energy storage system may produce **chilled water or ice** off-peak for later use in **cooling** a facility, or produce **heated air or water** off-peak for later use in **heating** a facility.
- The high-demand electrically powered chillers are shifted to operation during off-peak periods where, **cool storage systems operate by producing and storing chilled water or ice during the evening and night when electric rates are low**, **and drawing on that stored water or ice during the day when the cooling load is greatest**.
- Cost-effective for facilities that have time-of-day rates which offer low-cost energy during the night.
- The storage of chilled water or ice also allows the facility to operate with smaller-sized chillers since the peak cooling load is handled with the combination of the small chiller and the cool storage.
- Many electric utilities offer rebates or incentives for facilities to install thermal storage systems. The incentive may be in the form of low rates for off-peak energy use, or in the form of a direct rebate based on the number of kW moved off-peak.

Thermal storage



Thermal Storage System Schematic

Part VII : Lighting

Introduction

- In many cases, lighting can be improved and operation costs can be reduced at the same time.

- Lighting accounts for a large part of the energy bill, ranging from **30-70% of the total energy cost** and represents only **5-25% of the total energy in industrial facilities.**

- The minimum lighting level standards of the **Illuminating Engineering Society (IES)** should be followed to insure worker productivity and safety.

- Inadequate lighting levels can decrease productivity, and they can also lead to a perception of poor indoor air quality.

Components

- **A lighting system consists of:**
  1. light sources (lamps)
  2. luminaires (or fixtures)
  3. ballasts.

- **Each component will affect the:**
  - Performance.
  - energy use.
  - annual operating cost of the lighting system.

Lighting characteristics

- Lamps are rated a number of different ways and each characteristic is a factor to consider in the lamp selection process.

- Lamps should carry recognizable name brands and should be purchased from a reputable vendor.

- **The basic ratings include:**
    1. luminous efficacy (lumens/watt).
    2. color temperature (Kelvins).
    3. color rendering index (CRI).
    4. cost (€).
    5. rated life (operation hours).
    6. labor required for relamping.

Lighting characteristics

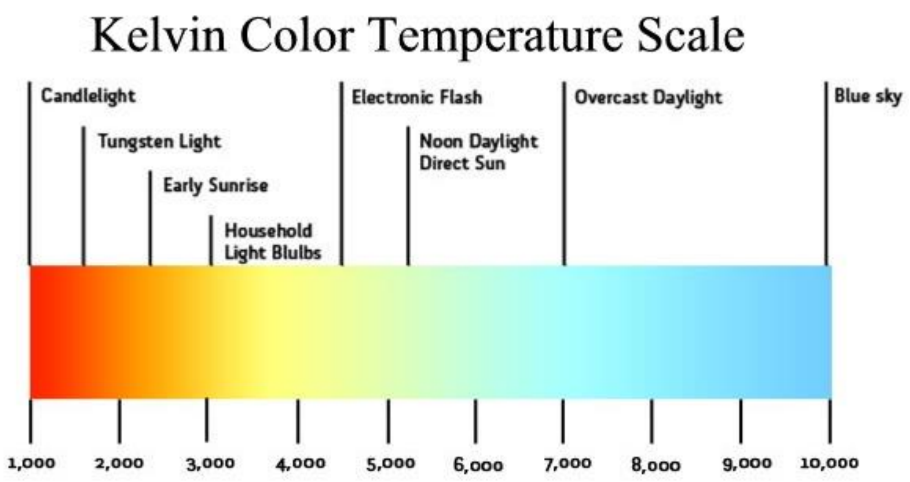
1. Luminous Efficacy

The estimation of the light output (lumens) divided by the electrical power input (watts) under test conditions.

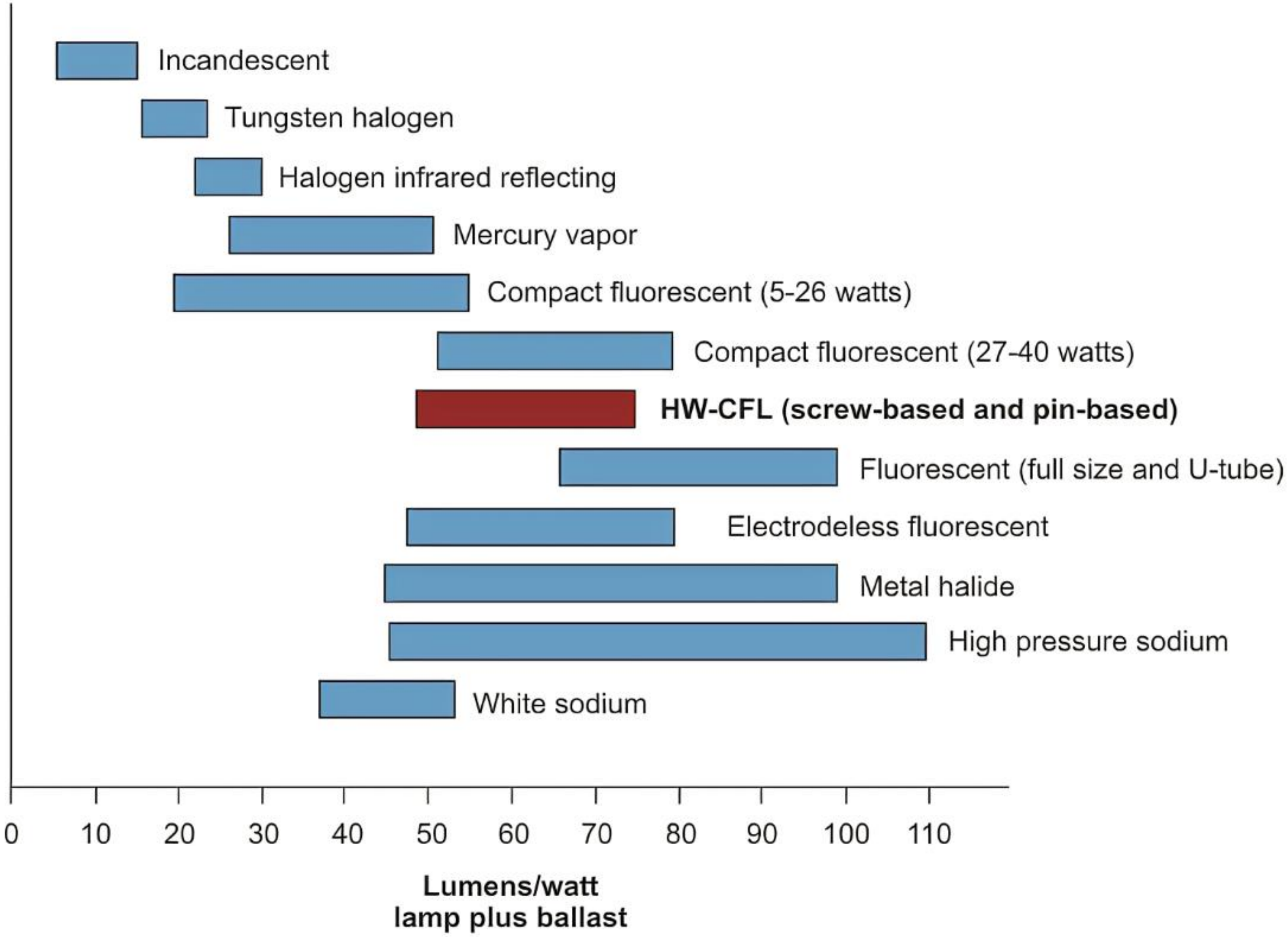
2. Color Temperature

The color temperature of a lamp describes the appearance of the light generated compared to the perceived color of a blackbody radiator at that temperature on the absolute temperature scale (i.e., Kelvin scale).

Source	Efficacy (lumen/watt)	Life Time (hours)
LED	4.5-150	25,000-30,000
Incandescent	10-30	More than 2,000-4,000
Fluorescent	60-90	More than 7,000
Neon	5-20	More than 12,000
Metal Halide	70-90	6,000- 20,000
High Pressure Sodium	90-125	25,000



Lighting charactarestics



Lighting characteristics

3. Color Rendering Index: (CRI)

- ✓ The relative indication of how well colors can be distinguished under the light produced by a lamp with a particular color temperature.
- ✓ The index runs from 0 to 1; where a high CRI indicates good color rendering.
- ✓ The energy manager should not recommend changing lamp color unless nearly everyone is in favor of the proposed change.

Color Rendition of various lamp types

	Fluorescent lamps						
	Cool[b] White	Deluxe[b] Cool White	Warm[a] White	Deluxe[a] Warm White	Daylight	White	Soft White/Natural
Efficacy (lm/w)	High	Medium	High	Medium	Medium-high	High	Medium
Lamp appearance effect on neutral surfaces	White	White	Yellowish white	Yellowish white	Bluish white	Pale yellowish white	Purplish white
Effect on "atmosphere"	Neutral to moderately cool	Neutral to moderately cool	Warm	Warm	Very cool	Moderately warm	Warm pinkish
Colors strengthened	Orange Yellow Blue	All nearly equal	Orange Yellow	Red Orange Yellow Green	Green Blue	orange Yellow	Red Orange
Colors grayed	Red	None appreciably	Red, green blue	Blue	Red, orange	Red, green blue	Green, blue
Effect on complexions	Pale pink	Most natural	Sallow	Ruddy	Grayed	Pale	Ruddy pink
Remarks	Blends with natural daylight; good color acceptance	Best overall color rendition; simulates natural daylight	Blends with incandescent light; poor color acceptance	Good color rendition; simulates incandescent light	Usually replaceable with CW	Usually replaceable with CW or WW	Tinted source; usually replaceable with CWX or WWX

Lamp types

1. Incandescent Lamps:

- Render colors well, are inexpensive to purchase, easily dimmed, small, and controllable which is useful for product display.
- However, they have relatively short lifespans, low efficacy and are susceptible to failure from heat and vibration.
- Most incandescent lamps tend to darken with age as tungsten is lost from the filament and deposited on the lamp walls.

Lamp types

1. Incandescent Lamps:

- A Lamps, These lamps are low cost and commonly used in sizes of 20-1500 Watts.
- Reflector (R) Lamps. These lamps are usually more expensive than A-lamps and offer better control of the direction in which light is cast due to a reflective paint on the lamp wall.
- Ellipsoidal Reflector (ER) Lamps. These lamps cost about the same as R-lamps, but they are longer and have a focal point in front of the lamp.
- Quartz-Halogen Lamps. These lamps have a short life and low efficacy. They can be a good choice for areas which need lighting on an irregular basis. These lamps should not be cleaned.
- Halogen Lamps. These lamps have a higher efficacy and cost more than the lamps listed above and are available in many of the same lamp configurations

Lamp types

2. Fluorescent Lamps:

- Fluorescent lamps have high efficacy, long life, and low surface luminance; they are cool and are available in a variety of colors.

- Fluorescent lamps are available in standard, high output (HO), and very high output (VHO) configurations. The HO and VHO lamps are useful for low-temperature environments and areas where a lot of light is needed with minimal lamp space.

- Energy-saving Lamps. reduce power demand and energy use by about 15%. They will also decrease light levels about 3-10%. These lamps can only be used with ballasts designed and rated for energy saving lamps and should not be used in areas in which the temperature falls below 15°C.

Lamp types

2. Fluorescent Lamps:

- T-Measures for Lamps. The T-measure for a fluorescent lamp is the measure of the diameter of the lamp (originally in eighths of an inch).
- T10 Lamps. T10 lamps typically contain phosphors which produce high efficacy and color rendition. They will operate on most ballasts designed for T12 lamps.
- T8 Lamps with Electronic Ballasts. T8 lamps (26 mm) produce an efficacy of up to 100 lumens/Watt, the highest efficacy of any fluorescent lamp.
- Compact Fluorescent Lamps (CFLs). It can be used to reduce energy use and power demand by over 70%. have a lifetime of at least 10,000 hours.

Energy Saving Fluorescent Lamps

Lamp description	Lamp watts	Lamp watts replaced	Lamp current (A)	Lamp volts (V)	Lamp life[†] (h)	Nominal length		Base (end caps)	Nominal lumens[‡§]						
						(mm)	(in.)		3000K RE70	3500K RE70	4100K RE70	3000K RE80	3500K RE80	4100K RE80	5000K RE80
Rapid start															
F17T8	17	—	0.265	70	20,000	610	24	Med. Bipin	1325	1325	1325	1375	1375	1375	—
F25T8	25	—	0.265	100	20,000	914	36	Med. Bipin	2125	2125	2125	2200	2200	2200	—
F3278	32	—	0.265	137	20,000	1219	48	Med. Bipin	2850	2850	2850	2975	2975	2975	2700[b]
F40T8	40	—	0.265	172	20,000	1524	60	Med. Bipin	3600	3600	3600	3725	3725	3725	—
F40T12/U/3	36	40	—	—	12,000	610	24	Med. Bipin	—	—	—	—	—	—	—
F40T12/U/6	34	40	0.45	84	16,000	610	24	Med. Bipin	2800[b]	2800[b]	2800[b]	—	—	—	—
F30T12	25	30	0.453	64	18,000	914	36	Med. Bipin	2090	2090	2090[a]	—	—	—	—
F40T12	34-36[‖]	40	0.46	73	20,000	1219	48	Med. Bipin	2800	2800	2880	2800	2800	2800	—
F48T12/HO	55	60	—	—	12,000	1219	48	Reces. DC	3850[a]	4075	3850[a]	4400[b]			—
F96T12/1500	95	110	0.83	126	12,000	2438	96	Reces. DC	8430	8430	8430	8620	8500[a]	8600[c]	—
F96T12/1500	195	215	1.58	137	12,000	2438	96	Reces. DC	—	—	—	—	—	—	—
F48PG17	95	110	1.53	64	12,000	1,219	48	Reces. DC	—	—	—	—	—	—	—
F96PG17	185	215	1.57	144	12,000	2438	96	Reces. DC	—	—	—	—	—	—	—
Preheat start															
F40T12	34	40	0.45	84	15,0000	1219	48	Med. Bipin	—	—	—	—	—	—	—
F90T17	86	90	—	—	9000	1524	60	Mog. Bipin	—	—	—	—	—	—	—
Instant start (Slimline)															
F48T12	30-32	38-40	—	—	9000	1219	48	Single pin	2610	2610	2610	2700[b]	—	—	—
F96T8	40-41	50-51	—	—	7500	2438	96	Single pin	—	—	—	—	—	—	—
F96T8[b]	56	—	0.26	267	15,000	2438	96	Single pin	—	—	—	5800	5800	5800	—
F96T12	60	75	044	153	12,000	2438	96	Single pin	5675	5675	5675	5850	5850	5850	—

Lamp types

3. High Intensity Discharge (HID) Lamps :

- These lamps are relatively expensive initially but offer low life-cycle costs due to long life and high efficacy.
- Mercury Vapor Lamps. It offer good color rendering and low-to-moderate efficacy.
- Metal Halide lamps.
- High Pressure Sodium (HPS) Lamps.

Lamp types

4. Low-Pressure Sodium (LPS) Lamps :

- LPS lamps offer the highest efficacy of any light source (i.e., up to 180 lumens/Watt). They have a long life but are fairly large compared to HID lamps.
- Their size requires a larger, more complex reflector design to efficiently utilize the light produced.
- LPS lamps are common in European street lighting systems.

YOU USED TO BUY — YOUR CHOICES NOW

LEAST EFFICIENT → MOST EFFICIENT

LESS BRIGHT → MORE BRIGHT	Standard Incandescents	New Halogen Incandescents	CFLs	LEDs
450 lumens	40W	29W	10W	5W
800 lumens	60W	43W	13W	10W
1100 lumens	75W	53W	16W	15W
1600 lumens	100W	72W	20W	19W
	TYPICAL LIFE = 1 year*	TYPICAL LIFE = 1-2 years*	TYPICAL LIFE = 10 years*	TYPICAL LIFE = 15-25+ years*

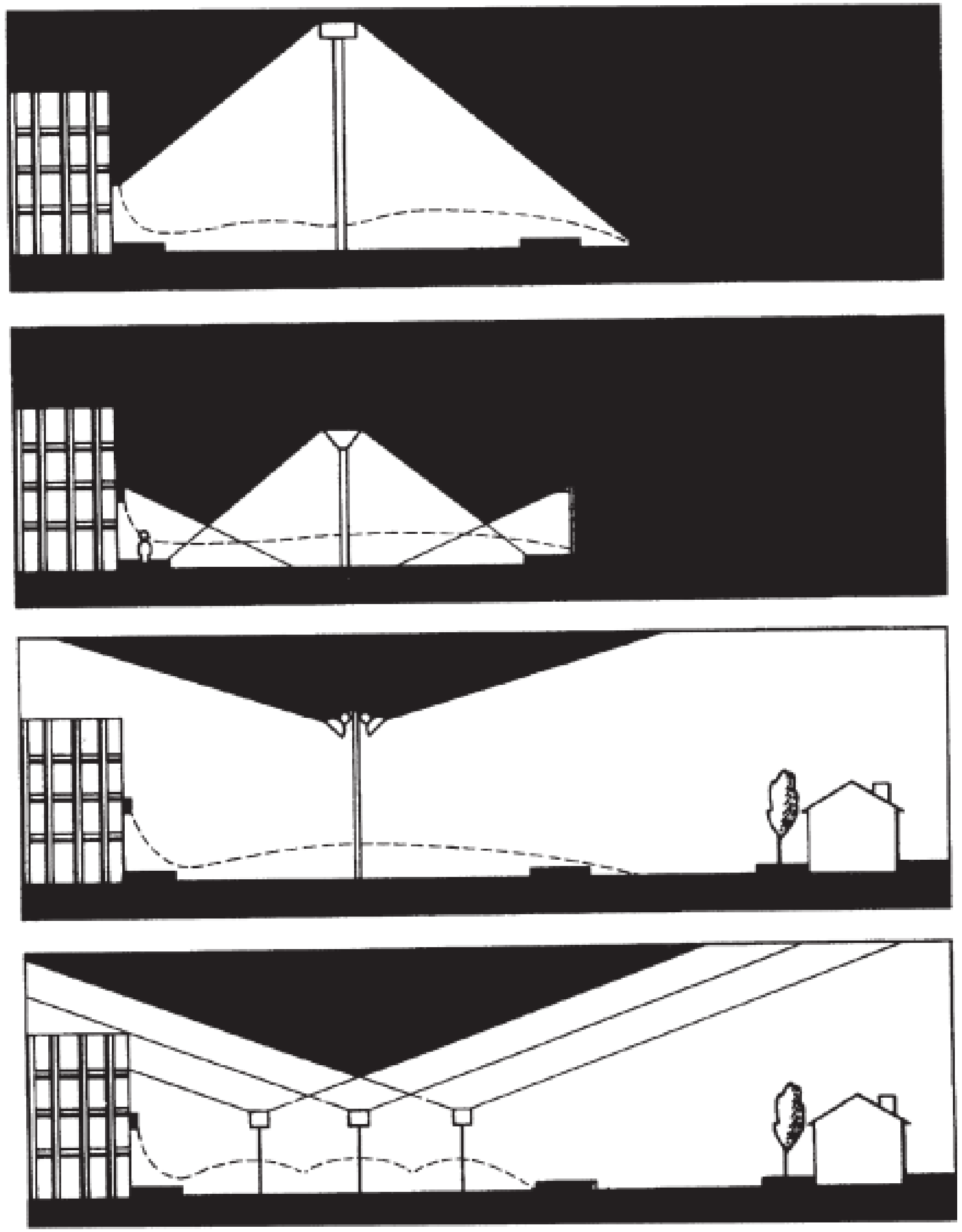
* Rated life is based on 3 hours of use per day

Light Source Characteristics

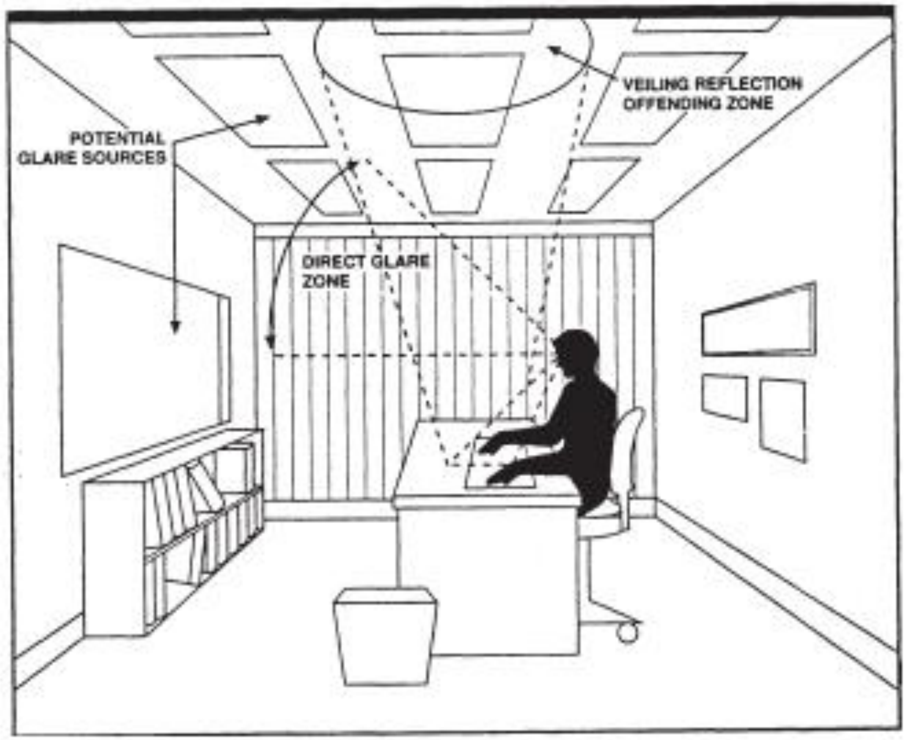
	Incandescent, Including Tungsten Halogen	Fluorescent	High-Intensity Discharge: Mercury Vapor (Self-Ballasted)	High-Intensity Discharge: Metal Halide	High-Intensity Discharge: High-Pressure Sodium (Improved Color)	Low-Pressure Sodium
Wattages (lamp only)	15-1500	15-219	40-1000	175-1000	70-1000	35-180
Life[a] (hr)	750-12,000	7500-24,000	16,000-15,000	1500-15,000	24,000 (10,000)	18,000
Efficacy[a] (lumens/W) lamp only	15-25	55-100	50-60 (20-25)	80-100	75-140 (67-112)	Up to 180
Lumen maintenance	Fair to excellent	Fair to excellent	Very good (good)	Good	Excellent	Excellent
Color rendition	Excellent	Good to excellent	Poor to excellent	Very good	Fair (very good)	Poor
Light direction control	Very good to excellent	Fair	Very good	Very good	Very good	Fair
Source size	Compact	Extended	Compact	Compact	Compact	Extended
Relight time	Immediate	Immediate	3-10 min	10-20 min	Less than 1 min	Immediate
Comparative fixture cost	Low: simple fixtures	Moderate	Higher than incandescent and fluorescent	Generally higher than mercury	High	High
Comparative operating cost	High: short life and low efficiency	Lower than incandescent	Lower than incandescent	Lower than mercury	Lowest of HID types	Low
Auxiliary equipment needed	Not needed	Needed: medium cost	Needed: high cost	Needed: High cost	Needed: High cost	Needed: high cost

[a]Life and efficacy ratings subject to revision. Check manufacturers' data for latest information.

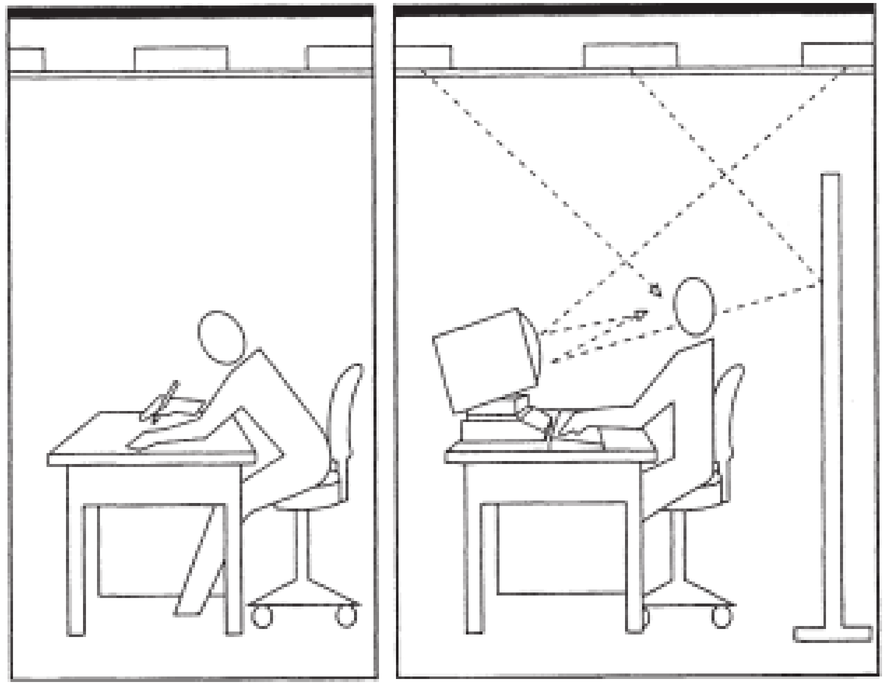
Effective outdoor lighting



The top two illustrations indicate effective ways of achieving desired lighting for the area involved (indicated by the dotted line). The bottom two approaches waste energy and the "light trespass" effect of the "spill light" can irritate neighbors.



Veiling reflections commonly occur when the light source is directly above and front of the viewer, in the "offending zone."



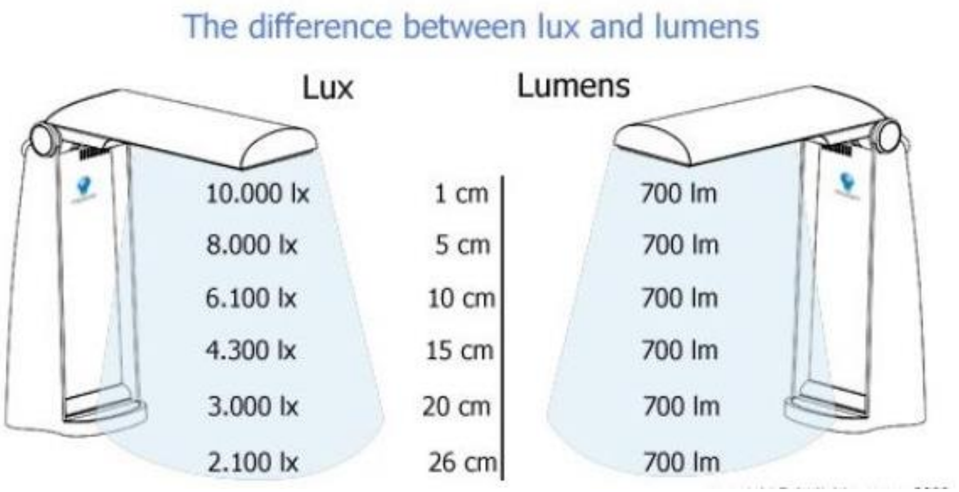
Prevailing relationships between workers, their tasks, and their environments are altered significantly when traditional "white paper tasks" (on left) are changed to VDT-based tasks (on right).

The difference between lux and lumens

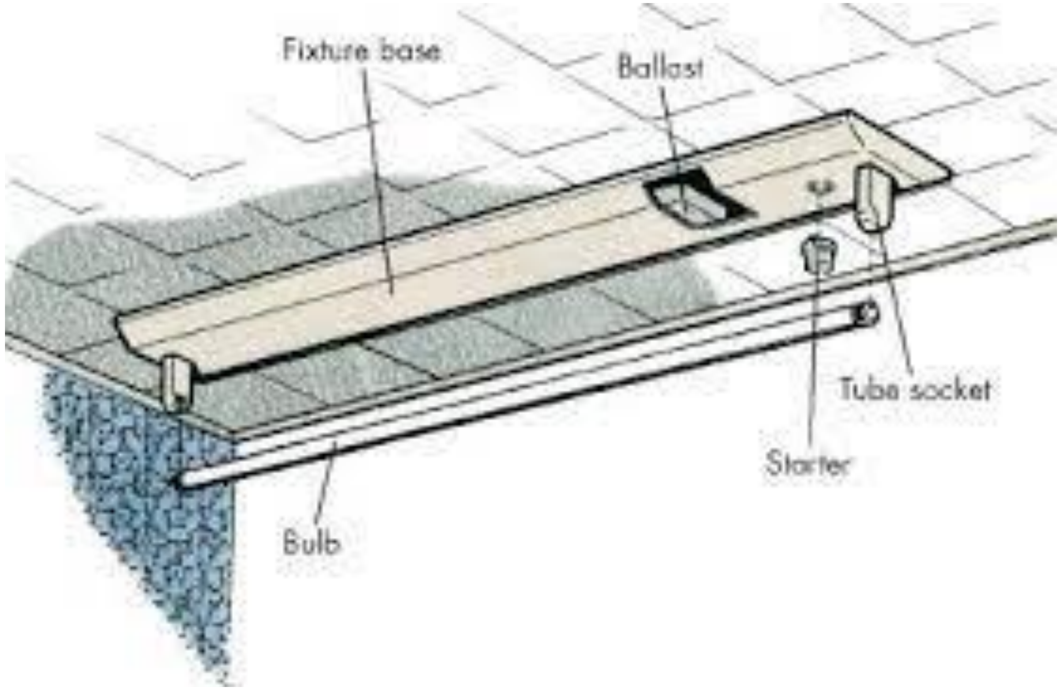
- The relationship between lumens and distance is the amount of lux, which is the illumination intensity of an area.

$$Lux = \frac{lumens}{d^2}$$

- Where, d is the distance between the luminaire and the received surface.



Ballasts



Ballasts

- A **ballast** is required **to start and operate all discharge lamps.**
- Each lamp/ballast combination should have test results which state the **ballast factor (BF)**
- The lumen rating for a lamp is based on a particular lamp/ballast combination with a ballast factor of 1.0.
- The ballast factor indicates the light output of a particular system relative to a standard test ballast on which the lamp lumen ratings are based.
- **For example**, if a four-foot F32T8 has a rated lamp light output of **3000 lumens**, and it is used with a ballast which has a **ballast factor of 1.1** for the lamp/ballast combination, the system produces about **3300 lumens**.
- **Some electronic ballasts can be dimmed**, but they also can produce significant levels of harmonic distortion. When recommending electronic ballasts, specify ballasts with a **total harmonic distortion (THD) less than 15%**.

