Fundamentals of Compressed Air Systems

COMPRESSED AIR CHALLENGE

800-862-2086
www.knowpressure.org
Fundamentals of Compressed Air Systems

HOST LIST
June 11, 1999
Richmond, VA

U.S. Department of Energy
OIT Resource Center, EE-20/5F-064
1000 Independence Ave., SW
Washington, DC 20585
Phone: 800-862-2086
Phone: 202-586-2090
Web: www.oit.doe.gov

TENCARVA Machinery Company
P.O. Box 24067
2231 East Belt Blvd.
Richmond, VA 23324
Phone: 804-231-6266
Fax: 804-231-9265

Cummins-Wagner Co., Inc.
10901 Pump House Road
Annapolis, MD 20701
Phone: 301-490-9007
Fax: 301-490-7156

Tate Engineering Systems, Inc.
8131 Virginia Pine Ct.
Richmond, VA 25237
Phone: 804-271-1250
Fax: 804-743-0415
Acknowledgment

The Compressed Air Challenge Advisory Board would like to acknowledge and thank the following individuals for their contribution to the Fundamentals of Compressed Air Systems training materials. It was only through their efforts and dedication that this training is possible.

Chris Beals  
Joe Ghislain  
Dave McCulloch  
Aimee McKane  
Bill Scales  
Dean Smith

In addition, the Advisory Board extends its appreciation to the following individuals who participated in the further refinement of these materials. Their timely contribution resulted in a strong comprehensive training package.

Henry Kemp  
Mike Lenti  
Frank Moskowitz  
Gary Shafer  
Jody Sutter  
Tom Toranto  
Hank Van Ormer  
Greg Wheeler
Compressed Air Challenge Training

Fundamentals of Compressed Air Systems

Presented by

Compressed Air Challenge

Prepared by:
Laurel and Associates, Ltd.
and
Resource Dynamics Corporation
Notice of Disclaimer

This Fundamentals of Compressed Air Systems Training has been prepared by the Compressed Air Challenge (CAC). Neither CAC nor any of its members, nor any person acting on behalf of them, make any representation or warranty whatsoever, whether expressed or implied, or assume any legal liability, regarding the completeness or accuracy of the information contained herein, with respect to the use of any information, apparatus, method, process, or similar item disclosed in this training manual, including merchantability and fitness for a particular purpose; or that any such use does not infringe on or interfere with privately owned rights, including any party's intellectual property. Any person wishing to use the information, technologies, or procedures described herein should consult with a qualified expert to ascertain their fitness for the intended use.

Copyright © 1999 Compressed Air Challenge. All rights reserved.
# Fundamentals of Compressed Air Systems

## Table of Contents

<table>
<thead>
<tr>
<th>Page</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>Introduction</strong></td>
</tr>
<tr>
<td></td>
<td>Agenda</td>
</tr>
<tr>
<td>2</td>
<td>What is the Compressed Air Challenge?</td>
</tr>
<tr>
<td>3</td>
<td>Learning Objectives</td>
</tr>
<tr>
<td>4</td>
<td>Seven Step Action Plan</td>
</tr>
<tr>
<td>5</td>
<td><strong>Why Care About Air?</strong></td>
</tr>
<tr>
<td></td>
<td>Comparing Notes</td>
</tr>
<tr>
<td>6</td>
<td>Compressed Air Challenge Questionnaire</td>
</tr>
<tr>
<td>7</td>
<td>What You Don’t Know Will Hurt You</td>
</tr>
<tr>
<td>10</td>
<td>Why Use Compressed Air At All?</td>
</tr>
<tr>
<td>11</td>
<td>A Typical Compressed Air System</td>
</tr>
<tr>
<td>12</td>
<td>Application of Compressed Air System Equipment</td>
</tr>
<tr>
<td>13</td>
<td>The Systems Approach and System Dynamics</td>
</tr>
<tr>
<td>14</td>
<td>Compressed Air Costs in Perspective</td>
</tr>
<tr>
<td>16</td>
<td>Compressed Air Versus Other Energy Sources</td>
</tr>
<tr>
<td>17</td>
<td>The Cost of Poor System Performance</td>
</tr>
<tr>
<td>18</td>
<td>Computing Energy Costs</td>
</tr>
<tr>
<td>20</td>
<td>Estimating Energy Costs</td>
</tr>
<tr>
<td>21</td>
<td>Compressor Annual Energy Cost Estimation</td>
</tr>
<tr>
<td>22</td>
<td>Key Points</td>
</tr>
<tr>
<td>23</td>
<td><strong>Study Your Supply Side</strong></td>
</tr>
<tr>
<td>24</td>
<td>What is the Supply Side?</td>
</tr>
<tr>
<td>25</td>
<td>Types of Compressors</td>
</tr>
<tr>
<td>26</td>
<td>Positive-Displacement Compressors</td>
</tr>
<tr>
<td>27</td>
<td>Dynamic Compressors</td>
</tr>
<tr>
<td>30</td>
<td>Compressor Selection</td>
</tr>
<tr>
<td>32</td>
<td>Compressor Types</td>
</tr>
<tr>
<td>34</td>
<td>Compressor Control Types</td>
</tr>
<tr>
<td>35</td>
<td>Multiple Compressor Controls</td>
</tr>
<tr>
<td>36</td>
<td>Flow/Pressure Controllers</td>
</tr>
<tr>
<td>37</td>
<td>Other Major Supply System Components</td>
</tr>
<tr>
<td>38</td>
<td>Dryers</td>
</tr>
<tr>
<td>44</td>
<td>Dryer Types</td>
</tr>
<tr>
<td>45</td>
<td>Compressed Air Filters</td>
</tr>
</tbody>
</table>
## Table of Contents (Continued)

