Process Plant Optimisation & Energy Conservation

27 Nov - 01 Dec 2016
Jumeirah Creekside Hotel
Dubai, United Arab Emirates

Presented by:
Dr. Alhussein Albarbar
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Process Plant Optimisation & Energy Conservation

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By
Dr. Alhussein Albarbar
Senior Consultant

Your Name
PROCESS PLANT OPTIMISATION &
ENERGY CONSERVATION

27 Nov - 1 Dec 2016:
Dubai, UAE
Dr. Alhussein Albarbar

Administrative Points

- AZTech Welcomes you
- Fire Alarms & Emergency Exits
- Please put mobile phones to silent
- Complete the course registration form – this is for your certificate
- Any questions before we start?
Why Choose this Course?

• This course will feature the importance and relevance of the constant need to monitor and adjust Process Plant operation to maintain the optimum mode that produces the most efficient results, consistent with safe and reliable operation.

• Plant integrity and reliability is the cornerstone of process plant optimisation. For optimisation benefits to be sustainable, production interruptions must be kept to a minimum, which requires effective management of degradation processes that affect equipment and systems and effective inspection and maintenance strategies, plans and methods. Plant optimisation can be an effective way to achieve improved profitability without the large investment associated with building a new plant.

This course will feature:

• Risk Based Integrity Principles
• Process Plant Economics
• Industrial Energy Management Best Practises
• Implications of Plant Optimisation Activities
• Energy Conservation Opportunities
Who is this Course for?

- This course will benefit all levels of personnel in a process plant environment. It will enable them to understand the design considerations, construction details and operational parameters associated with process heat exchangers.
- This course is suitable to a wide range of process plant professionals but will greatly benefit:
  - Process Supervisors
  - Plant Operators
  - Operations Engineers
  - Engineering and Technical personnel involved in improving process plant, petrochemical plant and refinery profitability and energy efficiency

What are the Goals?

By the end of this course, participants will be able to:

- Recognize and understand what plant optimisation and energy conservation is
- Apply the business focus and equip them to make sustainable plant profitability
- Appraise the most attractive opportunities to identify energy savings
- Describe the managerial tools needed to effectively optimise plant operations
How will this be Presented?

• This course will utilise a variety of proven adult training techniques to ensure maximum understanding, comprehension and retention of the information presented; this includes PowerPoint presentation.
• The goals of each participant are discussed to ensure their needs are fulfilled, as far as possible. Questions are encouraged throughout, particularly at the daily wrap up sessions.
• This provides opportunities for participants to discuss specific issues and, if possible, find appropriate solutions.

The course content

Day 1: Process plant operation, integrity and reliability - overview
• Asset integrity management (AIM)
• Plant integrity and reliability
• Risk based integrity (RBI) approach
• Operation and maintenance impacts on plant integrity and reliability
• Asset management and maintenance management: process improvement
• Process plant economics

Day 2: Process plant optimisation
• Process control basics
• Elements of process plant optimisation
• Components required to optimise industrial processes
• Process or mathematical model of process and process variables
• Application of simulation technology to plant and control
• The basics of heat integration
Day 3: Industrial energy management – energy efficiency: good for business and for the environment
• Energy use and in process industry
• Energy management standard: details
• Energy management standard: features
• Obstacles for energy management programs

Day 4: Energy conservation opportunities
• Energy audit
• Energy audit types
• Benchmarking energy intensity and usage
• Technology options – new energy efficient technologies
• Technical and economic evaluation of potential opportunities: renewable energy

Day 5: Implications of plant optimisation activities
• Impact of optimisation activities and technological modifications to the plant
• Technology licenses
• Impact on human resources
• Good safety - good business
• Safety costs: costs of injuries
## Consultant’s Profile

**Alhussein Albarbar:**

**Academic Qualification:** PhD, CEng, MSc, BSc, MIET, LCGI

**Professional Posts:**
- Senior Consultant with AZTech,
- Professor of Mechanical Engineering,
- Chartered Engineer with Oil and Power Industry

**Skills and Experience:**
- Specialist on:
  - Electromechanical plants design, maintenance and diagnostics.
  - Vibration and Noise analysis methods,
  - NDE Techniques.

**Profile:**
- **1993 - 2000:** Alhussein served as an oil field maintenance engineer for 7 years. His main duties included daily maintenance activities and troubleshooting of Oil Refineries and Power Generation Plants. He also served as a supervisor for the condition monitoring unit and was responsible for the day to day run of the unit and for the training of team consists of 15 engineers. 2000 - present; he worked with Manchester University on a number of projects related to industrial equipment monitoring, control and maintenance techniques. He regularly delivers training courses and consultancy to Oil, Gas, Automotive and Pharmaceutical industries in the UK, Spain, Italy, Sweden and North Africa. Besides undertaking consultancy and training activities, Alhussein develops and delivers new courses and learning materials for professionals. He has also supervised over 17 research degrees on projects related to the above-mentioned industries. He has published over 100 articles and two books; on maintenance engineering for electromechanical systems, power plants and on performance evaluation of hybrid power system.

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<td>Course Overview and Fundamentals of Asset Management</td>
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<tr>
<td></td>
<td>10:15 – 10:30</td>
<td>Asset reliability and risk based inspections</td>
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<tr>
<td></td>
<td>10:30 – 12:15</td>
<td>Process Modelling and Simulation</td>
</tr>
<tr>
<td></td>
<td>12:15 - 12:45</td>
<td>Energy Management Standards and Features</td>
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<td></td>
<td>12:45 – 14:15</td>
<td>Impacts of Operating and Maintenance</td>
</tr>
<tr>
<td></td>
<td>15:15 – 16:15</td>
<td>Modern Technologies on Heat Integration</td>
</tr>
<tr>
<td>Sun</td>
<td></td>
<td>Open Session</td>
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<td>Coffee Break</td>
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<tr>
<td>Mon</td>
<td>Methods for Process Control and Optimisation</td>
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<tr>
<td></td>
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<td>Options for New Energy Efficient Technologies</td>
</tr>
<tr>
<td></td>
<td>10:30 – 12:15</td>
<td>Impacts on Human Resources and Safety Aspects</td>
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<tr>
<td></td>
<td>12:15 - 12:45</td>
<td>Concluding Remarks and Course Closure</td>
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<tr>
<td></td>
<td>12:45 – 14:15</td>
<td></td>
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<tr>
<td></td>
<td>15:15 – 16:15</td>
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<tr>
<td>Tue</td>
<td>Industrial Energy Consumption and Management</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10:15 – 10:30</td>
<td>Options for New Energy Efficient Technologies</td>
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<tr>
<td>Wed</td>
<td>Energy Audit, Auditing Types and Benchmarking</td>
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## Day 1: Process plant operation, integrity and reliability -overview

- Asset integrity management (AIM)
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Asset integrity management (AIM)

- Pinch Analysis
- Optimization by Mathematical Programming
- Stochastic Search Methods
- Life Cycle Analysis
- Data-Driven Process Modeling
- Integrate Process Design and Control
- Business Model And Supply Chain Modeling
- Real Time Optimization
- Process Simulation
  - Steady state
  - Dynamic
- Data Reconciliation
- Process Data

Plant integrity and reliability
Thrilling Solution

Typical Plant Equipment
Left: Aligned, Right: Misaligned

Effects on power consumption

% increase in energy consumption

offset in mm

Courtesy of OPC PLC
Risk based integrity (RBI) approach

- Most inspection codes/standards based on Likelihood of Failure (LOF), not Consequence of Failure (COF)
- Reduce risk of high consequence failures
- Improve the cost effectiveness of inspection and maintenance resources
- Provide a basis for shifting resources from lower to higher risk equipment
- Measure and understand the risks associated with current inspection programs
- Measure risk reduction as a result of inspection practices
 Definitions

- **Risk Assessment**: is a concept that allows people to view potential hazards in a way that simultaneously accounts for both the likelihood and consequences of an event.

- **Failure (PS)**: is a leak to the atmosphere or breach of containment

- **Failure (Machines)**: is a degradation of the intended functionality—maybe still functioning

- **Risk Based Inspection (RBI)**: is a systematic tool that helps users make informed business decisions regarding inspection and maintenance spending.

Where Inspection Can Help

About half of the containment losses in a typical petrochemical process plant can be influenced by inspection activities.
With the New Philosophy

Risk with typical inspection program
Risk using RBI
Uninspectable risk

LEVEL OF INSPECTION ACTIVITY

Managing Risk Acceptable Profile

Focus on High Risk Items to Drive Risk Down
Avoid Unnecessary Inspection Cost
Acceptable Risk Profile
Limitations of RBI

- Human error
- Natural disasters
- External events (e.g., collisions or falling objects)
- Secondary effects from nearby units
- Deliberate acts (e.g., sabotage)
- Inherent risk in handling hazardous materials
- Fundamental limitations of the inspection method
- Design Errors
- Unknown/Unidentified Mechanisms of Deterioration
API RBI Risk Matrix

<table>
<thead>
<tr>
<th>Likelihood Category</th>
<th>Consequence Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Medium</td>
</tr>
<tr>
<td>B</td>
<td>High</td>
</tr>
<tr>
<td>C</td>
<td>High</td>
</tr>
<tr>
<td>D</td>
<td>Low</td>
</tr>
<tr>
<td>E</td>
<td>Medium</td>
</tr>
</tbody>
</table>

Operation and maintenance impacts on plant integrity and reliability

Damage Mechanisms

- **Thinning Module**
  - CUI
  - Atmospheric
  - Acid Soak
  - HT Sulfide, & Nap Acid
  - H₂S/H₂
  - H₂SO₃
  - HCl
  - CO₂
  - Acid Sour Water
  - Amines
  - HT Oxidation
  - Cooling Water
  - Solid Interface

- **Stress Corrosion Cracking**
  - Caustic
  - Amines
  - SSC
  - HIC/SCC
  - Carbonate
  - PTA
  - Cl SCC
  - HIC-HF
  - HIC/SCC-HF

- **High Temperature Hydrogen Attack**
  - HTIA

- **Furnace Tubes**
  - Wrought Furnace Tubes
  - Cont. Case Tubes

- **Mechanical Damage**
  - Erosion
  - Brittle Fracture
  - Fatigue (Thermal)
  - Fatigue (Cyclic)
  - Creep/Cracking

- **Metallurgical Damage**
  - Tempering
  - Embrittlement
  - SIF
  - Embrittlement
  - Sigma Phase
Key Input Requirements

- Material of Construction
- Process Operation/Upset Conditions
  - Temperature
  - Corrosive elements and concentrations
- Damage Mechanism(s)
  - Including Localized vs. General corrosion
- Years in Service/Installation
- Thickness (at start of services/installation)
- Corrosion Rate/Damage Severity
- Inspection Effectiveness/Number of Inspections

Damage Related Calculations

1. Screen for damage mechanisms and establish an expected damage rate (normal and upset operating conditions).
2. Determine the effectiveness of inspection programs in confirming damage levels and damage rates.
3. Calculate the effect of the inspection program on improving the confidence level in the damage rate.
4. Calculate the probability that a given level of damage will exceed the damage tolerance of the equipment and result in failure.
5. Calculate the Damage factor (DF).
6. Calculate the composite DF for all damage mechanisms.
Effectiveness Categories

A - Highly Effective  Inspection methods correctly identify the anticipated in-service damage in nearly every case.
B - Usually Effective The inspection methods will correctly identify the true damage state most of the time.
C - Fairly Effective  The inspection methods will correctly identify the true damage state about half of the time.
D - Poorly Effective The inspection method will provide little information to correctly identify the true damage state.
E - Ineffective  The inspection method will provide almost no information that will correctly identify the true damage state.