Maintaining the Lighting System

1. Luminaire Maintenance

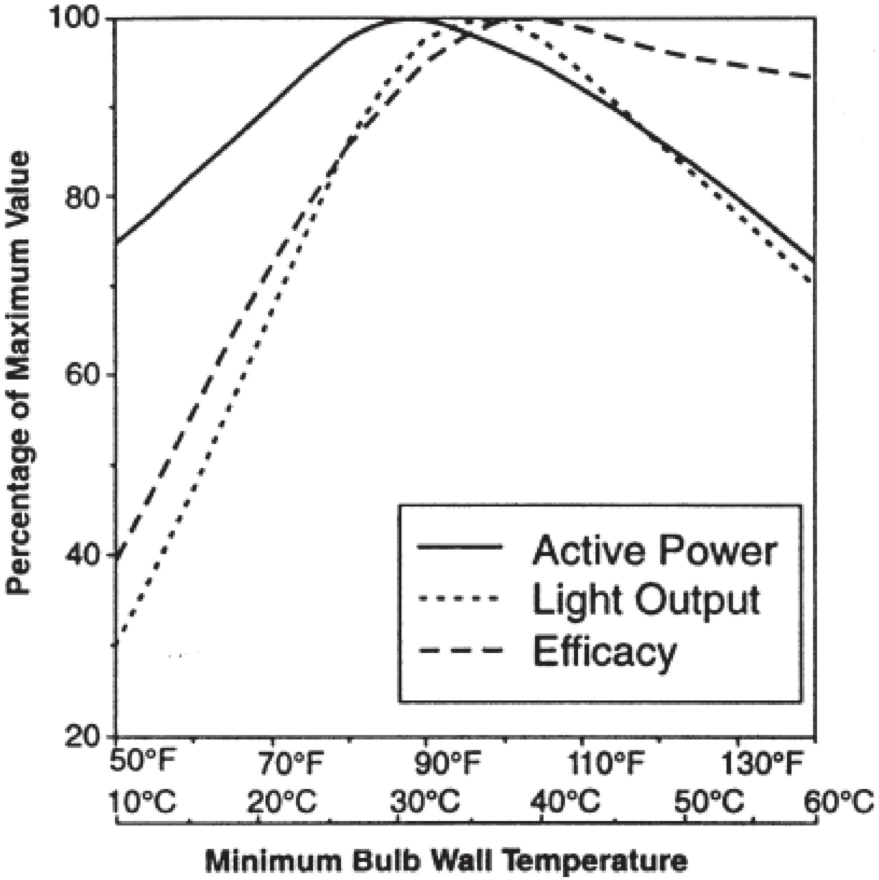
- Maintenance includes both **cleaning and relamping**.
- Dust accumulation on lighting fixtures and on surfaces adjacent to lighting fixtures reduces light utilization by up to 40% and increases heat production.

- Outdoor lighting has some special maintenance problems;

1. Poorly sealed gaskets allow insects to clog the lenses of outdoor lighting fixtures. Dead insects can completely block out light.
2. Overgrown vegetation can also reduce lighting levels from outside fixtures.

- All lamps should be cool before cleaning, and gloves should be worn when cleaning any mirror-like reflective part of a luminaire.

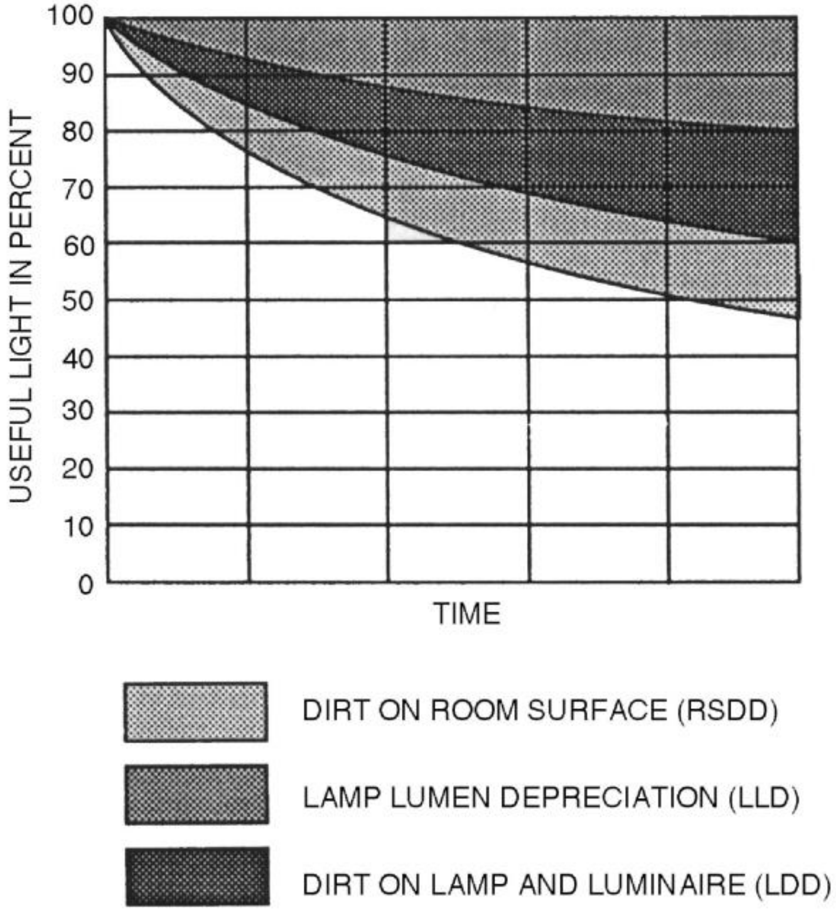
Lamp percentage Vs temperature



Maintaining the Lighting System

2. Establishing the Lighting System Maintenance Schedule

- Lumen maintenance curve for fluorescent lighting systems



Maintaining the Lighting System

2. Establishing the Lighting System Maintenance Schedule

- **Important notes**
  - Lamp life ratings indicate the point at which half of the lamps are likely to have failed.
  - Fluorescent lamp lifetimes are rated at three hours per start; HID lamps are rated at five hours per start. Operating the lamps for shorter periods will reduce lamp life

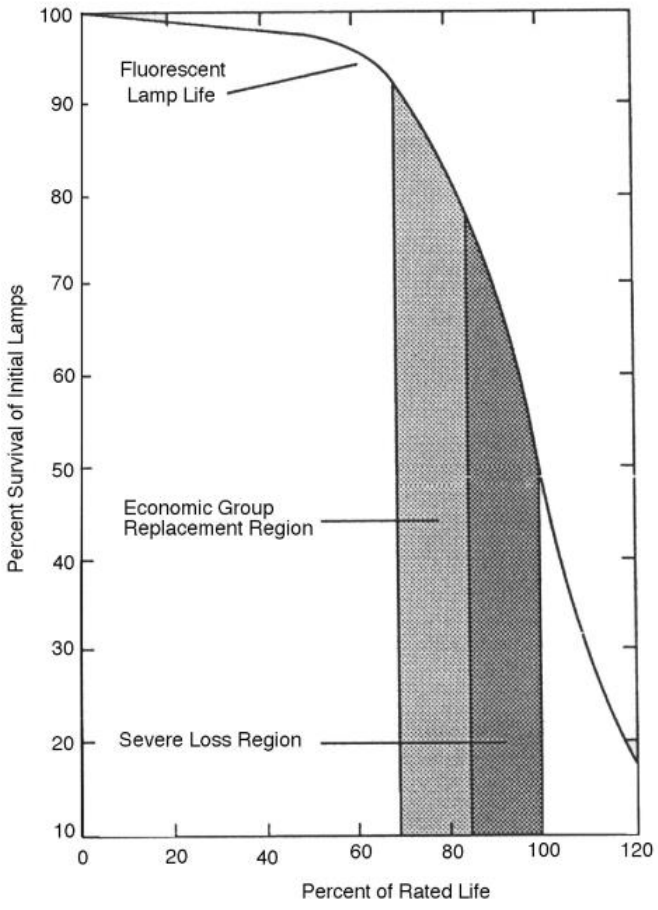
Maintaining the Lighting System

3. Relamping Strategies

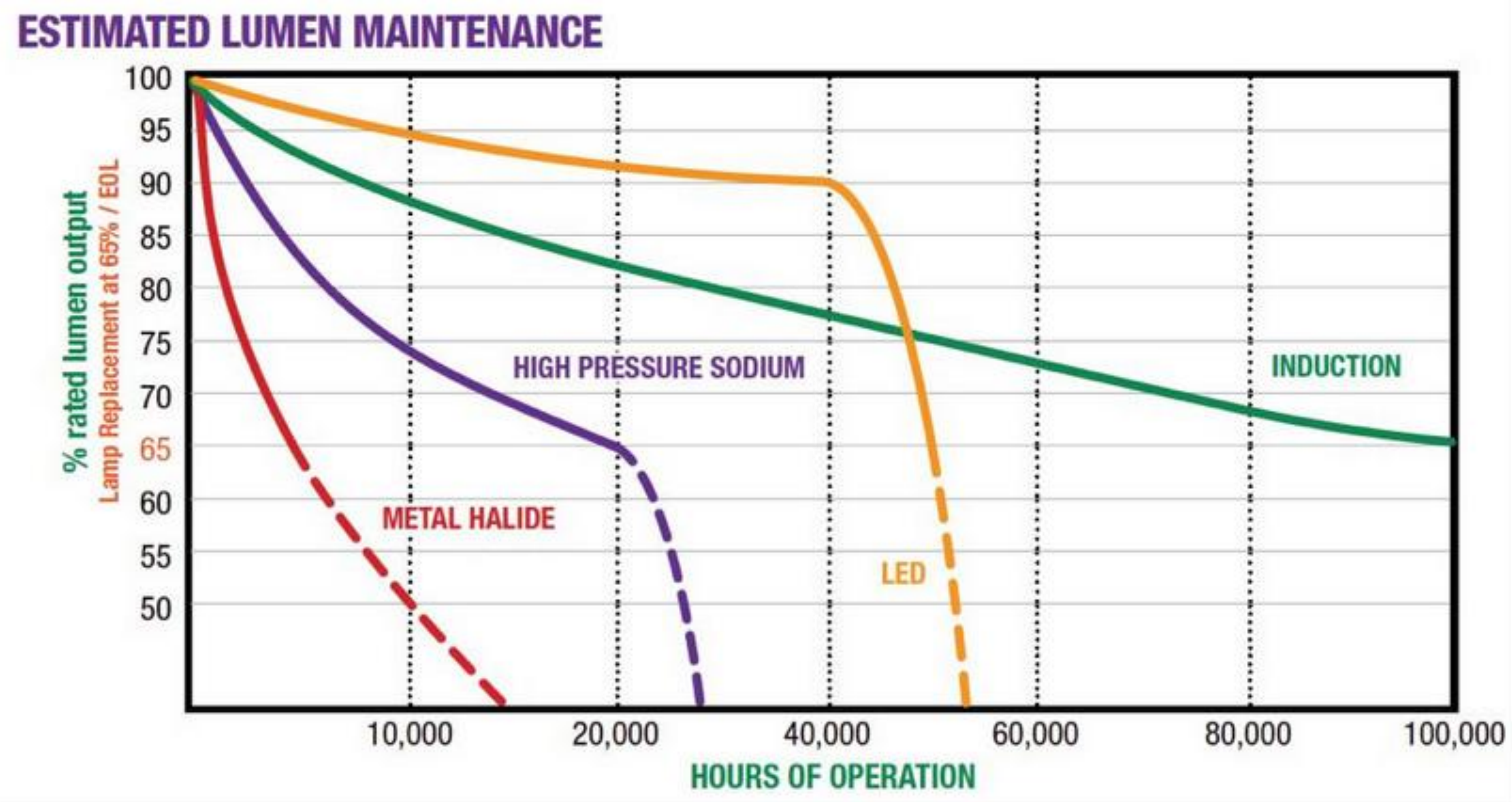
- The usual strategy for replacing lamps in many facilities is to wait until a lamp burns out and then replace it (called **spot relamping**).
- **Spot relamping** does not consider such factors as labor costs or lumen depreciation.
- It is often more economical to replace all of the fluorescent and HID lamps in a facility at one time (called **group relamping**).
- Note that the life of a lamp is measured in hours of use rather than installed hours.
- Lamp mortality at 85-100% of rated life is about twenty-five times that of lamps aged 0-70% of rated life. Therefore, **fixtures should be group relamped when lamps are between 70-80% of the rated lamp life**.

Maintaining the Lighting System

3. Relamping Strategies



Maintaining the Lighting System



Maintaining the Lighting System

Group relamping can:

1. **Reduce labor costs**

Spot relamping can require up to 30 minutes to move furnishings or equipment, set up, replace the lamp, and put equipment away (e.g., ladder, lamps, tools). In group relamping, a fixture can usually be relamped and cleaned in 5 minutes.

2. **Reduce lamp costs (discounts).**
3. **Allow lamp maintenance to be scheduled.**
4. **Maintain higher and more uniform lighting levels.**
5. **Reduce inventory needs.**
6. **Insure the correct lamp use: provides an opportunity to install the newest energy-efficient lamp.**
7. **Extend ballast life.**
8. **Reduce interruptions in work area**.

Relamping Costs

- General Electric has provided the following cost formulas for determining relamping costs:

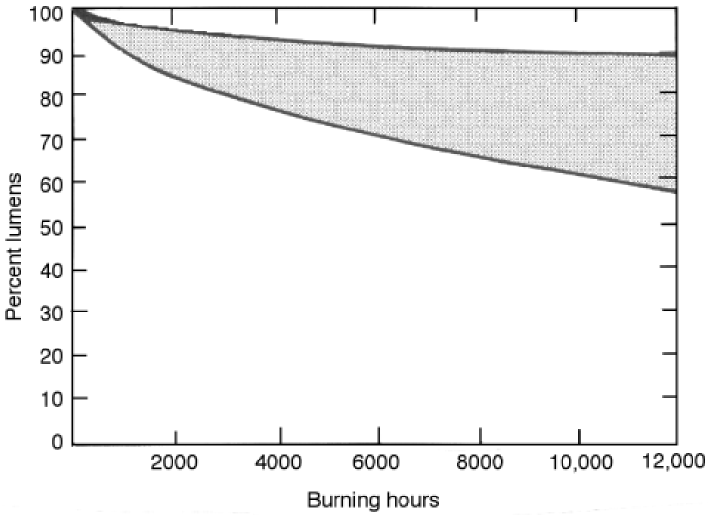
Spot replacement costs: $C = L + S$

Group replacement costs: $C = (L + G) / I$

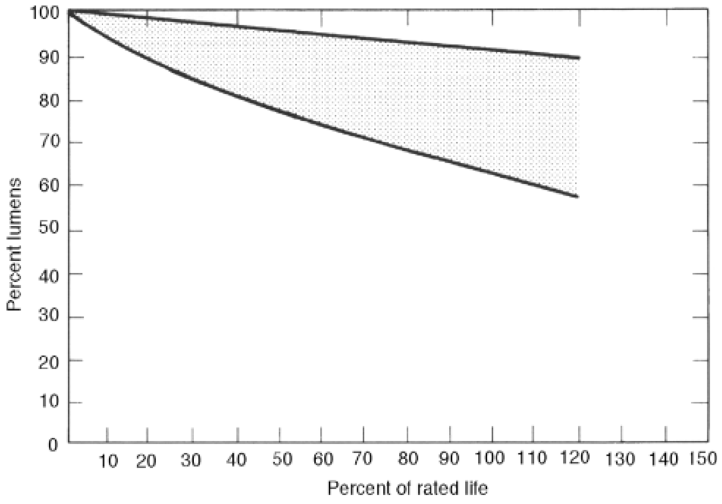
where:

C = total replacement cost per lamp
L = net price per lamp
S = spot replacement labor cost per lamp
G = group replacement labor cost per lamp
I = group relamping interval (% of rated lamp life)

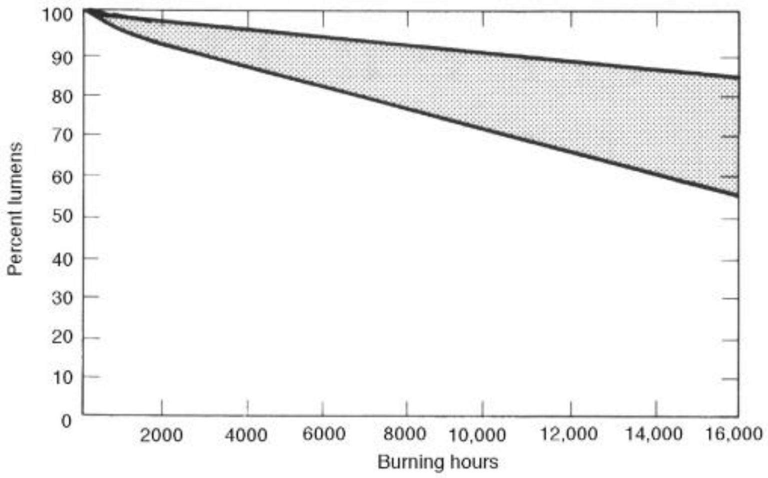
Relamping Strategies



Typical lumen maintenance curve for fluorescent lamps

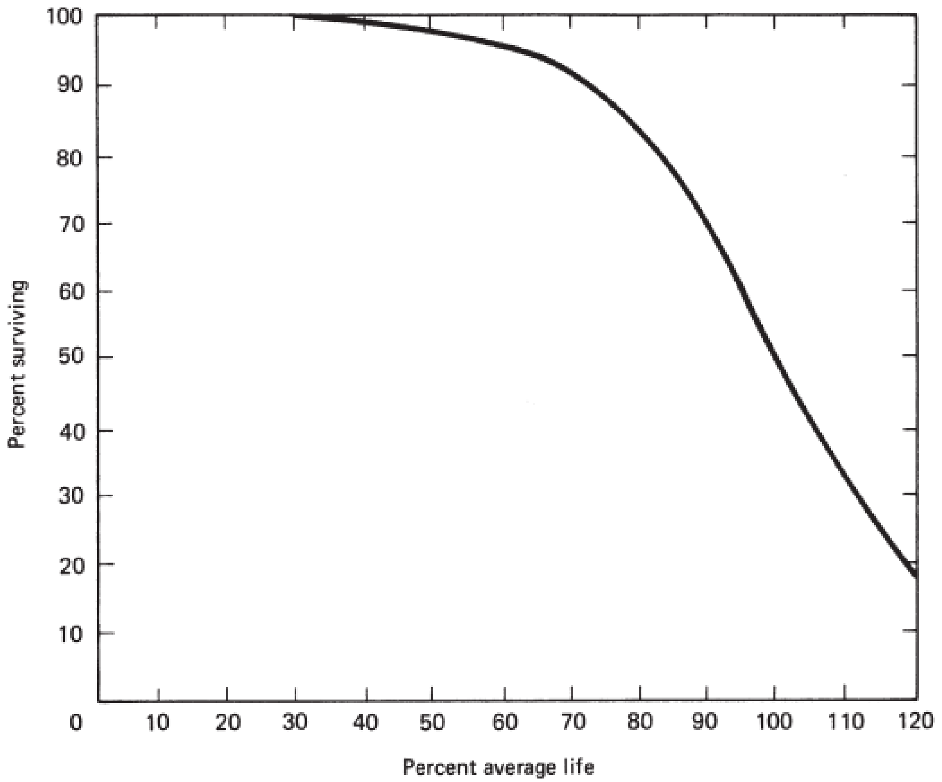


Typical lumen maintenance curve for filament lamps

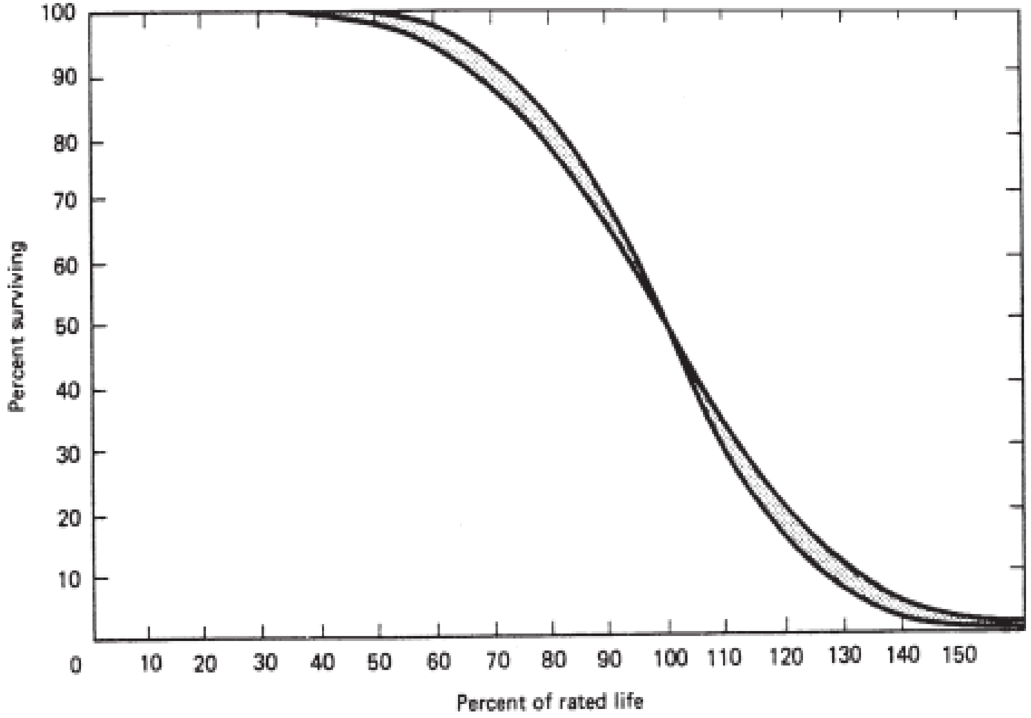


Typical lumen maintenance curve for HID lamps

Relamping Strategies

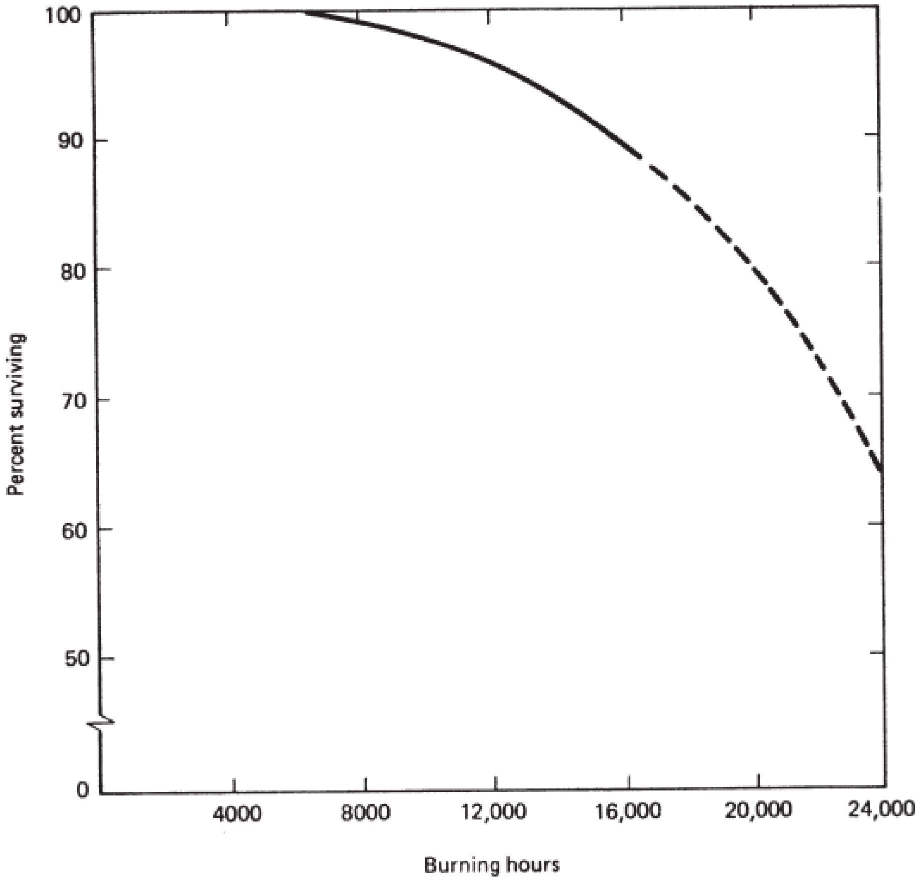


Typical mortality maintenance curve for fluorescent lamps



Typical mortality maintenance curve for filament lamps

Relamping Strategies



Typical mortality maintenance curve for HID lamps

Identifying Potential EMOS

- Lighting is used primarily for workplace illumination, for safety, and for decoration. In each of these uses, the same **three questions** can be asked:
    1. How much light is needed?
    2. How must the light be controlled?
    3. How can lighting be provided most efficiently?

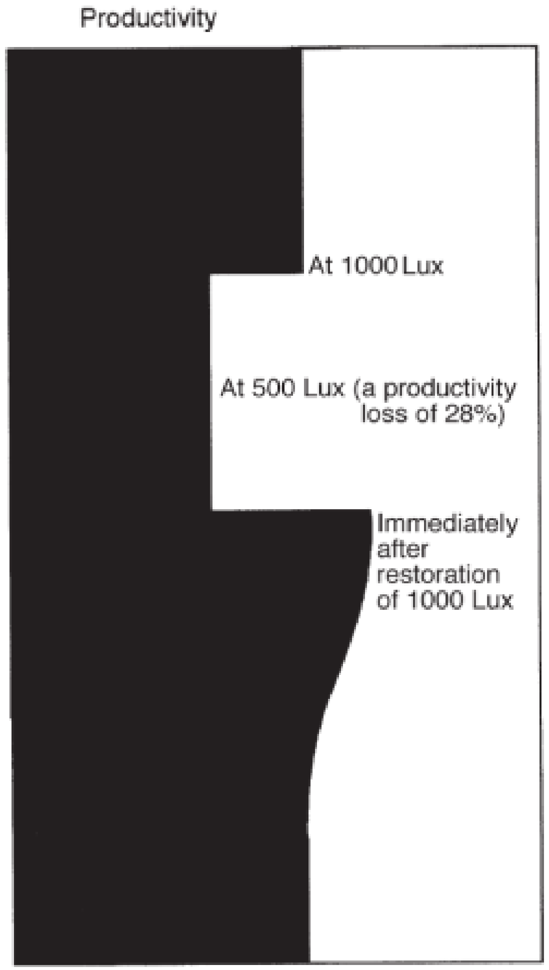
- When examining an existing system of lighting, the answers to these questions can be used to decrease lighting cost and improve lighting efficiency.

Identifying Potential EMOS

- **Two basic surveys should be conducted to look for savings opportunities:**

1. To see how the facility operates while in production.
2. To determine the lighting practices when the facility is dormant or shut down for the night.

- **Lighting improvements provide cost savings in a number of ways:**
    1. Reduced energy use and power demand;
    2. Reduced heat production;
    3. Lower life-cycle lamp costs;
    4. Reduced need for maintenance;
    5. Increases in safety and productivity.



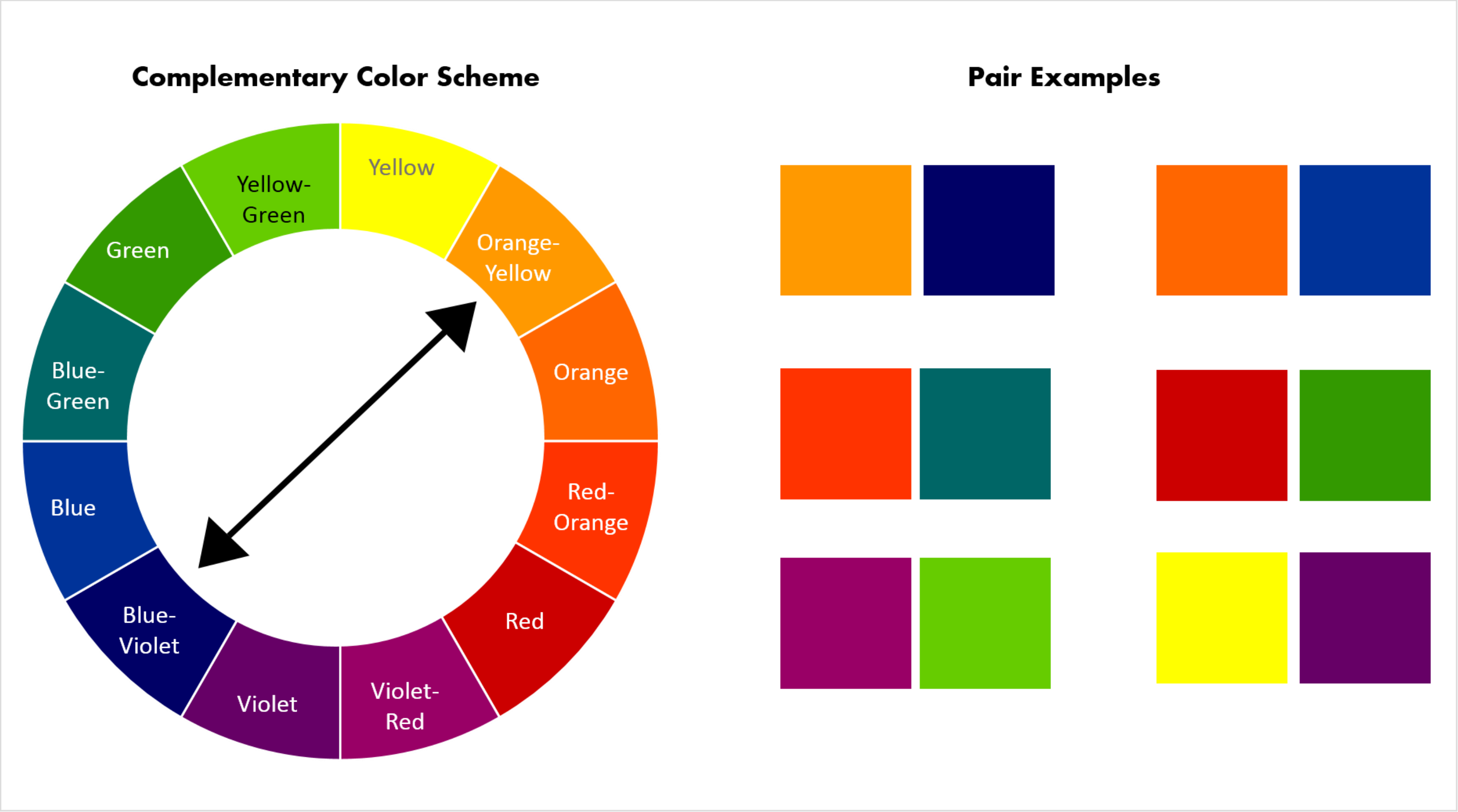
Identifying Potential EMOS

- **In examining the lighting system, the energy auditor should ask three questions:**
  - whether the light is needed;
  - whether the correct amount of light is being used;
  - what is the most cost-effective lighting technology to use to supply the correct amount and quality of light.

- To locate the energy management opportunities, the auditor should specifically:
  - Identify and characterize the visual tasks, and determine the contrast of the work to the surrounding surfaces.
  - Look for the potential to use daylighting and task-specific lighting to displace high ambient, artificial lighting levels.
  - Determine the appropriate lighting levels and the quality of light needed.
  - Select alternative lighting systems to meet the needs, and analyze the cost-effectiveness of each alternative.
  - Select the best alternative to implement.