<table>
<thead>
<tr>
<th>Page</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>47</td>
<td>Study Your Supply Side (Continued)</td>
</tr>
<tr>
<td>49</td>
<td>Traps and Drains</td>
</tr>
<tr>
<td>53</td>
<td>Compressed Air System Component Functions</td>
</tr>
<tr>
<td>54</td>
<td>Key Points</td>
</tr>
<tr>
<td>55</td>
<td>Understand Your Demands</td>
</tr>
<tr>
<td>56</td>
<td>What is the Demand Side?</td>
</tr>
<tr>
<td>57</td>
<td>Compressed Air Versus Other Energy Sources</td>
</tr>
<tr>
<td>58</td>
<td>Typical Components of Demand</td>
</tr>
<tr>
<td>59</td>
<td>Inappropriate Uses of Compressed Air</td>
</tr>
<tr>
<td>60</td>
<td>Leaks and How Demand is Affected by Pressure</td>
</tr>
<tr>
<td>61</td>
<td>Common Leak Locations</td>
</tr>
<tr>
<td>62</td>
<td>Leaks are a Source of Waste</td>
</tr>
<tr>
<td>63</td>
<td>How Do You Find Leaks?</td>
</tr>
<tr>
<td>64</td>
<td>Key Points</td>
</tr>
<tr>
<td>63</td>
<td>Are You on Base?</td>
</tr>
<tr>
<td>64</td>
<td>Process of Baselining</td>
</tr>
<tr>
<td>65</td>
<td>Power and Energy</td>
</tr>
<tr>
<td>68</td>
<td>Unloaded and Part-Load Operation</td>
</tr>
<tr>
<td>69</td>
<td>Energy Costs of Unloaded Operation</td>
</tr>
<tr>
<td>70</td>
<td>Pressure</td>
</tr>
<tr>
<td>71</td>
<td>Pressure Measurement Locations</td>
</tr>
<tr>
<td>72</td>
<td>Estimating Pressure Drop</td>
</tr>
<tr>
<td>73</td>
<td>Leak Load</td>
</tr>
<tr>
<td>74</td>
<td>Estimating Leak Load</td>
</tr>
<tr>
<td>75</td>
<td>Leak Load for Systems with Other Controls</td>
</tr>
<tr>
<td>76</td>
<td>When to Baseline</td>
</tr>
<tr>
<td>77</td>
<td>Additional Measurements</td>
</tr>
<tr>
<td>78</td>
<td>Key Points</td>
</tr>
</tbody>
</table>
# Table of Contents (Continued)