Asset management and maintenance management: process improvement

• Fix when equipment fails or break
• Conduct a full inspection on all equipment at fixed intervals
• Compliance based with the codes / law
• Condition based approach (Likelihood of failure)
• Risk based approach
  – Qualitative
  – Quantitative
  – Semi-Quantitative
Objectives of an Inspection Program

• Prioritization of equipment and piping for inspection
• Develop a specific inspection plan for equipment or piping
• Minimize downtime during turnarounds
• Identify on-stream inspection candidates
• Achieve more effective use of resources
• Assess the impact of turnarounds deferrals
• Special Emphasis inspection programs

Inspection Planning

• Required User Inputs
  – Plan Ending Date
  – Target Criteria
• Damage Factor
• Risk, ft^2/yr
• Risk, $/yr
• Risk will increase until the date of inspection.
• The calculated risk will decrease after RBI inspection plan is implemented.
Day 2: Process plant optimisation

- Process control basics
- Elements of process plant optimisation
- Components required to optimise industrial processes
- Process or mathematical model of process and process variables
- Application of simulation technology to plant and control
- The basics of heat integration

Process control basics
• Multiple Process Vessel Protection
  • ASME paragraph UG-133(c)
    • Vessels connected together by piping not containing valves which can isolate any vessel may be considered as one unit when figuring the required relieving capacity

• Isolation Block Valves Related to PRDs (con’t.)
  • UG-135(d): There shall be no stop valves between the vessel and its PRDs except:
    ▪ when they are so constructed or positively controlled that the closing of the maximum number of block valves possible at one time will not reduce the relieving capacity provided by the unaffected PRDs below the required relieving capacity, or
    ▪ Appendix M is met
This is repeated for EACH piece of equipment or component protected by the PRD

Elements of process plant optimisation

Risk = Chance x Consequence

**Chance Reduction Strategies**
- remove opportunity for failure to start

- Engineering and Maintenance Standards
- Standard Operating Procedures (ACE 3T SOPs)
- Failure Mode Effects Criticality Analysis (FMECA)
- Hazard and Operability Study (HAZOP)
- Hazard Identification (HAZID)
- Root Cause Failure Analysis (RCFA)
- Precision Maintenance (shaft alignment, oil particle filtration, deformation prevention, etc)
- Training and Up-cycling
- Quality Management Systems
- Planning and Scheduling
- Continuous Improvement
- Supply Chain Management
- Total Quality Control
- Design and Operations Cost: Totally Optimised Risk (DOCTOR)
- Defect and Failure True Cost (DAFTC)
- De-rated/Oversize Equipment
- Reliability Engineering

**Consequence Reduction Strategies**
- reduce the loss after a failure has started

- Preventive Maintenance
- Corrective Maintenance
- Total Productive Maintenance (TPM)
- Non-Destructive Testing
- Vibration Analysis
- Oil Analysis
- Thermography
- Motor Current Analysis
- Prognostic Analysis
- Emergency Management
- Computerised Maintenance Management System (CMMS)
- Key Performance Indicators (KPI)
- Risk Based Inspection (RBI)
- Operator Watch-keeping
- Value Contribution Mapping (Process step safety-based costing)
- Logistics, stores and warehouses
- Maintenance Engineering
Plant Optimisation Using Condition Monitoring

- The effect on availability depending on business focus in using CM

Combined Heat Power (CHP) Plant

- Approx. size of person in relation to the CHP plant
- Air inlet filter
- Gas turbine
- Waste heat recovery unit (boiler)
- Supplementary burner
- High temp. heat exchanger for campus heating
Components required to optimise industrial processes

HF Alkylation Unit
Process or mathematical model of process and process variables

Tools of process modeling

- Process Modeling
  - System Theory
  - Physics and Chemistry
  - Application
  - Computes Science
  - Statistics
  - Numerical Methods

Process Simulation

Process modeling

What is a model?

“A model is an abstraction of a process operation used to build, change, improve, control, and answer questions about that process”

Process modeling is an activity using models to solve problems in the areas of the process design, control, optimization, hazards analysis, operation training, risk assessment, and software engineering for computer aided engineering environments.
Process modeling is an understanding of the process phenomena and transforming this understanding into a model.

What is a model used for?

Nilsson (1995) presents a generalized model, which, as depicted in the figure below, can be used for different basic problem formulations: Simulation, Identification, estimation and design.

If the model is known, we have two uses for our model:
Direct: Input is applied on the model, output is studied (Simulation)
Inverse: Output is applied on the model, Input is studied
Demands set to models:

- **Accuracy** → Requirements placed on quantitative and qualitative models.
- **Validity** → Consideration of the model constraints. A typical model process is non-linear, nevertheless, non-linear models are linearized when possible, because they are easier to use and guarantee global solutions.
- **Complexity** → Models can be simple (usually macroscopic) or detailed (usually microscopic). The detail level of the phenomena should be considered.
- **Computational** → The models should currently regard computational orientation.
- **Robustness** → Models that can be used for multiple processes are always desired.

![Figure showing input and output comparison for a process and its model. Note that always n > m and k > t.]

In the process industry we find, two levels of models; Plant models, and models of unit operations such as reactor, columns, pumps, heat exchangers, tanks, etc.
Types of models:

- Intuitive: the immediate understanding of something without conscious reasoning or study. This are seldom used.
- Verbal: If an intuitive model can be expressed in words, it becomes a verbal model. First step of model development.
- Causal: as the name implies, these model are about the causal relations of the processes.
- Qualitative: These models are a step up in model sophistication from causal models.
- Quantitative: Mathematical models are an example of quantitative models. These models can be used for (nearly) every application in process engineering. The problem is that these models are not documented or can be too costly to construct when there is not enough knowledge (physical and chemical phenomena are poorly understood). Sometimes the application encountered does not require such model sophistication.

Simulation: “what if” experimentation with a model

Simulation involves performing a series of experiments with a process model.

Steady State
- Snapshot
- Algebraic equations

Dynamic
- Movie (time functions)
- Time is an explicit variable → differential equations
- Certain phenomena require dynamic simulation (e.g. control strategies, real time decision).
The steady-state simulation does not solve time-dependent equations. The Subroutines simulate the steady-state operation of the process units (operation subroutines) and estimate the sizes and cost the process units (cost subroutines).

A simulation flowsheet, on the other hand, is a collection of simulation units (e.g., reactor, distillation columns, splitter, mixer, etc.), to represent computer programs (subroutines) to simulate the process units and areas to represent the flow of information among the simulation units represented by arrows.
To convert from a process flow sheet to a simulation flow sheet, one replaces the process unit with simulation units (Models). For each simulation unit, one assigns a subroutine (or block) to solve its equations. Each of the simulators has an extensive list of subroutines to model and solve the equations for many process units.

The Dynamic simulation enables the process engineer to study the dynamic response of potential process design or the existent process to typical disturbances and changes in operating conditions, as well as, strategies for the start up and shut down of the potential process design or existing process.
### Differences between Steady State and Dynamic Simulation

<table>
<thead>
<tr>
<th>Steady-State Simulation</th>
<th>Dynamic Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snapshot of a unit operation or plant</td>
<td>Mimic of plant operation</td>
</tr>
<tr>
<td>Balance at equilibrium condition</td>
<td>Time dependent results</td>
</tr>
<tr>
<td>Equilibrium results for all unit operations</td>
<td>It doesn’t assume equilibrium conditions for all units</td>
</tr>
<tr>
<td>Equipment sizes in general not needed</td>
<td>Equipment sizes needed</td>
</tr>
<tr>
<td>Amount of information required: small to medium</td>
<td>Amount of information required: medium to large</td>
</tr>
</tbody>
</table>

### Solution Strategies

- **The Sequential Modular Strategy**
  - flow sheet broken into unit operations (modules)
  - each module is calculated in sequence
  - problems with recycle loops
- **The Simultaneous Modular Strategy**
  - develops a linear model for each unit
  - modules with local recycle are solved simultaneously
  - flowsheet modules are solved sequentially
- **The Simultaneous Equation-solving Strategy**
  - describe entire flowsheet with a set of equations
  - all equations are sorted and solved together
  - hard to solve very large equations systems
Why steady-state simulation is important:

- Better understanding of the process
- Consistent set of typical plant/facility data
- Objective comparative evaluation of options for Return On Investment (ROI) etc.
- Identification of bottlenecks, instabilities etc.
- Perform many experiments cheaply once the model is built
- Avoid implementing ineffective solutions

Why dynamic simulation is important:

- Online system
  - OPTIMIZATION of plant operations
  - ADVANCEMENT OF PLANT OPERATIONS/OPERATIONAL SUPPORT / OPTIMIZATION
    - Predictive simulation
    - Optimal conditions
- Quasi-online system
  - EDUCATION, TRAINING CONTROL SYSTEM
    - Operation training simulator
    - DCS control logic
    - Plant diagnosis system
- Off-line system
  - PROCESS DESIGN / ANALYSIS
    - Examination of operations
    - Control strategies
    - Advanced control systems
    - Batch scheduling
• Simulation is not the highest priority in the plant facilities
  • Production or quality issues take precedence
  • Hard to get plant facilities resources for simulation
• “Up front” time required before results are available
  • Model must be calibrated, and results validated, before they can be trusted
  • At odds with “quarterly balance sheet culture”
  • May need to structure project to get some results out early
The basics of heat integration

Process Integration Tasks

- Efficient Use of Energy
- Efficient Use of Materials
- Efficient Process Operation
- Process Debottlenecking
- Total Cost Reduction
- Pollution Reduction

Case Study

Which one is better out of them?

Countercurrent Packed Bed

Yield = 69.5%
Volume = 16 m³

Mechanically Agitated Vessel

Yield = 73.8%
Volume = 12 m³

Bubble Column

Yield = 72.2%
Volume = 12.1 m³
Key Design Parameters

Process Integration

- Process Analysis
  - Analysis of process elements for study of performance
- Process Synthesis
  - Definition of process elements and their interconnection
- Process Optimization
  - Maximizing or minimizing of desired function for the best option
Process integration Goals

- Maximization of Production
- Capital Cost Minimization
- Improved Energy Performance

Simply to
- Reduce: costs, energy and pollution
- Increase: outputs, yields (stresses) and profile
Day 3: Industrial energy management – energy efficiency: good for business and for the environment

• Energy use and in process industry
• Energy management standard: details
• Energy management standard: features
• Obstacles for energy management programs

Energy use and in process industry

The requirements and specifications should include:
• Display asset performance data – such as early warnings
• Current, Temperature, Pressure, etc.
• Other operating / asset condition data
• Diagnostic display — pinpointing problem areas
• Use of modular and standard components
• Use of redundant parts / components to increase reliability
• Minimize special tools — parts
• Operations and maintenance training material
• FMEA / RCM-based maintenance plan
• Maximum use of CBM technologies
• Basis of spares recommendations
• Life Cycle cost analysis
• O&M cost estimates
Simple Real Example

- An electric motor consumes 100 watts (a joule per second (J/s)) of power to obtain 90 watts of mechanical power. Determine its efficiency?

\[
\text{Efficiency} = \frac{90 \text{ W} \times 100}{100 \text{ W}} = 90\%
\]

Typical efficiencies of equipment used in industry

<table>
<thead>
<tr>
<th>Device</th>
<th>Efficiency</th>
</tr>
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<tbody>
<tr>
<td>Electric Motor</td>
<td>90</td>
</tr>
<tr>
<td>Home Oil Furnace</td>
<td>65</td>
</tr>
<tr>
<td>Home Coal Furnace</td>
<td>55</td>
</tr>
<tr>
<td>Steam Boiler (power plant)</td>
<td>89</td>
</tr>
<tr>
<td>Power Plant (thermal)</td>
<td>36</td>
</tr>
<tr>
<td>Automobile Engine</td>
<td>25</td>
</tr>
<tr>
<td>Light Bulb-Fluorescent</td>
<td>20</td>
</tr>
<tr>
<td>Light Bulb -Incandescent</td>
<td>5</td>
</tr>
</tbody>
</table>
25% of the gasoline is used to propel a car, the rest is “lost” as heat. I.e an efficiency of 0.25

Heat Engine

• A heat engine is any device which converts heat energy into mechanical energy.