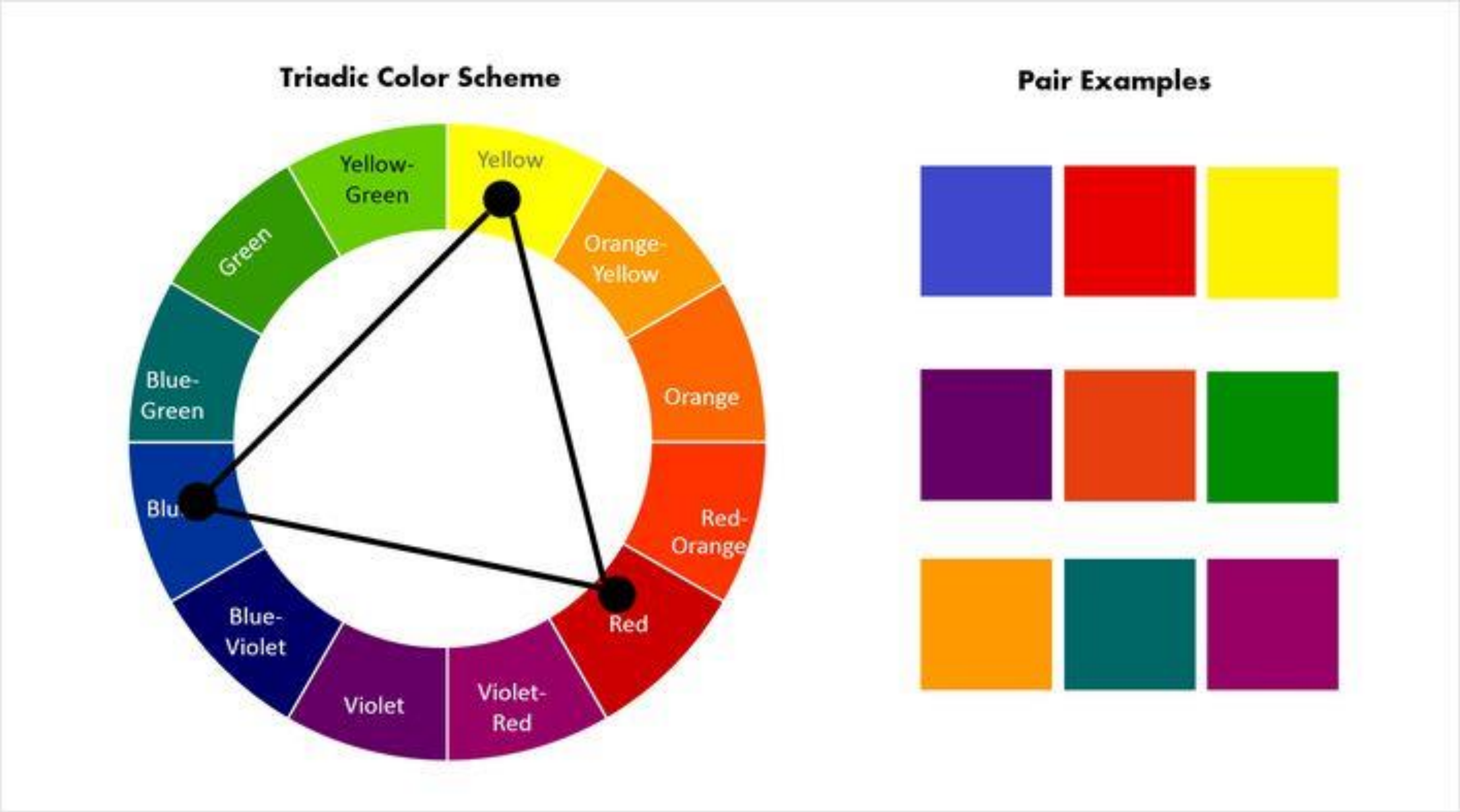
Identifying Potential EMOS

- Contrast



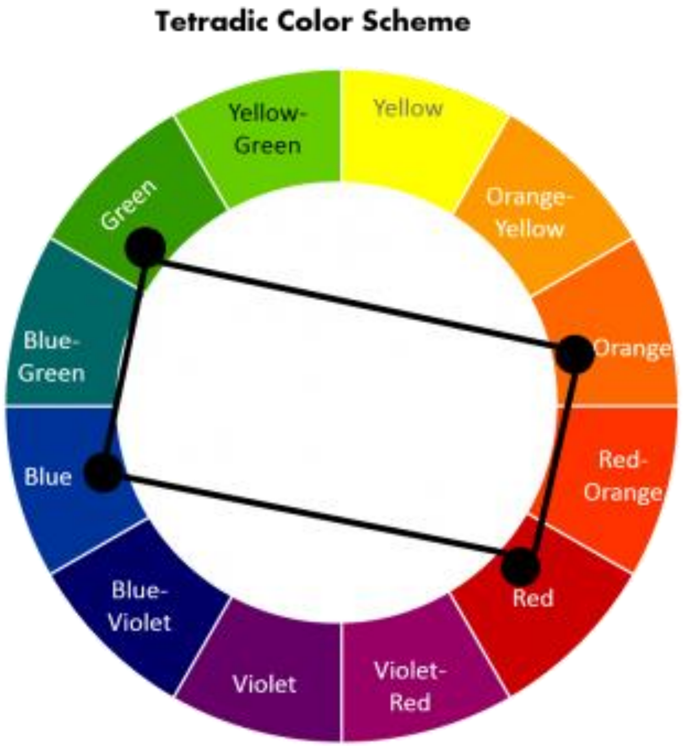
Identifying Potential EMOS

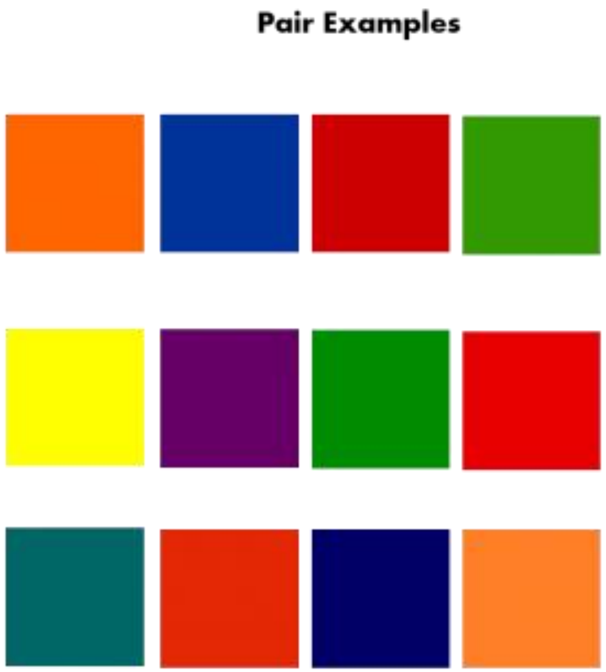
- **Contrast (continued)**



Identifying Potential EMOS

- **Contrast (continued)**





Lighting Survey Example

Location ____________________ Light type (HPS, FL, etc.)______________

Lamps __________

Lighting level (Lux)	No.	Watts Each	Watts Total	% burning	Condition of system* Luminaires	Condition of system* Reflective surfaces

Location	Hours when light is needed	Importance of color rendition	Task lighting possible?	Light levels required (Lux)

Saving Methods

1. Delampling

- Major savings can be obtained by removing some of the lamps that are producing excessive levels of illumination.
- There is usually one ballast for each two fluorescent lamps. The ballast for rapid-start lamps will continue to consume some power even when the lamps are removed. Leaving burned-out lamps in IS (instant start) fixtures reduces ballast life.

2. Task Lighting

- Ambient lighting levels can be reduced when adequate task lighting is supplied for the work.
- Ambient lighting levels of 250 Lux or less are frequently sufficient if the individual work areas have sufficient light from task-dedicated lighting fixtures.

Task Lighting

Saving Methods

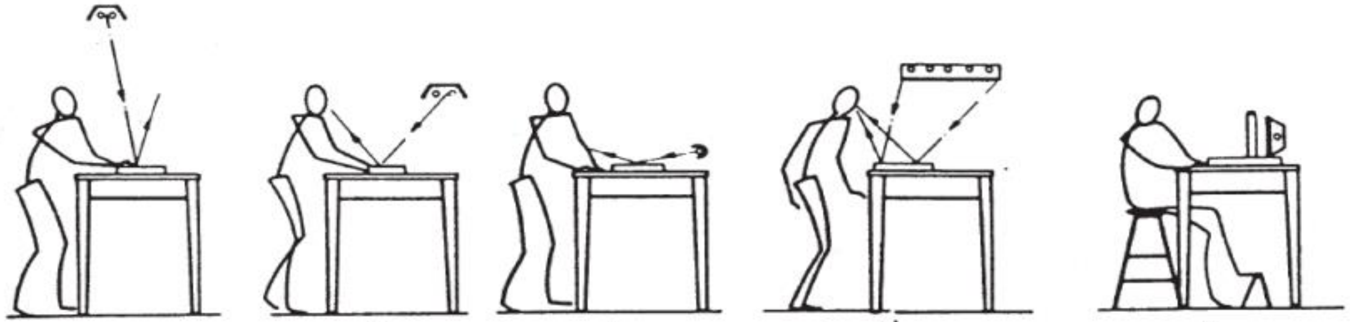


Figure 5-23. Supplementary luminaires [ref 1, Figure 9-11]. Examples of placement of supplementary luminaires: a. Luminaire located to prevent veiling reflections and reflected glare; reflected light does not coincide with angle of view. b. Reflected light coincides with angle of view. c. Low-angle lighting to emphasize surface irregularities. d. Large-area surface source and pattern are reflected toward the eye. e. Transillumination from diffuse source.

Saving Methods

3. Relamping

Replacing existing lamps, ballasts and luminaires with newer, because more energy efficient models offers the potential for significant savings.

4. Ballast

An important part of a lighting system, and each ballast uses from 5 TO 20 %of the power of the lamp it is associated with.

When a lamp is removed from a fixture, the ballast should usually be removed too.

5. Lighting control technologies

Such as: switches, timers, occupancy sensors, and dimmers.

Saving Methods

6. Other lighting EMOs

Exterior lighting (use photocell), daylighting, and environmental factors.

7. Selecting correct lights for a new facility.

Lamp Substitutions

Present lamp	Substitute	Light level	Energy saved (w/%)
60-W In	30-W RI	100%	30/50
(1000 h)	50-W RI	200%	10/16
60-W In	50-W RI	200 + %	10/16
(2500 h)	55-W PAR/FL	200 + %	5/8
75-W In	55-W PAR/FL	150%	20/27
100-W In	75-W IR	125%	25/25
(750 h)	75-W PAR/FL	200 + %	25/25
	75-W ER	200 + %	25/25
100-W In (2500 h)	75-W PAR/FL	100 + %	25/25
150-W PAR/FL	100-W PAR/FL	70%	50/33
150-W R/FL	100-W PAR/FL	150%	50/33
200-W In (750 h)	150-W PAR/FL (2000 h)	200 + %	50/33
30-W F	30-W EEL	87%	5/16
40-W F	40-W EEL	89%	6/15
96-W F	96-W EEL	91%	15/20
96-W F/HO	96-W EEL/HO	91%	15/14
96-W F/SHO	96-W EEL/SHO	90%	30/14
175-W MD	100-W HPS	104%	75/42
400-W MD	200-W HPS	96%	200/50
300-W In	150-W HPS	250%	120/50
750-W In	150-W HPS	104%	570/80
1000-W In	200-W HPS	93%	770/80

[a]Abbreviations:

EEL	energy-efficient fluorescent light (such as Watt-Mizer, Super-Saver, etc.)
ER	elliptical reflector (shape and inside coating of lamp)
F	fluorescent
FL	floodlight
HO	high output: 1000-ma filament
HPS	high-pressure sodium
h	hour (mean life expectancy)
In	incandescent
MD	mercury deluxe: mercury vapor corrected to improve color
PAR	parabolic aluminized reflector (see ER)
RI	reflective coated incandescent
SHO	superhigh output: 1500-ma filament
W	Watt

Lamp Substitutions

Standard Lamp	Replacement Lamp	Wattage Savings[2]	Comparative Light Output of Replacement Lamp[3]	Value of Energy Savings over Life of Replacement Lamp at €0.08/kWh	Other Benefits[4]
60W Incandescent	55W Reduced-Wattage Incandescent	5	=	€0.40	
	13W TT Compact Fluorescent with Ballast Adapter	44.5	+	€35.60	x
75W Incandescent	70W Reduced-Wattage Incandescent	5	=	€0.40	
	22W Circline Fluorescent	45	=	€43.20	x
	18W Compact Fluorescent	57	=	€34.20	
100W Incandescent	95W Reduced-Wattage Incandescent	5	=	€0.40	
	44W Circline Fluorescent	56	=	€33.60	x
75W PAR-38 Spot or Flood Incandescent	65W PAR-38 Spot or Flood Incandescent	10	=	€1.60	
	45W Incandescent (Halogen)	30	=	€4.80	
150W R-40 Flood Incandescent[5]	75W ER-30 Incandescent[5]	75	=	€12.00	
	120W ER-40 Incandescent[5]	30	+ +	€4.80	x
150W PAR-38 Spot or Flood Incandescent	90W PAR-38 Spot or Flood Incandescent (Halogen)	60	=	€9.60	
	120W PAR-38 Incandescent	30	=	€4.80	
300W R-40 Flood Incandescent[5]	120W ER-40 Incandescent[5]	180	=	€28.80	

Regulatory/Safety Issues

- The lighting industry is encountering increasing safety and environmental concerns.
- Some of the materials used in lighting fixtures are, or will soon be, labeled hazardous for disposal.
  - For example, older ballasts and capacitors may contain polychlorinated biphenyl (PCB) oil which should be sent to a facility certified for handling hazardous wastes.
- Fluorescent lamps contain mercury vapor (Hg), antimony (Sb), cadmium (Cd) and other toxic chemicals.
- The new T8 lamps (e.g., 26 mm diameter) use less phosphor material and mercury gas than the conventional T12 lamps (e.g., 38 mm diameter).
- Using T8 lamps should reduce disposal costs and environmental impacts.
- **New T5 lamps (16 mm diameter) are even less of a problem.**

Regulatory/Safety Issues

- Lamps are fragile and break easily.
- Areas subject to vibration or other mechanical stress should be illuminated with durable lamps or with fixtures which have adequate containment for broken lamps within the fixture housing.
- Delamping inexpensive fluorescent lighting fixtures can also be hazardous if the lamp pins come in contact with the fixture housing. Insulation placed on top of lighting fixtures recessed in the ceiling may pose a fire hazard unless the fixture is rated for insulation contact.
- The insulation can increase the operating temperature of the lamps and ballasts of fluorescent or high intensity discharge (HID) fixtures, which will reduce the lifespan of all the system components.
- HID lamps have arc tubes which operate at high temperatures. Pieces of hot arc tube can fall from the fixture if the lamp wall is fractured. Some manufacturers recommend using lenses or fixture housings capable of containing incendiary materials.

Part VIII: Electric Motors and Drives

Introduction

- Electric motors, taken together, make up the single largest end use of global electricity.
- Despite these advantages, however, they can be costly to operate if they are not properly selected and maintained.
- motors that typically run at more than one-half to full load usually operate much more efficiently than they do at less than one-half load.
- The annual cost of operating a motor can often be five to ten times the original purchase price of the motor.

Electric Motors

- Electric motors are devices that convert electrical energy into rotary mechanical energy.
- **Motors can be purchased to operate on AC or DC power**.
- Most AC motors are induction motors, which are simpler, lighter and cheaper than the alternative—an AC synchronous motor.
- Motors account for almost half of all electricity used in the world.
- Electric motor output is in **units of kW**.

Electric Motors

Motors	46%
Lights	19%
Heat	19%
Electronics	10%
Electrolysis	3%
Standby	3%

Figure 7-1 Shows estimated share of global electricity demand by end use in 2006 Source A&B International, 2009

Electric Motors

Industrial	68.9%
Transportation	60%
Commercial	38.3%
Residential	20-25%
Agricultural	20-25%

Figure 7-2 Global Electric Use by Motors Sector (approximate) Source: DeAlmeida et al, A&B International, 2009 www1 cetim fr/eemods09/ pages/programme/038-Brunner-final.pdf

Electric Motors

Compressors	32%
Mechanical movement	30%
Pumps	19%
Fans	19%

Fig 7-3 Estimated Share of Global Motor Electricity Demand by Applications Source: DeAlameida et al, 2008, A&B International, 2009 www ecomotors.org/files/lot11-Motors_1-8-280408_final.pdf

AC Induction Motors

- The majority of electric motors in use today draw less than 0.75 kW of power in a variety of small applications, mostly in the residential and commercial sectors, These motors account for about 9% of all global electric motor power consumption.

- The largest motor electricity consumption is from mid-sized AC induction motors with a range of output power of 0.75 kW to 375 kW.

- Almost all AC induction motors over 1 kW use three phase power.

Speeds of Induction Motors

- **Synchronous Speed**

The no-load speed of an AC induction motor.

- Since without any load, the speed of the induction motor is keyed to the electrical power line frequency.
- Thus, the synchronous or no-load speeds of AC induction motors are always multiples of 50 in most of the world, and multiples of 60 in North America and some of the other countries.
- Some care must be taken in understanding this definition, since one might conclude that induction motors are also synchronous motors. This would be a mistake, **since synchronous motors are physically very different from induction motors**.
- All induction motors have a rating which is the no-load—or synchronous speed—but this does not make them synchronous motors.
- To calculate RPM for an AC induction motor, you multiply the frequency in Hertz (Hz) by 60 — for the number of seconds in a minute — by two for the negative and positive pulses in a cycle. You then divide by the number of poles the motor has:

(Hz x 60 x 2) / number of poles = no-load RPM

AC Induction Motors

- **Example**
- For a 50 Hz motor with 2 poles, or one pole pair, the speed would be:

  rpm = 50 x 60 / 1 = 3000 rpm

- For a 50 Hz motor with 4 poles, or two pole pairs, the speed would be:

  rpm = 50 x 60 / 2 = 1500 rpm

AC INDUCTION MOTORS

- **Full Load Speed**—The full load speed of a motor is stamped on the nameplate, and is 2-3% lower than the no load or synchronous speed.
  - — For a 1500 rpm motor, the full load speed might be 1460 rpm.

- **Slip**—Slip is the term for the difference between the synchronous speed of a motor and the actual speed of the motor at any time.
  - The full load slip is the largest value, and it is the difference between the synchronous speed and the full load speed.
  - For a 1500 rpm motor, the full load slip is around 40 to 50 rpm.

AC INDUCTION MOTORS

- **Efficiency, Power Factor and Load Factor of AC Induction Motors**
  - *Efficiency*
    - Larger motors usually have higher efficiencies than smaller motors.

$$\boldsymbol{Efficiency = \frac{Mechanical\ Power\ output}{Electrical\ Power\ Input}}$$

- **Example**
  - A motor delivers a shaft output power of 20 kW, and has an electrical power input of 23 kW. What is its efficiency?

AC INDUCTION MOTORS

- **Typical efficiency** of mid-size AC induction motors is **87% to 92%.**

- Most countries have **increased the efficiencies** of their larger AC induction motors in the last ten years. The efficiencies of these motors is **91% to 95%.**

- The European Union has greatly increased their efficiencies of mid-sized AC induction motors, and these efficiencies are shown in following Table.

- Nominal efficiency is the average efficiency obtained by testing a representative group of motors; and minimum efficiency accounts for the lowest efficiency of the group of motors tested.

AC INDUCTION MOTORS

kW2 pole	4 pole 50 HZ/60 HZ	6 pole 50 HZ/60 HZ	50 HZ/60 HZ
0.75	80.7/77.0	82.5/85.5	78.9/82.5
1.1	82.7/84.0	84.1/86.5	81.0/87.5
1.5	84.2/85.5	85.3/86.5	82.5/88.5
2.2	85.9/86.5	86.7/89.5	84.3/89.5
3	87.1/-	87.7/-	85.6/-
3.7	-/88.5	-/89.5	-/89.5
4	88.1/-	88.6/-	86.8/-
5.5	89.2/89.5	89.6/91.7	88.0/91.0
7.5	90.1/90.2	90.4/91.7	89.1/91.0
11	91.2/90.0	91.4/92.4	90.3/91.7
15	91.9/91.0	92.1/93.0	91.2/91.7
18.5	92.4/91.7	92.6/93.6	91.7/93.0
22	92.7/91.7	93.0/93.6	92.2/93.0
30	93.3/92.4	93.6/94.1	92.9/94.1
37	93.7/93.0	93.9/94.5	93.3/94.1
45	94.0/93.6	94.2/95.0	93.7/94.5
55	94.3/93.6	94.6/94.4	94.1/94.5
75	94.7/94.1	95.0/95.4	94.6/95.0
90	95.0/95.0	95.2/95.4	94.9/95.0
110	95.2/95.0	95.4/95.8	95.1/95.8
132	95.4/-	95.6/-	95.4/-
150	-/95.4	-/96.2	-/95.8
160	95.6/-	95.8/-	95.6/-
185	-/95.8	-/96.2	-/95.8
200	95.8/-	96.0/-	95.8/-
220	95.8/95.8	96.0/96.2	95.8/95.8
250	95.8/95.8	96.0/96.2	95.8/95.8
300	95.8/95.8	96.0/96.2	95.8/95.8
330	95.8/95.8	96.0/96.2	95.8/95.8
375	95.8/95.8	96.0/96.2	95.

AC INDUCTION MOTORS

- The European Union adopted a set of electric motor efficiencies called the Unifying worldwide efficiency classifications, which was defined by **IEC 60034-30** specifies electrical efficiency classes for single-speed, three-phase, 50 Hz and 60 Hz, cage-induction motors that:
  - have 2, 4, or 6 poles (3,000; 1,500; and 1,000 RPM at 50 Hz)
  - have rated output between 0.75 and 375 kW
  - have a rated voltage up to 1000 V
  - are rated on the basis of either duty type S1 (continuous duty) or S3 (intermittent duty) with a rated cyclic duration factor of 80% or higher.
- The following table shows the IEC 60034-30 (2008) efficiency classes and comparable efficiency levels.

AC INDUCTION MOTORS

Table 7-1 IEC Efficiency Classes & Comparable Efficiciency Levels

	Efficiency Levels	*Comparison*
IE1	Standard efficiency	
IE2	High efficiency	For 50 Hz considerably higher than EFF2 of CEMEP and identical to the U.S. EPAct for 60 Hz
IE3	Premium efficiency	New efficiency class in Europe for 50 Hz, higher than EFF1 on CEMEP and with some exceptions identical to NEMA Premium in the United States for 60 Hz.

AC INDUCTION MOTORS

- ***Power Factor (PF or Cos Phi)***

$$PF = \cos(Phi) = \frac{kW}{kVA}$$

- Larger motors usually have higher power factors than smaller motors. Larger motors will usually have power factors (or Cos Phi) around 85%.

AC INDUCTION MOTORS

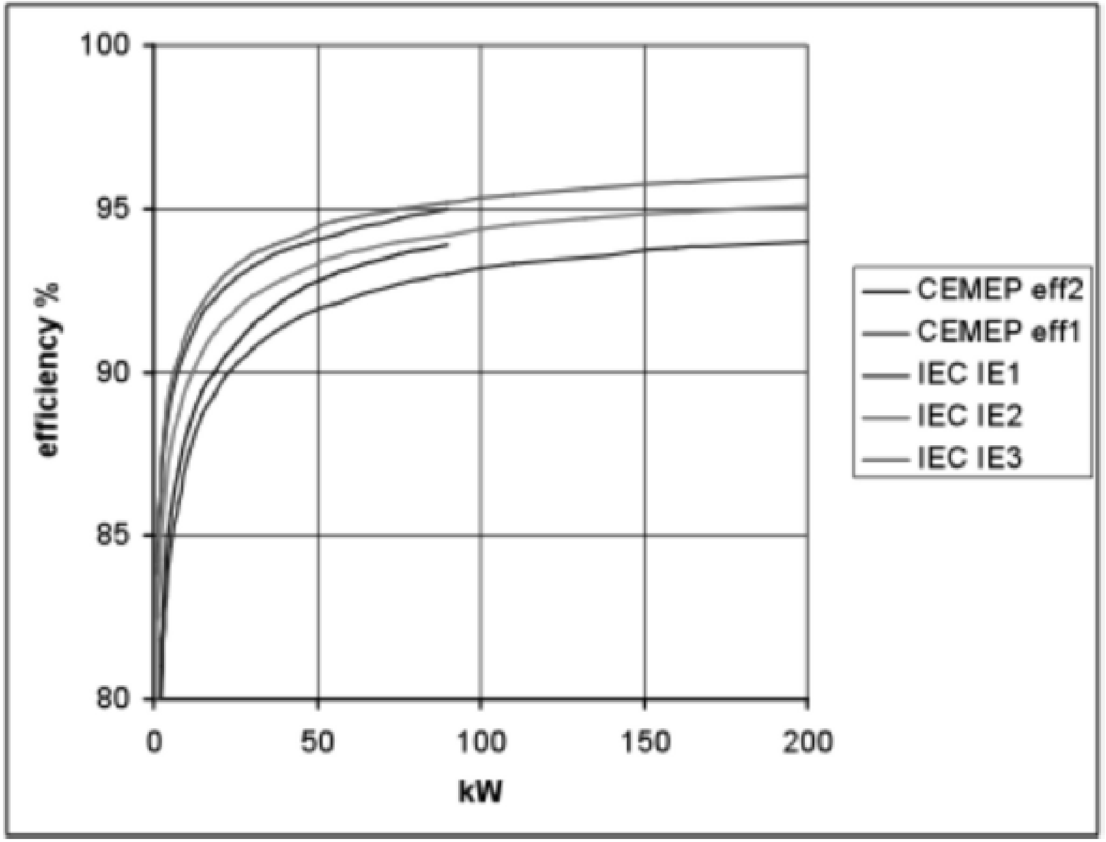


Figure 7-4 Shows how the European Union standards have improved the energy efficiency of mid-sized AC induction motors over time.

AC INDUCTION MOTORS

- **Example :**

A three-phase, 380-volt motor is drawing 80 amperes. and a real power of 45 kW. What is the power factor or Cos Phi of the motor?

AC INDUCTION MOTORS

Load Factor (LF)

- The load factor is **a mechanical operating parameter of a motor**, and is found from the ratio of the actual shaft power being provided to the maximum shaft power that could be provided by the motor.
- A motor is what we call a “load driven device.” This means that the motor only provides the exact amount of power required by the load. If the load on a 20 kW motor is a fan requiring only 10 kW to drive it, the load factor on the motor is 10 kW/20 kW, or 50%.
- The **input power to the motor will only be what is needed to drive the actual load**—and most often it will not be the full rated load power of the motor.
- **Typical motor load factors on an annual basis are in the range 40-60%.**

AC INDUCTION MOTORS

- A common assumption made by many energy auditors and analysts is that motor load factors are around 80%. This value is rarely seen in many motors other than those specifically sized for known maximum loads in heating, ventilating and air conditioning systems for buildings.
- In most other applications, motors experience variable loads that average well below 80%.
- Pumps and fans with variable loads are usually ideal candidates for use of variable speed drives to reduce the energy input when the motor load is low.

$$kw = \frac{NPkW \times LF}{efficiency}$$

AC INDUCTION MOTORS

- **Example**

A 40 kW motor is connected to a 25 kW fan. What is the load factor of the motor?

POWER INPUT TO AC INDUCTION MOTORS

$$P = \sqrt{3} \times V \times I \times PF \text{ (or Cos Phi) watts}$$

$$\text{Or, } P = \sqrt{3} \times kV \times I \times PF \text{ (or Cos Phi) kW}$$

$$P_{in} = \frac{NPkW \times LF}{efficiency}$$

- **Example**

A 50 kW motor with an efficiency of 89% is operating at a load factor of 70%. What is the input power in kW to the motor?

MOTOR NAMEPLATE DATA

- **Typical Nameplate Data**
  - kW Shaft power design- output).
  - FLRPM (running RPM at design load).
  - FLA full load amps (amps at design load and voltage).
  - Volts (design voltage).
  - Efficiency (test vs. guaranteed).
  - Service factor.

MOTOR NAMEPLATE DATA

Parameters of the motor operation that may not commonly be-found on motor nameplates, but are still useful information that might help us:

- **NLRPM** (synchronous speed as 1500 or 3000 rpm for 50 Hz motors)
- **LRA** – Locked rotor amps. This is a test value for the motor, but it is useful for knowing the maximum starting current surge into the motor.
- **Service Factor**—A multiplier on the nameplate horsepower of the motor. This tells how much overload the motor can safely handle on a short-term basis.
- **Maximum capacitor size**

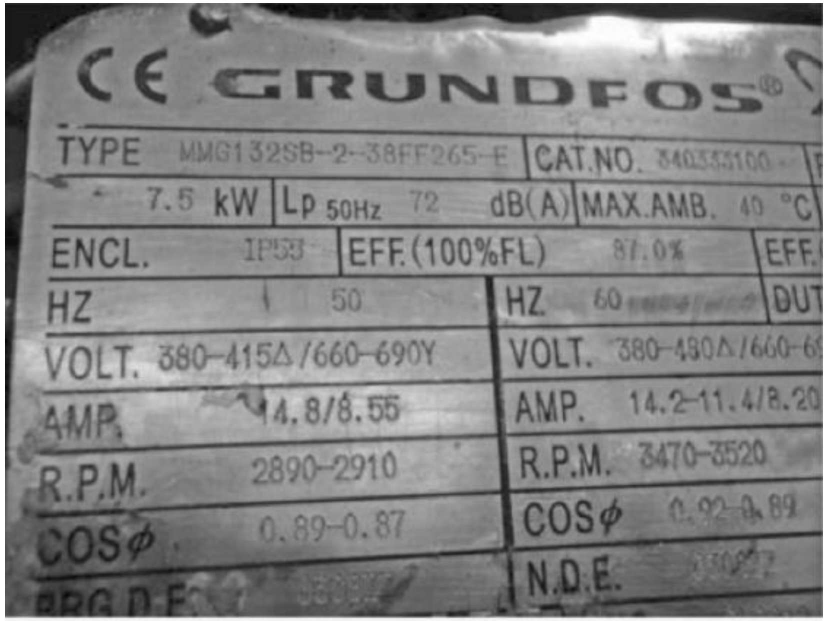


Figure 7-5 Motor nameplate

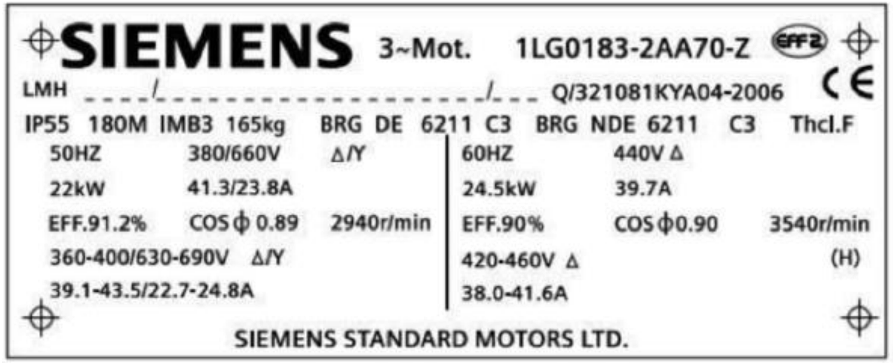


Figure 7-6
More information is shown on this nameplate for a Siemens motor

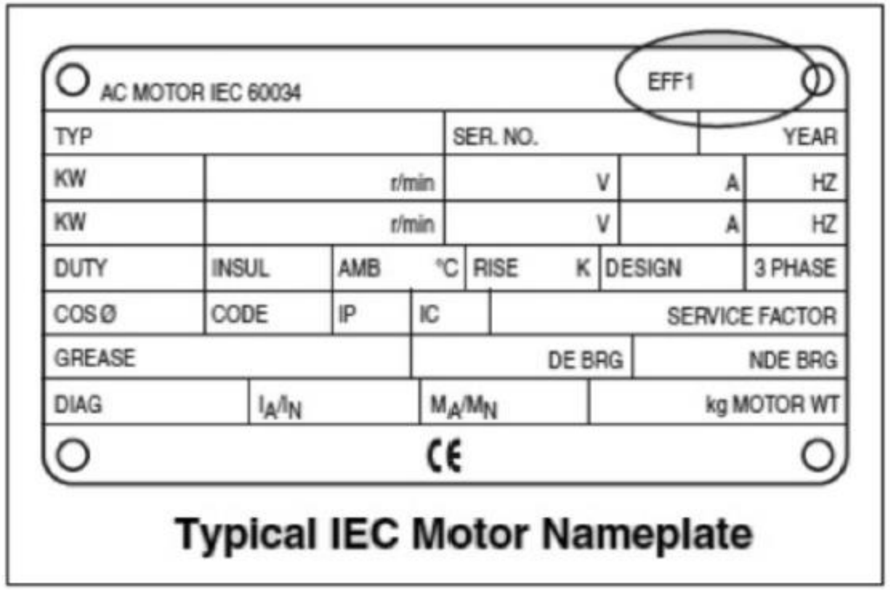


Figure 7-7 Typical IEC Motor Nameplate

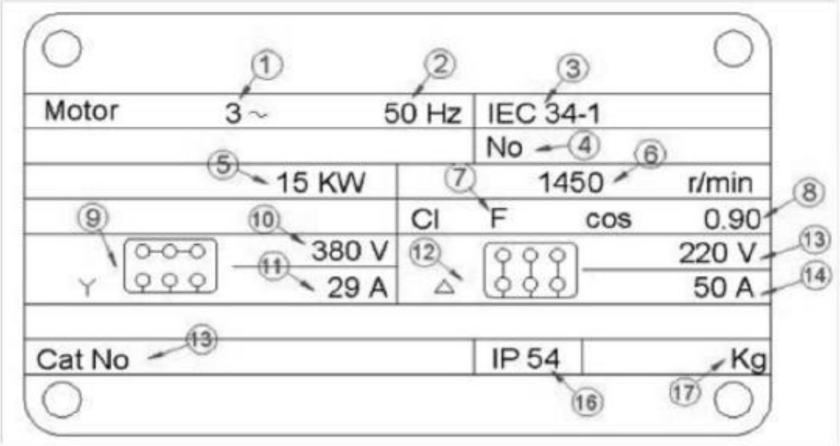


Figure 7-8

SAVINGS FROM INSTALLING MORE EFFICIENT MOTORS

$$P_{saving} = kW_e = \left(\frac{kW \times LF}{Eff}\right)_{Stan} - \left(\frac{kW \times LF}{Eff}\right)_{EE}$$

- This formula allows us to solve examples where both the motor kW changes and the motor efficiency changes.
- Since all parameters except efficiencies are the same, kW savings equals:

kW = (kW x LF) x [(1/old efficiency) – (1/new efficiency)]

SAVINGS FROM INSTALLING MORE EFFICIENT MOTORS

- **Example**

A 20 kW enclosed motor with a load factor of 70% and an efficiency of 87.5% will be replaced by a new 20 kW enclosed motor operating at the same load factor, but will now have a higher efficiency of 91%. How many kW of power savings will be obtained from this project?