<table>
<thead>
<tr>
<th>Page</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>78</td>
<td><strong>Stay Under Control</strong></td>
</tr>
<tr>
<td></td>
<td><em>Controls Discussion Questions</em></td>
</tr>
<tr>
<td>79</td>
<td>Compressor Control Pros and Cons</td>
</tr>
<tr>
<td>81</td>
<td>Controls, Part-Load Efficiency, and Storage</td>
</tr>
<tr>
<td>86</td>
<td>The Mineral Processing Facility</td>
</tr>
<tr>
<td>91</td>
<td><em>Using Controls</em></td>
</tr>
<tr>
<td>95</td>
<td><em>Controlling Your Own System</em></td>
</tr>
<tr>
<td>96</td>
<td>Key Points</td>
</tr>
<tr>
<td>97</td>
<td><strong>Maintain System Efficiency</strong></td>
</tr>
<tr>
<td></td>
<td>Do You Want to Cut Costs?</td>
</tr>
<tr>
<td>98</td>
<td>Checklist for STA-COLM</td>
</tr>
<tr>
<td>99</td>
<td>Case Study: The Auto Parts Manufacturer</td>
</tr>
<tr>
<td>105</td>
<td><em>Simple, Quick Cost Cutting Measures</em></td>
</tr>
<tr>
<td>112</td>
<td>System Demand Profile – Flow Reduction Potential</td>
</tr>
<tr>
<td>115</td>
<td>Key Points</td>
</tr>
<tr>
<td>116</td>
<td><strong>Get With the Plan</strong></td>
</tr>
<tr>
<td></td>
<td>Seven Step Action Plan</td>
</tr>
<tr>
<td>117</td>
<td><em>Personal Action Plan</em></td>
</tr>
<tr>
<td>118</td>
<td>Implementing Step 7</td>
</tr>
<tr>
<td>122</td>
<td>Key Points</td>
</tr>
<tr>
<td>123</td>
<td><strong>Summary and Evaluation</strong></td>
</tr>
<tr>
<td></td>
<td><em>Action Plan Questionnaire</em></td>
</tr>
<tr>
<td>125</td>
<td>Summary</td>
</tr>
<tr>
<td>126</td>
<td><em>How Much Can You Save?</em></td>
</tr>
</tbody>
</table>
Fundamentals of Compressed Air Systems

Agenda

Introduction

Why Care About Air?

Study Your Supply Side

Understand Your Demands

Are You on Base?

Stay Under Control

Maintain System Efficiency

Get with the Plan

Summary and Evaluation
What is the Compressed Air Challenge?

The Compressed Air Challenge is a voluntary collaboration of:

- Industrial users,
- Manufacturers,
- Distributors and their associations,
- Facility operating personnel and their associations,
- Consultants,
- State research and development agencies,
- Energy efficiency organizations, and
- Utilities.

This group has one purpose in mind—helping you enjoy the benefits of improved performance of your compressed air system.

The Compressed Air Challenge has already developed a series of training sessions to help you learn more about the fundamentals of compressed air systems. A sourcebook is also available.

The Compressed Air Challenge also plans to develop additional training, technical information, case studies, reports and other resources.
Learning Objectives

As a result of this workshop, the participants will:

1. Explain the benefits of improving compressed air system performance;
2. Estimate the current cost of compressed air for their plant;
3. Identify the pros and cons of different compressor types;
4. Describe the components on the supply side;
5. Recognize inappropriate uses of compressed air and common leak locations;
6. Explain the measurement points for baselining;
7. Determine the impact of different compressor control types;
8. Identify steps for proper system operation and maintenance;
9. Assess quick and simple cost cutting measures; and
10. Tailor a compressed air system management action plan.
Seven Step Action Plan

1. Develop a basic block diagram.

2. Measure your baseline (kW, pressures, and leak load) and calculate energy use and costs, with tools available.

3. Work with your compressed air system specialist to implement an appropriate compressor control strategy.

4. Once controls are adjusted, re-measure to get more accurate readings of kW and pressures, and to determine leak load. Recalculate energy use and costs.

5. Walk through to check for obvious preventive maintenance items and other opportunities to reduce costs and improve performance.

6. Identify and fix leaks and correct inappropriate uses – know costs, re-measure, and adjust controls as above.

7. Evaluate Steps 1-6, begin implementation of awareness and continuous improvements programs, and report results to management.
Comparing Notes

Directions: Please refer to your completed Pre-Workshop Assignment pages, in which you developed a block diagram of your system and identified the types of compressors you currently use. Please compare notes with the other people at your table.
## Compressed Air Challenge Questionnaire

<table>
<thead>
<tr>
<th></th>
<th>True</th>
<th>False</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Production staff think that compressed air is free.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Compressed air is an efficient source of energy in a plant.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Compressed air is often the biggest end-use of electricity in a plant.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. I know exactly how much compressed air my plant uses and how much it costs.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Acfm, scfm, icfm, and fad are all the same.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Adding horsepower is the best way to increase system pressure.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Compressed air systems that are inefficient also frequently have reliability problems that affect production.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. There are actions that I can take to save more than 20 percent of my current cost of air.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
What You Don’t Know Will Hurt You