• Accounts for 50% of our energy conversion devices
For a coal-fired utility boiler, the temperature of high pressure steam would be about 540°C and \( T_c \) cold, the cooling tower water temperature would be about 20°C. Calculate the Carnot efficiency of the power plant?

\[
540 \degree C = 540 + 273 \degree K = 813 \degree K \\
20 \degree C = 20 + 273 = 293 \degree K
\]

A maximum of 64% of the fuel energy can go to generation. To make the Carnot efficiency as high as possible, either \( T_{hot} \) should be increased or \( T_{cold} \) should be decreased.

---

**Schematic Diagram of a Power Plant**

[Diagram of a power plant]

- Products of Combustion
- Electricity
- High Pr. Steam
- Boiler
- Turbine
- Generator
- Cooling Water Condenser
- Stack
- Coal
- Air

[Diagram showing the flow of steam, water, and heat through the various components of a power plant]
Thermal Efficiency

Overall Eff = Electric Energy Output (BTU) x 100
Chemical Energy Input (BTU)

= 35 BTU x 100
100 BTU
= 35%

Overall Efficiency of a series of devices =
(Thermal Energy) x (Mechanical Energy) x (Electrical Energy)
Chemical Energy  Thermal Energy  Mechanical Energy

= E boiler x E turbine x E generator
= 0.88 x 0.41 x 0.97
= 0.35 or 35%
System Efficiency

The efficiency of a system is equal to the product of efficiencies of the individual devices (sub-systems).

<table>
<thead>
<tr>
<th>Step Efficiency</th>
<th>Cumulative Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction of Coal</td>
<td>96%</td>
</tr>
<tr>
<td>Transportation</td>
<td>98%</td>
</tr>
<tr>
<td>Electricity Generation</td>
<td>38%</td>
</tr>
<tr>
<td>Transportation Elec.</td>
<td>91%</td>
</tr>
<tr>
<td>Lighting</td>
<td></td>
</tr>
<tr>
<td>Incandescent</td>
<td>5%</td>
</tr>
<tr>
<td>Fluorescent</td>
<td>20%</td>
</tr>
</tbody>
</table>

System Efficiency of an Automobile

<table>
<thead>
<tr>
<th>Step Efficiency</th>
<th>Cumulative Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production of Crude</td>
<td>96%</td>
</tr>
<tr>
<td>Refining</td>
<td>87%</td>
</tr>
<tr>
<td>Transportation</td>
<td>97%</td>
</tr>
<tr>
<td>Thermal to Mech. E</td>
<td>25%</td>
</tr>
<tr>
<td>Mechanical Efficiency-Transmission</td>
<td>50%</td>
</tr>
<tr>
<td>Mechanical Efficiency-Rolling</td>
<td>20%</td>
</tr>
<tr>
<td>Efficiency</td>
<td>6.6%</td>
</tr>
</tbody>
</table>

The efficiency of a system is equal to the product of efficiencies of the individual devices (sub-systems).
Techniques for Improving Thermal Efficiency

- Heat Mover: any device that moves heat "uphill", from a lower temperature to a higher temperature reservoir.
- Examples:
  - Heat pump.
  - Refrigerator.

Heat Pump Heating Cycle

Source: http://energyoutlet.com/reec/heatpump/pumping.html
Heat Pump Cooling Cycle

Coefficient of Performance (C.O.P)

Effectiveness of a heat pump is expressed as coefficient of performance (C.O.P).

Example

Calculate the ideal coefficient of performance (C.O.P.) For an air-to-air heat pump used to maintain the temperature of a house at 70 °F when the outside temperature is 30 °F.

\[
\begin{align*}
T_{\text{hot}} &= 70 \text{ °F} = 21 \text{°C} = 21 + 273 = 294K \\
T_{\text{cold}} &= 30 \text{ °F} = -1 \text{°C} = -1 + 273 = 272K \\
\text{C.O.P} &= \frac{294}{294 - 272} \\
&= \frac{294}{22} \\
&= 13.3
\end{align*}
\]

Source: http://energyoutlet.com/res/heatpump/pumping.html
Impacts and consequences

• For every watt of power used to drive this ideal heat pump, 13.3 W is delivered from the interior of the house and 12.3 from the outside.

• Theoretical maximum is never achieved in practice

• This example is not realistic. In practice, a C.O.P in the range of 2 - 6 is typical.

More on COP

Compare the ideal coefficients of performance of the of the same heat pump installed in Miami and Buffalo.

Miami: \( T_{\text{hot}} = 70^\circ\text{F}, T_{\text{cold}} = 40^\circ\text{F} \)
Buffalo: \( T_{\text{hot}} = 70^\circ\text{F}, T_{\text{cold}} = 15^\circ\text{F} \)

Miami: \( T_{\text{hot}} = 294^\circ\text{K}, T_{\text{cold}} = 277^\circ\text{K} \)
Buffalo: \( T_{\text{hot}} = 294^\circ\text{K}, T_{\text{cold}} = 263^\circ\text{K} \)

\[
\begin{align*}
\text{Miami} & = \frac{294}{(294-277)} = 17.3 \\
\text{Buffalo} & = \frac{294}{(294-263)} = 9.5
\end{align*}
\]
Energy management standard: details

“The judicious and effective use of energy to maximize profits (minimize costs) and enhance competitive positions”

“The strategy of adjusting and optimizing energy, using systems and procedures so as to reduce energy requirements per unit of output while holding constant or reducing total costs of producing the output from these systems”

Objectives of Energy Management

➢ To achieve and maintain optimum energy procurement and utilization, throughout the organization
➢ To minimize energy costs / waste without affecting production & quality
➢ To reduce import dependency
➢ To enhance energy security, economic competitiveness, and environmental quality

- This Draft International Standard was released in April 2010 and may be ready for publication by mid-2011.
- Energy Management Systems offers a comprehensive and structured approach for energy efficiency improvement.
- ISO/FDIS 50001: 2011(E) defines EnMS as “set of interrelated or interacting elements to establish an energy policy and energy objectives, and processes and procedures to achieve those objectives”
- Applicable to any organization, whatever the size, industry or geographical location
- An organization embracing ISO 50001 is likely to further accelerate adoption of energy efficiency practices and to continuously improve its energy performance and cost.

- Application of the standard can be tailored to fit the requirements of the organization, including degree of documentation, resources and complexity of the system.
- This International Standard can be used for certification/registration and/or self-declaration of an organization’s energy management system.
- The fact that it's based on measurement and verification will help organization stay on track to meet their declared energy policies.
- Adoption of ISO 50001 by any organization will:
  - Reduce energy bills
  - Make manufacturing more sustainable
  - Promotes energy efficiency throughout the supply chain
  - Helps in meeting National GHG reduction targets

Need for ISO 50001

- Need to minimize fossil fuel use and mitigate GHG

Fossil fuels such as coal, petroleum, and natural gas make up the bulk of the India’s primary energy sources and, their consumption is a major source of greenhouse gas emissions, leading to concerns about global warming if not used efficiently.

- Need to adopt Energy Management.

With India’s demand for energy growing, the need to adopt alternative approaches (like increased energy efficiency, renewable energy, etc.) to meet energy demand is also growing. Just in this respect, ‘Energy Management’ comes on the scene, which although is not new to India, yet its penetration and adoption is slow due to various reasons.
ISO 50001-EnMS Requirement

- ISO 50001 specifies requirements for an organization to establish, implement, maintain and improve an energy management system.
- Specifies energy management system (EnMS) to:
  - develop and implement an energy policy,
  - establish objectives, targets, and action plans which take into account legal requirements
- This International Standard specifies requirements for all factors affecting:
  - energy supply, uses and consumption
  - measurement, documentation and reporting,
  - design and procurement practices for energy using equipment, processes, systems, and personnel.

ISO 50001 does not prescribe specific performance criteria with respect to energy

Plan - Do - Check – Act (PDCA)

- ISO 50001 is based on the Plan - Do - Check - Act (PDCA) continual improvement framework and incorporates energy management practices into everyday organizational activities. As per ISO/FDIS 50001:2011(E):
  - Plan: conduct the energy use assessment, establish the baseline, energy performance indicators (EnPIs), objectives, targets and action plans necessary to deliver results that will improve energy performance (measurable results related to energy efficiency, use and consumption) in line with the organization’s energy policy;
  - Do: implement the energy management action plans;
  - Check: monitor and measure processes and the key characteristics of operations that determine energy performance against the energy policy and objectives, and report the results;
  - Act: take actions to continually improve energy performance and the EnMS.
Plan

- ENERGY POLICY
  - ISO/FDIS 50001 defines Energy Policy as “Statement by the organization of its overall intentions, and direction of an organization related to its energy performance, as formally expressed by top management.”
  - The energy policy provides a framework for action and for the setting of energy objectives and energy targets and is documented, communicated, and understood well within the organization.
  - Appropriate to the scale and nature of the organization energy use.
  - Availability of necessary resources and support.
  - Commitment to comply with applicable regulations and other requirements.
  - Setting and reviewing of energy objectives and targets.
  - Supports the purchase of energy efficient technology and services.
  - In India, energy policy declaration by an organization is seen as a top management commitment to continual improvement of organization's energy performance.
Example: Energy Policy

Jindal Steel & Power Ltd. Raigarh is committed to work for effective utilization of all types of energy. This is achieved by:

- Taking specific objective of energy conservation through process / equipment modification.
- Monitoring of energy consumption.
- Creating innovativeness in employees through awareness.
- Converting waste as resource.
- Benchmarking the energy consumption norms.
- Adherence to statutory requirements.

Energy Conservation Approach

Reduce specific consumption of energy by 2% every year over next ten years

Intent
To lessen the burden on the environment by reducing energy on a continuous basis and conserve natural resources.

Requirements
Implement the following fundamental practices related to energy consumption in our organization. These practices have to be taken up on a continuous basis.
1. Monitor energy and water consumption for the whole plant with section wise breakup
2. Establish specific energy (kWh or kCal or kL / ton or unit of production)
3. Develop an in house program to sustain energy conservation activities in the plant.
Energy Policy

- Periodic review of the Energy aspects and finding new opportunities for Energy Efficiency.
- Adopting programmes for Energy Efficient operation of our activities.
- Promoting Renewable Energy usage and reduction in GHG emissions.
- Ensuring availability of information and all necessary resources to achieve objectives and targets.
- Creating awareness among employees and vendors about Energy Efficiency.
- Adopting participatory approach to motivate employees towards Energy Efficiency.
- Complying Energy management related Legal obligations and other requirements.
ENERGY PLANNING
- Consistent with energy policy and has the following activities:
  - Energy review- determination of Energy performance for identification of energy saving opportunities
  - Energy baseline- establishing basis for energy performance comparison.
  - Energy performance indicators (EnPIs)- setting EnPIs, measure of energy performance.
  - Objectives- establishing, implementing and maintaining documented energy objectives.
  - Targets- setting targets consistent with the objectives.
  - Action plans- formulating action plans to achieve objectives and targets, legal/ regulations and other requirements and shall include:
    - designation of responsibility;
    - the means and time frame by which individual targets are to be achieved;
    - a statement of the method by which an improvement in energy performance shall be verified;
    - a statement of the method of verifying the results.

IMPLEMENTATION AND OPERATION
- Organization to use the action plans and other outputs resulting from the planning process for implementation and operations and would require:
  - Competence, training and awareness of work force on their role, responsibilities and duties
  - Communicate internally with workforce on energy performance, EnMS and establish a process through which suggestions can be invited to improve EnMS
  - Records and document of the implementation and operation of the EnMS- scope and boundaries, energy policy, objectives, targets, action plan and other documents as required
  - Operational Controls of those operation and maintenance activities related to significant use of energy
  - Design of new, modified and renovated facilities, equipment, systems and processes that can have a significant impact on energy performance.
  - Procurement of energy efficient products, services and energy.
Check

- MONITORING, MEASUREMENT AND ANALYSIS
  - Key characteristics of operations that determine energy performance are monitored, measured and analysed at planned intervals
  - Corrective and preventive actions
  - Significant energy uses and other outputs.
  - Energy Performance Indicators (EnPIs).
  - Effectiveness of Action plans.
  - Energy measurement plan.
  - Evaluation and correction of deviations of the energy performance.
  - Control of records.