Example

Ace Industries has a 50 kW air compressor that operates at full-load (LF = 1), all day for 365 days per year. If the motor for the air compressor cost €1400, the motor efficiency is 90%, and electricity costs €7.00/kW/ month and €0.10/kWh, how much does it cost to operate the air compressor for one year? How much money will be spent to operate the air compressor over a ten-year period?

SAVINGS FROM INSTALLING MORE EFFICIENT MOTORS

- **Example**

ACE Industries has been experiencing a period of rapid growth in the success of their products, and they plan to expand their production capacity by building a second plant nearby. They determine that they need another 50-kW air compressor which will also run continuously at full load. They can purchase either the Standard or the Deluxe Model air compressor with the difference being that the Deluxe Model has a high efficiency motor. The motor efficiency for the Standard Model is 91.5%, and for the Deluxe Model it is 93.8%. The additional cost for the Deluxe Model is €470. Is this a good investment for ACE Industries?

ACE Industries also wants to know what kind of "cushion" they have on this decision, since their forecast for new business could be too optimistic. If the new air compressor will only run for two shifts a day, for a total of 5000 hours per year, is the additional investment still worthwhile?

REWINDING ELECTRIC MOTORS

- There are three options available for a facility that has just experienced a motor failure:
    1. they can buy a NEMA Premium efficiency motor to replace the failed one.
    2. they can buy a higher efficiency replacement.
    3. they can send the failed motor out to be repaired, and potentially rewound.

- **The cost of rewinding a motor is often about 60% less than the cost of purchasing a new motor**, whether it is a NEMA Premium efficiency model or a higher-efficiency model.
- **It is fairly common for motors to be damaged during the rewinding process, and to suffer losses in efficiency of 1-2%.**
- **Example**

Showed the economic impact of a 2.3% point difference in motor efficiency. Often, a 1% point loss in efficiency will result in the cost of the additional electricity being greater than the total cost of rewinding. Thus it is important to consider this factor when replacing a motor.

- Not all rewinding operations damage motors, but the loss of efficiency is quite common.

MOTOR DRIVES TO REDUCE MOTOR SPEEDS

- The operating speed of an AC motor depends on:
  1. the rotor type
  2. the number of poles
  3. the frequency of the power supply
  4. slip characteristics.

- Most induction motors operate within 1% to 3% of this speed, depending on the motor's slip characteristics. Common synchronous speeds are **3000, 1500, 1000, 750, and 500 rpm.**

- Many applications require speeds different from these, however, so motors are usually combined with various types of speed adjustment devices. **These devices include gears, belts, eddy-current couplings, hydraulic couplings, variable frequency drives (VFDs),** etc.

MOTOR DRIVES TO REDUCE MOTOR SPEEDS

- **For example**, in many pumping system and fan system applications, flow is controlled by using restrictive devices, such as throttle valves or dampers, or bypass methods. Although these flow control methods have advantages, speed control is often a more efficient and cost-effective option for many systems.
- Similarly, in many material handling systems, **variable speed drives can increase system efficiency and improve system reliability.**
- **For example**, in many conveyor systems, lines are controlled by energizing and de-energizing a series of motors. These frequent starts and shutdowns are tough on motors and line components because of repeated stresses from starting currents and acceleration and deceleration of mechanical components.
- Using variable speed drives can smooth out line motion for more efficient and effective operation. The advantages and benefits of motor speed control include **lower system energy costs**, **improved system reliability, fewer maintenance requirements, and more effective process control**.

USING VARIABLE FREQUENCY DRIVES (VFDS)

- They are highly efficient, reliable, and flexible, and motor users can bypass them for maintenance or repairs without having to take the motor out of service.

- They are not recommended for all motor/drive applications, so understanding their performance and application is essential in deciding whether to use them.

- VFDs are used in a wide range of applications, including fluid (gas and liquid) systems, material handling systems, and machining and fabrication processes.

- Another common method of controlling speed is to use induction motors combined with VFDs.
- However, not all in-service induction motors can be combined with a VFD; engineers should evaluate motors case-by-case to see if such combinations are feasible. Misapplying VFDs to in-service motors can quickly cause motor failures.

Example

In one industrial application, three cyclone fans used for ventilating stack gases were replaced with one larger fan motor having a VFD. The cost of the new fan, motor, and installation of new ductwork was €18,250. The cost of the VFD was €20,000. The electrical consumption from the new system dropped 500,000 kWh/yr from that of the old fan system. If the facility paid €0.061/kWh, determine the cost-effectiveness of this EMO.

CENTRIFUGAL FAN AND PUMP LAWS

- Much of the biggest energy savings using VFDs comes from applications using centrifugal fans for air based systems, and centrifugal pumps for water based systems, particularly those for HVAC systems.

- When we use centrifugal fans (squirrel cage fans) and centrifugal pumps (pumps with impellers) we have a rather strange relationship between speed, flow, and power.

- Sometimes called the affinity laws for fans and pumps.

CENTRIFUGAL FAN AND PUMP LAWS

Flow and Speed where LPS is liters per second

$$\frac{LPS_{new}}{LPS_{old}} = \frac{RPM_{new}}{RPM_{old}}$$

Pressure(or Head) and Speed where P is total differential pressure or head pressure in Pascals

$$\frac{P_{new}}{P_{old}} = \frac{[RPM_{new}]^2}{[RPM_{old}]^2} = \frac{[LPS_{new}]^2}{[LPS_{old}]^2}$$

Power or Speed where power in is kW

$$\frac{kW_{new}}{kW_{old}} = \frac{[LPS_{new}]^3}{[LPS_{old}]^3}$$

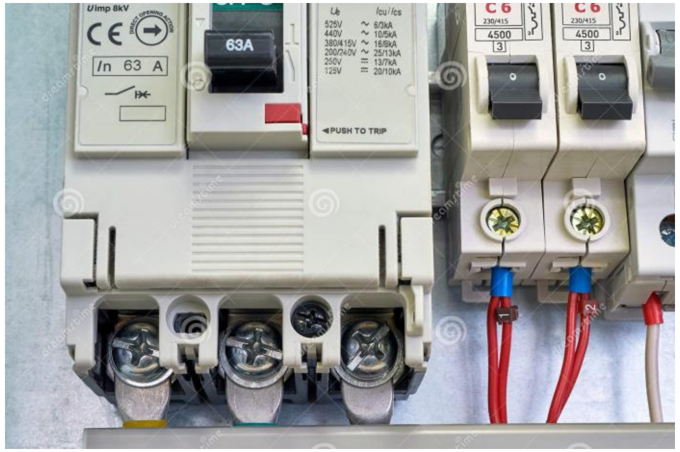
Figure 7-9. Centrifugal Fan or Pump Laws or Affinity Laws

CENTRIFUGAL FAN AND PUMP LAWS

- **Example:** A 5 kW centrifugal pump is used on a chilled water line to supply the largest L/s (LPS) flow needed on the hottest day of the year, and runs at 1400 RPM. On a mild day, only 60% of the maximum L/s (LPS) is needed. Answer the following questions:

1. **What is the new speed of the motor to supply 60% of the L/s (LPS)?**
2. **What is the head pressure to supply 60% of the LPS?**
3. **What is the new kW needed to supply 60% of the LPS?**

How to Audit Electric Motors?



How to Audit Electric Motors?

Part IX : Insulation

Introduction

- Good engineering design of **insulation** systems will **reduce undesirable heat loss or gain by at least 90% in most applications and will often improve environmental conditions at the same time.**

- The two basic areas of insulation applications are buildings and process equipment.

Insulation Theory

- In our discussion of the **theory of insulation**, we cover the topics of **heat transfer**, **thermal conductivity**, and **thermal resistance**.

- The discussion of **heat transfer** explains the three ways that heat is moved into or out of a material.

- **Thermal conductivity** relates to the material itself and the ease with which heat moves through the material.

- **Thermal resistance** is the inverse of thermal conductivity, and relates to how well a given material will block or retard the movement of heat through it.

- We also develop the heat transfer calculations for flat surfaces and for cylindrical surfaces such as pipes.

Insulation Theory

- There are **three basic modes of heat transfer**. They are conduction, convection, and radiation.
  - **Conduction** is the transfer of heat from a hot side to a cooler side through a dividing medium. The hot side heats the molecules in the dividing medium and causes them to move rapidly, heating the adjacent molecules until the cool side is heated. The transfer stops when the temperature of the hot side equals that of the cool side.
  - **Convection** is the transfer of heat between a moving liquid or gas and some conducting surface. Usually the heated fluid rises, causing cooler fluid to come in contact with the conducting surface, which is then heated and rises, etc.
  - **Radiation** is the transfer of heat based on the properties of electromagnetic waves so no transfer medium is necessary. For example, the sun heats by radiation.

Insulation Theory

- The **thermal conductivity (K)** of a material is a physical property that describes the ability of the material to conduct heat.

- K is measured by the amount of energy per hour (watts) that can pass through one square meter of surface 1 mm thick for a one-degree C temperature difference between the two environments being separated. The units in which K is measured are ($W/m^2 \circ C$).

- **Thermal conductivity will vary with temperature**, which can be important for process applications, as will be seen

Insulation Theory

Thermal conductivity values for various materials at room temperature

Description	K		$\frac{W}{m^2 °C}$
Aluminum (alloy 1100)	221	×	10^3
Aluminum bronze (76% Cu, 22% Zn, 2% Al)	100	×	10^3
Brass:			
Red (85% Cu, 15% Zn)	150	×	10^3
Yellow (65% Cu, 35% Zn)	119	×	10^3
Bronze	29	×	10^3
Copper (electrolytic)	393	×	10^3
Gold	298	×	10^3
Iron:			
Cast	48	×	10^3
Wrought	60	×	10^3
Nickel	60	×	10^3
Platinum	69	×	10^3
Silver	424	×	10^3
Steel (mild)	45	×	10^3
Zinc:			
Cast	112	×	10^3
Hot-rolled	107	×	10^3

Source: Albert Thumann, *The Plant Engineer's and Manager's Guide to Energy Conservation*, ©1977. Reprinted with permission of Van Nostrand Reinhold Co., New York.

Insulation Theory

Values for good insulating materials

Material	Description	Conductivity K^a	Conductance $C^{b,c}$
Building boards	Asbestos-cement board	0.58	
	Gypsum or plaster board... 13 mm		12.8
	Plywood	0.115	
	Plywood... 9.5 mm		6.08
	Sheathing (impregnated or coated)	.054	
	Sheathing (impregnated or coated) 20 mm		2.78
	Wood fiber—hardboard type	0.20	
Insulating materials	Blanket and Batt:		
	Mineral wool fibers (rock, slag, or glass)	0.039	
	Wood fiber	0.036	
	Boards and slabs:		
	Cellular glass	0.056	
	Corkboard	0.039	
	Glass fiber	0.036	
	Insulating roof deck... 51 mm		1.02
Masonry materials	Loose fill:		
	Mineral wool (glass, slag, or rock)	0.039	
	Vermiculite (expanded)	0.066	
	Concrete:		
	Cement mortar	0.72	
	Lightweight aggregates, expanded shale, clay, slate, slags; cinder; pumice; perlite; vermiculite	0.245	
	Sand and gravel or stone aggregate	1.73	
	Stucco	0.72	
	Brick, tile, block, and stone:		
	Brick, common	0.72	
	Brick, face	1.30	
	Tile, hollow clay, 1 cell deep, 102 mm		5.1
	Tile, hollow clay, 2 cells, 153 mm		3.1

Material	Description	Conductivity K^a	Conductance $C^{b,c}$
Masonry materials (cont'd)	Block, concrete, 3 oval core:		
	Sand & gravel aggregate .... 102 mm		7.9
	Sand & gravel aggregate .... 153 mm		5.1
	Cinder aggregate .... 102 mm		5.1
	Cinder aggregate .... 153 mm		3.3
	Stone, lime or sand	1.80	
Plastering materials	Cement plaster, sand aggregate	0.72	
	Gypsum plaster:		
	Lightweight aggregate... 13 mm		17.7
	Lt. wt. agg. on metal lath... 19 mm		12.1
	Perlite aggregate	0.22	
	Sand aggregate	0.81	
	Sand aggregate on metal lath 19 mm		43.7
	Vermiculite aggregate	0.25	
Roofing	Asphalt roll roofing		36.9
	Built-up roofing... 9.5 mm		17.0
Siding materials	Asbestos-cement, 6.5 mm lapped		27.0
	Asphalt insulating (13 mm board)		39.2
	Wood, bevel, 13 mm × 152 mm, lapped		6.98
Woods	Maple, oak, and similar hardwoods	0.16	
	Fir, pine, and similar softwoods	0.115	
	Fir, pine & sim. softwoods 20 mm		5.79

[c]Same as *U* value.
[a]Conductivity given in W/(m²°C)
[b]Conductance given in W/m²°C
Source: Extracted with permission from *ASHRAE Guide and Data Book*, 1965. Reprinted with permission from the Trane Co., La Crosse, WI.

Insulation Theory

- The rate of heat transfer is directly proportional to the temperature difference and the thermal conductivity.

$$Q \propto K \Delta t$$

where Q = rate of heat transfer per m^2 of surface
Δt = temperature difference
K = thermal conductivity

Insulation Theory

- The insulating property of a material is generally specified in terms of the thermal resistance (R) of the material, also called the R-value. Thermal resistance is related to the K value as follow.

$$R = \frac{d}{K}$$

where d = thickness of material in meters
K = thermal conductivity

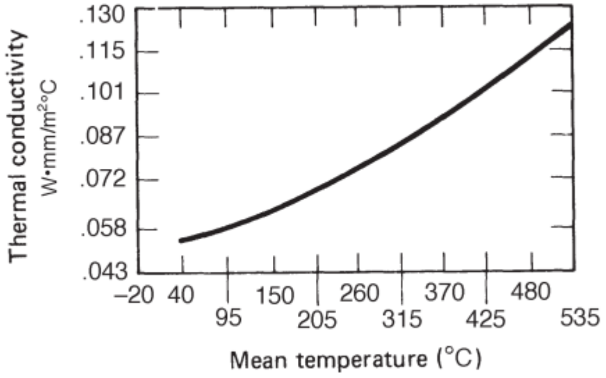
- To determine the thermal resistance of something composed of several materials:

$$R_{total} = R_1 + R_2 + \ldots + R_N$$

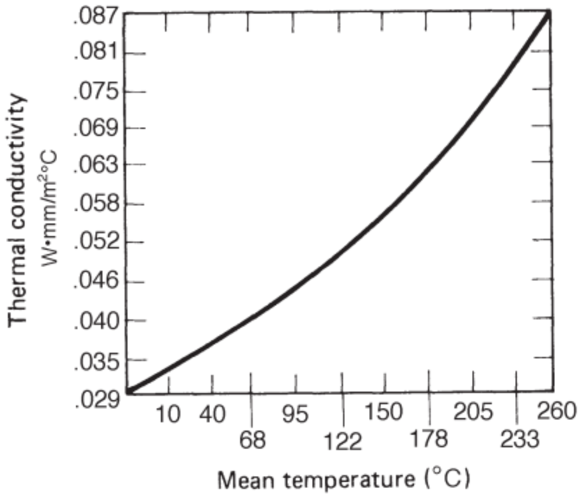
where R_i = the thermal resistance of the ith component,
i = 1, 2, 3,..., N.

Insulation Theory

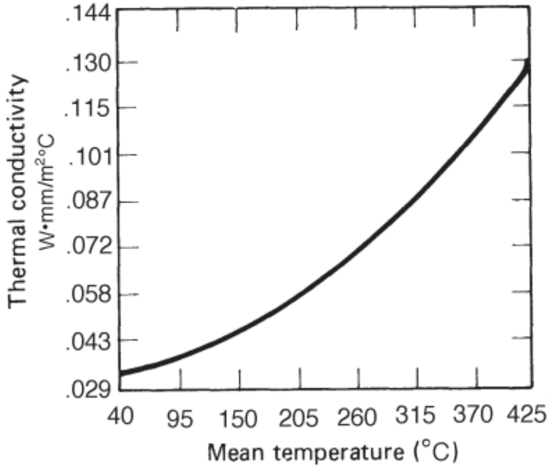
Thermal conductivities at varying temperatures



Calcium silicate



Fiberglass pipe insulation



Fiberglass board, 48 kg/m³

Insulation Theory

- The insulating property of a material is often measured in terms of conductance rather than resistance. Conductance (U) is the reciprocal of resistance.

$$U = \frac{1}{R}$$

The overall conductance of a total structure is

$$U_{total} = \frac{1}{R_{total}}$$

Insulation Theory

- **Heat Transfer calculations summary**

$$Q = \frac{1}{R_1 + R_2 + \ldots + R_N} A\Delta t$$

$$Q = \frac{1}{R_{total}} A\Delta t$$

$$Q = U A\Delta t$$

$$Q_{total} = U A\Delta t$$

where Q_{total} = rate of heat transfer for total surface area involved
A = area of heat transfer surface

Insulation Theory

- Heat Transfer Calculations for Flat Surfaces

- The surface film coefficient is the amount of heat transferred from a surface to air or from air to a surface per square meter of surface for each degree of temperature difference.

- Surface film coefficients are usually specified in terms of the surface resistance, as shown in following.

Insulation Theory

Surface film coefficients, Rs Values (m^2 °C/W)

	Still air		
$t_s - t_a$ (°C)[b]	Plain fabric, dull metal, ε =.95	Aluminum, ε =.2	Stainless steel, ε =.4
10	.093	.158	.143
25	.092	.155	.139
50	.088	.151	.134
75	.085	.148	.132
100	.081	.140	.127
	With wind velocities		
Wind velocity (kilometers per hour)			
8	.062	.072	.070
17	.053	.062	.060
33	.042	.049	.047

[a]For heat loss calculations, the effect of R_s is small compared to R_1, so the accuracy of R_s is not critical. For surface temperature calculations, R_s is the controlling factor and is therefore quite critical. The values presented are commonly used values for piping and flat surfaces.

[b]Note that t_s = surface temperature. Knowing the surface temperature requires measurement or calculation through the concept of thermal equilibrium, which will be discussed.

Source: Courtesy of Manville Corp.

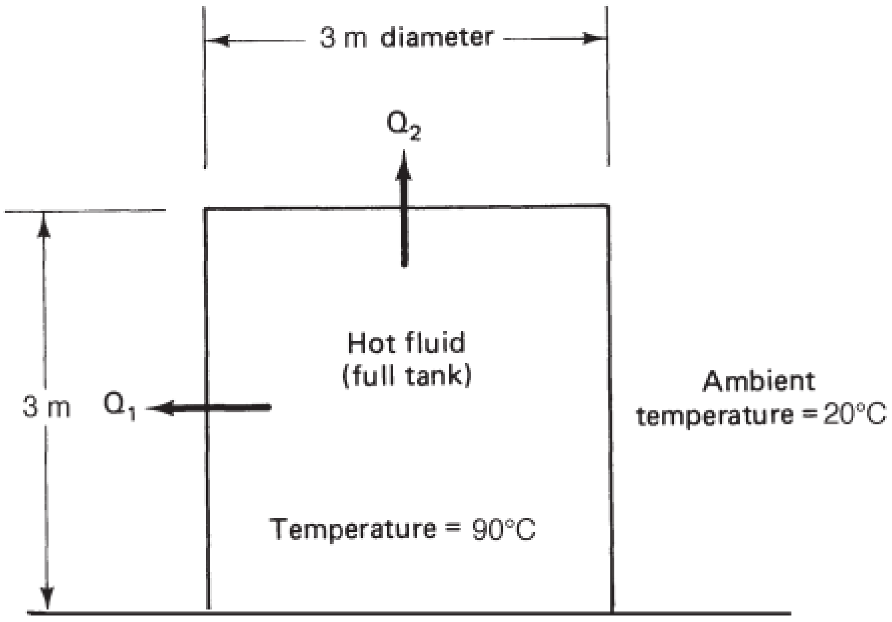
Insulation Theory

- **Example 1**:

Assume we have a 1 cm-thick uninsulated mild steel tank storing a hot fluid as shown below. (The K value for mild steel is 45×10^3 W / m^2 ^{o}C) The fluid is heated to 90°C, while ambient air is 20°C. What is the heat loss for the uninsulated tank? Ignore the heat loss to the ground.

Actually, transfer to the ground is a rather significant heat loss, but we will ignore it here.) The tank is 3 meters in diameter and 3 meters tall. Although this cylindrical tank is not truly a flat surface, it is large enough that it can be reasonably approximated as a flat surface. Smaller diameter cylinders such as pipes must be treated in a different way which is explained in the next section.

Take Rs from previous slide tables.



Tank storage of hot fluid

Insulation Theory

- Heat Transfer Calculations for Pipes:
  - The calculations become a bit more difficult because the heat flow is in a radial direction away from the pipe through the insulation to a larger surface area.
  - The effect of dispersing the heat over a larger surface is to increase the insulation thickness.
  - This effect is manifested in the calculations through a concept known as equivalent thickness d':

$$d' = r_2 \ln \frac{r_2}{r_1}$$

where d' = equivalent thickness
r_1 = outside radius of pipe
r_2 = outside radius of pipe plus insulation

Insulation Theory

Outside radius of a pipe if the nominal size—or inside diameter—is given

Nominal pipe size (cm)	Outside radius (cm)	Nominal pipe size (cm)	Outside radius (cm)
1	.84	18	9.80
2	1.40	20	10.78
3	1.97	22	11.77
4	2.66	24	12.90
5	3.17	26	13.88
6	3.56	28	14.88
7	4.03	30	15.00
8	4.67	35	17.50
9	5.14	40	20.00
10	5.63	45	22.50
12	6.67	50	25.00
14	7.79		
16	8.83		

Insulation Theory

- **Example 2:**

A 20-cm nominal size pipe (meaning a pipe with a 20-cm inside diameter) with 5 cm of insulation would have an equivalent thickness of insulation of

Solution

d' = r2 ln(r2/r1)

where $r_1 = 10.78$ cm

$r_2 = 10.78 + 5.00 = 15.78$ cm

$$d' = 15.78 \ln \frac{15.78}{10.78} = 6.01 \text{ cm}$$

Insulation Theory

- **Example 3**:

The same 20-cm pipe carrying fluid at 95°C and insulated by 5 cm of aluminum-jacketed fiberglass in a 20°C ambient area would have a heat loss of:

Solution

$$R_{insulation} = \frac{d'}{K} = \frac{.0601}{.039} = 1.541$$

$$Q_{total} = UA\,\Delta t$$

$$= \left(\frac{1}{1.541 + .155}\right) A\,(95 - 20)$$

$$= \frac{44.2\ \text{W}}{\text{m}^2}$$

$$\text{Area} = 2\,\pi \times .1078\ \text{m} = .677\ \text{m}^2$$

To determine the savings from insulating the pipe we must calculate the heat loss for the uninsulated pipe. The heat loss per one-meter length of insulated pipe is:

$$\frac{(44.2\ \text{W})}{\text{m}^2}\frac{(.677\ \text{m}^2)}{\text{m}} = 29.94\ \frac{\text{W}}{\text{m}}$$

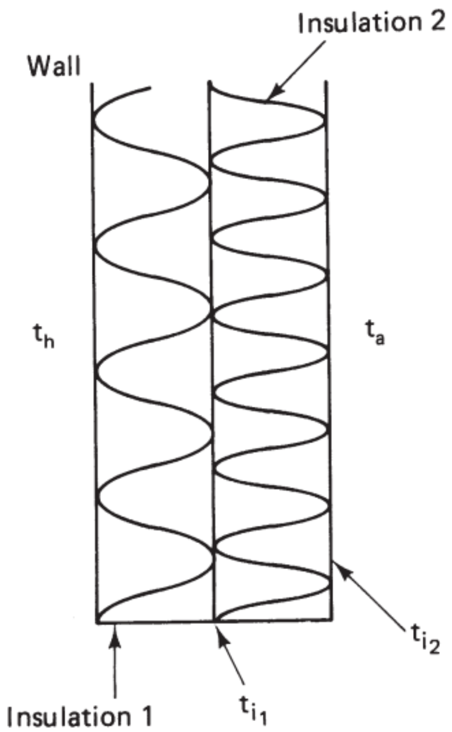
Insulation Theory

- Thermal equilibrium and its applications

Thermal equilibrium simply says that the total heat flow through a system is equal to the heat flow through any part of the system.

$$Q_{total} = \frac{t_h - t_a}{R_{i1} + R_{i2} + R_s} = \frac{t_h - t_{i1}}{R_{i1}} = \frac{t_{i1} - t_{i2}}{R_{i2}} = \frac{t_{i2} - t_a}{R_s}$$

$$= \frac{t_{i1} - t_a}{R_{i2} + R_s}$$



Insulation System

Insulation Theory

- **Example 4:**

The tank example demonstrated in example 1 assumed a surface temperature of 35°C. If we know the total heat loss, we can check this assumption by setting the total heat loss equal to one of the expressions shown in the following equation:

Total heat flow $= \dfrac{t_{i1} - t_a}{R_{i2} + R_s}$

Solution

$$\frac{Q_{total}}{m^2} = (3{,}664 \text{ W})\left(\frac{1}{35.34 \text{ m}^2}\right) = \frac{t_h - t_s}{R_{tank} + R_{insul.}}$$

$$= \frac{90 - t_s}{.00022 + .52}$$

$$\underline{t_s = 36.1°C}$$

As a further check:

$$Q_{total} = \left(\frac{t_s - t_a}{R_s}\right)(35.34 \text{ m}^2)$$

$$= \left(\frac{36.1°C - 20°C}{.155}\right)(35.34 \text{ m}^2)$$

$$= 3670 \text{ W}$$

Insulation Theory

- **Example 5:**

Suppose the pipe in Example 3 carried hot fluid 24 hours/day for 365 days/year. Further, assume that the unit generating the hot fluid is 80 percent efficient using natural gas costing €20.0/GJ = €.072/kWh. Find the energy cost savings per meter of pipe from insulating it with 5 cm of aluminium jacketed fiberglass. Assume the pipe is made from mild steel.

Solution

The total heat loss for a year for the uninsulated system is:

$$Q_{total} = UA\,\Delta t \text{ (assume } T_s \approx 49°\text{C)}$$

$$= \left(\frac{1}{0.088}(1)(95°\text{C} - 20°\text{C})\right)$$

$$= 852\,\frac{W}{\text{m}^2} = \frac{.852\,kW}{\text{m}^2}$$

Insulation Theory

Solution

$$Q_{total\,(€)} = \left(\frac{.852\ \text{kW}}{\text{m}^2}\right)\left(\frac{1}{.8}\right)\left(\frac{€\ 0.072}{\text{kWh}}\right)\left(\frac{8760\ \text{h}}{\text{year}}\right)$$

$$= €672/\text{m}^2$$

$$\left(\frac{852\ \text{W}}{\text{m}^2} - \frac{44.2\ \text{W}}{\text{m}^2}\right)\left(\frac{1}{.8}\right)\left(\frac{€\ 0.072}{\text{kWh}}\right)\left(\frac{8760\ \text{h}}{\text{year}}\right) = €\ 637/\text{m}^2$$

Savings for insulating the pipe would be

$$\left(\frac{852\ \text{W}}{\text{m}^2} - \frac{44.2\ \text{W}}{\text{m}^2}\right)\left(\frac{1}{.8}\right)\left(\frac{€\ 0.072}{\text{kWh}}\right)\left(\frac{8760\ \text{h}}{\text{year}}\right) = €\ 637/\text{m}^2$$

Savings per linear meter of pipe would be

$$\left(\frac{€\ 637}{\text{m}^2}\right)\left(\frac{.677\ \text{m}^2}{\text{m}}\right) = €\ 431/\text{m}$$

Consequently, insulation can be a real money saver.

Insulation Theory

- **Example 6:**

Assume a building wall has an R value of 0.47. The temperature inside is kept at 20°C during the winter and 25°C during the summer. The plant operates 365 days/year, 24 hours/day. Assuming a heating plant efficiency of 0.80 and a cooling coefficient of performance (COP) of 2.5, what is the cost of energy loss through the wall? Electricity costs €.072/kWh and gas €6.00/GJ. The plant experiences 2200°C heating days and 1100°C cooling days. The total wall area is 300 m2.

Solution

$$\text{heat lost } (€\ ) = \left(\frac{2200°\text{C days}}{\text{year}}\right)\left(\frac{.001\ \text{kW}}{.047\ °\text{C}}\right)\left(\frac{24\ \text{h}}{\text{day}}\right)(300\ \text{m}^2)$$

$$\cdot\ \left(\frac{1}{.8}\right)\left(\frac{€\ .0216}{\text{kWh}}\right) \text{ See note below.}$$

$$= €910/\text{year}$$

Insulation Theory

Solution

$$\text{cooling gain}\ (€\ ) = \left(\frac{1100°\text{C days}}{\text{year}}\right)\left(\frac{.001\ 1\text{W}}{0.47\ \text{m} \cdot \text{h} \cdot °\text{C}}\right)\left(\frac{24\ \text{h}}{\text{day}}\right)(300\ \text{m}^2)$$

$$\cdot\ \left(\frac{1}{2.5}\right) \cdot\ \left(\frac{€\ .072}{.072}\right)$$

$$= €485/\text{year}$$

$$\text{Total energy loss} = €910 + €485 = €1395/\text{year}$$

NOTE: €0.0216/kWh is the equivalent of €6.00/GJ and is the cost of gas energy used for heating; €0.072/kWh is the cost of electricity for cooling.