The Bakery

Compressed Air Uses:

- Air motors and lifters
- Pneumatic controls and cylinders
- Baggers

Compressed Air System:

- Two 75 hp lubricant injected rotary screw compressors
- 1.5-2.0 inch distribution system
- Equipment connected with 0.5 inch pipe

Performance Improvement Measures:

- Reduce leaks by 70% (initial leak load was 34.5%)
- Reduce compressor discharge pressure by 10 psi after improving distribution system
- Increase diameter of portions of the main header
- Remove secondary oil separator
- Use unloading controls

Performance Improvement Summary:

- Energy consumption reduced by 35%
- $7,800 in annual energy cost savings
- 1.5 year simple payback for the project
What You Don’t Know Will Hurt You (Continued)

The Foundry

Compressed Air Uses:

- Sand transport system
- Pneumatic controls and cylinders
- Hand tools

Compressed Air System:

- One 150 hp and one 200 hp lubricant injected rotary screw compressor
- 6 inch schedule 40 air line

Performance Improvement Measures:

- Reduce leaks
- Install fans to replace compressed air used to supply combustion air
- Adjust compressor control unloading points

Performance Improvement Summary:

- Energy consumption reduced by 36%
- $16,300 in annual energy cost savings
- 1.3 year simple payback for the project
What You Don’t Know Will Hurt You (Continued)

The Defense Products Company

Compressed Air Uses:
- Diaphragm Pumps
- Pneumatic Controls and Cylinders
- Filter Press
- Mold Blowoffs
- Pressurization of Process Vessel
- Open Blowing
- Cooling of Lathe Cutting Tool
- Mixers
- Shop Vacuums
- Control Valve Actuators
- Parts Clamps

Compressed Air System:
- Four lubricant injected rotary screw machines (Two 100 hp, a 75 hp and a 50 hp)
- Three separate compressor rooms supplying one distribution system

Performance Improvement Measures:
- Reduce system pressure
- Reduce leaks by 80% (initial leak load was 31%)
- Reduce pressure to and install speed controls on diaphragm pumps
- Apply dedicated storage with metered recovery where appropriate
- Install air shutoff valves on end use equipment, mister to cool cutting tools, explosion-proof electric mixers, and central vacuum system
- Use one compressor room for base load & convert second compressor room into trim station behind flow/pressure controller w/ control storage
- Reduce online horsepower from 200 hp down to 125 hp

Performance Improvement Summary:
- Pressure swings reduced from 23 psig to 2 psig
- Energy consumption reduced by 34%
- $16,171 in annual energy cost savings (not including reduced scrap, increase project quality, etc.)
- 2.8 year simple payback for the project
Why Use Compressed Air At All?

Compressed air systems are used in almost every sector of the economy, and there are thousands of different uses for compressed air.

Uses in the manufacturing sector include powering pneumatic tools, packaging, automation equipment, conveyors, controls systems, and others.

Pneumatic tools are used because they:

- Tend to be smaller, lighter, and more maneuverable than electric motor-driven tools,
- Deliver smooth power and are not damaged by overloading,
- Have the capability for infinitely variable speed and torque control, can reach a desired speed and torque very quickly, and
- Can be safer because they do not have the potential hazards of electric devices, particularly where water and gases are present.

Although they have many advantages, pneumatic tools are generally much less energy-efficient than electric tools.

Many manufacturing industries also use compressed air and gas for combustion and process operations such as oxidation, fractionation, cryogenics, refrigeration, filtration, dehydration, and aeration.

There are many applications where compressed air is the best overall solution. However, if there are other, more cost-effective sources of power, compressed air may be used inappropriately.

Air may be free, but compressed air is expensive. When compressed air is needed to make a product, it should be used wisely.
Compressed air systems consist of a supply side, which includes compressors and air treatment, and a demand side, which includes distribution and storage systems and end-use equipment.

A properly managed supply side will result in clean, dry, stable air being delivered at the appropriate pressure in a dependable, cost-effective manner.

A properly managed demand side minimizes wasted air and uses compressed air for appropriate applications.

Improving and maintaining peak compressed air system performance requires addressing both the supply and demand sides of the system and how the two interact.
Application of Compressed Air System Equipment

Hundreds of manufacturers produce the various pieces of equipment that are used in a compressed air system, from the compressor packages to the end use tools.