Check (contd.)

- INTERNAL AUDIT
  - Conduct internal audits to ensure that Energy Management System (EnMS) confirms to:
    - planned arrangements for energy management
    - energy objectives and targets established;
    - effective implementation
Act

- MANAGEMENT REVIEW
  - Top management shall review the organization's EnMS to ensure its continuing suitability, adequacy and effectiveness.
  - Inputs for review will include:
    - Calendar of review.
    - Records.
    - Follow-up actions from previous management reviews.
    - Energy policy.
    - Energy Performance Indicators (EnPIs).
    - Legal compliance and other requirements.
    - Energy objectives and targets.
    - Results of the audit.

- CORRECTIVE AND PREVENTIVE ACTIONS.
  - Projected energy performance.
  - Recommendations for improvement.
  - Resources.

Act

- Continual Improvement
  - A recurring process which results in enhancement of overall energy performance and the EnMS
  - Output of Management Review will include:
    - Changes in the energy policy.
    - Changes in the EnPIs.
    - Changes in the targets, goals and objectives.
    - Allocation of resources.
Comparison between ISO 50001, ISO 9001 and ISO 14001

- ISO 50001 is proposed to be in line with ISO 9001 and ISO 14001 standards that address quality management and environmental management issues.
- ISO 50001 is based on the same Plan-Do-Check-Act approach of ISO 9001 and ISO 14001 and it draws extensively on the structure and content of the QMS and EMS.
- Implementation of ISO 9001 means what the organization does to fulfill the customer's quality requirements, and applicable regulatory requirements, while aiming to enhance customer satisfaction,
- Implementation of ISO 14001 means what the organization does to minimize harmful effects on the environment caused by its activities, and to achieve continual improvement of its environmental performance.
- Similarly ISO 50001 implementation is expected to address what the organization does to effectively manage energy resources and performance that is relevant to global standards.

Case Study: ISO 50001

- India has enacted the Energy Conservation Act in 2001, which has been amended in 2010
- The five major provisions of EC Act relate to:
  - Designated Consumers (mainly energy intensive industries) to comply with the specific energy consumption norms for the manufactured products and services and establishment of energy management system,
  - Standard and Labeling of energy consuming appliances, gadgets and equipment to ensure promotion of energy efficiency of the new stocks entering the market
  - Energy Conservation Building Codes ensuring that new commercial buildings constructed in the country have less electricity consumption
  - Creation of Institutional Set up (Bureau of Energy Efficiency) for effective coordination of the energy conservation efforts in the country and
  - Establishment of Energy Conservation Fund at Centre and States to provide necessary financial support for energy efficiency initiatives in the country.
- Energy efficiency institutional practices and programs in India are now mainly being guided through various voluntary and mandatory provisions of the Energy Conservation Act
The National Action Plan on Climate Change was released by Honorable Prime Minister of India in June 2008

The Action Plan Outlines 8 missions including National Mission for Enhanced Energy Efficiency (NMEEE)

The basic objective of the NMEEE mission is to ensure a sustainable growth by an approximate mix of 4 E's, namely- Energy, Efficiency, Equity and Environment

In one of the four components of NMEEE, namely, Perform Achieve and Trade (PAT), energy baseline parameters and energy saving targets are being fixed for 8 sectors of energy intensive industry including Thermal Power Stations under EC Act (amended)

PAT process has really made aware the manufacturing sector to how to establish energy performance baseline, normalized energy performance indicators, targets fixation process and action plans to achieve targets.

In order to achieve the targets, as set, the plant is required to have a strong energy management system, well defined energy policy and qualified human resource.

More than 200 industrial units and other establishments have already declared their energy policy and have certified energy managers and energy auditors.

India has now about 8414 Certified Energy Managers, out of which 6073 are also qualified as Certified Energy Auditors, from the previous 11 examinations conducted by Bureau of Energy Efficiency since 2004.

These professionally qualified energy managers and energy auditors have expertise in energy management, project management, financing and implementation of energy efficiency projects, and policy analysis

In view of the above, it may be relatively easier for Indian industry to adopt ISO 50001 Standard.
Important points

- A new international ISO 50001 standard, applicable to any organization whatever the size, industry or geographical location, will benchmark energy management, and establish a framework for organization to manage energy use efficiently.
- It is estimated that the standard could influence up to 60 percent of the world’s energy use.
- This International Standard is based on the Plan-Do-Check-Act continual improvement framework and incorporates energy management in organization practices.
- It does not establish absolute requirements for energy performance beyond the commitments in the energy policy of the organization and its obligation to comply with relevant legislation.

- Developing Best Practice Guides on sector specific energy conservation technologies and methodologies will facilitate the implementation of ISO 50001
- ISO 50001 is designed to be used independently, but can be aligned or integrated with other management systems (e.g., ISO 9001 and 14001).
- ISO 50001 will be a voluntary system, but may tend to become de facto essential requirement as rapid uptake by competitors will drive non-participating organizations to adopt it as well.
- An organization embracing ISO 50001 is likely to further accelerate adoption of energy efficiency practices and to continuously improve its energy performance and cost.
Energy management standard: features

- Three fundamental goals of Strategic Energy Management (SEM):
  1. Credible Energy Savings
  2. Continuous Improvement of the Energy Management System (EnMS)
  3. Persistence (i.e., sustained savings)
  
  (Source: Paul Birkeland’s presentation just a few min ago!)

- SEM: A structured approach to energy management that integrates energy efficiency into daily organizational management practices, resulting in greater sustained savings than a project-by-project approach

- Hopefully you are convinced of the importance of SEM…

- So, how do I implement SEM at my organization? How do I get started??

Benefits of Strategic Energy Management:
- Improved profits
- Reduced energy costs
- Improved processes
- Reduced emissions
- Reduced risk to energy price fluctuations

Getting Started with SEM…

[Google search interface]
Getting Started with SEM…

Google

how do i implement a strategic energy management program?

About 27,100,000 results (0.43 seconds)

Strategic Mgmt Programs - SNHU.edu

Online Learning

Competitive Tuition Rates

Transfer up to 90 Credits

Energy Management Plan - Sustainability Roadmap

www.sustainabilityroadmap.org › Strategies

Jump to Consider adopting a strategic energy management plan - Implementing a
Getting Started with SEM…

[Image of a man looking at multiple street signs with different directions.]
What’s the eGuide?

• The DOE eGuide to Energy Management ("eGuide") is an online resource with a step-by-step approach and tools to help organizations implement a strategic approach to energy management at their facilities.


• Soft-launched a few months ago, now available at: www.energy.gov/eGuide or just google “DOE eGuide”.

• eGuide audience:
  • Industrial end users
    • Large manufacturing facilities
    • Small and medium enterprises (SMEs)
  • Commercial end users
    • Small, medium, or large commercial buildings, facilities staff, schools, etc.
  • Federal & State
    • Public facilities with or without energy managers,
    • DOD facilities
  • Utilities & Program Administrators

Strategic Energy Management Continuum

ISO 50001 used as baseline for eGuide v2.0 design

ISO 50001
Standard Energy Management System (EnMS) framework for global industrial operations

Foundational Energy Management (e.g., ENERGY STAR For Buildings & Plants)
Fundamental approach to developing a systematic energy management program based on industry best practices and benchmarking tools

Source: U.S. DOE Advanced Manufacturing Office
**eGuide Structure: 3 Levels**

- **Level 1:** Provides a structured approach to energy management that any commercial, industrial, or government organization can implement, even organizations with little or no experience in energy management.

- **Level 2:** Provides guidance resources and examples to help organizations understand the ISO 50001 energy management standard requirements and the actions to implement the standard.

- **Level 3:** Builds upon Level 2, providing guidance on the additional requirements to achieve DOE Superior Energy Performance.

**Structured for all 3 SEM Levels with 5 Core Steps**

1. Step 1 - Engage Management
2. Step 2 - Plan for Energy Management
3. Step 3 - Implement Energy Management
4. Step 4 - Measure and Check Results
5. Step 5 - Review for Continual Improvement
## eGuide Structure: 5 Core Steps

### 5 Core Steps
Common across all 3 Levels

1. **Step 1** - Engage Management
2. **Step 2** - Plan for Energy Management
3. **Step 3** - Implement Energy Management
4. **Step 4** - Measure and Check Results
5. **Step 5** - Review for Continual Improvement

---

## eGuide Structure: Substeps

- Assigned to each core step are **substeps** that guide the user through the required tasks that need to be accomplished.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>5 Core Steps</strong></td>
<td><strong>5 Core Steps</strong></td>
<td><strong>5 Core Steps</strong></td>
</tr>
<tr>
<td>4. Measure and Check Results</td>
<td>4. Measure and Check Results</td>
<td>4. Measure and Check Results</td>
</tr>
<tr>
<td>5. Review for Continual Improvement</td>
<td>5. Review for Continual Improvement</td>
<td>5. Review for Continual Improvement</td>
</tr>
</tbody>
</table>

- **24 Substeps**
- **36 Substeps**
- **26 Substeps**
The 5 core steps and 36 substeps are based on the ISO 50001 energy management standard.

Sections and Tasks

- Each substep is organized into four sections:
  1. **Overview**: Provides an introduction to the substep
  2. **How to do it**: Contains guidance on the **specific tasks** that you will need to complete in order to accomplish the substep. Each substep contains a fixed number of tasks.
    - For example, Level 1, Step 2.2 (Identify Energy Sources and Uses) has three associated tasks:
  3. **Resources & Examples**: Provides links to resources including spreadsheets, guidance documents, templates to fill out, or weblinks to helpful websites with additional information.
    - e.g., relevant ENERGY STAR resources are shown in each substep
Obstacles for energy management programs

- Identify current energy sources
- Identify energy uses
- Identify data needs

A typical asset life cycle chart is shown below.
Day 4: Energy conservation opportunities

- Energy audit
- Energy audit types
- Benchmarking energy intensity and usage
- Technology options – new energy efficient technologies
- Technical and economic evaluation of potential opportunities: renewable energy

Energy audit

Step 1: Engage Management

1.1 Learn energy management basics
1.2 Communicate the benefits
1.3 Secure top management commitment
1.4 Appoint energy management lead
1.5 Establish energy team

For ISO 50001 and SEP only
1.6 Identify Energy Management System (EnMS) scope and boundaries
Step 2: Plan for Energy Management

2.2 Identify energy uses
2.3 Gather and input energy bills
2.4 Analyze energy
2.5 Determine significant energy uses
2.6 Prioritize opportunities
2.7 Determine metrics
2.8 Establish baseline
2.9 Establish performance objectives and targets
2.10 Select energy opportunities
2.11 Prepare action plans

For ISO 50001 and SEP only
2.1 Identify and evaluate legal requirements

Step 3: Implement Energy Management

3.1 Secure resources
3.2 Execute action plans
3.4 Address training and communication needs
3.5 Establish operational controls

For ISO 50001 and SEP only
3.3 Manage and control information
3.6 Manage energy considerations in design
3.7 Incorporate energy considerations in procurement
3.8 Define specs for purchasing energy supply
Step 4: Measure and Check Results

4.1 Measure, monitor and analyze metrics
4.2 Correct deviations in energy performance

For ISO 50001 and SEP only
4.3 Evaluate compliance with legal requirements
4.4 Plan and conduct internal audit
4.5 Correct and prevent nonconformities

Step 5: Review for Continual Improvement

5.1 Management review of performance
5.2 Recognize success and communicate results
5.3 Take action to continually improve
Energy audit types

- The eGuide Status Tracker is where you can track your team’s progress as you work through the eGuide steps and tasks

Benchmarking energy intensity and usage

- The eGuide Status Tracker is where you can track your team’s progress as you work through the eGuide steps and tasks
The eGuide Status Tracker is where you can track your team’s progress as you work through the eGuide steps and tasks:

- **Step 1 Engage Management**: 12/12 (100%)
- **Step 2 Plan for Energy Management**: 21/21 (100%)
- **Step 3 Implement Energy Management**: 8/8 (100%)
- **Step 4 Measure and Check Results**: 4/4 (100%)
- **Step 5 Review for Continual Improvement**: 4/4 (100%)

**Technology options – new energy efficient technologies**

Conventional Energy System Based on Fossil Fuel

[Diagram showing the conventional energy system based on fossil fuel: O₂, CO₂, Fossil fuel, Combustion, Electricity, Heat, Propulsion.

https://www.youtube.com/watch?v=LMWlgwvbrcM]
Wind Power

A wind turbine converts kinetic energy in the wind into mechanical and electrical energy. Turbine blades remove energy from wind. Higher velocity results in more kinetic energy, while lower velocity results in less kinetic energy.