INSULATION TYPE

- Properties of materials used for insulation

1. **Cell structure**. Cell structures are either open or closed. A closed cell is relatively impervious to moisture, especially in a moderate environment, so insulation with a closed cell structure may not need any additional moisture barrier. Open cells pass moisture freely and therefore probably require vapor barriers. For extremely cold applications where a lot of condensation occurs, a vapor barrier is probably required regardless of cell structure.

2. **Temperature use**. Different insulating materials react to extreme temperatures in different ways. All insulation materials have temperature ranges for which they are recommended.

INSULATION TYPE

- Properties of materials used for insulation

3. **Thermal conductivity (K).** The energy manager must be familiar with the different types of insulation, their K values, and how the temperature affects the K values.

4. **Fire hazard**.

5. **Forms**. Insulation is available in a number of different forms. Flexible blankets, batts, rigid board, blocks, and pipe half sections are some of the more popular ones. Insulation is also available in a number of sizes and thicknesses.

INSULATION TYPE

- Common Industrial insulation Materials

Insulation type and form[a]	Temp. range (°C)	Thermal conductivity $W/m^2 \bullet °C$ at T_m (°C) 25	95	260	Fire hazard Compressive strength (kPa) at % deformation	Cell structure classification or flame spread-smoke developed	(permeability and moisture absorption)
Calcium silicate blocks, shapes, and P/C	To 815	.053	.059	.076	690-1725 at 5%	Noncombustible	Open cell
Glass fiber blankets	To 650	.035-.045	.046-.071	.062-.105	.14-24 at 10%	Noncombustible to 25/50	Open cell
Glass fiber boards	To 540	.032	.040	.074-.080			
Glass fiber pipe covering	To 455	.033	.043	.089			
Mineral fiber blocks and P/Cto 25/50	To 1040	.033-.049	.040-.055	.065-.118	7-125 at 10%	Noncombustible	Open cell
Cellular glass blocks and P/C	–265 to 480	.055	.065	.704	690 at 5%	Noncombustible	Closed cell
Expanded perlite blocks, shapes, P/C	To 815	—	.066	.091	620 at 5%	Noncombustible	Open cell
Urethane foam blocks and P/Ccell	(–75 to –270) to 105	.023-.026	—	—	110-515 at 10%	25-75 to 140-400	95% closed
Isocyanurate foam blocks and P/Ccell	To 175	.22	—	—	117-515 at 10%	25-55 to 100	93% closed
Phenolic foam P/C	–40 to 120	.033	—	—	90-152 at 10%	25/50	Open cell
Elastomeric closed cell sheets and P/C	–40 to 105	.036-.039	—	—	275 at 10%	25-75 to 115-490	Closed cell
MIN-K blocks and blankets	To 980	.027-.030	.029-.033	.030-.035	690-1310 at 8%	Noncombustible	Open cell
Ceramic fiber blankets	To 1430	—	—	.055-.078	3.4-6.9 at 10%	Noncombustible	Open cell

[a] P/C means pipe covering.

INSULATION TYPE

Economic Thicknesses

- As thickness of insulation is increased, the cost of material and installation goes up. The cost of lost energy, on the other hand, goes down, but at a decreasing rate.

- The **total cost**, which is the sum of the lost **energy cost** and the **material cost**, reaches a minimum point. That amount of insulation is called the **economic thickness**.

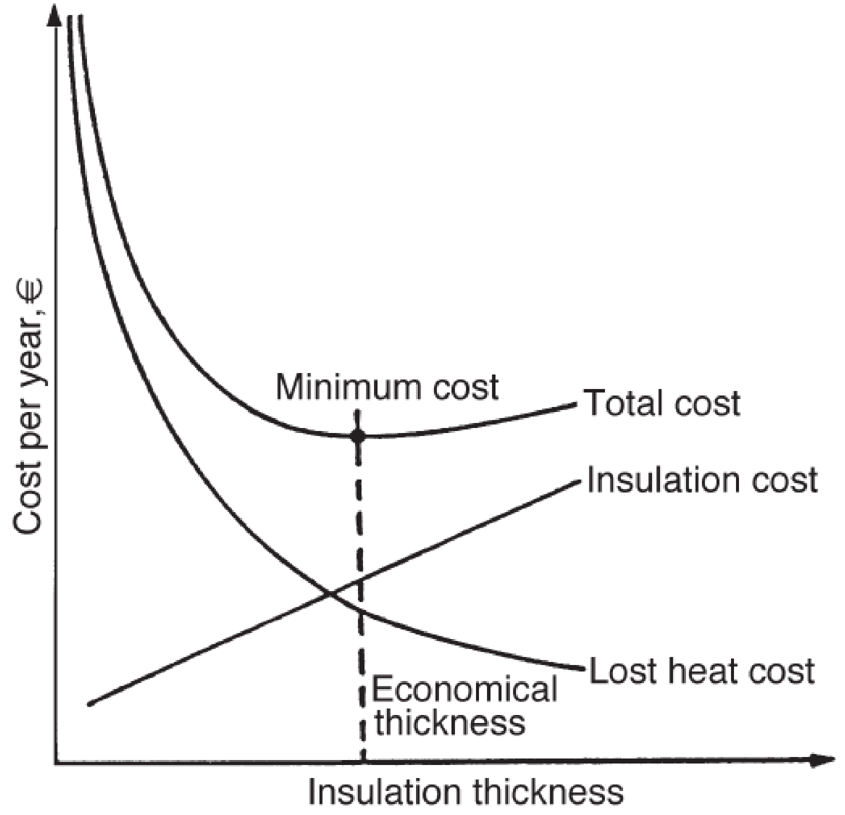


Illustration of the economic thickness of insulation

Part X: Building envelope

Introduction

- Building “envelope” generally refers to those building components that enclose conditioned spaces and through which thermal energy is transferred to or from the outdoor environment.

- Without a good understanding of how the envelope performs, a complete understanding of the interactive relationships of lighting and mechanical systems cannot be obtained.

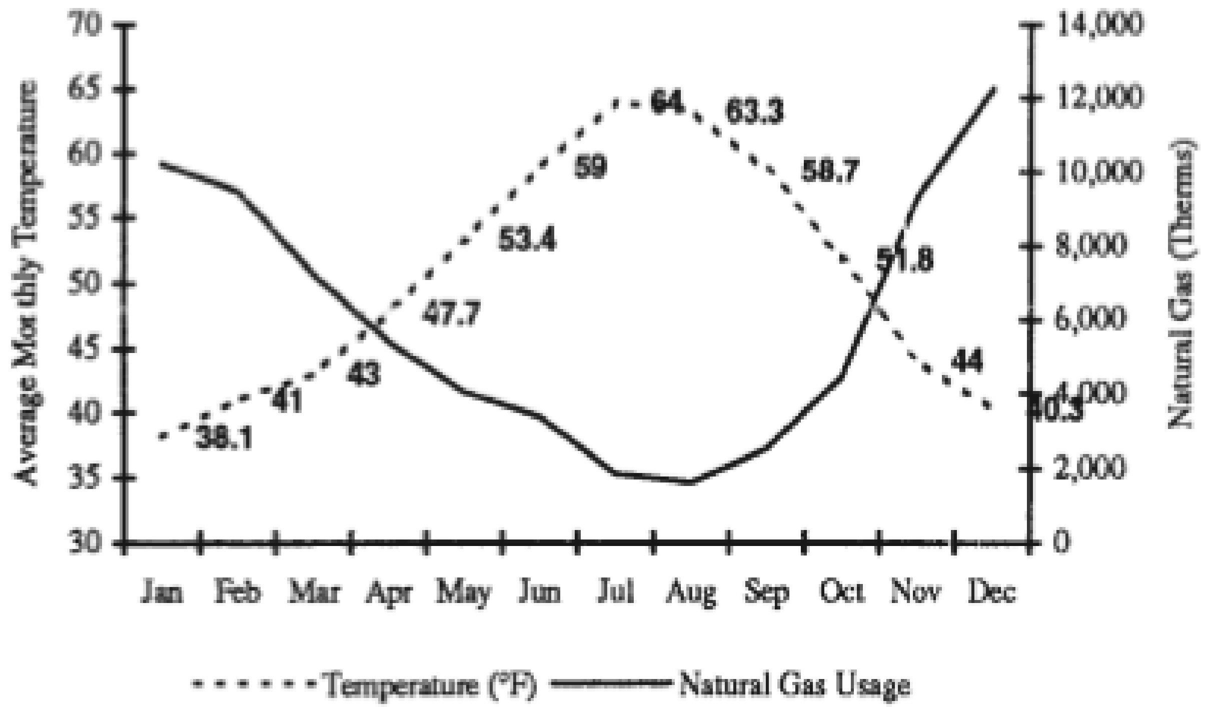


Figure 9-1

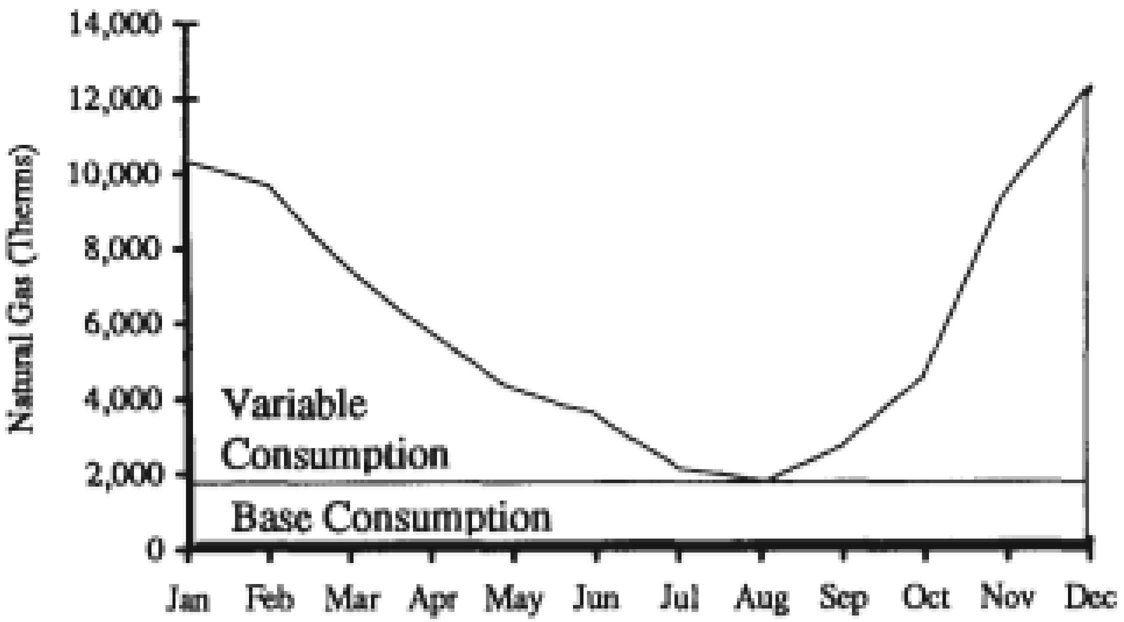


Figure 9-2

Quantifying building envelope performance

- The rate of heat transfer through the building envelope will be found by:

$$q = UA(T_i - T_o)$$

Where:

- q = the component heat loss, Btu/hr
- U = the overall heat transfer coefficient, Btu/ (hr-ft^2-°F)
- A = the area of the component, ft^2
- T_i = the indoor temperature, °F
- T_o = the outdoor temperature, °F

For **heating conditions in the winter**, indoor temperatures maintained between **68 and 72°F** result in comfort to the greatest number of people. Indoor temperatures maintained between **74 and 76°F** result in the greatest comfort to the most people during the **summer (cooling) period**.

PRINCIPLES OF ENVELOPE ANALYSIS

$$U = \frac{1}{R_t}$$

$$R_t = R_1 + R_2 \ldots + R_n$$

- R_1, R_2 and **R_n** represent the **thermal resistance** of each of the elements in the path of the "heat flow."
- The **outdoor resistance due to forced convection (winter) is usually taken as 0.17** (hr–ft^2–°F)/Btu and the **indoor resistance** due to free convection of a vertical surface is usually taken to be **0.68** (hr–ft^2 – °F)/Btu.

PRINCIPLES OF ENVELOPE ANALYSIS

Example

Calculate the heat loss for 10,000 square feet of wall with 4-inch face brick, R-11 insulation, and 5/8-inch sheet rock when the outdoor temperature is 20°F and the indoor temperature is 70°F.

In the ASHRAE Handbook we find that a conservative resistance for brick is 0.10 per inch. Four inches of brick would therefore have a resistance of 0.40. Sheet rock (called gypsum board by ASHRAE) has a resistance of 0.90 per inch, which would be 0.56 for 5/8-inch sheet rock. Batt insulation with a rating of R-11 will have a resistance of 11.0, if expanded to its full rated depth.

Answer: 39,000 Btu/hr

PRINCIPLES OF ENVELOPE ANALYSIS

- **The accuracy of the previous calculation is dependent on at least two important assumptions.**

  - **The calculation assumes:**
    1. The insulation is not compressed
    2. The layer(s) of insulation has not been compromised by penetrations of more highly conductive building materials.

Compression of Insulation

- The example assumes that the **insulation is installed according to the manufacturer's instructions.**

- Insulation is always assigned its R-value rating according to a specific standard thickness.

- If the insulation is compressed into a smaller space than it was rated under, **the performance will be less than that published by the manufacturer**.

- For example, R-19 batt insulation installed in a 3-1/2-inch wall might have an effective rating as low as R-13.

- Table 9-1 is a summary of the performance that can be expected from various levels of fiberglass batt insulation types installed in different envelope cavities.

Table 9-1. R-Value of fiberglass batts compressed within various depth cavities.[10]

Insulation R-Value at Standard Thickness									
R-Value		38	30	22	21	19	15	13	11
Standard Thickness		12"	9-1/2"	6-3/4"	5-1/2"	6-1/4"	3-1/2"	3-5/8"	3-1/2"
Nominal Lumber Size, in.	Actual Depth of Cavity, in.	Insulation R-Values when Installed in a Confined Cavity							
2 x 12	11-1/4	37							
2 x 10	9-1/4	32	30						
2 x 8	7-1/4	27	26						
2 x 6	5-1/2		21	20	21	18			
2 x 2	3-1/2			14		13	15	13	11

Insulation Penetrations

- The use of this method is **appropriate** for situations where the materials in the wall section are sufficiently similar that little or no lateral, or “sideways” heat transfer takes place.

- Of course a certain amount of lateral heat transfer does take place in every wall, resulting in some error in the above calculation procedure.

- The amount of error depends on how thermally dissimilar the various elements of the wall are.

- **The application of this procedure** to walls in which the penetrating members’ conductivities deviate from the insulation conductivities by **less than an order of magnitude (factor of 10)** should provide sufficiently accurate results for most analysis of construction materials.

- Because the unit R-value for wood is approximately 1.0 per inch and fiberglass batt insulation is R 3.1 per inch, this approach is justified for wood-framed building components.

METAL ELEMENTS IN ENVELOPE COMPONENTS

- Most commercial building construction is not wood framed.

- Economics and the need for fire-rated assemblies have increased the popularity of metal-framing systems over the years.

- **The conductivity of metal framing is significantly more than an order of magnitude greater than the insulation it penetrates**. In some instances it is several thousand times greater.

- However, for many years, the impact of this type of construction on envelope thermal performance was ignored by much of the design industry.

METAL ELEMENTS IN ENVELOPE COMPONENTS

- The introduction of the metal stud framing system into a wall has the potential to nearly **double its heat loss!** Just how is this possible, given that a typical metal stud is only about 1/20 of an inch thick?

- The magnitude of this effect is counter-intuitive to many practicing designers, because they have been trained to think of heat transfer through building elements as a one-dimensional phenomenon (as in the previous examples).

- But when a highly conductive element such as a metal stud is present in an insulated cavity, **two and three-dimensional considerations become extremely important**, as illustrated in Figure 9-5.

- The heat flow is more intense through regions where the isotherms are closer together.

- It is possible to visualize both the direction and intensity of heat flow through the wall section by observing the isotherms alone.

- If the heat flow was indeed one-dimensional and occurring through a thermally homogeneous material, the lines would be horizontal, evenly distributed; exhibiting a linear temperature-drop progression from the warm side of the wall to the cold side.

- Note that the area with the greatest amount of heat flow is not necessarily restricted to the metal part of the assembly.

- The metal stud has had a negative influence on the insulation in the adjacent region as well.

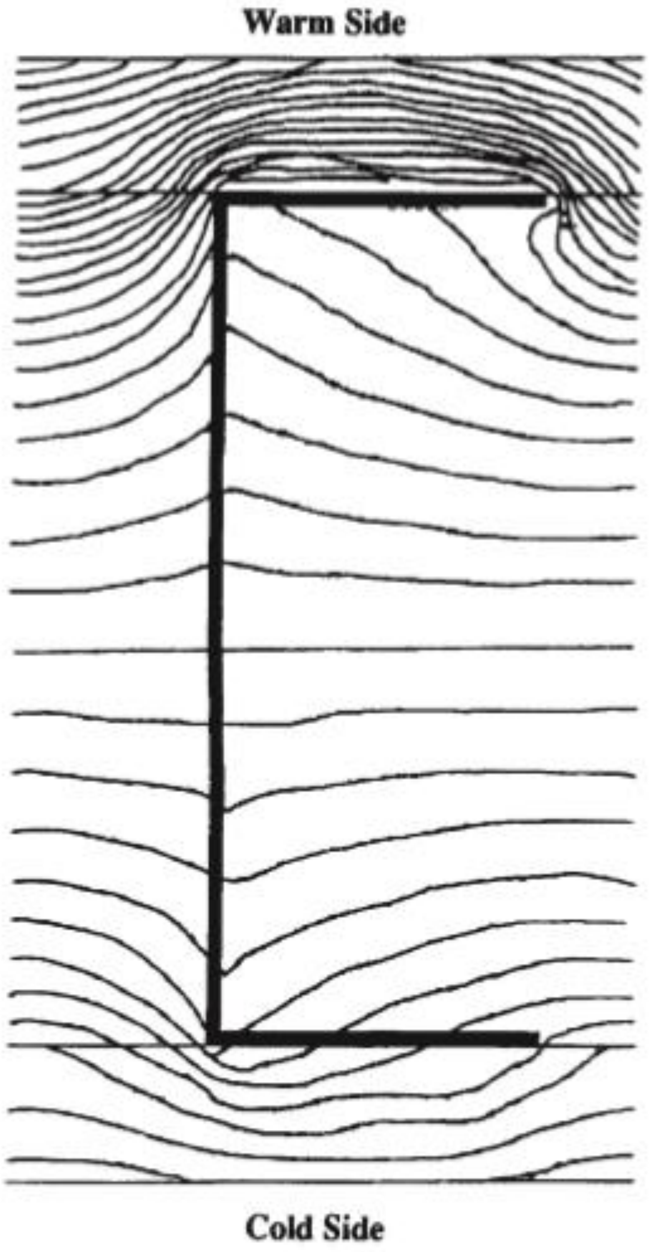
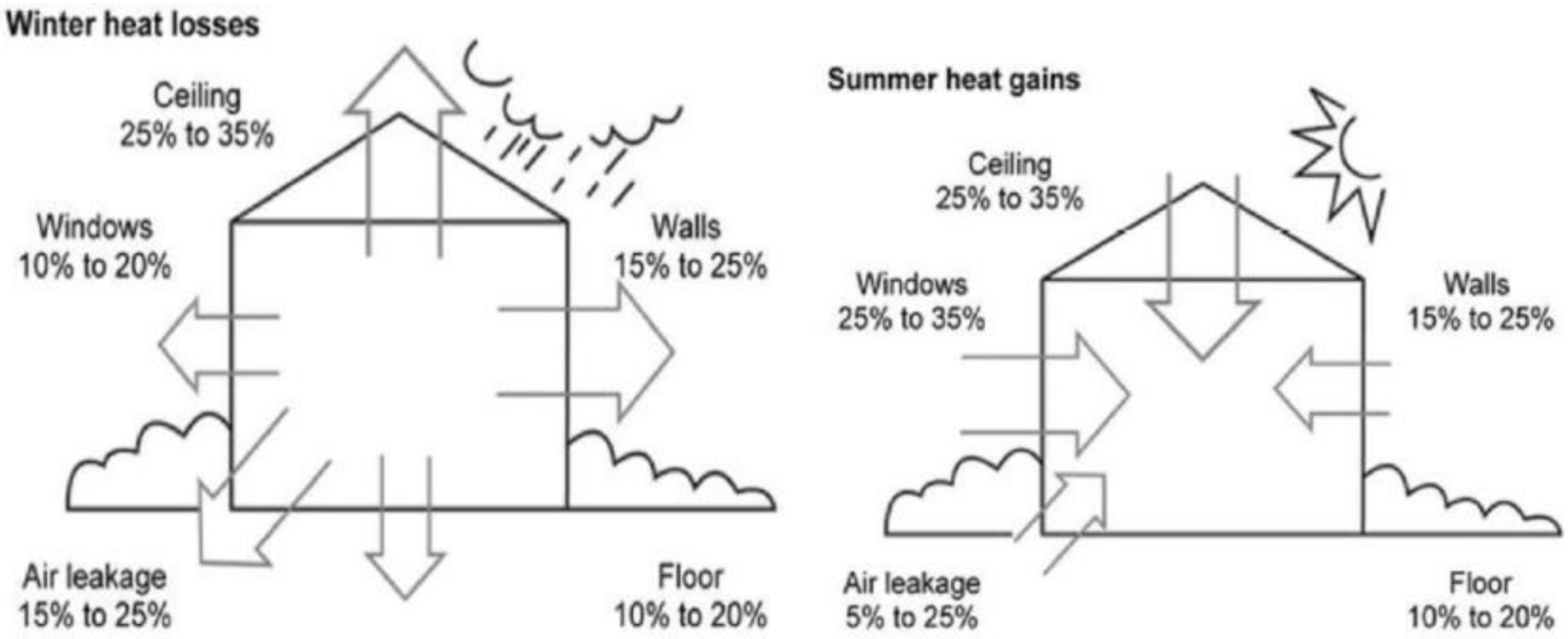


Figure 9-5. Metal stud wall section temperature distribution.

Building envelope average performance



Summarizing Envelope Performance with The Building Load Coefficient

- Building heat loss is proportional to the indoor-outdoor temperature difference.
- Each individual component can be assigned a proportionality constant that describes that particular component's behavior with respect to the temperature difference imposed across it.

  - For a **wall or window**, the proportionality constant is the **U-factor** times the component area, or "UA."
  - For a **slab-on-grade floor**, the proportionality constant is the **F-factor** times the slab perimeter, or "FP.".
  - For **infiltration**, the proportionality constant is **0.019** times the air flow rate in cubic feet per hour.
  - While not attributed to the building envelope, the effect of ventilation must be accounted for in the building's overall temperature-dependent behaviour. The proportionality constant for ventilation is the same for infiltration, **except that it is commonly expressed as 1.10 times the ventilation air flow in cubic feet per *minute***

Summarizing Envelope Performance with The Building Load Coefficient

- The instantaneous temperature-dependent performance of the total building envelope is simply the sum of all the individual component terms. This is sometimes referred to as the **building load coefficient (BLC)**. The BLC can be expressed as:

$$BLC = \Sigma UA + \Sigma FP + 0.018\ Q_{INF} + 1.1\ Q_{VENT}$$

Where:

  - ΣUA = the sum of all individual component "UA" products
  - ΣFP = the sum of all individual component "FP" products
  - Q_{INF} = the building infiltration volume flow rate, in cubic feet per *hour*
  - Q_{VENT} = the building ventilation volume flow rate, in cubic feet per *minute*

- From the above and Equation, it follows that the **total instantaneous** building heat loss can be expressed as:

$$q = BLC\,(t_{indoor} - t_{outdoor})$$

Thermal "Weight"

- Thermal weight is a qualitative description of the extent to which the building energy consumption occurs in "lock-step" with local weather conditions.
- **Thermally "light"** buildings are those whose heating and cooling requirements are proportional to the weather.
- **Thermally "heavy"** buildings are those buildings whose heating and cooling requirements are not proportional to the weather.
- **The "heavier" the building**, the less temperature-dependent the building's energy consumption appears to be, and the less accuracy that can be expected from simple temperature-dependent energy consumption calculation schemes.
- **The "heavier" the building, the less savings** per square foot of improved envelope can be expected for the same "UA" improvement.
- **The "lighter" the building, the greater the savings that can be expected.**

Envelope Analysis for Existing Buildings

- **Degree Days**

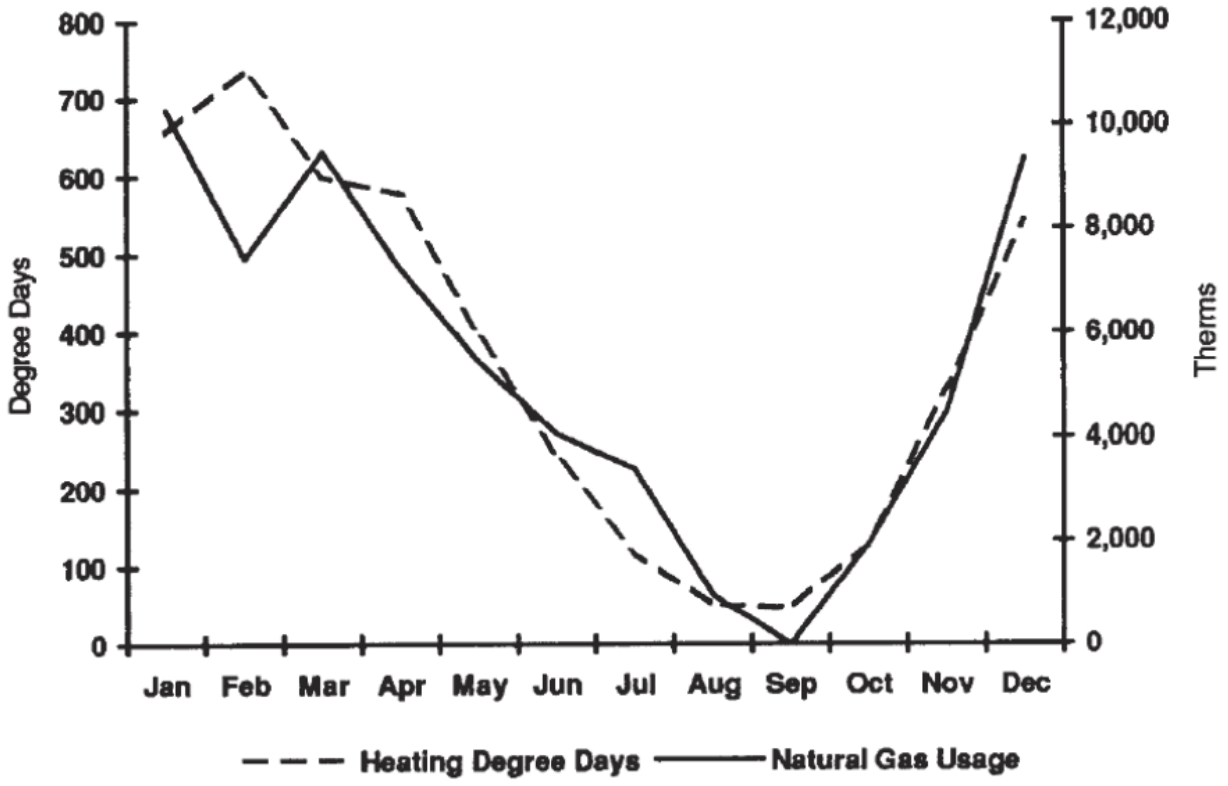
$$Degree - days = \frac{\left(T_{reference} - T_{average}\right)^{n}}{24}$$

Where

- ✓ "n" represents the number of hours in the period for which the degree-days are being reported
- ✓ $t_{reference}$ is a reference temperature at which no heating is assumed to occur. Typically, a reference temperature of 65°F is used. Units of degree-hours can be obtained by multiplying the results of any degree-day tabulation by 24.

Envelope Analysis for Existing Buildings

- Figure shows the monthly natural gas consumption of a metropolitan newspaper building overlaid on a plot of local heating degree-days.
- Because of the clear relationship between heating degree days and heating fuel consumption for many buildings, such as the above, the following formula has been used since the 1930s to predict the future heating fuel consumption.



Envelope Analysis for Existing Buildings

$$E = \frac{q \times DD \times 24}{\Delta T \times H \times Eff}$$

- Where:
  - ✓ E = Fuel consumption, in appropriate units, such as therms natural gas per year
  - ✓ q = The design-day heat loss, *Btu/hr*
  - ✓ DD = The annual heating degree-days (usually referenced to 65$^\circ F$)
  - ✓ 24 = Converts degree-days to degree-hours
  - ✓ Δt = The design day indoor-outdoor temperature difference, $^\circ F$
  - ✓ H = Conversion factor for the type of fuel used
  - ✓ Eff = The annualized efficiency of the heating combustion process

Envelope Analysis for Existing Buildings

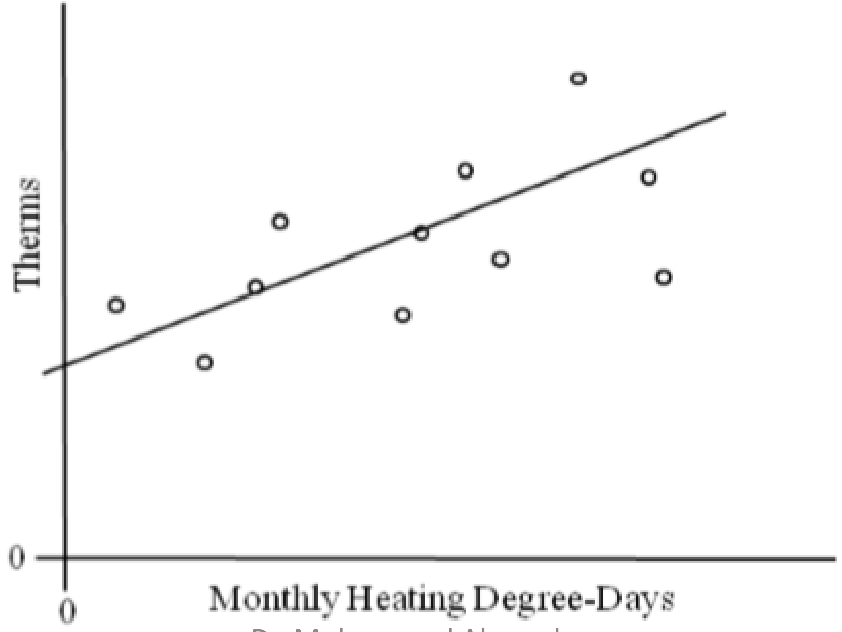
- Note that if the BLC is substituted for $q/\Delta t$, Equation becomes:

$$\boldsymbol{E = \frac{BLC \times DD \times 24}{H \times Eff}}$$

- As building construction techniques have improved over the years and more and more heat-producing equipment has found its way into commercial and even residential buildings; a variety of correction factors have been introduced to accommodate these influences.
- The degree-day method, in its simpler form, is not presently considered a precise method of estimating future building energy consumption.
- However, it is useful for indicating the severity of the heating season for a region and can prove to be a very powerful tool in the analysis of existing buildings (i.e. ones whose energy consumption is already known).