There are generally many different options for accomplishing a given task with compressed air, and it is important to apply the equipment properly.

Often, if a system is performing poorly, it is not because the equipment is faulty, but because it has been applied improperly or poorly maintained.

Almost every compressed air system has room for performance improvement, from a modern system in a two-year old plant to one that has been modified and updated over the last forty years.
The Systems Approach and System Dynamics

Improving and maintaining peak compressed air system performance requires not only addressing individual components, but also analyzing both the supply and demand sides of the system and how they interact. This practice is often referred to as taking a "systems approach" because the focus is shifted away from components to total system performance. Applying the systems approach usually involves the following:

- Developing a basic block diagram of your system.
- Measuring your baseline (kW, pressures, and leak load) and determining costs, with tools available.
- Working with your compressed air system specialist to implement an appropriate compressor control strategy.
- Once controls are adjusted, re-measuring to get more accurate readings of kW and pressures, and to determine leak load.
- Walking through to check for obvious preventive maintenance items and other opportunities to reduce costs and improve performance.
- Identifying and fixing leaks and correcting inappropriate uses – knowing costs, re-measuring, and adjusting controls as above.
- Evaluating the above and implementing an awareness and continuous improvement program.

The above are part of the seven step action plan for implementing the systems approach to the compressed air systems at your plant.

With compressed air systems, system dynamics (i.e. changes in demand over time) are especially important. Using controls, storage, and demand management to effectively design a system that meets peak requirements but also operates efficiently at part-load is key to a high performance compressed air system.
Compressed Air Costs in Perspective

Generating compressed air is expensive, requiring:

- Equipment
- Energy (usually electricity)
- Maintenance (scheduled and unscheduled)
- Cooling water supply and disposal (water-cooled units)
- Ventilation
- Overhead (floor space, insurance, taxes, etc.)
- Condensate disposal
- Rental units

Most companies don’t know how much it costs to make compressed air. Some companies use 15-30 cents per 1,000 cubic feet.

Over the life of a system, the energy costs far exceed any of the other costs.

Simplified example:

- 75 hp compressor (capital cost = $20,000)
- 5-day per week, 2-shift operation
- Electricity costs of $0.05/kWh (annual cost = $13,000)

<table>
<thead>
<tr>
<th>Year</th>
<th>Equipment</th>
<th>Maintenance</th>
<th>Electricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$20,000</td>
<td>$2,000</td>
<td>$13,000</td>
</tr>
<tr>
<td>2</td>
<td>$2,000</td>
<td>$13,000</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>$2,000</td>
<td>$13,000</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>$2,000</td>
<td>$13,000</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>$2,000</td>
<td>$13,000</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>$2,000</td>
<td>$13,000</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>$2,000</td>
<td>$13,000</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>$2,000</td>
<td>$13,000</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>$2,000</td>
<td>$13,000</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>$2,000</td>
<td>$13,000</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>$20,000</td>
<td>$20,000</td>
<td>$130,000</td>
</tr>
</tbody>
</table>
Compressed Air Costs in Perspective (Continued)

Costs Over 10 Years

- Maintenance: 12%
- Equipment: 12%
- Electricity: 76%
Compressed Air Versus Other Energy Sources

Compressed air is a necessary part of most plant operations, but is probably the most inefficient source of energy in a plant.

To operate a 1 hp air motor, you need 7-8 horsepower of electrical power into the compressor. At higher than typical pressures, even more power is needed.

- 30 scfm @ 90 psig is required by the 1 hp air motor
- 6-7 bhp at compressor shaft is required for 30 scfm
- 7-8 hp electrical power is required for 6-7 bhp at shaft

The overall efficiency of a typical compressed air system can be as low as 10-15 percent.

Annual energy costs for a 1 hp air motor vs. a 1 hp electric motor, 5-day per week, 2 shift operation, $0.05/kWh.

$1,164 (compressed air) vs. $194 (electric)

---

**1 Horsepower Motor**

**Annual Energy Cost ($)**

<table>
<thead>
<tr>
<th>Annual Energy Cost ($)</th>
<th>Compressed Air</th>
<th>Electric</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>800</td>
<td></td>
<td></td>
</tr>
<tr>
<td>600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The Cost of Poor System Performance

Systems with leaks waste money. The diagram below shows the cost of leaks in a compressed air system.