Efficiency - Wind Power

\[ P_a = \frac{1}{2} \rho \cdot A \cdot V^3 \left( 1 + \frac{V_a}{V} \right) \left( 1 - \left( \frac{V_a}{V} \right)^2 \right) \]

\[ P_{in} \rightarrow \text{Turbine} \quad C_p \quad \omega_{in} \rightarrow \text{Transmission} \quad \eta_{in} \quad \omega_{i} \rightarrow \text{Generator} \quad \eta_{g} \quad \omega_{g} \rightarrow P_e \]
Sizes

- 57.3 meters
- 60 meters

Solar Energy

- Sun
  - Solar cells
    - Photovoltaic modules
    - Solar photovoltaic energy
    - Electricity
  - Sensors
    - Solar water heaters
    - Thermal heat exchangers
    - Solar thermal energy
    - Heat
How to Harvest Useful Energy?

Light Spectrum
Efficiency Comparison

Efficiency Comparison of Solar Technologies

Energy System Based on Hydrogen

Water → Water (Current from sun, wind and water) → Electrolysis → H₂ → Fuel cell → H₂O → H₂O (Electricity, Heat, Propulsion)
Hybrid Power System (Solar Hydrogen Technology)

Fuel cell theory

- First demonstrated in principle by British Scientist Sir William Robert Grove in 1839.
- Grove’s invention was based on idea of reverse electrolysis.
- In electrolysis, an electric current is introduced into electrolyte.
- This flow between two electrodes causes the splitting of water.
Fuel cell theory

- A fuel cell consists of two electrodes - Anode and Cathode.
- Hydrogen and Oxygen are fed into the cell.
- Catalyst at Anode causes hydrogen atoms to give up electrons leaving positively charged protons.
- Oxygen ions at Cathode side attract the hydrogen protons.
- Protons pass through electrolyte membrane.
- Electrons are redirected to Cathode through external circuit.
- Thus producing the current - power

What is a fuel cell?

- A fuel cell combines fuel and oxidant electrochemically to produce electricity
- Two to three times more efficient than an internal combustion engine
- Fuel cell stack is quiet, has no moving parts, produces zero emissions
Fuel cells for direct energy conversion

Types of fuel cells

- Alkaline (AFC)  
  Application: Space
- Phosphoric Acid (PAFC)  
  Application: Commercially available
- Solid Polymer (PEMFC)  
  Application: Automotive application
- Moltan Carbonate (MCFC)  
  Application: Power generation
- Solid Oxide (SOFC)  
  Application: Power generation
- Direct Methanol (DMFC)  
  Application: Under development
**Voltage = 0.6 V**

**Anode Reaction**

\[ 2H_2 \rightarrow 4H^+ + 4e^- \]

**Cathode Reaction**

\[ O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \]

**PEM fuel cell “stack”**

A small stack of about 10 cells

3kW, 48V
Why fuel cell technology is favoured?

- Batteries are the cleanest automotive energy source.
- To liberate electric cars from electro-chemical battery.
- Electric cars have a limit range and slow charging.
- GM's EV-1 and Honda's EV-Plus have limited range.
- Decades of research and investment on electro-chemical batteries.

Fuel cell vehicle configuration
Automotive fuel cells (PEM)

Honda FCX Clarity

GM’s skateboard chassis idea.


European Fuel Cell Bus Project, which saw 30 fuel cell buses operating on the roads of Europe over the past two years.

Toyota: The FCHV-BUS2 is a large, low-floor, fuel-cell hybrid bus.

Since its exhaust is free of NOx (nitrogen oxides) and PM (particulate matter), it can help improve air quality in urban areas.
**Fuel cells for portable power (DMFC)**

- **Casio**: World’s smallest fuel cell for use in laptop PC. The polymer electrolyte fuel can power a typical laptop computer for eight to 16 hours.

- **Samsung Electronics**: 100Wh laptop PC fuel cell using 100cc of methanol solution, enabling continuous usage for more than 10 hours without recharging.

**Fuel cells for stationary power (SOFC)**

- **UTC Fuel Cells**: 5kW fuel cell power plants for backup power for telecommunications towers, power for small businesses, and residential use.

- **UTC Fuel Cells (PureCell™ 200)**: 200kW of electricity and 900,000 BTUs of usable heat. This system provides clean, reliable power at locations including a New York City police station, a major postal facility in Alaska, a credit-card processing system facility in Nebraska, and a science center in Japan.
Advantages of Fuel Cells

<table>
<thead>
<tr>
<th>Advantages of Fuel Cells</th>
<th>Challenges Facing Fuel Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Higher efficiency compared to IC engines</td>
<td>1. Cost (materials, labor, economy of scale)</td>
</tr>
<tr>
<td>2. Zero emissions at the point-of-use</td>
<td>2. Durability (membrane, catalyst)</td>
</tr>
<tr>
<td>3. No moving parts in the stack, so quieter</td>
<td>3. Lack of H₂ Infrastructure: H₂ is difficult to produce, transport, and store</td>
</tr>
</tbody>
</table>

How do fuel cell cars work?

Components of a fuel cell car
- Fuel cell stack
- Balance of plant: Air compressor, hydrogen recirculating pump, air and hydrogen humidifiers, coolant pump and radiator
- Hydrogen storage tank
- Battery for hybrid operation
- Boost converter and inverter
- Traction motor and transmission
- Computer for control and management
Schematic of direct-hydrogen pressurized FCS

Schematic of electric drive train for FCHEV
Energy flow within components for FCHEV

Energy flow within the components of FCHEV for FUDS: FCHEV with 65kwe FCS and 55kw

Series and parallel hybrid fuel cell vehicles

**Series Hybrid:**
- Small fuel cell, large battery bank
- Battery drives motor at all times
- Fuel cell operates continuously and keeps battery charged
- Fuel cell is not “load-following”

**Parallel Hybrid:**
- Large fuel cell, small battery bank
- Fuel cell drives motor at all times, it is “load-following”
- Battery provides boost power as and when required
The Honda FCX clarity

How FCX Clarity Works

1. Hydrogen tank
   Stores hydrogen
2. Y Flow fuel cell stack
   Generates electricity
3. Lithium-ion battery
   Stores electricity
4. Power Drive Unit (PDU)
   Governs electrical flow
5. Electric drive motor
   Propels vehicle

Engine: 100 kW, 57 liters, 148 lb
Fuel economy: 74 mpgge
Range: 280 miles
H2 Storage: 4.1 kg at 5000 psi

Variable-speed wind turbine with hydrogen storage system
Technical and economic evaluation of potential opportunities: renewable energy

Practical data: PV Cell Performance

A. The dependence of the photoelectric current on distance

B. The dependence of the no-load voltage on distance

C. The dependence of the photoelectric current on the angle of incidence

D. The dependence of the no-load voltage on the angle of incidence

Current-voltage characteristic of the solar cell

The maximum power point is the point in which the product of voltage and current is the greatest. It can be determined in two different ways.
Case Study: Solar Grid-Connected Power Plant

- Manchester Metropolitan University (MMU) installed three PV power stations on its campus in Manchester (~ 55.8kW).

- **The problem:** after some time of operation one of the installed plants was found started to perform much lower than expected (efficiency degradation).

- **This work’s aims:** at finding why such degradation and to develop an online PV monitoring system to determine degradation level and possible causes.
The Philosophy of the Proposed Monitoring System

Solar irradiation and panel temperature distribution during the year for Manchester (2009/2010)
Photo Voltaic Cell Model

\[ I_{ph} - I_s - \frac{V_{oc}}{R_s} - I_{sh} = 0 \]

KCL solved for \( V_{oc} \) using Algebraic Constraint block

\[ V_{oc} = N_i V_{ocen} \]

Measuring the photocurrent \( (I_{ph}) \)

Measuring the cell’s saturation current \( (I_s) \)

Algebraic Constraint block solves for \( I_{ph} \) that results in \( V_{oc} \) (KVL)

---

Test Configuration

- Cells terminal operating voltage
- Varying
- 1000
- Reference irradiation
- Select solar irradiance
- Reference temperature
- Varying1
- Select cell’s working temperature
- Power Output
- Instance
- Current Output
- Temp
- PV Module
- Vpv
- P-V characteristic
- Ppv
- 1-V characteristic
- PV
- To Workspace
Results showing comparison for the simulated and experimental approaches during a sunny day in June 2013 (850W/m², 45°C - BP 380J)
System performance over a 10 day period (1\textsuperscript{st} to 10\textsuperscript{th} Jun 2013)

System Performance over a twelve month period (2013/2014)
Day 5: Implications of plant optimisation activities

• Impact of optimisation activities and technological modifications to the plant
• Technology licenses
• Impact on human resources
• Good safety - good business
• Safety costs: costs of injuries

Impact of optimisation activities and technological modifications to the plant

• The standard definition of reliability leaves much unsaid about the effects of equipment failure on businesses and people.

• You know when you have unreliable plant and equipment because people are angry that it fails so often.

• In companies with equipment reliability problems people are busy „doing”, often repairing failures over and over again.

• It never ends, and you go home each day knowing there will be more troubles tomorrow. You also know when you have reliable equipment because it performs as its design intended without failures.

• The business likely makes good profits with low operating costs controlled to a narrow, known range. You have the time to do your work well.
• A place with reliable equipment is a happy and safe place. Measuring equipment reliability is important if you want to improve it.

• Reliability is measured as the average time between failures, known as „Mean Time Between Failure“ (MTBF).

• One drawback with only measuring time is that there is no indication of the value of that level of reliability.

• If you do not know what reliability is worth, you may spend lots of money on small improvements that have little impact on profitability.

• Or worst still, not spend enough money on highly profitable improvements. Reliability measured only by expected time in service is a poor business indicator.

For a company that measures production by weight a standard profitability indicator that reflects reliability is:

\[
\text{Unit Cost of Production (S/T)} = \frac{\text{Operating Costs in the Period (S)}}{\text{Total Saleable Throughput (Tonnage)}}
\]

If a plant intended to operate for another 10 years (87,600 Hr) producing 1,000 T/Hr which currently has only 90% Availability due to equipment breakdowns.
• If it continues to be run with unimproved reliability, it will lose 876 hours of potential production per year, or over 5 weeks lost yearly, which represents about 10% of annual production.

• For a plant where little attention has been paid to reliability improvement it is possible to double MTBF (i.e. halve the number of breakdowns) using failure elimination methods such as precision maintenance, and machinery improvement projects aimed at defect removal.

• With focused efforts on better planning, improved maintainability and skills upgrading, the MTTR (Mean Time To Repair) for maintenance work could be halved.

• Of the 5 plus weeks lost we could expect to recover 3.8 weeks with the above strategy. That is an additional 507 hours per year and represents an increase from 90% to above 97% Availability.

• Under this simple example the effect on the Unit Cost of Production is to lift the Saleable Throughput by 7% while driving costs down. In halving the breakdowns the direct maintenance component of the Operating Cost (such as parts, manpower, and supervision) falls markedly.

• To this must be added the huge reductions in indirect costs, plus the opportunity and knock-on costs no longer lost.

• Together these three cost categories can easily be ten times the value of the direct maintenance saved.

• In such a case, for every $1,000 dollars of direct maintenance cost reduction through improved reliability, you also gain back $10,000 in additional profit previously lost.
Equipment Reliability Depends on the Reliability of Parts and Components

- Equipment is made of parts and components combined in assemblies that work together to allow it to operate.