Analyzing Utility Billings

- To the extent this line fits the data, it gives us two important pieces of information:
  1. The monthly base consumption.
  2. The relationship between the weather and energy consumption beyond the monthly base, which we have been calling the building load coefficient.



Analyzing Utility Billings

- Using Linear Regression for Envelope Analysis
- $y = mx + b$
- Fuel Consumption = BLC × DD + base energy
- The determination of the building load coefficient is useful in the analysis of building envelope for a number of reasons:

1. Often the information necessary for the analysis of building envelope components is not available.
2. If envelope information is readily available and the building load coefficient has been determined by analysis of all the individual components, the regression derived BLC gives us a “real-world” check on the calculated BLC.
3. Linear regression also gives feedback in terms of how “good” the relationship is between fuel consumption and local climate, giving a good indication as to the thermal “weight” of the building.

Analyzing Utility Billings

$$BLC = \frac{n\sum D_i E_i - \sum D_i \sum E_i}{n\sum D_i^2 - (D_i)^2}$$

- Where:
  - n = the number of degree-day/fuel consumption pairs
  - D_i = the degree days accumulated for an individual month
  - E_i = the energy or fuel consumed for an individual month.
  - The monthly base fuel consumption can be calculated as:

$$Base = \frac{\sum E_i}{n} - BLC\frac{\sum D_i}{n}$$

  - The units of the BLC will be in terms of the fuel units per degree day. The BLC will be most valuable for additional analysis if it is converted to units of Btu/(hr-°F) or Watts/°C.

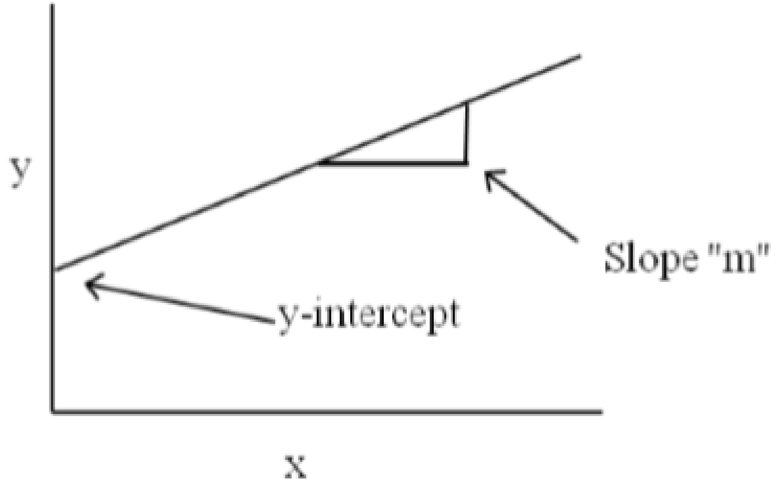
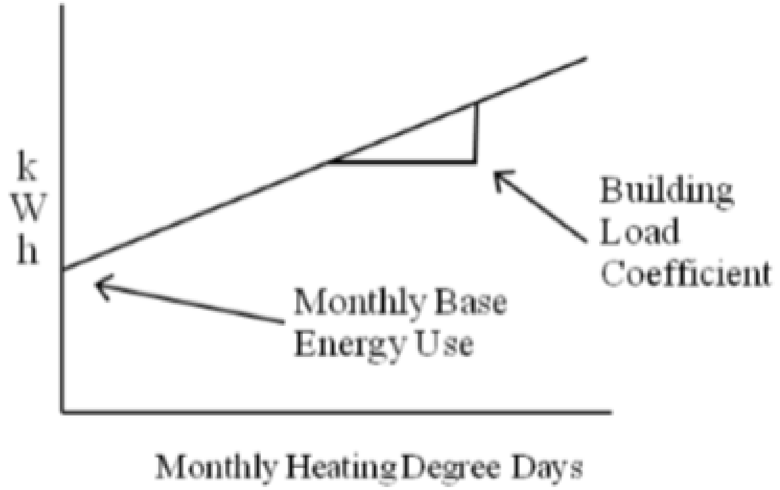


Figure 9-12



Example

A proposal has been made to replace 5,000 ft^2 of windows in an electrically heated building. The building envelope has been analyzed on a component-by-component basis and found to have an overall analytical BLC = 15,400 Btu/(hr-°F). Of this total, 6,000 Btu/(hr-°F) is attributable to the single pane windows, which are assumed to have a U-factor of 1.2 Btu/(hr-ft^2-°F). A linear regression is performed on the electric utility data and available monthly degree-day data (65°F reference). The BLC is found to be 83.96 kWh/degree-day, which can be converted to more convenient units by the following:

solution

$$BLC = 83.96\ \frac{kWh}{°\mathrm{F} - day} \times 3413\,\frac{Btu}{kWh} \times \frac{1day}{24hour} = 11{,}940\,\frac{Btu}{hr - °\mathrm{F}}$$

Evaluating the Usefulness of the Regression Results

- The correlation coefficient, R, is a useful term that describes how well the derived linear equation accounts for the variation in the monthly fuel consumption of the building.

$$R = BLC\sqrt{\frac{D_i^2 - \frac{(\sum D_i)^2}{n}}{E_i^2 - \frac{(\sum E_i)^2}{n}}}$$

- The square of the correlation coefficient, R^2, provides an estimate of the number of independent values (fuel consumption) whose variation is explained by the regression relationship.
- For example, an R^2 value of 0.75 tells us that 75% of the monthly fuel consumption data points evaluated can be accounted for by the linear equation given by the regression analysis. As a general rule of thumb, an R^2 value of 0.80 or above describes a thermally “light” building, and a building whose fuel consumption indicates an R^2 value significantly less than 0.80 can be considered a thermally “heavy” building.

Evaluating the Usefulness of the Regression Results

- **Example**

➢ Sample summary of energy usage and costs

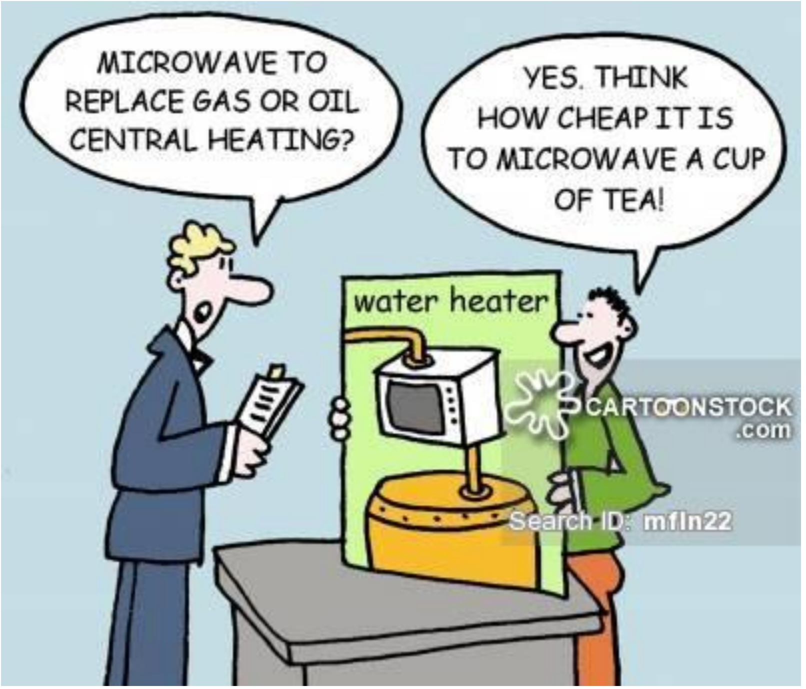
Month	kWh Used (kWh)	kWh Cost ($)	Demand (kW)	Demand Cost ($)	Total Cost ($)
Mar	44960	1581	213	1495	3076
Apr	47920	1859	213	1495	3354
May	56000	2318	231	1621	3939
Jun	56320	2423	222	1558	3981
Jul	45120	1908	222	1558	3466
Aug	54240	2410	231	1621	4032
Sept	50720	2260	222	1558	3819
Oct	52080	2312	231	1621	3933
Nov	44480	1954	213	1495	3449
Dec	38640	1715	213	1495	3210
Jan	36000	1591	204	1432	3023
Feb	42880	1908	204	1432	3340
Totals	569,360	24,243	2,619	18,385	42,628
Monthly Averages	47,447	2,020	218	1,532	3,552

This example is simplified for the sake of illustration. Most rate structures that include demand charges also include time of use charges for on/off peak, and power factor charges.

Part XI: BOILERS AND FIRED SYSTEMS

Introduction

- Over 68% of the electricity generated in the USA is produced through the combustion of coal, fuel oil, and natural gas.
- The remainder is produced through nuclear, 22%; hydroelectric, 10%; and geothermal and others, <1%.

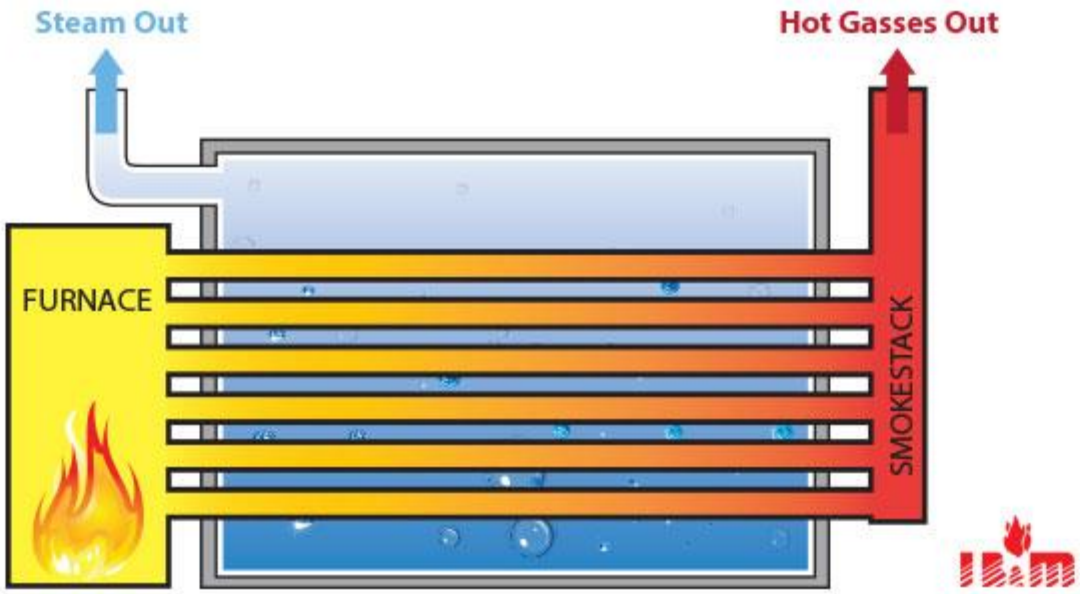


Boiler Types

- A boiler is either a fire tube boiler with tubes containing flame and surrounded by water or a water tube boiler—with tubes containing water surrounded by flame.
- A third kind of boiler is the *fluidized bed* boiler.
- The fuel is burned on a bed of limestone fragments that are kept suspended by air forced into the bed from below.
- There are many advantages to such a system. First, many different fuels can be burned-waste plastic, municipal solid waste.
- High sulfur coal can be burned without the need of flue gas scrubbers.
- The temperature is low enough that lower amounts of NOx are produced than with other combustion methods.
- Finally, less slag is produced on the water-cooled furnace walls.

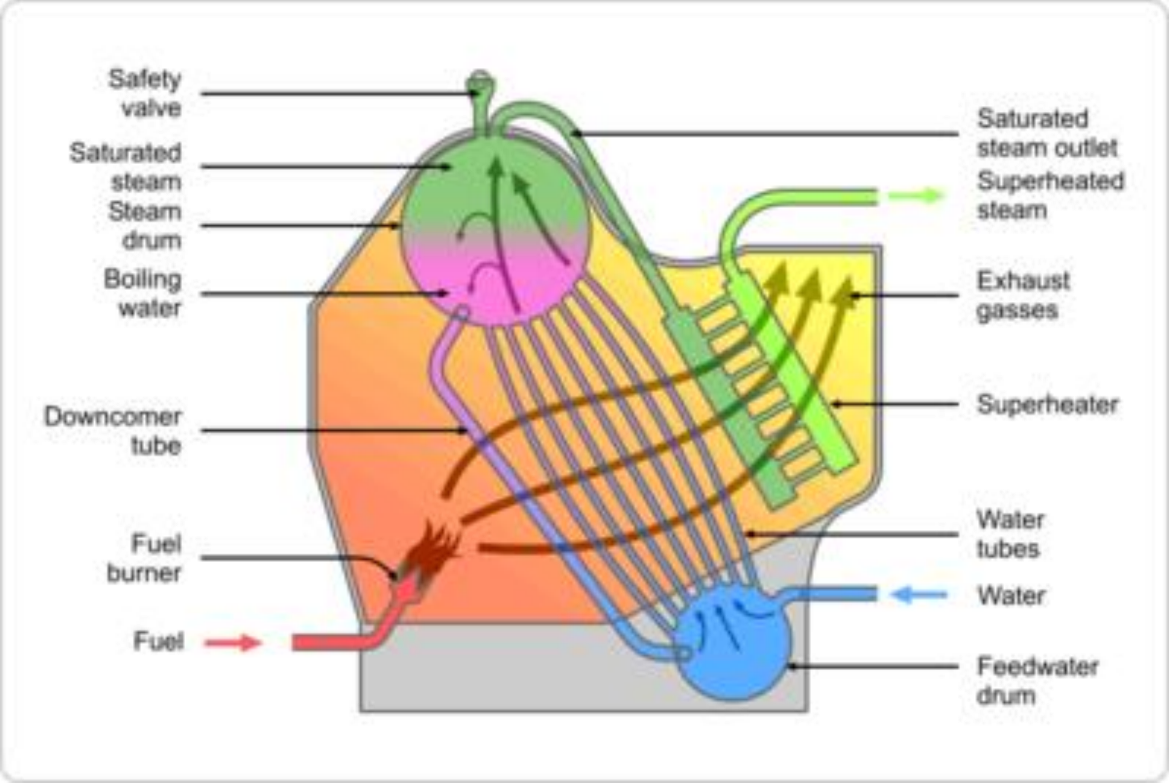
Boiler Types

- Fire Tube Boiler

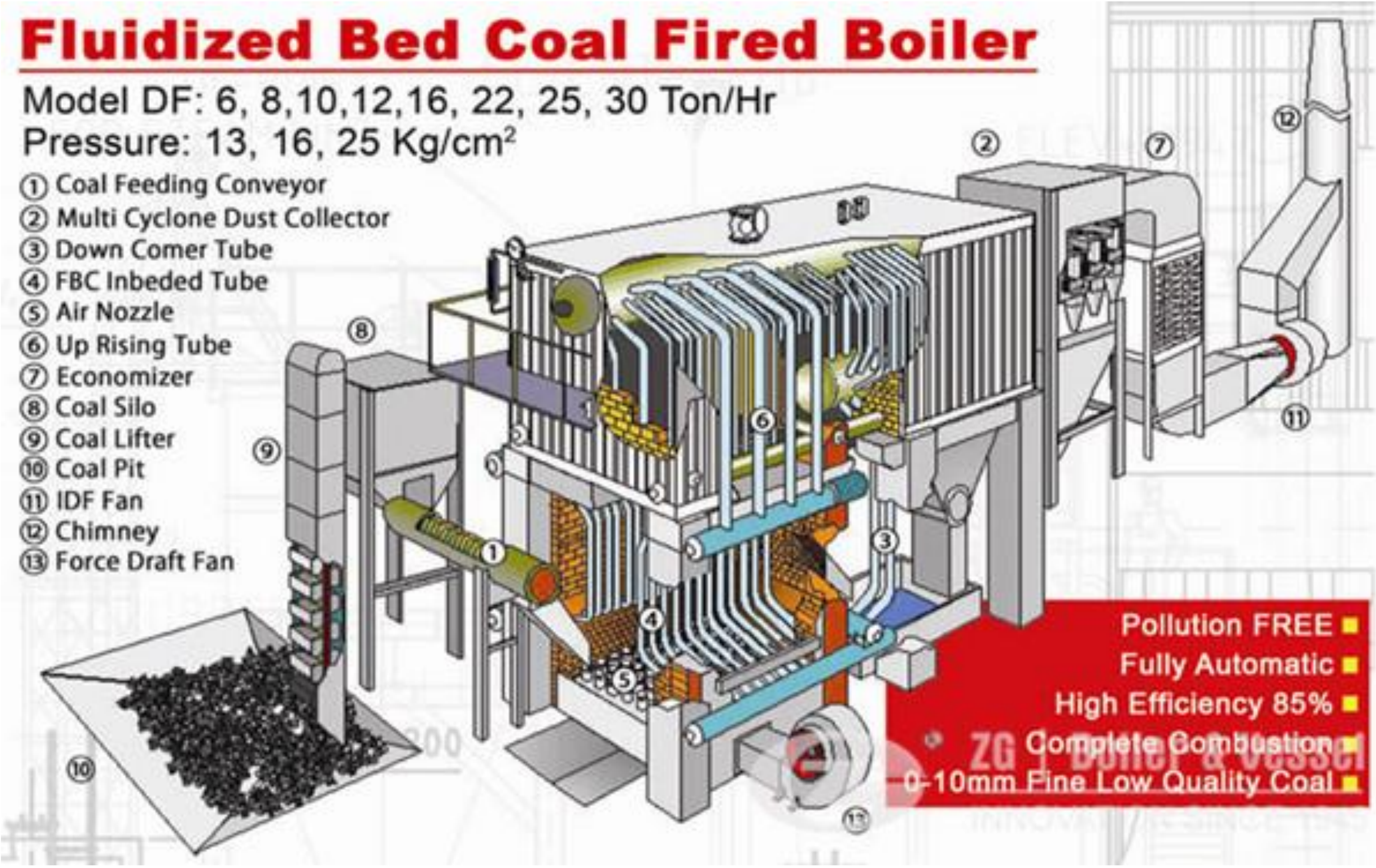


Boiler Types

- Water Tube Boiler



Boiler Types



Water tube Vs Fire tube

S.No.	Particulars	Fire-tube boilers	Water-tube boilers
1.	*Position of water and hot gases*	Hot gases inside the tubes and water outside the tubes.	Water inside the tubes and hot gases outside the tubes.
2.	*Mode of firing*	Generally internally fired.	Externally fired.
3.	*Operating pressure*	Operating pressure limited to 16 bar.	Can work under as high pressure as 100 bar.
4.	*Rate of steam production*	Lower	Higher.
5.	*Suitability*	Not suitable for large power plants.	Suitable for large power plants.
6.	*Risk on bursting*	Involves lesser risk on explosion due to lower pressure.	Involves more risk on bursting due to high pressure.
7.	*Floor area*	For a given power it occupies more floor area.	For a given power it occupies less floor-area.

System Analysis

- The purpose of the system may be to raise the temperature of an industrial product as part of a manufacturing process, it may be to generate high-temperature high-pressure steam in order to power a turbine, or it may simply be to heat a space so the occupants will be comfortable.
- The energy consumption of boilers, furnaces, and other fi re systems can be determined simply as a function of load and efficiency as expressed in the equation:

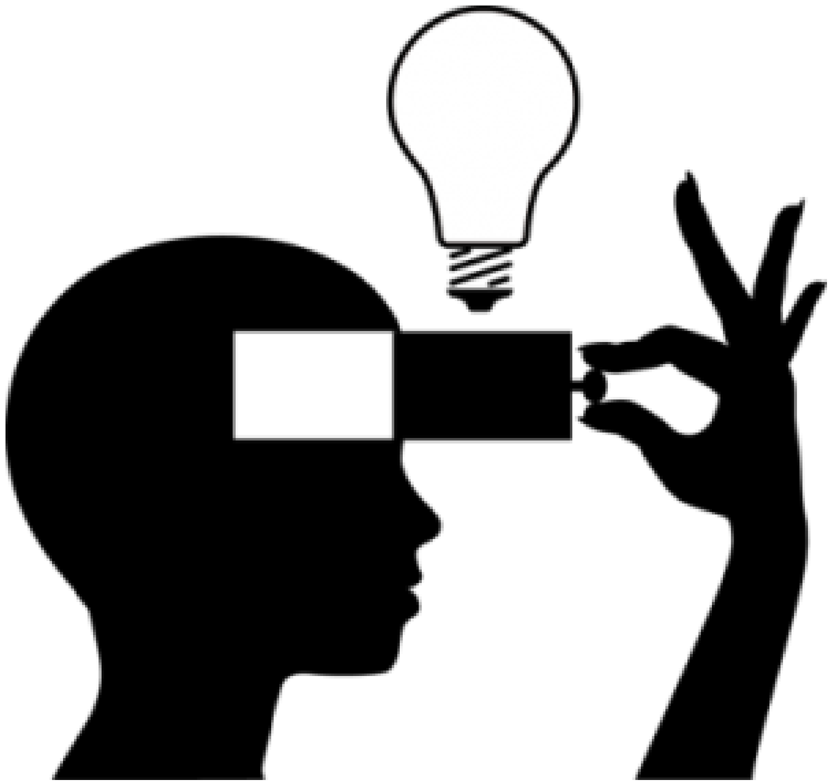
$$\text{Energy consumption} = \int (\text{load}) \times (1/\text{efficiency})\, dt$$

$$\text{Energy cost} = \int (\text{load}) \times (1/\text{efficiency}) \times (\text{fuel cost})\, dt$$

- However, solving the equation for the energy consumption or energy cost may not always be simplistic.

System Analysis

- In order to reduce boiler energy consumption, one can either:
  1. Reduce the load,
  2. Increase the operating efficiency,
  3. Reduce the unit fuel energy cost,
  4. Or combinations thereof.



System Analysis

- **Balance Equations**

Balance equations are used in an analysis of a process which determines inputs and outputs to a system.

- **Heat Balance**

A heat balance is used to determine where all the heat energy enters and leaves a system.

In a simple **furnace** system, energy enters through the combustion air, fuel, and mixed-air duct. Energy leaves the furnace system through the supply-air duct and the exhaust gases.

System Analysis

Heat Balance – cont.

- In a **boiler** system, the analysis can become more complex. Energy input comes from the following: condensate return, make-up water, combustion air, fuel, and maybe a few others depending on the complexity of the system. Energy output departs as the following: steam, blowdown, exhaust gases, shell/surface losses, possibly ash, and other discharges depending on the complexity of the system.

System Analysis

- **Mass Balance**
  - A mass balance is used to determine where all mass enters and leaves a system.
  - In the case of a steam boiler, a mass balance can be used in the form of a water balance (steam, condensate return, makeup water, blowdown, and feedwater.)
  - A mass balance can also be used for water quality or chemical balance (total dissolved solids, or other impurity.)
  - The mass balance can also be used in the form of a combustion analysis (fireside mass balance consisting of air and fuel in and combustion gasses and excess air out.)

- For analyzing complex systems, the mass and energy balance equations may be used simultaneously such as in solving multiple equations with multiple unknowns.

Efficiency

- There are several different measures of efficiency.
- The American Society of Mechanical Engineers (ASME) Power Test Code 4.1 (PTC-4.1-1964.)
- This procedure defines and established two primary methods of determining efficiency: the input- output method and the heat-loss method.
- Both of these methods result in what is commonly referred to as the gross thermal efficiency.
- The efficiencies determined by these methods are “gross” efficiencies as apposed to “net” efficiencies which would include the additional energy input of auxiliary equipment such as combustion air fans, fuel pumps, stoker drives, etc.

Efficiency

- Another efficiency term commonly used for boilers and other fired systems is combustion efficiency.
- Combustion efficiency is similar to the heat loss method, but only the heat losses due to the exhaust gases are considered.

Energy Conservation Measures

Energy Conservation Measures

Load Reduction

Insulation

—steam lines and distribution system

—condensate lines and return system

—heat exchangers

—boiler or furnace

Repair steam leaks

Repair failed steam straps

Return condensate to boiler

Reduce boiler blowdown

Improve feedwater treatment

Improve make-up water treatment

Repair condensate leaks

Shut off steam tracers during the summer

Shut off boilers during long periods of no use

Eliminate hot standby

Reduce flash steam loss

Install stack dampers or heat traps in natural draft boilers

Replace continuous pilots with electronic ignition pilots

Energy Conservation Measures

Waste Heat Recovery (a form of load reduction)

Utilize flash steam

Preheat feedwater with an economizer

Preheat make-up water with an economizer

Preheat combustion air with a recuperator

Recover flue gas heat to supplement other heating system, such as domestic or service hot water, or unit space heater

Recover waste heat from some other system to preheat boiler make-up or feedwater

Install a heat recovery system on incinerator or furnace

Install condensation heat recovery system

—indirect contact heat exchanger

—direct contact heat exchanger

Energy Conservation Measures

Efficiency Improvement
Reduce excess air
Provide sufficient air for complete combustion
Install combustion efficiency control system
—Constant excess air control
—Minimum excess air control
—Optimum excess air and CO control
Optimize loading of multiple boilers
Shut off unnecessary boilers
Install smaller system for part-load operation
—Install small boiler for summer loads
—Install satellite boiler for remote loads
Install low excess air burners
Repair or replace faulty burners
Replace natural draft burners with forced draft burners
Install turbulators in firetube boilers
Install more efficient boiler or furnace system
—high-efficiency, pulse combustion, or condensing boiler or furnace system
Clean heat transfer surfaces to reduce fouling and scale
Improve feedwater treatment to reduce scaling
Improve make-up water treatment to reduce scaling

Energy Conservation Measures

Fuel Cost Reduction

Switch to alternate utility rate schedule

—interruptible rate schedule

Purchase natural gas from alternate source, self procurement of natural gas

Fuel switching

—switch between alternate fuel sources

—install multiple fuel burning capability

—replace electric boiler with a fuel-fired boiler

Switch to a heat pump

—use heat pump for supplemental heat requirements

—use heat pump for baseline heat requirements

Energy Conservation Measures

Other Opportunities

Install variable speed drives on feedwater pumps
Install variable speed drives on combustion air fan
Replace boiler with alternative heating system
Replace furnace with alternative heating system
Install more efficient combustion air fan
Install more efficient combustion air fan motor
Install more efficient feedwater pump
Install more efficient feedwater pump motor
Install more efficient condensate pump
Install more efficient condensate pump motor

Key Elements for μmaximum

- Excess Air (EA)
- It is defined as air in excess of the amount required for stoichiometric conditions.
- In combustion processes, EA is generally defined as air introduced above the stoichiometric or theoretical requirements to effect complete and efficient combustion of the fuel.

Key Elements for μmaximum

- As illustrated in Figure 5.1, the amount of carbon dioxide, percent by volume, in the exhaust gas reaches a maximum with no excess air stoichiometric conditions.
- While carbon dioxide can be used as a measure of complete combustion, it can not be used to optimally control the air-to-fuel ratio in a fired system. A drop in the level of carbon dioxide would not be sufficient to inform the control system if it were operating in a condition of excess air or insufficient air.
- However, measuring oxygen in the exhaust gases is a direct measure of the amount of excess air. So, it is more common and preferred method of controlling the air-to-fuel ratio in a fired system.

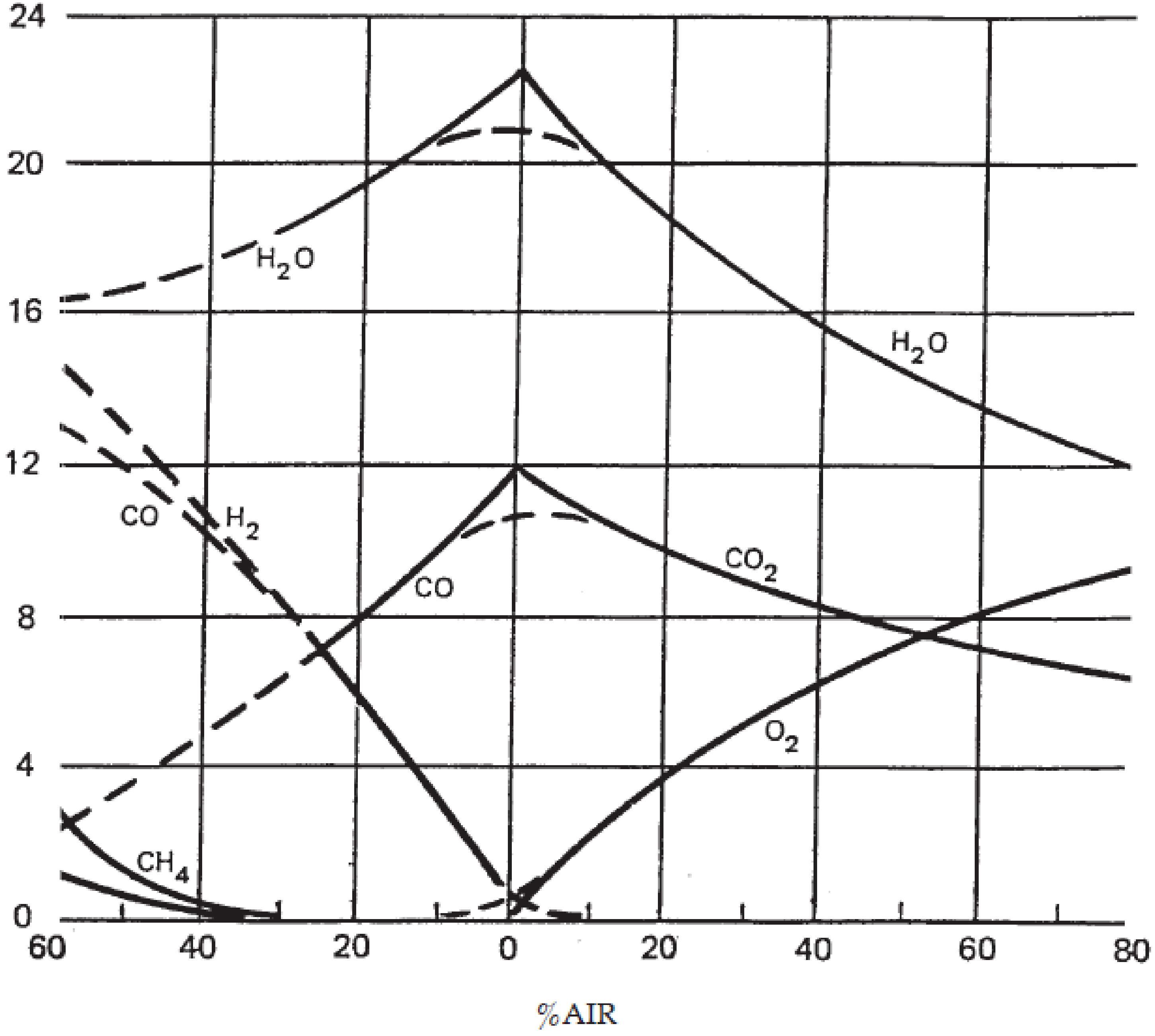


Figure 5.1 Theoretical flue gas analysis versus air percentage for natural gas.

Key Elements for μmaximum

- To identify the point of minimum excess-air operation for a particular fi red system, curves of combustibles as a function of excess O2 should be constructed similar to that illustrated in Figure 5.2.

- The curves should be developed for various firing rates as the minimal excess-air operating point will also vary as a function of the fi ring rate (percent load).