<table>
<thead>
<tr>
<th>Size</th>
<th>Air Flow</th>
<th>Cost per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/16&quot;</td>
<td>6.49 cfm</td>
<td>$523</td>
</tr>
<tr>
<td>1/8&quot;</td>
<td>26.0 cfm</td>
<td>$2,095</td>
</tr>
<tr>
<td>1/4&quot;</td>
<td>104 cfm</td>
<td>$8,382</td>
</tr>
</tbody>
</table>

Costs calculated using electricity rate of $0.05 per kWh, assuming constant operation, 100 psig, and a typical compressor.

Note: Holes shown are actual size.
Computing Energy Costs

Annual electricity cost (simple formula)

\[
\frac{bhp \times 0.746 \times \text{hours} \times \text{cost}}{\text{motor efficiency}}
\]

Where:
- \(bhp\) = motor full-load horsepower
- 0.746 = kW/hp
- hours = annual hours of operation
- cost = electricity cost in $/kWh
- motor efficiency = motor nameplate full-load efficiency

Example:

200 bhp compressor, 95% efficient motor, 4,160 hours per year of operation, and $0.05/kWh electricity cost

\[
\frac{200 \times 0.746 \times 4,160 \times 0.05}{0.95} = \text{annual electricity costs} = \$32,667 \text{ per year}
\]

Factors that can affect the calculation:

- Motors operating in service factor
- Part-load operation
- Utility rate structures (using average $/kWh)
- Motor efficiency (especially after poor-quality repairs and rewinds)

Note: Service factor is defined as the capacity of a motor to withstand continuous overload conditions. A motor with a service factor of 1.15 can run continuously serving a load 15% greater than the nameplate horsepower. Most compressors operate at loads greater than their motor nameplate rating, and thus are into their motor's service factor.
Computing Energy Costs (Continued)

Annual electricity cost (three-phase formula with measurements)

\[(\text{full-load amps}) \times (\text{line-to-line voltage}) \times (1.732) \times (\text{pf}) \times (\text{hours}) \times (\text{cost}) \div 1000\]

Where:

- full-load amps = average of three phases measured in amps
- line-to-line voltage = voltage measured in volts
- pf = power factor (assumed to be 0.85)
- hours = annual hours of operation
- cost = electricity cost in $/kWh

Note: full-load amps and line-to-line voltage are measured values

Example:

\[(230 \text{ amps}) \times (460 \text{ volts}) \times (1.732) \times (0.85 \text{ pf}) \times (4160 \text{ hrs}) \times (\$0.05/\text{kWh}) \div 1000\]

annual electricity costs = $32,398 per year

Factors that can affect the calculation:

- part-load operation
- utility rate structures (using average $/kWh)
Why Care About Air?

Estimating Energy Costs

Make a guess at your annual compressed air energy cost and write it down.

Dollars per year

1. Use the form on the next page to estimate your annual compressed air energy cost.

You will need information from the Compressor Information Form and Electricity Cost Form you completed prior to the workshop.

1. How close was your guess?

2. Please realize that your estimated cost may not be accurate if your calculations have not accounted for certain factors, including but not limited to: differences between actual motor efficiency and estimates, marginal electricity costs versus average (blended) costs, and other issues.
Compressor Annual Energy Cost Estimation

Directions: Please complete this form using information from the Compressor Information form and the Electricity Cost form you completed prior to the workshop.

Data Needed:

Motor Horsepower _______ bhp
Annual Days of Operation _______ days
Number of Hours per Day _______ hours
Average Cost of Electricity _______ $/kWh

Calculation (repeat for each compressor and then sum):

annual electricity costs =

\[
\frac{\text{bhp} \times 0.746 \times \text{hours} \times \text{cost}}{\text{motor efficiency}}
\]

Where:

- \text{bhp} = \text{motor full-load horsepower}
- 0.746 = \text{kW/hp}
- \text{hours} = \text{annual hours of operation (days x hours/day)}
- \text{cost} = \text{electricity cost in $/kW}
- \text{motor efficiency} = \text{motor nameplate efficiency}

Calculations:
Key Points

If you want to cut costs, realize that compressed air:

✓ Is the most inefficient source of energy in a plant

✓ Is often the biggest end use of electricity in a plant

✓ Is frequently used inappropriately

✓ Should be viewed as a system that can be managed

✓ Has costs that can be measured
What is the Supply Side?