- The bearing of electric motor housing carrying a shaft; a typical situation in many industrial machines.

- All industrial equipments are built as a series arrangement of parts and components working together to perform the required duty.

- Once you have a series arrangement of working parts, the series reliability depends on each one working properly.

- Without correct lubrication the series connection has been lost and the assembly cannot survive in-service.

- If this assembly were in a piece of equipment, the equipment would be failed. A sequence arrangement of parts only requires one item in the series to fail and the whole assembly fails. When the assembly fails, the equipment stops.
An assembly of parts (i.e., a machine) can never be more reliable than its least reliable part! You can never improve an equipment item’s reliability more than its least reliable part.

Understanding this reliability principle is important for everything you do in the field of maintenance and reliability improvement.

If you want to improve your machines’ and equipment reliability, you first must ensure each of their parts are even more highly reliable.

When Machines and Equipment Fail We Replace Parts

- After maintenance; the new parts start their life, while the parts not replaced continue theirs.
- Perhaps parts which were minimally stressed before the invasive maintenance become stressed and even that some of the new parts installed are stressed during assembly.
- There are old parts still in good health, parts that have accumulated stress and approaching end-of-life, distressed parts ready to fail from accumulated overloads.
- New parts starting into service with their inherent design limitations. What is the reliability of the whole machine now?
- Equipment reliability depends on individual part reliability. The distressed parts have a very poor reliability (likely to fail soon); while the new parts should have much higher reliability, (likely to fail sometime in the future).
• The equipment is no more reliable that the most distressed part. What could you do right now to improve the reliability of the distressed part?

• You could stop the equipment and replace that part with new. The Operations Group would be very unhappy to learn that the equipment again needs to stop.

• You must know which parts are in distress, else you may replace the wrong ones and the equipment will still fail soon.

• If the chance of excess stress is substantially reduced, the distressed part has a greater prospect of lasting longer.

• This can be as simple as improved housekeeping, such as keeping breathers clear of dust to prevent lubricant contamination and cleaning rubbish/rags and dust/dirt build-up off electric motors, bearing housings and gearboxes to improve heat loss. CM can monitor the stress from „rough operation” induced by poor operating practices and bring the likely implications on production to the attention of Operations and Plant Managers.

Measuring the Rate of Equipment Failure

A machine’s rate of occurrence of failure (ROCOF) changes as its parts do, or do not fail.

When a part fails it is replaced and starts a new ‘life’. But the machine’s life does not start from new. It continues to accumulate time from the second it was first put to work and the parts not replaced continue to age and degrade.

Machine Failures are the Accumulated Effect of its Parts Failures
ROCOF Curve for a Machine (i.e. a System of Parts) Design

The failure curve for a machine has a special name: ROCOF - Rate of Occurrence of Failure.

With more parts, ROCOF becomes approximately constant.

A Single System (machine)

Time or Usage Age of System

Mean of Many Systems (machines)

Time or Usage Age of Parts

Improving the Reliability of Machines and Equipment

• Better quality control
• More training
• Precision assembly
• Precision installation
• More parts on PM
• Better materials
• Do more preventive maintenance
• Better operator training
• Total Productive Maintenance
• Precision Maintenance
• Better design/material choices
• Machine protection devices

When we remove parts' failure by changing our policies and using better practices, the old ROCOF reduces to the new ROCOF.
Stop the Risk of Excessive Stress and You Stop Equipment Failures

- How long will your equipment last before the next failure?
- You cannot possibly know with certainty because it depends on the chance its parts will survive to a point in time.
- The best you can offer is a guess. Gambling the future of your business when you work in Engineering, Operations or Maintenance.
- Reliability worsens and plant availability falls if you do not understand the game you are playing.
- You only need to control what stresses you permit your equipment parts to experience.

Stress at Microstructure Destroys Machines Parts

Uncoil a paper clip and 1) bend it and 2) twist it as instructed by the Presenter. Carefully count the number of cycles until it breaks.

![Graph showing the relationship between stress cycles and failure](image)

- Have you ever bent a metal wire back and forth until it breaks from being worked? If you have then you were performing a stress life-cycle test. The wire does not last long when severely bent one way and then back the other way. Each bend is an overstress, and eventually the overstressing accumulates as damage to the microstructure. The wire fatigue and fails. The very same thing happens with the parts in your machines. If you want your parts to NEVER FAIL FROM OVERSTRESS—KEEP OPERATING STRESSES BELOW INFINITE LIFE LEVELS.
Control the Chance of an Equipment Failure Event

Only accept this range of outcomes because they give very low risk.

Value of a Critical Parameter

Number of Events

Very Bad Outcome

Acceptable Outcome

Very Bad Outcome

controls are applied intentionally to reduce the range of outcomes to those that are beneficial.

Effects of Stress on Machinery Condition

Range of Operating Stress

Factor of Safety

OVERLOAD causes local stress to rise

Range of Material Strength

Parts fail whose strength is weaken to this level

Material strength fails from FATIGUE

Why do parts fail? Because they can no longer handle the stress they suffer. When the load is too great the part fails from ‘overload’, when the material weakens and degrades it fails from ‘fatigue’.

Parts ‘age’ as they are used. Loads stress the physical structure and it breaks under high loads. The weakest parts fail early; the strongest take more stress before they too fail. We show the degradation as a curve of material strength from most strong to least strong.
Effects of Out of Roundness

Filing Roller Bearing Degradation Curve and the Worsening Defect Severity
Technology licenses

Impact on human resources

Role of staff & supervisors
Good safety - good business

Reliability of the process is

\[ R_s = R_1 \times R_2 \times R_3 = .90 \times .80 \times .99 = .713 \text{ or } 71.3\% \]

Failure Rate Example

20 air conditioning units designed for use in NASA space shuttles operated for 1,000 hours. One failed after 200 hours and one after 600 hours. Calculate FR and MTBF.

\[ \text{FR(\%)} = \frac{2}{20} (100\%) = 10\% \]

\[ \text{FR(}N\text{)} = \frac{2}{20,000 - 1,200} = .000106 \text{ failure/unit hr} \]

\[ \text{MTBF} = \frac{1}{.000106} = 9,434 \text{ hrs} \]

Failure rate per trip

\[ \text{FR} = \text{FR(}N\text{)}(24 \text{ hrs})(6 \text{ days/trip}) \]
\[ \text{FR} = (.000106)(24)(6) \]
\[ \text{FR} = .153 \text{ failures per trip} \]
Providing Redundancy

Provide backup components to increase reliability

\[
\left( \text{Probability of first component working} \right) + \left( \text{Probability of second component working} \right) \times \left( \text{Probability of needing second component} \right)
\]

\[
= (.8) + (.8) \times (1 - .8)
\]

\[
= .8 + .16 = .96
\]

Redundancy Example

A redundant process is installed to support the earlier example where

\[ R_s = .713 \]

\[
R_1 = .90 \\
R_2 = .80 \\
R_3 = .99
\]

Reliability has increased from .713 to .94

\[
= [.9 + .9(1 - .9)] \times [.8 + .8(1 - .8)] \times .99
\]

\[
= [.9 + (.9)(.1)] \times [.8 + (.8)(.2)] \times .99
\]

\[
= .99 \times .96 \times .99 = .94
\]
Implementing Preventive Maintenance

- Need to know when a system requires service or is likely to fail
- High initial failure rates are known as infant mortality
- Once a product settles in, MTBF generally follows a normal distribution
- Good reporting and record keeping can aid the decision on when preventive maintenance should be performed

Computerized Maintenance System

**Data Files**
- Equipment file with parts list
- Maintenance and work order schedule
- Repair history file
- Inventory of spare parts
- Personnel data with skills, wages, etc.

**Output Reports**
- Inventory and purchasing reports
- Equipment parts list
- Equipment history reports
- Cost analysis (Actual vs. standard)
- Work orders
  - Preventive maintenance
  - Scheduled downtime
  - Emergency maintenance

**Data entry**
- Work requests
- Purchase requests
- Time reporting
- Contract work
Maintenance Costs

- The traditional view attempted to balance preventive and breakdown maintenance costs.
- Typically this approach failed to consider the true total cost of breakdowns:
  - Inventory
  - Employee morale
  - Schedule unreliability
Example

- The following example compares preventive maintenance with breakdown maintenance. The Figure summarizes the failures that a sheet metal press in a stamping department recorded over the last 36 months.

<table>
<thead>
<tr>
<th>Number of failures</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of months failures occurred</td>
<td>3</td>
<td>12</td>
<td>10</td>
<td>8</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

- Currently this department doesn’t have a formal PM program.
- Each failure costs on average $450, which comprises of $ 350 labour and $100 material costs.
- The press manufacturer has proposed performing PM on all the presses at a cost of $300/month; they guarantee not more than one failure per month.

Should we accept their proposal to establish this PM program?

- For the sake of simplicity, ignore production losses due to failures.
- We can use the expected value process to evaluate the PM proposal.
- The PM proposal should be accepted as it will save a little over $112/month.
- Note that this potential saving doesn’t include increased production resulting from reduced equipment downtime.
Maintenance Cost Example

<table>
<thead>
<tr>
<th># of Breakdowns</th>
<th>Number of Months That Breakdowns Occurred</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>20</td>
</tr>
</tbody>
</table>

Average cost of breakdown = $300

Should the firm contract for maintenance on their printers?
Solution

1. Compute the expected number of breakdowns

<table>
<thead>
<tr>
<th>Number of Breakdowns</th>
<th>Frequency</th>
<th>Number of Breakdowns</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2/20 = .1</td>
<td>2</td>
<td>6/20 = .3</td>
</tr>
<tr>
<td>1</td>
<td>8/20 = .4</td>
<td>3</td>
<td>4/20 = .2</td>
</tr>
</tbody>
</table>

\[
\text{Expected number of breakdowns} = \sum \left( \frac{\text{Number of breakdowns}}{20} \times \text{Corresponding frequency} \right) \\
= (0)(.1) + (1)(.4) + (2)(.3) + (3)(.2) \\
= 1.6 \text{ breakdowns per month}
\]

2. Compute the expected breakdown cost per month with no preventive maintenance

\[
\text{Expected breakdown cost} = \text{Expected number of breakdowns} \times \text{Cost per breakdown} \\
= (1.6)(\$300) \\
= \$480 \text{ per month}
\]
3. Compute the cost of preventive maintenance

\[
\text{Preventive maintenance cost} = \left( \text{Cost of expected breakdowns if service contract signed} \right) + \left( \text{Cost of service contract} \right)
\]

\[
= (1 \text{ breakdown/month})(\$300) + \$150/\text{month}
\]

\[
= \$450 \text{ per month}
\]

Hire the service firm; it is less expensive

---

Increasing Repair Capabilities

1. Well-trained personnel
2. Adequate resources and material planning
3. Ability to establish repair plan and priorities
4. Ability to identify the cause of breakdowns
5. Ability to design ways to extend MTBF
Is Predictive Maintenance Cost Effective?

- In most industries the average rate of return is 7:1 to 35:1 for each predictive maintenance dollar spent
- Vibration analysis, IR thermography and oil/water analysis are all economically proven technologies
- The real savings is the avoidance of manufacturing downtime – especially crucial in JIT
Predictive Maintenance and Effective Reliability

- Effective Reliability ($R_{eff}$) is an extension of Reliability that includes the probability of failure times the probability of not detecting imminent failure.

- Having the ability to detect imminent failures allows us to plan maintenance for the component in failure mode.

- Thus avoiding the cost of an unplanned breakdown.

- $R_{eff} = 1 - (P_{(failure)} \times P_{(not \ detecting \ failure)})$

How Predictive Maintenance Improves Effective Reliability

- Example: a large gearbox with a reliability of .90 has vibration transducers installed for vibration monitoring.

- The probability of early detection of a failure is .70. What is the effective reliability of the gearbox?