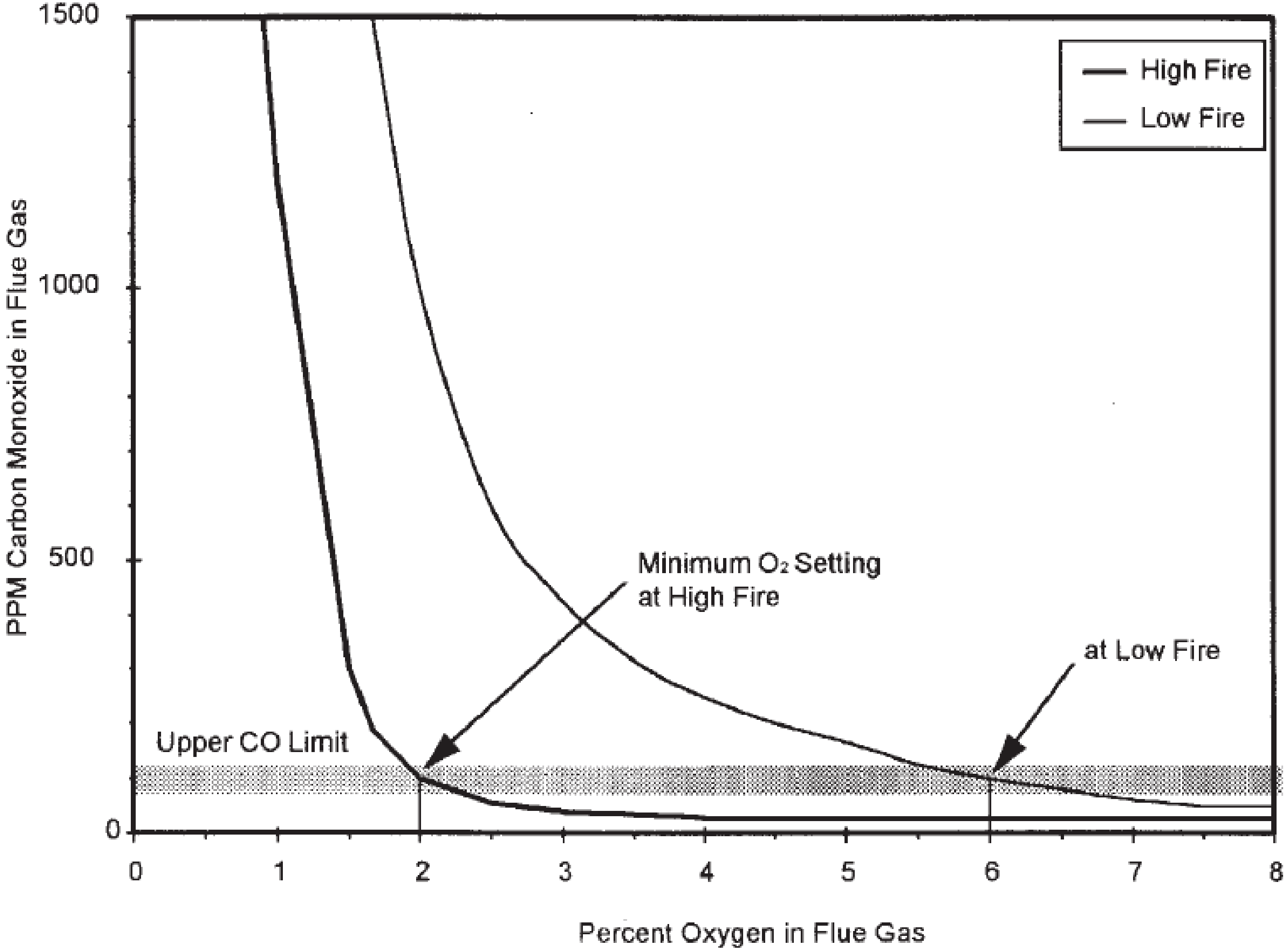


Figure 5.2 Hypothetical CO-O2 characteristic curve for a gas-fired industrial boiler.

Key Elements for μmaximum

- The optimal excess-air-control set point should be set at some margin (generally 0.5 to 1%) above the minimum O_2 point to allow for response and control variances.
- It is important to note that some burners may exhibit a gradual or steep CO-O_2 behavior and this behavior may even change with various firing rates.
- It is also important to note that some burners may experience potentially unstable operation with small changes in O_2 (steep CO-O_2 curve behavior).

Table 5.2 Typical Optimum Excess Air[a]

Fuel Type	Firing Method	Optimum Excess Air (%)	Equivalent O_2 (by Volume)
Natural gas	Natural draft	20-30	4-5
Natural gas	Forced draft	5-10	1-2
Natural gas	Low excess air	.04-0.2	0.1-0.5
Propane	—	5-10	1-2
Coke oven gas	—	5-10	1-2
No. 2 oil	Rotary cup	15-20	3-4
No. 2 oil	Air-atomized	10-15	2-3
No. 2 oil	Steam-atomized	10-15	2-3
No. 6 oil	Steam-atomized	10-15	2-3
Coal	Pulverized	15-20	3-3.5
Coal	Stoker	20-30	3.5-5
Coal	Cyclone	7-15	1.5-3

[a]To maintain safe unit output conditions, excess-air requirements may be greater than the optimum levels indicated. This condition may arise when operating loads are substantially less than the design rating. Where possible, check vendors' predicted performance curves. If unavailable, reduce excess-air operation to minimum levels consistent with satisfactory output.

Key Elements for μmaximum

- Excess oxygen (O_2) measured in the exhaust stack is the most typical method of controlling the air-to-fuel ratio. However, for more precise control, carbon monoxide (CO) measurements
- may also be used to control air flow rates in combination with O_2 monitoring. Careful attention to furnace operation is required to ensure an optimum level of performance.

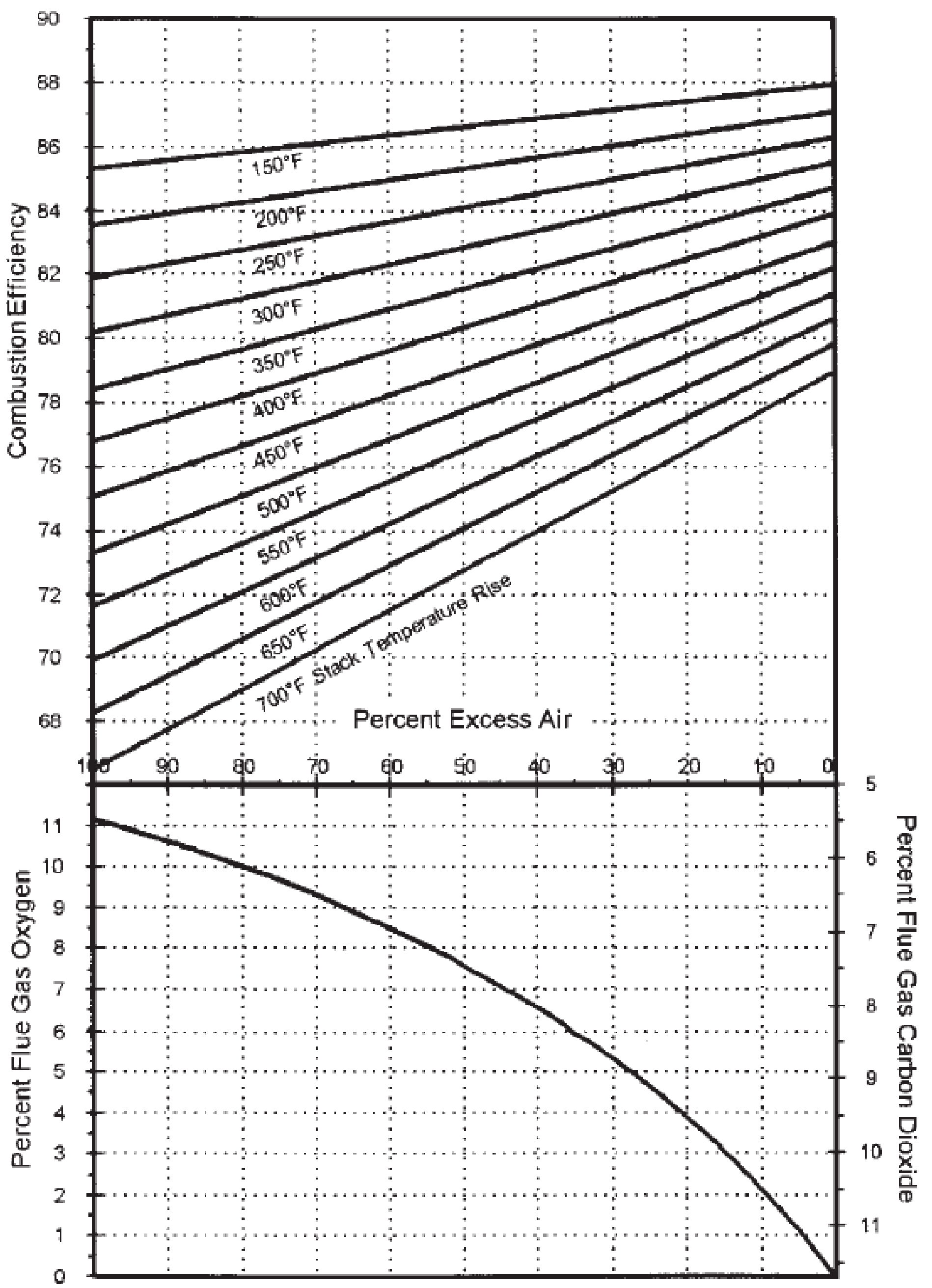


Figure 5.3 Combustion efficiency chart for natural gas.

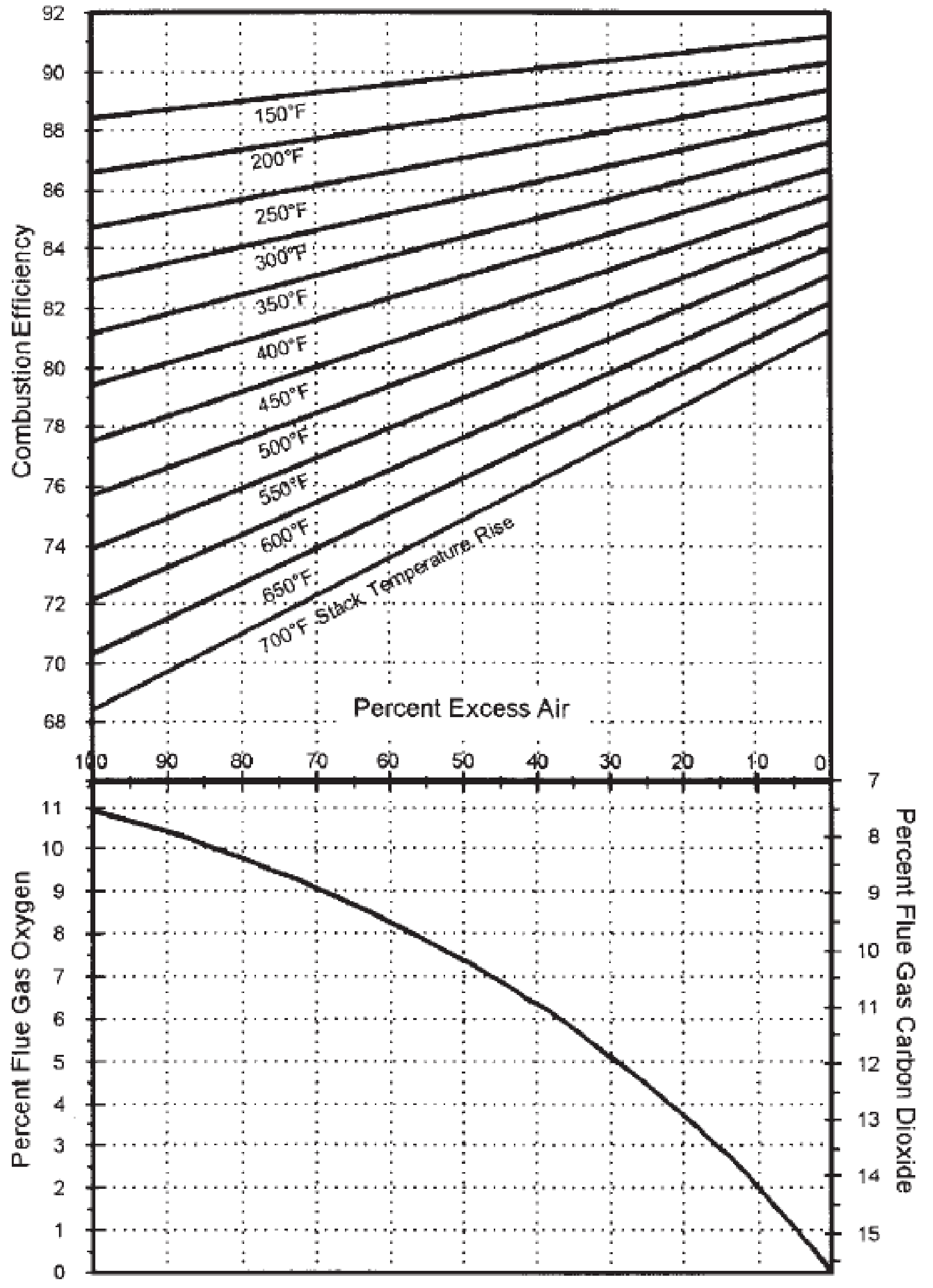


Figure 5.4 Combustion efficiency chart for number 2 fuel oil.

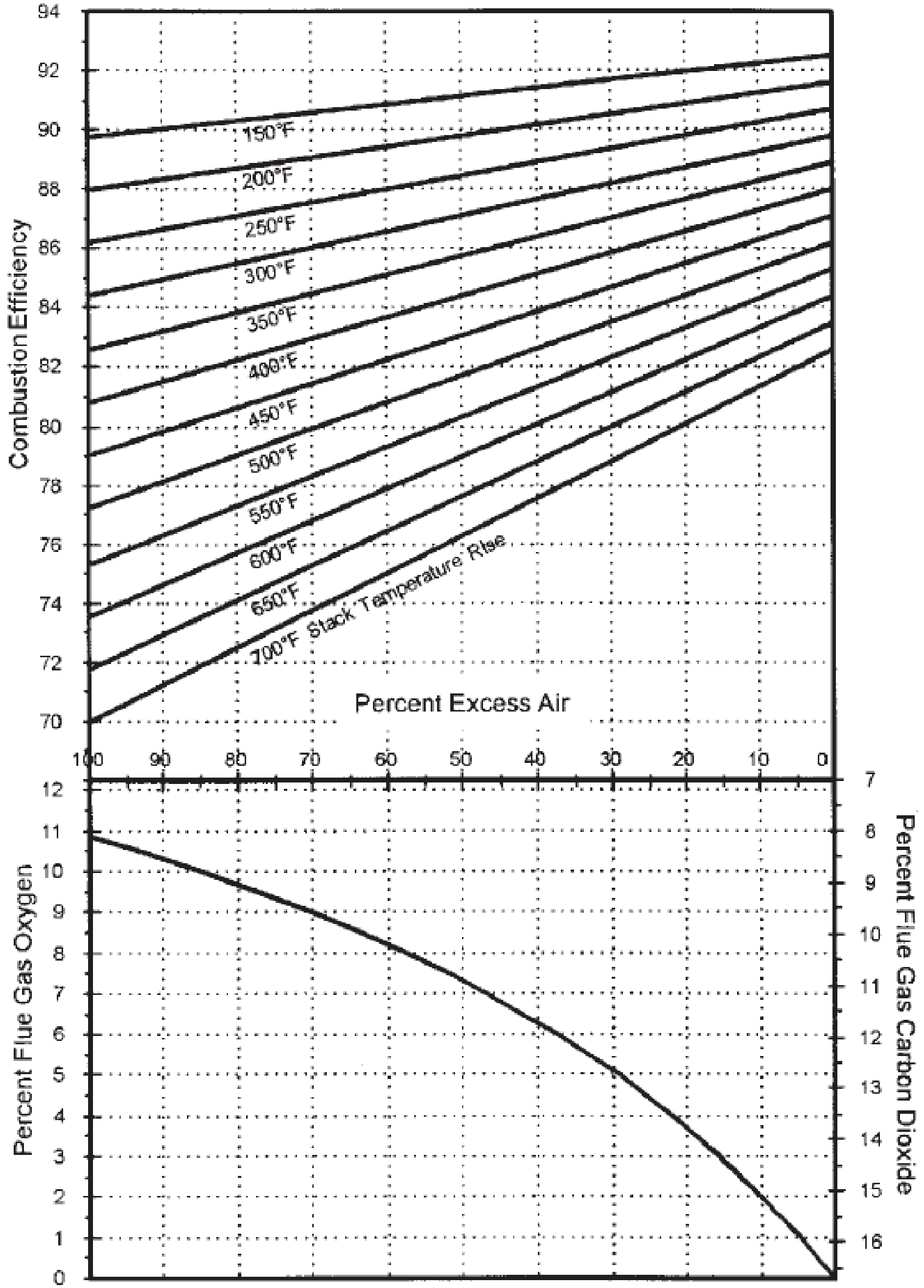


Figure 5.5 Combustion efficiency chart for number 6 fuel oil.

How to Test for Relative Efficiency

- To establish energy conservation benefits for an EA control program, you must determine:

  1. O2% (by volume) in the flue gas (typically dry),
  2. Stack temperature rise (the difference between the flue gas temperature and the combustion air inlet temperature), and
  3. Fuel type.

How to Test for Relative Efficiency

- To accomplish optimal control, continuous measurement of the excess air is a necessity.

- There are two types of equipment available to measure EA level:
  1. Portable equipment such as an Orsat flue-gas analyzer, heat prover, electronic gas analyzer, or equivalent analyzing device;
  2. Permanent-type installations probe-type continuous oxygen analyzers .

- The major advantage of permanently mounted equipment is that the on-line indication or recording allows remedial action to be taken frequently.

How to Test for Relative Efficiency

- **Example**: Determine the potential energy savings associated with reducing the amount of excess air to an optimum level for a natural gas-fired steam boiler.

Operating Data.

Current energy consumption	1,100,000 therms/yr
Boiler rated capacity	600 boiler horsepower
Operating hours	8,500 hr/yr
Current stack gas analysis	9% Oxygen (by volume, dry)
	Minimal CO reading
Combustion air inlet temperature	80°F
Exhaust gas stack temperature	580°F
Proposed operating condition	2% Oxygen (by volume, dry)

Key Elements for μmaximum

Exhaust Stack Temperature

- Another primary factor affecting unit efficiency and ultimately fuel consumption is the temperature of combustion gases rejected to the stack. Increased operating efficiency with a corresponding reduction in fuel input can be achieved by rejecting stack gases at the lowest practical temperature consistent with basic design principles.
- In general, the application of additional heat recovery equipment can realize this energy conservation objective when the measured flue-gas temperature exceeds approximately 250°F.

Key Elements for μmaximum

- **Economizers** are used to extract heat energy from the flue gas to heat the incoming liquid process feed stream to the furnace.
- **Flue gas/air preheaters** lower the flue-gas temperature by exchanging heat to the incoming combustion air stream.
- In assessing overall efficiency and potential for heat recovery, the parameters of significant importance are temperature and fuel type/sulfur content.
- To obtain a meaningful operating flue-gas temperature measurement and a basis for heat-recovery selection, the unit under consideration should be operating at, or very close to, design and optimum excess-air values

Key Elements for μmaximum

- **To obtain a proper and accurate temperature measurement,** the following guidelines should be followed:
   1. Locate the probe in an unobstructed flow path and sufficient distance, approximately five diameters downstream or upstream, of any major change of direction in the flow path.
   2. Ensure that the probe entrance connection is relatively leak free.
   3. Take multiple readings by traversing the cross-sectional area of the flue to obtain an average and representative flue-gas temperature.

Key Elements for μmaximum

- There are no “firm” exit-temperature guidelines that cover all fuel types and process designs. However, certain guiding principles will provide direction to the lowest practical temperature level of heat rejection.

- The elements that must be considered to make this judgment include
  1. fuel type,
  2. flue-gas dew-point considerations,
  3. heat-transfer criteria,
  4. type of heat-recovery,
  5. surface,
  6. relative economics of heat-recovery equipment.

Key Elements for μmaximum

Economizers

Fuel Type	Test for Determination of Exit Flue-Gas Temperatures
Gaseous fuel (minimum percent sulphur)	Heat-transfer criteria: $T_g = T_1 + 100°F$ (minimum): typically the higher of (a) or (b) below.
Fuel oils and coal	(a) Heat-transfer criteria: $T_g = T_1 + 100°F$ (min.) (b) Flue-gas dew point (from Figure 5.8 for a particular fuel and percent sulphur by weight

Where: T_g = Final stack flue temperature
T_1 = Process liquid feed temperature

Key Elements for μmaximum

Flue gas/air preheaters

Fuel Type	Test for Determination of Exit Flue-Gas Temperatures
Gaseous fuel	Historic economic breakpoint: T_g (min.) = approximately 250°F
Fuel oils and coal	Average cold-end considerations; see Figure 5.9 for determination of T_{ce}; the exit-gas temperature relationship is $T_g = 2T_{ce} - T_a$

Where:
- T_g = Final stack flue temperature
- T_{ce} = Flue gas air preheater recommended average cold end temperature
- T_a = Ambient air temperature

Key Elements for $\mu_{maximum}$

- **Example**: Determine the energy savings associated with installing an economizer or flue-gas air preheater on the boiler from the previous example. Assume that the excess-air control system from the previous example has already been implemented.

Key Elements for μmaximum

Available Data

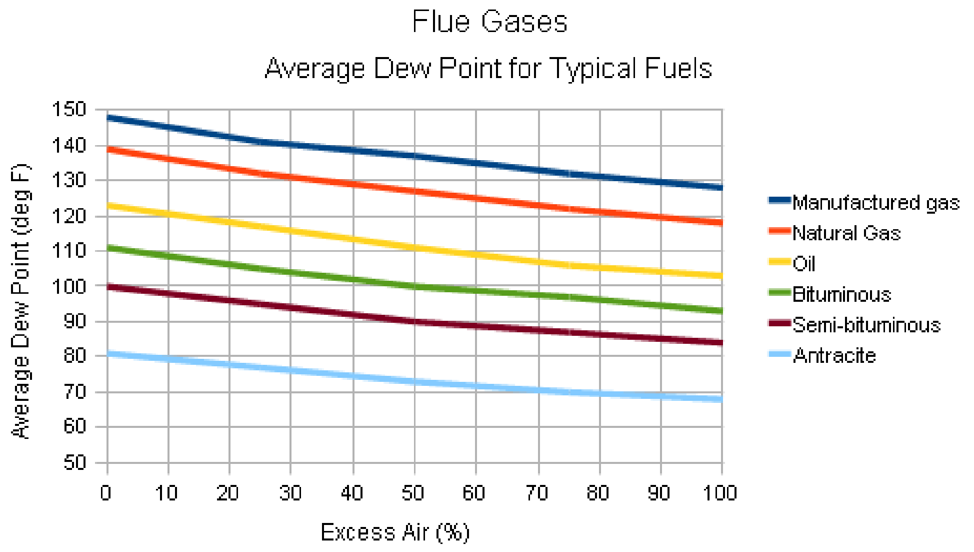
Current energy consumption	1,032,460 therms / yr
Boiler rated capacity	600 boiler horsepower
Operating hours	8,500 hr / yr
Exhaust stack gas analysis	2% Oxygen (by volume, dry)
	Minimal CO reading

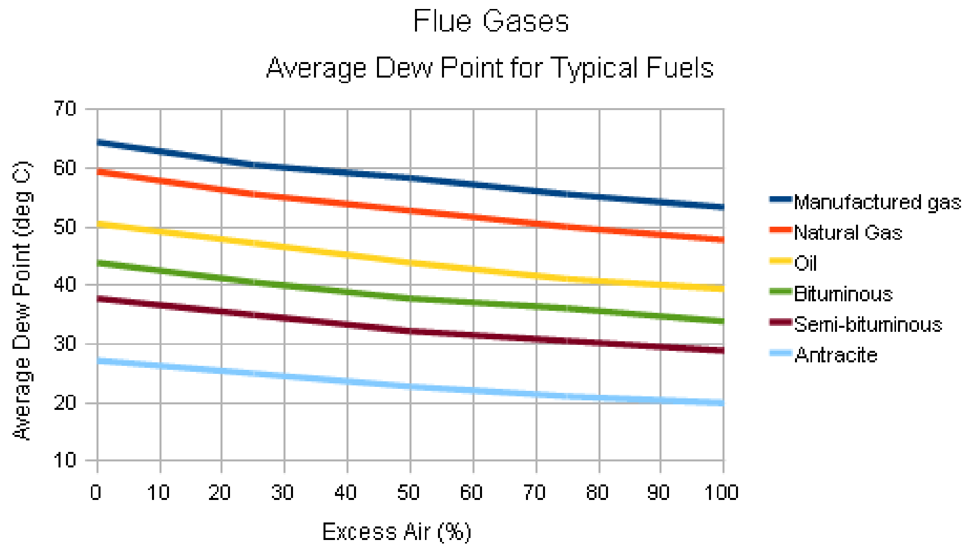
Current operating conditions:

Combustion air inlet temperature	80°F
Exhaust gas stack temperature	580°F
Feedwater temperature	180°F
Operating steam pressure	110 psia
Operating steam temperature	335°F

Proposed operating condition:

Combustion air inlet temperature	80°F
Exhaust gas stack temperature	380°F





Key Elements for μmaximum

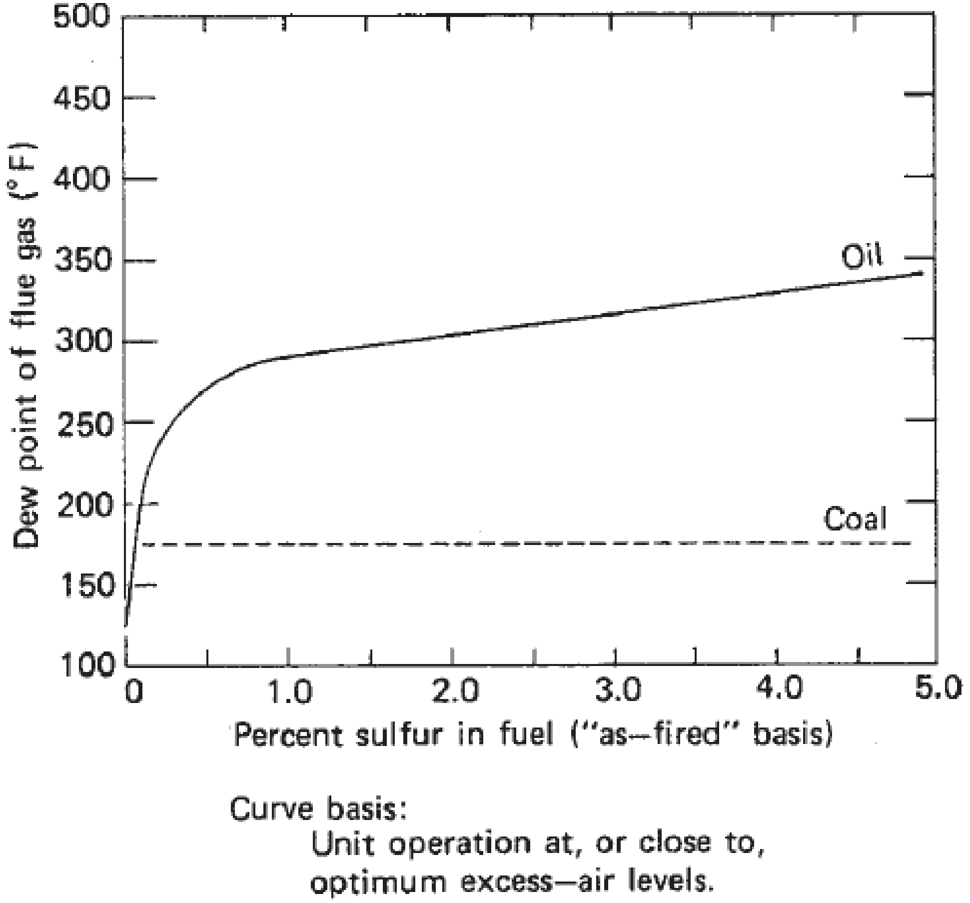


Figure 5.8 Flue-gas dew point. Based on unit operation *at* or *close to* "optimal" excess-air.

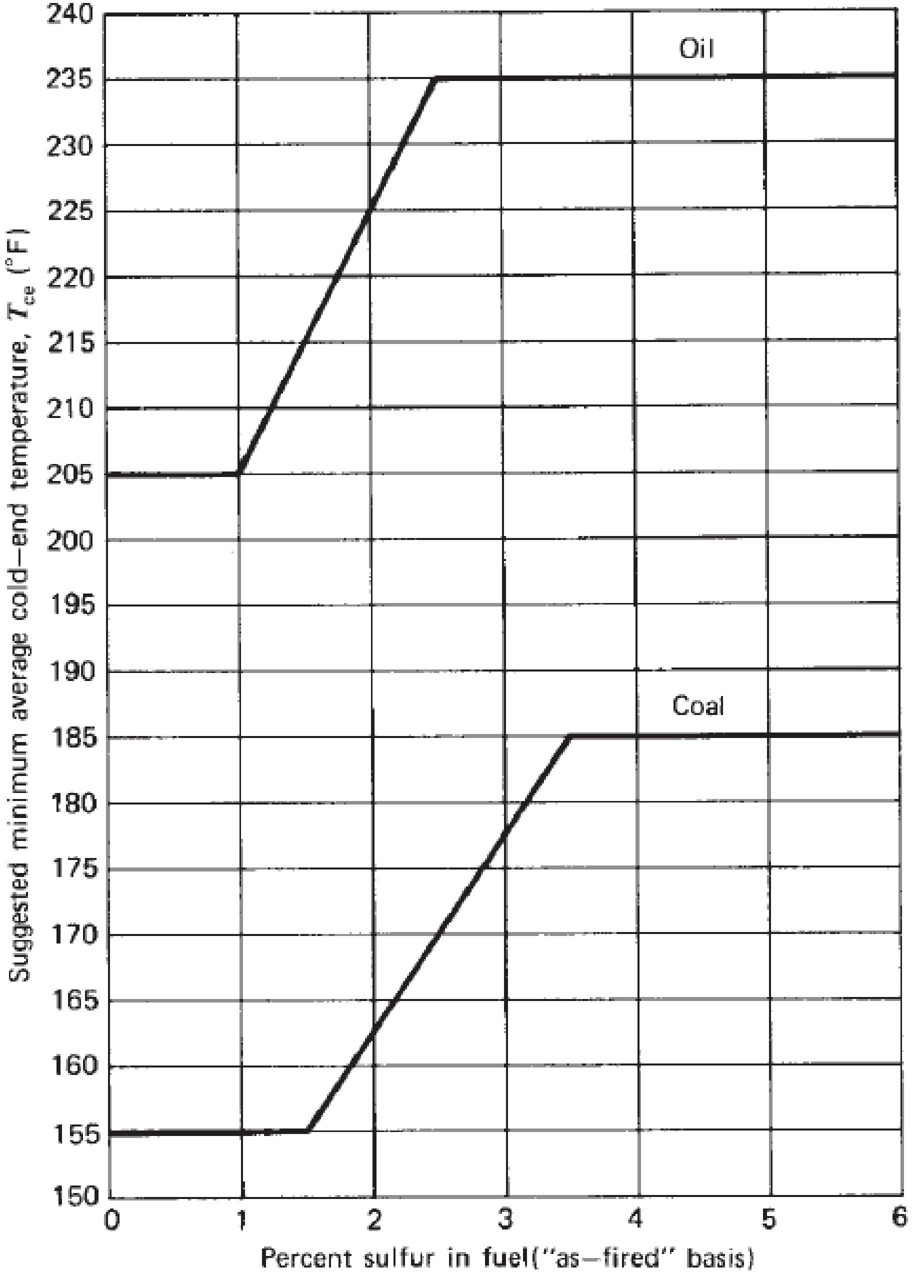


Figure 5.9 Guide for selecting flue-gas air preheaters.