A typical modern industrial compressed air system is composed of several major subsystems and many components. The entire system is usually divided into two major subsystems: the supply side and the demand side.

The supply side consists of components prior to and including the flow/pressure controller (or prior to and including the primary receiver for a system without a flow/pressure controller). The demand side consists of all components after the flow/pressure controller (or after the primary receiver in systems without a flow/pressure controller).

The following diagram shows the supply side and its components.
There are two basic compressor types: positive-displacement and dynamic.

In the positive-displacement type, a given quantity of air or gas is trapped in a compression chamber and the volume which it occupies is mechanically reduced, causing a corresponding rise in pressure prior to discharge. At constant speed, the air flow remains essentially constant with variations in discharge pressure.

Dynamic compressors impart velocity energy to continuously flowing air or gas by means of impellers rotating at very high speeds. The velocity energy is changed into pressure energy both by the impellers and the discharge volutes or diffusers.
Positive-Displacement Compressors

These compressors are available in two types: reciprocating and rotary.

Reciprocating compressors work like bicycle pumps. A piston, driven through a crankshaft and connecting rod by an electric motor reduces the volume in the cylinder occupied by the air or gas, compressing it to a higher pressure. There are two basic types used:

- Single acting
- Double acting

The most common type of rotary compressor is the helical twin screw-type (also known as rotary screw or helical lobe). Male and female screw-rotors mesh, trapping air, and reducing the volume of the air along the rotors to the air discharge point. There are two variations of rotary screws:

- Lubricant injected
- Lubricant free
Single Acting Reciprocating Air Compressors

This type of compressor is characterized by its "automotive" type piston driven through a connecting rod from the crankshaft. Compression takes place on the top side of the piston on each revolution of the crankshaft.

The most common air compressor in the fractional and single digit hp sizes is the air cooled reciprocating air compressor. In larger sizes, single acting reciprocating compressors are available up to 150 hp, but are much less common above 25 hp.

Advantages include:
- Small size and weight.
- Generally can be located close to point of use, avoiding lengthy piping runs and pressure drops.
- Do not require separate cooling systems.
- Simple maintenance procedures.

Disadvantages include:
- Lubricant carry-over, which should be avoided.
- Relatively high noise.
- Relatively high cost of compression.
- Generally are designed to run not more than 50% of the time, although some industrial designs have a duty cycle of 70-90%.
- Generally compress and store the air in a receiver at a pressure higher than required at the point of use. The pressure then is reduced to the required operating pressure but without recovery of the energy used to compress to the higher pressure.

Operating Cost: 22-24 kW/100 cfm* (please refer to notes on page 31)
Double Acting Reciprocating Air Compressors

These use both sides of the piston for air compression, doubling the capacity for a given cylinder size. A piston rod is attached to the piston at one end and to a crosshead at the other end. The crosshead ensures that the piston rod travels concentrically with the piston. These compressors may be single or multi-stage, depending on discharge pressure and hp size. These can range upwards from 10 hp and with pressures upwards from 50 psig. Lubricant free versions also are available.

Double acting air compressors generally have cooling water jackets around the cylinder body and in the cylinder head. This, combined with their relatively slow speed of operation and water cooled intercooling (on multi-stage units), results in excellent compression efficiency.

Advantages include:

- Efficient compression, particularly with multi-stage compressors.
- Three-step (0-50-100%) or Five-step (0-25-50-75-100%) capacity controls, allowing efficient part load operation.
- Relatively routine type maintenance procedures.

Disadvantages include:

- Relatively high first cost compared with equivalent rotary air compressors.
- Relatively high space requirements.
- Relatively high vibrations require high foundation costs.
- Lubricant carry-over on lubricant cooled units.
- Seldom sold as complete independent packages.
- Require flywheel mass to overcome torque and current pulsations in motor driver.
- Repair procedures require some training and skills.

Operating cost: 15-16 kW/100 cfm* (please refer to notes on page 31)
Lubricant Injected Rotary Screw Compressors

The lubricant injected rotary screw compressor has become a dominant type for a wide variety of applications. These compressors use two inter-meshing rotors in a stator housing having an inlet port at one end and a discharge port at the other.

Air flowing in through the inlet port is trapped between the lobes and the stator. As rotation continues, the point of intermeshing moves progressively along the axial length of the rotors, reducing the space occupied by the air, resulting in increased pressure. Compression continues until the inter-lobe spaces are exposed to the discharge port and the compressed air is discharged.