- $R_{eff} = 1 - (P_{(failure)} \times P_{(not \ detecting \ failure)})$
- $R_{eff} = 1 - (.10 \times .30) = 1 - .03 = .97$

- Vibration monitoring has increased the effective reliability from .90 to .97!
Effective Reliability Caveats

- Predictive maintenance only increases effective reliability if:
  - You select the method that can detect the most likely failure mode
  - You monitor frequently enough to have high likelihood of detecting a change in component behavior before failure
  - Timely action is taken to fix the issue and forestall the failure (in other words you don’t ignore the warning!)

Safety costs: costs of injuries

<table>
<thead>
<tr>
<th>Emission Source</th>
<th>Typical Distribution</th>
<th>Source Classification</th>
<th>General Control Techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Process Vents</td>
<td>5-20</td>
<td>Point Source</td>
<td>Flare, Incinerator, Restrict, Recycle / Recovery etc</td>
</tr>
<tr>
<td>2 Process Equipment Leaks</td>
<td>40-70</td>
<td>Fugitive (Non Point Source)</td>
<td>LDAR, Modification and / or High Integrity Equipment</td>
</tr>
<tr>
<td>3 Storage Tanks</td>
<td>5-15</td>
<td>Point Source</td>
<td>Improved Equipment / Seal Design, Recovery as Fuel / gas</td>
</tr>
<tr>
<td>4 Loading Stations</td>
<td>15-20</td>
<td>Point Source</td>
<td>Vapour Recovery, Modification, Flare</td>
</tr>
</tbody>
</table>
Practical case studies

Energy Efficiency Opportunities

1. Optimize process heat exchange
2. Maintain heat exchanger surfaces
3. Multi-staging systems
4. Matching capacity to system load
5. Capacity control of compressors
6. Multi-level refrigeration for plant needs
7. Chilled water storage
8. System design features

1. Optimize Process Heat Exchange

High compressor safety margins: energy loss

1. Proper sizing heat transfer areas of heat exchangers and evaporators
   • Heat transfer coefficient on refrigerant side: 1400 – 2800 Watt/m²K
   • Heat transfer area refrigerant side: >0.5 m²TR

2. Optimum driving force (difference Te and Tc):
   1°C raise in Te = 3% power savings
3. Selection of condensers

- Options:
  - Air cooled condensers
  - Air-cooled with water spray condensers
  - Shell & tube condensers with water-cooling

- Water-cooled shell & tube condenser
  - Lower discharge pressure
  - Higher TR
  - Lower power consumption

*Reciprocating compressor using R-22 refrigerant. Evaporator temperature: 0°C.
2. Maintain Heat Exchanger Surfaces

- Poor maintenance = increased power consumption
- Maintain condensers and evaporators
  - Separation of lubricating oil and refrigerant
  - Timely defrosting of coils
  - Increased velocity of secondary coolant
- Maintain cooling towers
  - 0.55°C reduction in returning water from cooling tower = 3.0 % reduced power

<table>
<thead>
<tr>
<th>Condition</th>
<th>Te (°C)</th>
<th>Tc (°C)</th>
<th>Refrigeration Capacity* (TR)</th>
<th>Specific Power Consumption (kW/TR)</th>
<th>Increase kW/TR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>7.2</td>
<td>40.5</td>
<td>17.0</td>
<td>0.69</td>
<td>-</td>
</tr>
<tr>
<td>Dirty condenser</td>
<td>7.2</td>
<td>46.1</td>
<td>15.6</td>
<td>0.84</td>
<td>20.4</td>
</tr>
<tr>
<td>Dirty evaporator</td>
<td>1.7</td>
<td>40.5</td>
<td>13.8</td>
<td>0.82</td>
<td>18.3</td>
</tr>
<tr>
<td>Dirty condenser and evaporator</td>
<td>1.7</td>
<td>46.1</td>
<td>12.7</td>
<td>0.96</td>
<td>38.7</td>
</tr>
</tbody>
</table>

(National Productivity Council)
3. Multi-Staging Systems

- Suited for
  - Low temp applications with high compression
  - Wide temperature range
  - Two types for all compressor types
    - Compound
    - Cascade

a. Compound
  - Two low compression ratios = 1 high
  - First stage compressor meets cooling load
  - Second stage compressor meets load evaporator and flash gas
  - Single refrigerant

b. Cascade
  - Preferred for -46 C to -101 C
  - Two systems with different refrigerants
4. Matching Capacity to Load System

- Most applications have varying loads
- Consequence of part-load operation
  - COP increases
  - but lower efficiency
- Match refrigeration capacity to load requires knowledge of
  - Compressor performance
  - Variations in ambient conditions
  - Cooling load

5. Capacity Control of Compressors

- Cylinder unloading, vanes, valves
  - Reciprocating compressors: step-by-step through cylinder unloading:
  - Centrifugal compressors: continuous modulation through vane control
  - Screw compressors: sliding valves
- Speed control
  - Reciprocating compressors: ensure lubrication system is not affected
  - Centrifugal compressors: >50% of capacity
• Temperature monitoring
  • Reciprocating compressors: return water (if varying loads), water leaving chiller (constant loads)
  • Centrifugal compressors: outgoing water temperature
  • Screw compressors: outgoing water temperature

• Part load applications: screw compressors more efficient

6. Multi-Level Refrigeration

Bank of compressors at central plant

• Monitor cooling and chiller load: 1 chiller full load more efficient than 2 chillers at part-load

• Distribution system: individual chillers feed all branch lines; Isolation valves; Valves to isolate sections

• Load individual compressors to full capacity before operating second compressor

• Provide smaller capacity chiller to meet peak demands
Packaged units (instead of central plant)

- Diverse applications with wide temp range and long distance
- Benefits: economical, flexible and reliable
- Disadvantage: central plants use less power

Flow control

- Reduced flow
- Operation at normal flow with shut-off periods

7. Chilled Water Storage

- Chilled water storage facility with insulation
- Suited only if temp variations are acceptable
- Economical because
  - Chillers operate during low peak demand hours: reduced peak demand charges
  - Chillers operate at nighttime: reduced tariffs and improved COP
8. System Design Features

- FRP impellers, film fills, PVC drift eliminators
- Softened water for condensers
- Economic insulation thickness
- Roof coatings and false ceilings
- Energy efficient heat recovery devices
- Variable air volume systems
- Sun film application for heat reflection
- Optimizing lighting loads

Pressure Drop Calculation and Selection of Pumps and Compressors

Objective of pumping system

- Transfer liquid from source to destination
- Circulate liquid around a system
Main pump components

- Pumps
- Prime movers: electric motors, diesel engines, air system
- Piping to carry fluid
- Valves to control flow in system
- Other fittings, control, instrumentation
- End-use equipment
- Heat exchangers, tanks, hydraulic machines

Pumping System Characteristics

- Head
  - Resistance of the system
  - Two types: static and friction

- Static head
  - Difference in height between source and destination
  - Independent of flow
• Static head consists of
  • Static suction head (hS): lifting liquid relative to pump center line
  • Static discharge head (hD) vertical distance between centerline and liquid surface in destination tank
  • Static head at certain pressure

\[
\text{Head (in feet)} = \text{Pressure (psi)} \times 2.31 \times \text{Specific gravity}
\]

• Friction head
  • Resistance to flow in pipe and fittings
  • Depends on size, pipes, pipe fittings, flow rate, nature of liquid
  • Proportional to square of flow rate
  • Closed loop system only has friction head (no static head)
Total head = Static head + friction head

- Relationship between head and flow
  - Flow increase
  - System resistance increases
  - Head increases
  - Flow decreases to zero
- Zero flow rate: risk of pump burnout

Pump performance curve
Pump operating point

- Duty point: rate of flow at certain head
- Pump operating point: intersection of pump curve and system curve

Pump suction performance (NPSH)

- Cavitation or vaporization: bubbles inside pump
- If vapor bubbles collapse
  - Erosion of vane surfaces
  - Increased noise and vibration
  - Choking of impeller passages
- Net Positive Suction Head
  - NPSH Available: how much pump suction exceeds liquid vapor pressure
  - NPSH Required: pump suction needed to avoid cavitation
Positive Displacement Pumps

- For each pump revolution
  - Fixed amount of liquid taken from one end
  - Positively discharged at other end
- If pipe blocked
  - Pressure rises
  - Can damage pump
- Used for pumping fluids other than water
Reciprocating pumps

- Displacement by reciprocation of piston plunger
- Used only for viscous fluids and oil wells

Rotary pumps

- Displacement by rotary action of gear, cam or vanes
- Several sub-types
- Used for special services in industry

Dynamic pumps

- Mode of operation
  - Rotating impeller converts kinetic energy into pressure or velocity to pump the fluid

- Two types
  - Centrifugal pumps: pumping water in industry – 75% of pumps installed
  - Special effect pumps: specialized conditions
Centrifugal Pumps

- Liquid forced into impeller
- Vanes pass kinetic energy to liquid: liquid rotates and leaves impeller
- Volute casing converts kinetic energy into pressure energy

Rotating and Stationary Components
Components of Centrifugal Pumps

Impeller

• Main rotating part that provides centrifugal acceleration to the fluid
• Number of impellers = number of pump stages
• Impeller classification: direction of flow, suction type and shape/mechanical construction

Shaft

• Transfers torque from motor to impeller during pump start up and operation

Casings

• Functions
  • Enclose impeller as “pressure vessel”
  • Support and bearing for shaft and impeller
• Volute case
  • Impellers inside casings
  • Balances hydraulic pressure on pump shaft
• Circular casing
  • Vanes surrounds impeller
  • Used for multi-stage pumps
Assessment of pumps

How to Calculate Pump Performance

- Pump shaft power (Ps) is actual horsepower delivered to the pump shaft

\[
Ps = \frac{Hp}{\eta_{Pump}}
\]

- Pump output/Hydraulic/Water horsepower (Hp) is the liquid horsepower delivered by the pump

\[
Hp = Q \times (hd - hs) \times \rho \times g
\]

\[
Hp = Q \times (hd - hs) \times \rho \times g / 1000
\]

- Absence of pump specification data to assess pump performance
- Difficulties in flow measurement and flows are often estimated
- Improper calibration of pressure gauges & measuring instruments
  - Calibration not always carried out
  - Correction factors used
Energy Efficiency Opportunities

1. Selecting the right pump
2. Controlling the flow rate by speed variation
3. Pumps in parallel to meet varying demand
4. Eliminating flow control valve
5. Eliminating by-pass control
6. Start/stop control of pump
7. Impeller trimming
• Oversized pump
  • Requires flow control (throttle valve or by-pass line)
  • Provides additional head
  • System curve shifts to left
  • Pump efficiency is reduced
• Solutions if pump already purchased
  • VSDs or two-speed drives
  • Lower RPM
  • Smaller or trimmed impeller

2. Controlling Flow: speed variation

Explaining the effect of speed
• Affinity laws: relation speed N and
  • Flow rate Q $\propto$ N
  • Head H $\propto$ N^2
  • Power P $\propto$ N^3
  • Small speed reduction (e.g. $\frac{1}{2}$) = large power reduction
  (e.g. 1/8)
Variable Speed Drives (VSD)

- Speed adjustment over continuous range
- Power consumption also reduced!
- Two types
  - Mechanical: hydraulic clutches, fluid couplings, adjustable belts and pulleys
  - Electrical: eddy current clutches, wound-rotor motor controllers, Variable Frequency Drives (VFDs)

Benefits of VSDs

- Energy savings *(not just reduced flow!)*
- Improved process control
- Improved system reliability
- Reduced capital and maintenance costs
- Soft starter capability
3. Parallel Pumps for Varying Demand

- Multiple pumps: some turned off during low demand
- Used when static head is >50% of total head
- System curve does not change
- Flow rate lower than sum of individual flow rates

4. Eliminating Flow Control Valve

- Closing/opening discharge valve ("throttling") to reduce flow
- Head increases: does not reduce power use
- Vibration and corrosion: high maintenance costs and reduced pump lifetime
5. Eliminating By-pass Control

- Pump discharge divided into two flows
  - One pipeline delivers fluid to destination
  - Second pipeline returns fluid to the source
- Energy wastage because part of fluid pumped around for no reason

6. Start / Stop Control of Pump

- Stop the pump when not needed
- Example:
  - Filling of storage tank
  - Controllers in tank to start/stop
- Suitable if not done too frequently
- Method to lower the maximum demand (pumping at non-peak hours)
7. Impeller Trimming

- Changing diameter: change in velocity
- Considerations
  - Cannot be used with varying flows
  - No trimming >25% of impeller size
  - Impeller trimming same on all sides
  - Changing impeller is better option but more expensive and not always possible

Impeller trimming and centrifugal pump performance
Comparing Energy Efficiency Options

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Change control valve</th>
<th>Trim impeller</th>
<th>VFD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impeller diameter</td>
<td>430 mm</td>
<td>375 mm</td>
<td>430 mm</td>
</tr>
<tr>
<td>Pump head</td>
<td>71.7 m</td>
<td>42 m</td>
<td>34.5 m</td>
</tr>
<tr>
<td>Pump efficiency</td>
<td>75.1%</td>
<td>72.1%</td>
<td>77%</td>
</tr>
<tr>
<td>Rate of flow</td>
<td>80 m³/hr</td>
<td>80 m³/hr</td>
<td>80 m³/hr</td>
</tr>
<tr>
<td>Power consumed</td>
<td>23.1 kW</td>
<td>14 kW</td>
<td>11.6 kW</td>
</tr>
</tbody>
</table>

Affinity Laws

- These relationships are very important rules for estimating the effects of changing geometrical dimensions and operating parameters.