Key Elements for μmaximum

- **Waste-Heat-Steam Generation**
- Plants that have fired heaters and/or furnaces of the type designed during the era of cheap energy may have significant energy saving opportunities.
- The major problem on older units is to determine a practical and economical approach to utilize the sensible heat in the exhaust flue gas.
- Typically, many vintage units have exhaust-flue-gas temperatures in the range 1050 to 1600°F.
- Conventional flue-gas air preheater normally is not a practical approach because of materials of construction requirements and significant burner front modifications. Additionally, equipping these units with an air preheater could materially alter the inherent radiant characteristics of the furnace, thus adversely affecting process heat transfer.

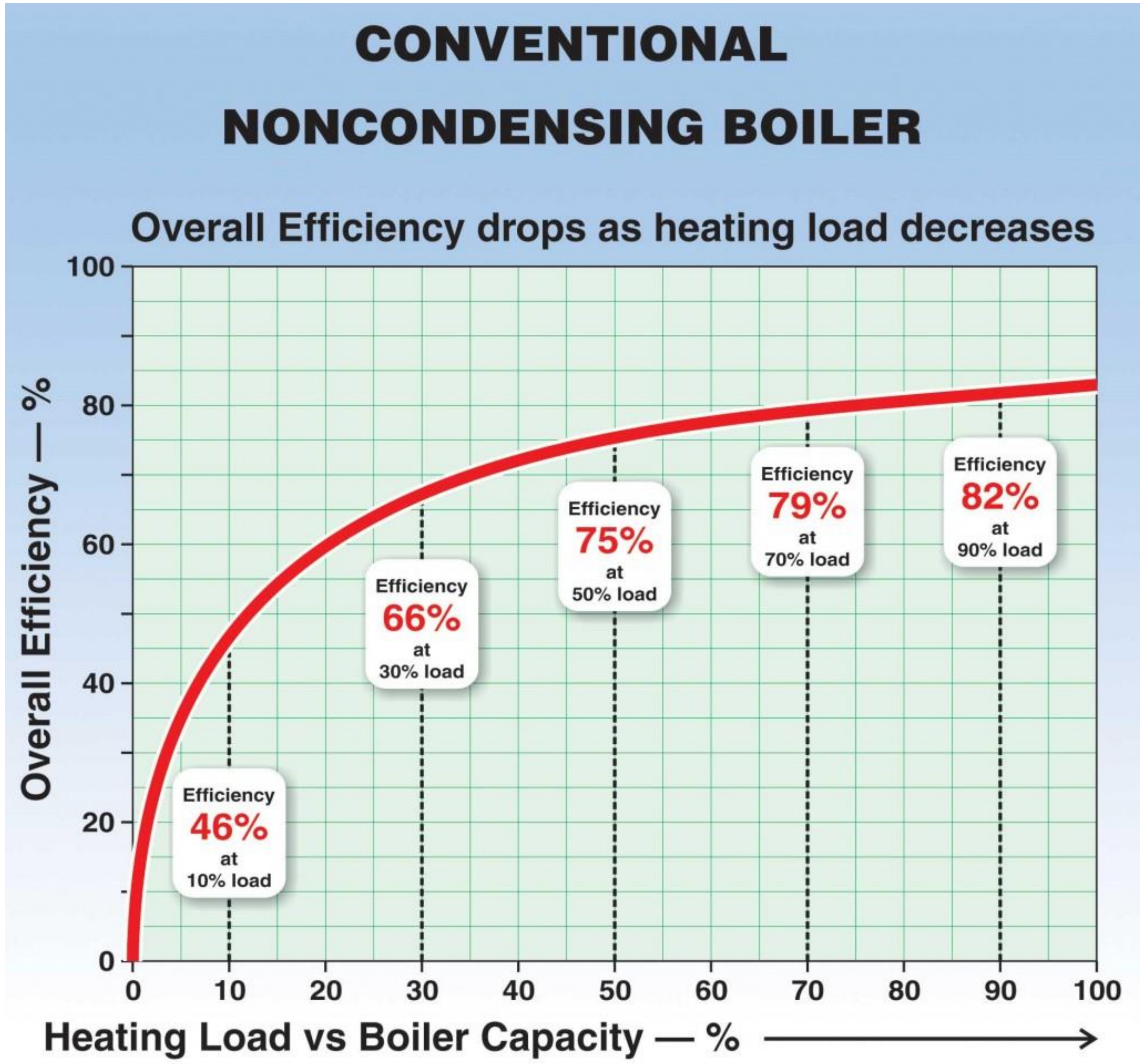
Key Elements for μmaximum

- An alternative approach to utilizing the available flue-gas sensible heat and maximizing overall plant energy efficiency is to consider:

  1. waste-heat-steam generation.
  2. installing an unfired or supplementary fired recirculating hot-oil loop to effectively utilize transferred heat to a remote location.
  3. installing a process feed economizer.

Key Elements for μmaximum

➢ **Load Balacing**



Key Elements for $\mu_{maximum}$

- **Example**: A plant has a total installed steam-generating capacity of 500,000 lb/hr, and is served by three boilers having a maximum continuous rating of 200,000, 200,000, and 100,000 lb/hr, respectively. Each unit can deliver superheated steam at 620 psig and 700°F with feedwater supplied at 250°F. The fuel fired is natural gas priced into the operation at $3.50/106 Btu. Total plant steam averages 345,000 lb/hr and is relatively constant. The boilers are normally operated according to the following loading. Determine the savings obtainable with optimum steam plant load-balancing conditions.

Key Elements for μmaximum

Boiler No.	Size Boiler (103 lb/hr)	Normal Boiler Load (103 lb/hr)	——Measured—— Stack Temp. (°F)	O2 (%)	Unit Eff. (%)
1	200	140	290	5	85.0
2	200	140	540	6	77.4
3	100	65	540	7	76.5
Plant steam demand		345			

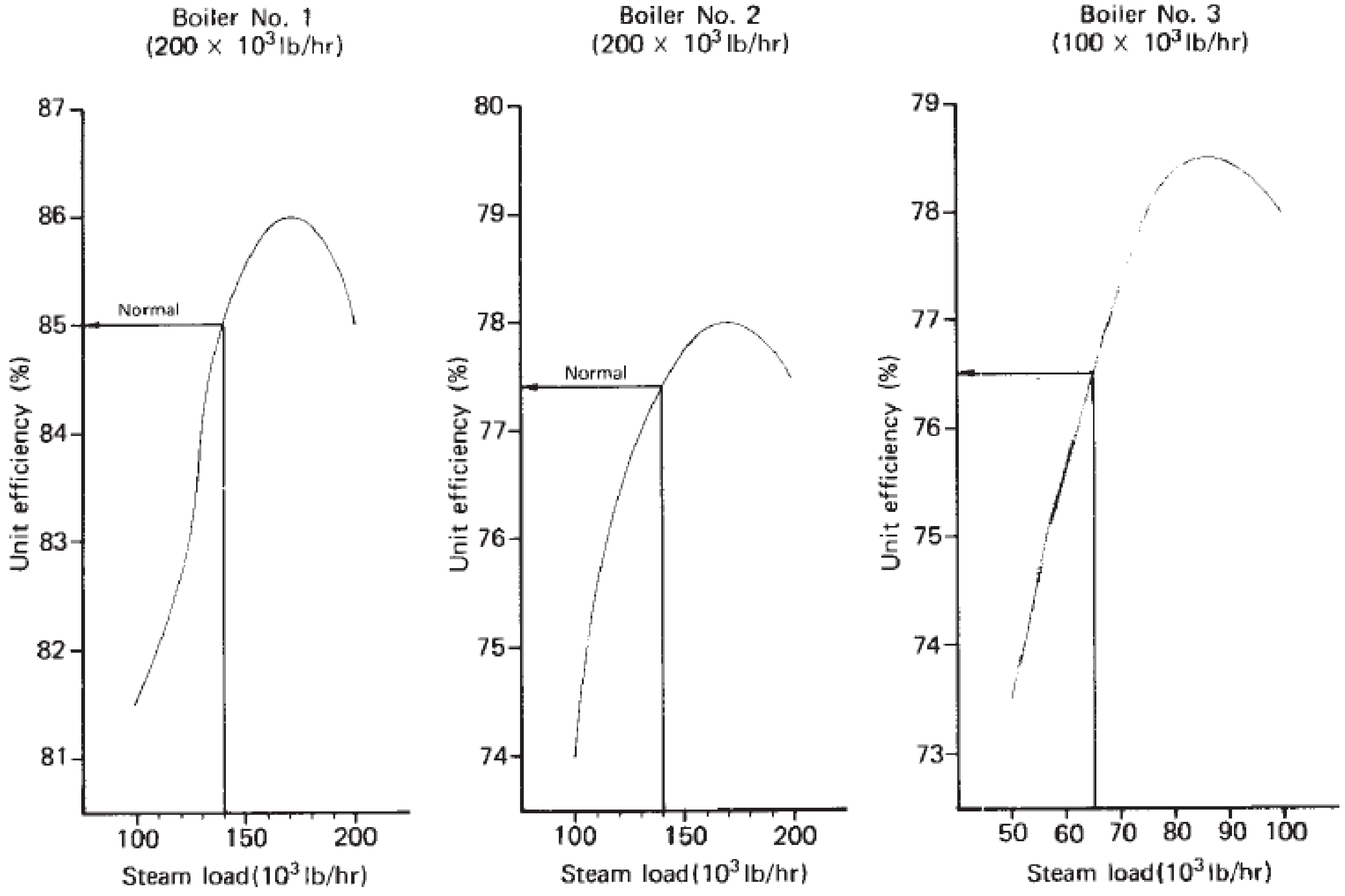


Figure 5.11 Unit efficiency vs. steam load.

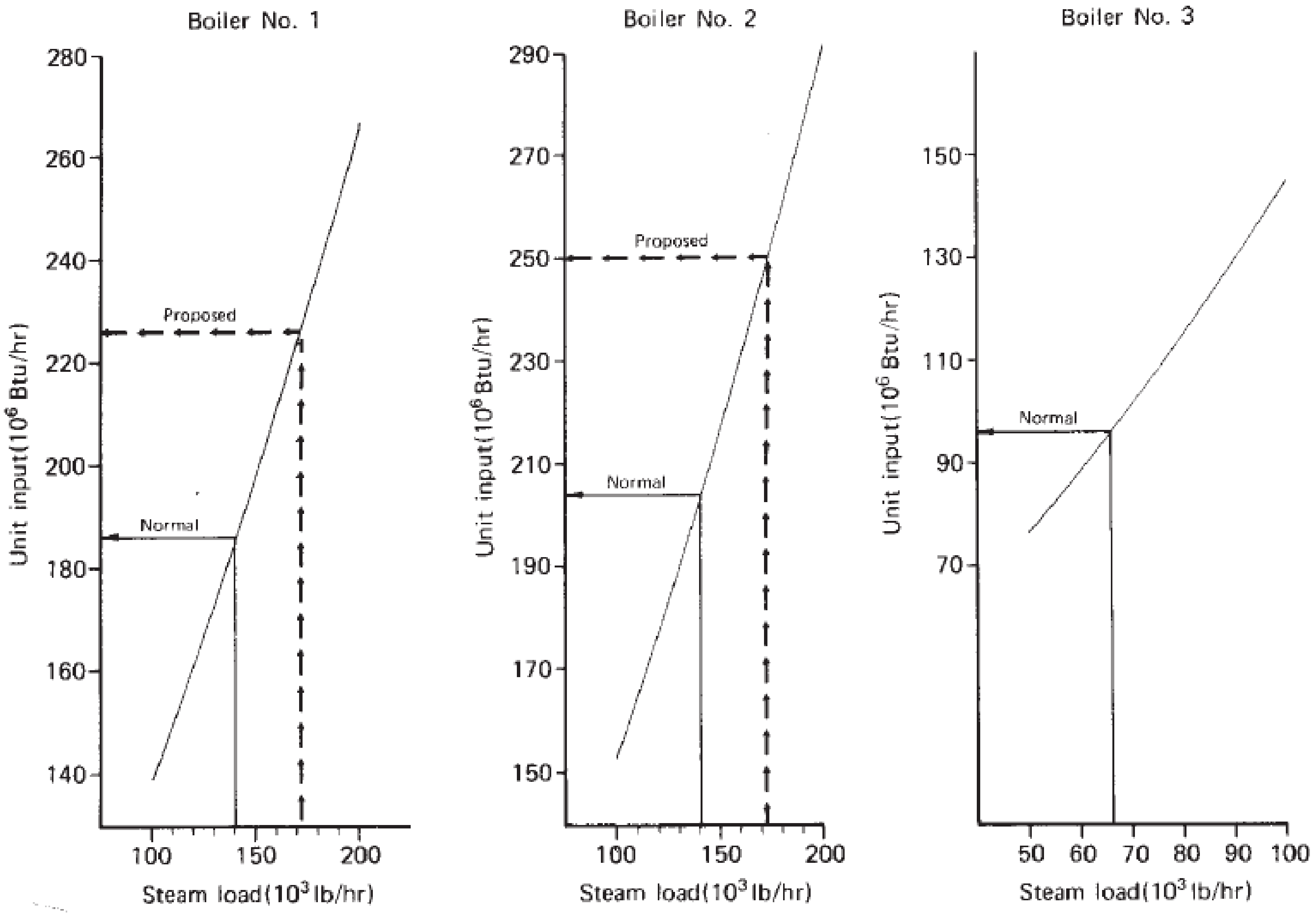


Figure 5.12 Unit input vs. steam load.

Key Elements for μmaximum

Boiler No.	Steam Load (10^3 lb/hr)	Heat Input (10^6 Btu/hr)
1	140	186
2	140	204
3	65	96
Plant totals	345	486

Table 5.8 Unit Efficiency and Input Tabulation

Boiler No.	Steam Load (10^3 lb/hr)	Stack Temperature (°F)	Measured Oxygen (%)	Combustion Efficiency (%)	Output (10^6 Btu/hr)	Fuel Input (10^6 Btu/hr)
1	200	305	2	85.0	226.2	266.1
	170	280	2	86.0	192.3	223.6
	130	300	7	84.0	147.0	175.0
	100	280	12	81.5	113.1	138.8
2	200	625	2	77.5	226.2	291.0
	170	570	4	78.0	192.3	246.5
	130	520	7	77.0	147.0	190.9
	100	490	11	74.0	113.1	152.8
3	100	600	2	78.0	113.1	145.0
	85	570	2	78.5	96.1	122.5
	65	540	7	76.5	73.5	96.1
	50	500	11	73.5	56.6	76.9

Key Elements for $\mu_{maximum}$

Boiler No.	Steam Load (10^3 lb/hr)	Heat Input (10^6 Btu/hr)
1	173	226
2	172	250
3	(Banked standby)	476
Plant totals	345	

Key Elements for µmaximum

Boiler Blowdown

- In the generation of steam, most water impurities are not evaporated, thus, concentrate in the boiler water.
- It is usually regulated by the adjustment of the continuous blowdown valve, which controls the amount of water (and concentrated impurities) purged from the steam drum.
- When the amount of blowdown is not properly established and/or maintained, either of the following may happen:
    1. If too little blowdown, sludge deposits and carryover will result.
    2. If too much blowdown, excessive hot water is removed, resulting in increased boiler fuel requirements, boiler feedwater requirements, and boiler chemical requirements.

Key Elements for μmaximum

Boiler Blowdown

- Significant energy savings may be realized by:
  1. Reduce blowdown (BD) by adjustment of the blowdown valve such that the controlling water impurity is held at the maximum allowable level.
  2. Maintain blowdown continuously at the minimum acceptable level.
  3. Minimize the amount of blowdown required by: Recovering more clean condensate, Establishing a higher allowable drum solids level than is currently, Selecting the raw-water treatment system which has the largest effect on reducing makeup water impurities.
  4. Recover heat from the hot blowdown water.

Key Elements for μmaximum

- **Example**: Determine the potential energy savings associated with reducing boiler blowdown from 12% to 10% using Figure 5.13.

Operating Data	
Average boiler load	75,000 lb/hr
Steam pressure	150 psig
Make up water temperature	60°F
Operating hours	8,200 hr/yr
Boiler efficiency	80%
Average fuel cost	$2.00/$10^6$ Btu

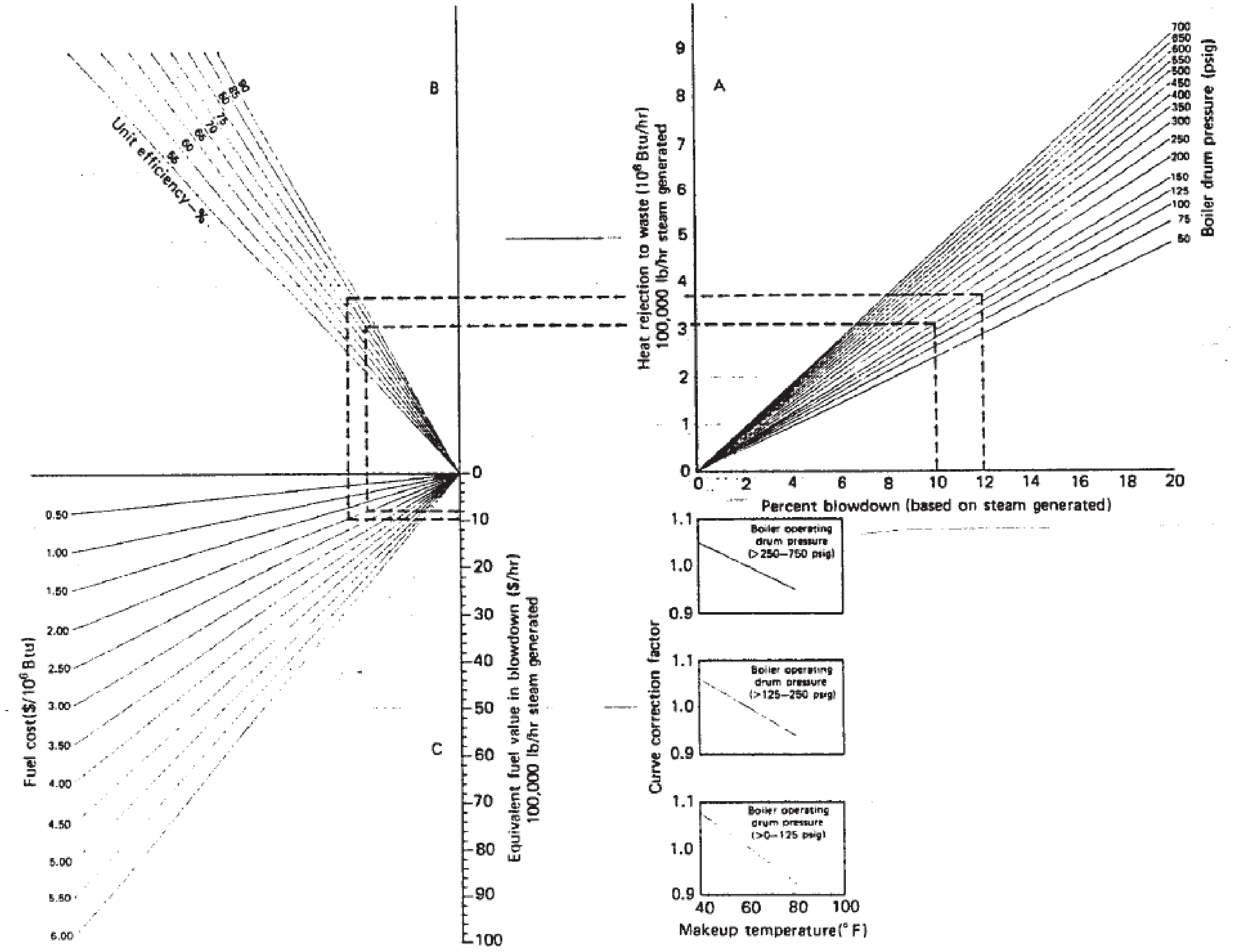


Figure 5.13 Hourly cost of blowdown.

Key Elements for μmaximum

Tests and Evaluations

STEP 1: *Determine Actual Blowdown.* Obtain the following data:

T	=	ppm of impurities in the makeup water to the deaerator from the treatment plant; obtain average value through lab tests
B	=	ppm of concentrated impurities in the boiler drum water (blowdown water); obtain average value through lab tests

Key Elements for µmaximum

lb/hr MU	=	lb/hr of makeup water to the deaerator from the water treatment plant; obtain from flow indicator
lb/hr BFW	=	lb/hr of boiler feedwater to each
lb/hr STM	=	lb/hr of steam output from each boiler; obtain from flow indicator
lb/hr CR	=	lb/hr of condensate return

Note: percentages for BFW, MU, and CR are determined as a percentage of STM.

Key Elements for μmaximum

Calculate the following:

%MU = lb/hr MU × 100%/(total lb/hr BFW)
= lb/hr MU × 100%/[(boiler no. 1 lb/hr BFW) + (boiler no. 2 lb/hr BFW) +...]

%MU = 100% – %CR (5.3)

A = ppm of impurity in BFW = T × %MU (5.4)

Now actual blowdown (BD) may be calculated as a function (percentage) of steam output:

%BD = (A × 100%)/(B-A) (5.5)

Converting to lb/hr BD yields

lb/hr BD = % BD × lb/hr STM (5.6)

Key Elements for µmaximum

Note: In using all curves presented in this section. Blowdown must be based on steam output from the boiler as calculated above. Boiler blowdown based on boiler feedwater rate (percent BD BFW) to the boiler should not be used. If blowdown is reported

Key Elements for µmaximum

STEP 2: *Determine Required Blowdown*. The amount of blowdown required for satisfactory boiler operation is normally based on allowable limits for water impurities as established by the American Boiler Manufacturers Association (ABMA).

These limits are presented in Table 5.9. Modifications to these limits are possible as discussed below. The required blowdown may be calculated using the equations presented above by substituting the ABMA limit for B (concentration of impurity in boiler).

$$\%\ BD_{required} = (A) / (B_{required} - A) \times 100\% \quad (5.8)$$

$$lb/hr\ BD_{required} = \%\ BD_{required} \times lb/hr\ STM \quad (5.9)$$

Key Elements for μmaximum

Table 5.9 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	3500	6000	700	1000	300	250	125
301 to 450	3000	5000	600	900	250	200	90
451 to 600	2500	4000	500	500	150	100	50
601 to 750	2000	2500	400	400	100	50	35
751 to 900	1500	—	300	300	60	—	20
901 to 1000	1250	—	250	250	40	—	8
1001 to 1500	1000	—	200	200	20	—	2

Key Elements for μmaximum

STEP 3: *Evaluate the Cost of Excess Blowdown.* The amount of actual boiler blowdown (as calculated in equation 5.4) that is in excess of the amount of required blowdown (as calculated in equation 5.6) is considered as wasting energy since this water has already been heated to the saturation temperature corresponding to the boiler drum pressure. The curves presented in Figure 5.13 provide an easy method of evaluating the cost of excess blowdown as a function of various fuel costs and boiler efficiencies.

Key Elements for μmaximum

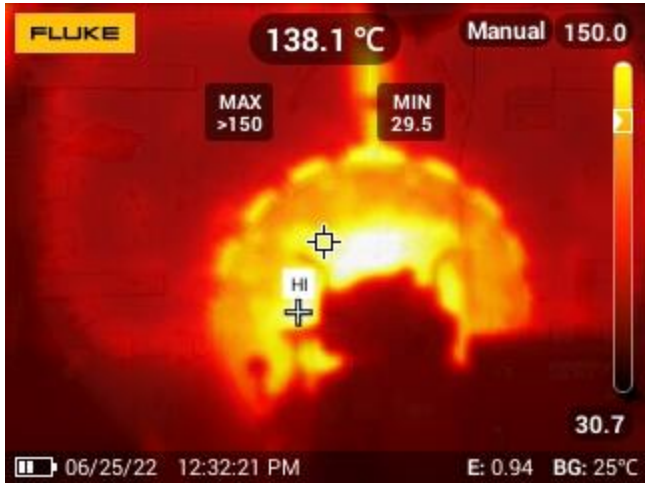
level of water contaminants. Literature has approximated that the average boiler plant can save about 20% blowdown by changing from manual control to automatic adjustment.

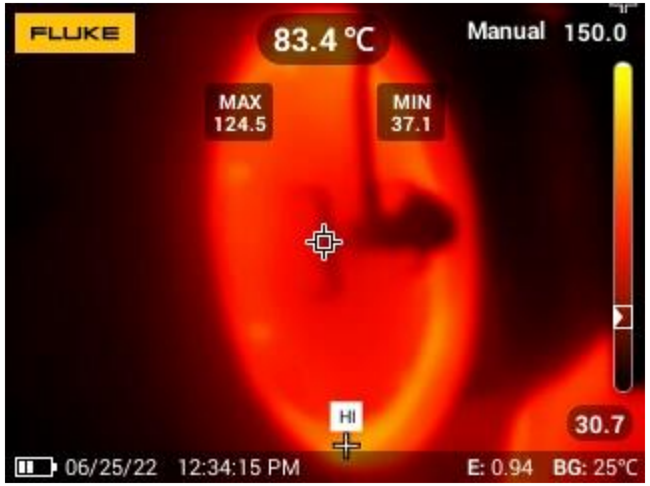
Boiler Nameplates

Boiler

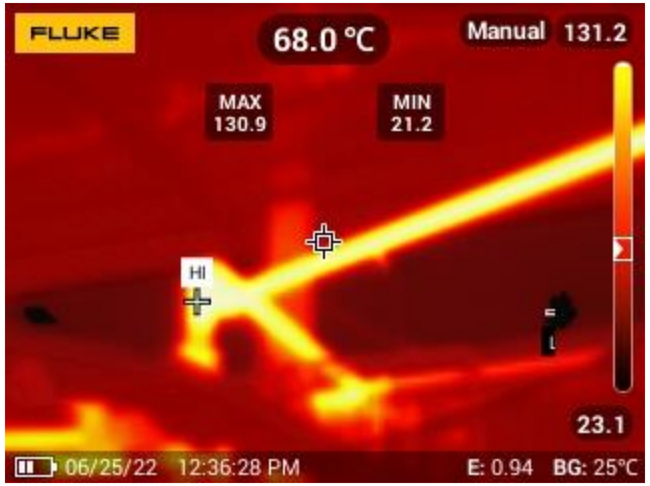
Burner

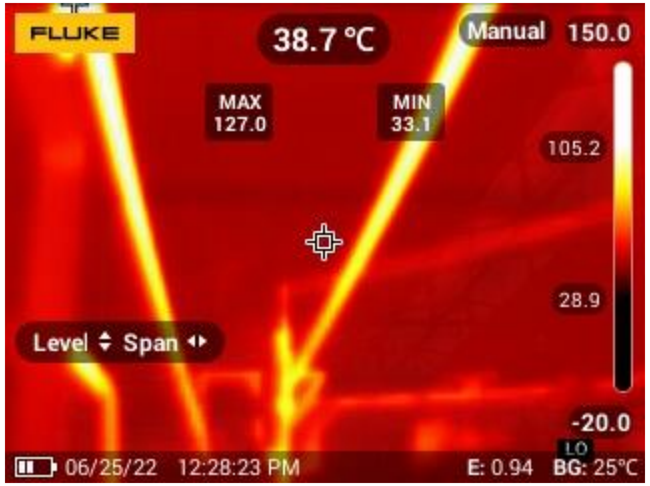
Case study: Insulation inspection of the boiler body

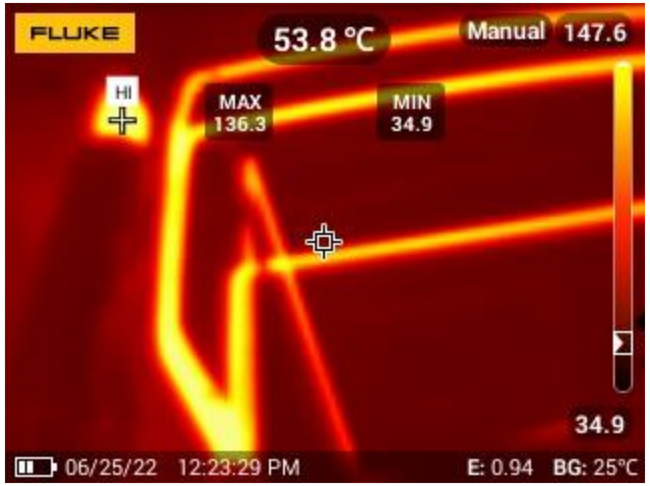




Case study: Insulation inspection of the boiler distribution network

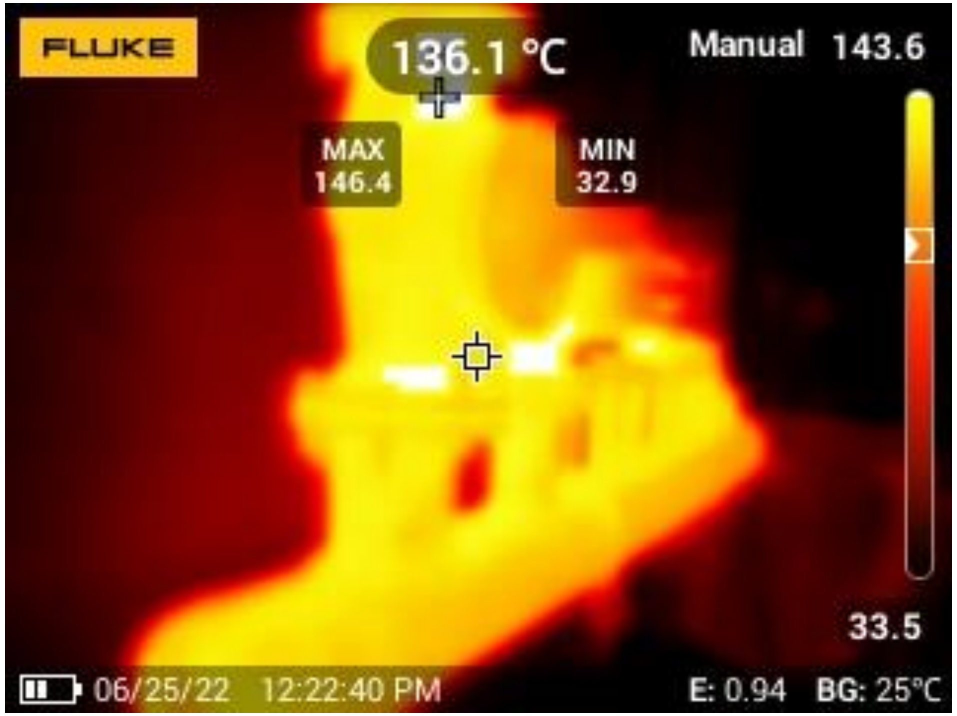






Case study: Insulation inspection of the boiler distribution network

Case study: Insulation inspection of the boiler distribution valves



Case study: Boiler return tank

Thanks for listening

Keep practice.