  I. Flow rate: \( \frac{Q_2}{Q_1} = \left(\frac{N_2}{N_1}\right) \left(\frac{D_2}{D_1}\right)^3 \)

  II. Head (pressure): \( \frac{H_2}{H_1} = \left(\frac{N_2}{N_1}\right)^2 \left(\frac{D_2}{D_1}\right)^2 \)

  III. Power: \( \frac{Power_2}{Power_1} = \left(\frac{\rho_2}{\rho_1}\right) \left(\frac{N_2}{N_1}\right)^3 \left(\frac{D_2}{D_1}\right)^5 \)

- These relationships lead to that:
  - Capacity (Q) is proportional to N
  - Head (H) is proportional to \( N^2 \)
  - Power (P) is proportional to \( N^3 \)
Assessment of a Boiler

1. Boiler performance
   • Causes of poor boiler performance
     - Poor combustion
     - Heat transfer surface fouling
     - Poor operation and maintenance
     - Deteriorating fuel and water quality
   • Heat balance: identify heat losses
   • Boiler efficiency: determine deviation from best efficiency

Heat Balance

An energy flow diagram describes geographically how energy is transformed from fuel into useful energy, heat and losses.
Balancing total energy entering a boiler against the energy that leaves the boiler in different forms.

Goal: improve energy efficiency by reducing *avoidable* losses.

Avoidable losses include:
- Stack gas losses (excess air, stack gas temperature)
- Losses by unburnt fuel
- Blow down losses
- Condensate losses
- Convection and radiation
Boiler Efficiency

Thermal efficiency: % of (heat) energy input that is effectively useful in the generated steam

**BOILER EFFICIENCY CALCULATION**

1) **DIRECT METHOD:**
The energy gain of the working fluid (water and steam) is compared with the energy content of the boiler fuel.

2) **INDIRECT METHOD:**
The efficiency is the different between losses and energy input

---

**Boiler Efficiency: Direct Method**

Boiler efficiency \( (\eta) = \frac{\text{Heat Input}}{\text{Heat Output}} \times 100 = \frac{Q \times (h_g - h_f)}{Q \times \text{GCV}} \times 100 \)

- \( h_g \) - the enthalpy of saturated steam in kcal/kg of steam
- \( h_f \) - the enthalpy of feed water in kcal/kg of water

Parameters to be monitored:
- Quantity of steam generated per hour \( (Q) \) in kg/hr
- Quantity of fuel used per hour \( (q) \) in kg/hr
- The working pressure (in kg/cm\(^2\)(g)) and superheat temperature (oC), if any
- The temperature of feed water (oC)
- Type of fuel and gross calorific value of the fuel (GCV) in kcal/kg of fuel
Advantages
• Quick evaluation
• Few parameters for computation
• Few monitoring instruments
• Easy to compare evaporation ratios with benchmark figures

Disadvantages
• No explanation of low efficiency
• Various losses not calculated

Boiler Efficiency: Indirect Method

Efficiency of boiler \( \eta \) = 100 – (i+ii+iii+iv+v+vi+vii)

Principle losses:
i) Dry flue gas
ii) Evaporation of water formed due to H2 in fuel
iii) Evaporation of moisture in fuel
iv) Moisture present in combustion air
v) Unburnt fuel in fly ash
vi) Unburnt fuel in bottom ash
vii) Radiation and other unaccounted losses
Required calculation data

- Ultimate analysis of fuel (H2, O2, S, C, moisture content, ash content)
- % oxygen or CO2 in the flue gas
- Fuel gas temperature in °C (Tf)
- Ambient temperature in °C (Ta) and humidity of air in kg/kg of dry air
- GCV of fuel in kcal/kg
- % combustible in ash (in case of solid fuels)
- GCV of ash in kcal/kg (in case of solid fuels)

Advantages

- Complete mass and energy balance for each individual stream
- Makes it easier to identify options to improve boiler efficiency

Disadvantages

- Time consuming
- Requires lab facilities for analysis
2. Boiler Blow Down

• Controls ‘total dissolved solids’ (TDS) in the water that is boiled
• Blows off water and replaces it with feed water
• Conductivity measured as indication of TDS levels
• Calculation of quantity blow down required:

\[
\text{Blow down (\%) } = \frac{\text{Feed water TDS} \times \% \text{ Make up water}}{\text{Maximum Permissible TDS in Boiler water}}
\]

Two types of blow down

• Intermittent
  • Manually operated valve reduces TDS
  • Large short-term increases in feed water
  • Substantial heat loss

• Continuous
  • Ensures constant TDS and steam purity
  • Heat lost can be recovered
  • Common in high-pressure boilers
Benefits

- Lower pretreatment costs
- Less make-up water consumption
- Reduced maintenance downtime
- Increased boiler life
- Lower consumption of treatment chemicals

3. Boiler Feed Water Treatment

- Quality of steam depend on water treatment to control
  - Steam purity
  - Deposits
  - Corrosion

- Efficient heat transfer only if boiler water is free from deposit-forming solids
Boiler Feed Water Treatment

Deposit control

- To avoid efficiency losses and reduced heat transfer
- Hardness salts of calcium and magnesium
  - Alkaline hardness: removed by boiling
  - Non-alkaline: difficult to remove
- Silica forms hard silica scales

Internal water treatment

- Chemicals added to boiler to prevent scale
- Different chemicals for different water types
- Conditions:
  - Feed water is low in hardness salts
  - Low pressure, high TDS content is tolerated
  - Small water quantities treated
- Internal treatment alone not recommended
External water treatment:

- Removal of suspended/dissolved solids and dissolved gases
- Pre-treatment: sedimentation and settling
- First treatment stage: removal of salts
- Processes
  a) Ion exchange
  b) Demineralization
  c) De-aeration
  d) Reverse osmoses

a) Ion-exchange process (softener plant)
- Water passes through bed of natural zeolite of synthetic resin to remove hardness
- Base exchange: calcium (Ca) and magnesium (Mg) replaced with sodium (Na) ions
- Does not reduce TDS, blow down quantity and alkalinity

b) Demineralization
- Complete removal of salts
- Cations in raw water replaced with hydrogen ions
c) De-aeration

- Dissolved corrosive gases (O\textsubscript{2}, CO\textsubscript{2}) expelled by preheating the feed water
- Two types:
  - *Mechanical de-aeration*: used prior to addition of chemical oxygen scavengers
  - *Chemical de-aeration*: removes trace oxygen

**Assessment of a Boiler**

**External Water Treatment**

**Mechanical de-aeration**
- O\textsubscript{2} and CO\textsubscript{2} removed by heating feed water
- Economical treatment process
- Vacuum type can reduce O\textsubscript{2} to 0.02 mg/l
- Pressure type can reduce O\textsubscript{2} to 0.005 mg/l

( National Productivity Council)
Chemical de-aeration

- Removal of trace oxygen with scavenger
- Sodium sulphite:
  - Reacts with oxygen: sodium sulphate
  - Increases TDS: increased blow down
- Hydrazine
  - Reacts with oxygen: nitrogen + water
  - Does not increase TDS: used in high pressure boilers

d) Reverse osmosis

- Osmosis
  - Solutions of differing concentrations
  - Separated by a semi-permeable membrane
  - Water moves to the higher concentration
- Reversed osmosis
  - Higher concentrated liquid pressurized
  - Water moves in reversed direction
Energy Efficiency Opportunities

1. Stack temperature control
2. Feed water preheating using economizers
3. Combustion air pre-heating
4. Incomplete combustion minimization
5. Excess air control
6. Avoid radiation and convection heat loss
7. Automatic blow down control
8. Reduction of scaling and soot losses
9. Reduction of boiler steam pressure
10. Variable speed control
11. Controlling boiler loading
12. Proper boiler scheduling
13. Boiler replacement
1. Stack Temperature Control
   • Keep as low as possible
   • If >200°C then recover waste heat

2. Feed Water Preheating Economizers
   • Potential to recover heat from 200 – 300 °C flue gases leaving a modern 3-pass shell boiler

3. Combustion Air Preheating
   • If combustion air raised by 20°C = 1% improve thermal efficiency

4. Minimize Incomplete Combustion
   • Symptoms:
     • Smoke, high CO levels in exit flue gas
   • Causes:
     • Air shortage, fuel surplus, poor fuel distribution
     • Poor mixing of fuel and air
   • Oil-fired boiler:
     • Improper viscosity, worn tops, carbonization on dips, deterioration of diffusers or spinner plates
   • Coal-fired boiler: non-uniform coal size
5. Excess Air Control

- Excess air required for complete combustion
- Optimum excess air levels varies
- 1% excess air reduction = 0.6% efficiency rise
- Portable or continuous oxygen analyzers

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Kg air req./kg fuel</th>
<th>%CO₂ in flue gas in practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Fuels</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bagasse</td>
<td>3.3</td>
<td>10-12</td>
</tr>
<tr>
<td>Coal (bituminous)</td>
<td>10.7</td>
<td>10-13</td>
</tr>
<tr>
<td>Lignite</td>
<td>8.5</td>
<td>9-13</td>
</tr>
<tr>
<td>Paddy Husk</td>
<td>4.5</td>
<td>14-15</td>
</tr>
<tr>
<td>Wood</td>
<td>5.7</td>
<td>11.13</td>
</tr>
<tr>
<td>Liquid Fuels</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Furnace Oil</td>
<td>13.8</td>
<td>9-14</td>
</tr>
<tr>
<td>LSHS</td>
<td>14.1</td>
<td>9-14</td>
</tr>
</tbody>
</table>

6. Radiation and Convection Heat Loss Minimization

- Fixed heat loss from boiler shell, regardless of boiler output
- Repairing insulation can reduce loss

7. Automatic Blow Down Control

- Sense and respond to boiler water conductivity and pH
8. Scaling and Soot Loss Reduction

- Every 22°C increase in stack temperature = 1% efficiency loss
- 3 mm of soot = 2.5% fuel increase

9. Reduced Boiler Steam Pressure

- Lower steam pressure
  - lower saturated steam temperature
  - lower flue gas temperature
- Steam generation pressure dictated by process

10. Variable Speed Control for Fans, Blowers and Pumps

- Suited for fans, blowers, pumps
- Should be considered if boiler loads are variable

11. Control Boiler Loading

- Maximum boiler efficiency: 65-85% of rated load
- Significant efficiency loss: < 25% of rated load
12. Proper Boiler Scheduling
- Optimum efficiency: 65-85% of full load
- Few boilers at high loads is more efficient than large number at low loads

13. Boiler Replacement
Financially attractive if existing boiler is
- Old and inefficient
- Not capable of firing cheaper substitution fuel
- Over or under-sized for present requirements
- Not designed for ideal loading conditions
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