Lubricant is injected into the compression chamber during compression and serves three basic functions: 1) it lubricates the intermeshing rotors and associated bearings, 2) it takes away most of the heat caused by compression, and 3) it acts as a seal in the clearances between the meshing rotors and between rotors and stator.

Single stage lubricant injected rotary screw compressor packages are available from 3-900 hp, or 8-5000 cubic feet per minute, with discharge pressures from 50-250 psig. More efficient two stage units are also available.

Advantages include:
- Compact size and complete package.
- Economic first cost.
- Vibration free operation does not require special foundation.
- Part load capacity control systems can match system demand.
- Routine maintenance includes lubricant and filter changes.

Disadvantages include:
- Less efficient at full and part load compared with water cooled reciprocating air compressors.
- Lubricant carry-over into delivered air requires proper maintenance of air/lubricant separator and the lubricant itself.

Operating cost: 18-19 kW/100 cfm (single stage), 16-17 kW/100 cfm (two stage)* (please refer to notes on page 31)
Lubricant Free Rotary Screw Compressors

The principle of compression is similar to that of the lubricant injected rotary screw compressor but without lubricant being introduced into the compression chamber. Two distinct types are available - the dry type and the water injected type.

In the dry type, the intermeshing rotors are not allowed to touch and their relative positions are maintained by means of lubricated timing gears external to the compression chamber. Since there is no injected fluid to remove the heat of compression, most designs use two stages of compression, with an intercooler between the stages and an aftercooler after the second stage.

Dry type lubricant free rotary screw compressors have a range from 25-4000 hp or 90-20,000 cubic feet per minute. Single stage units can operate up to 50 psig, two-stage units generally can achieve up to 150 psig.

In the water injected type, similar timing gear construction is used, but water is injected into the compression chamber to act as a seal in internal clearances and to remove the heat of compression.

Lubricant free rotary screw compressors utilize lubricant for lubrication of bearings and gears, which are isolated from the compression chamber. The lubricant also may be used for stator jacket cooling in lieu of water, to eliminate the effects of fouling.

Advantages include:

- Completely packaged.
- Designed to deliver lubricant free air.
- Do not require any special foundations.

Disadvantages include:

- Cost premium over lubricant injected type.
- Less efficient than lubricant injected type.
- Limited to Load/unload type capacity control.
- Higher maintenance costs than lubricant injected type.

Operating Cost: 20-22 kW/100 cfm* (please refer to notes on page 31)
Dynamic Compressors

These compressors raise the pressure of air or gas by imparting velocity energy and converting it to pressure energy. Dynamic compressors include centrifugal and axial types. The centrifugal is the most common and is widely used for industrial applications.

Centrifugal Air Compressors

A centrifugal air compressor has a continuously flowing air stream that is accelerated by an impeller(s), which rotates at speeds that may exceed 50,000 rpm. Approximately half of the pressure energy is developed in the impeller, with the other half achieved by converting the velocity energy to pressure energy as the air speed is reduced in a diffuser and volute. With centrifugal air compressors, as system pressure decreases, the compressor's capacity increases.

Centrifugal air compressors range from around 500 to over 100,000 cfm, but are more common from 1,000 to 5,000 cfm with discharge pressures up to 125 psig.

Centrifugal air compressors provide lubricant free air delivery as there is no lubricant in the compression chambers. Lubrication is kept away by means of shaft seals which may also have air purge and vent connections.

Advantages include:
- Completely packaged for plant or instrument air up through 1000 hp.
- Relative first cost improves as size increases.
- Designed to deliver lubricant free air.
- Do not require special foundations.

Disadvantages include:
- Limited capacity control modulation, requiring unloading for reduced capacities.
- High rotational speeds require special bearings, sophisticated monitoring of vibrations and clearances.
- Specialized maintenance considerations

Operating Cost: 16-20 kW/100 cfm* (please refer to notes on page 31)
Compressor Selection

Selection of air compressors must take into account the requirements of the different points of use, the air capacity for each when fully loaded, and the frequency of these requirements. Demands often are intermittent but the “worst case scenario” also must be considered. Standby compressor capacity also must be considered, taking into account the essential nature of an application and the cost of downtime compared with the cost of a spare compressor.

The capacity required will be a major factor in determining the type of compressor chosen. A general rule is that centrifugal and rotary air compressors are better suited to continuous base-load type of service. Reciprocating air compressors are better suited to swings in loads. This means that a centrifugal or rotary air compressor may be sized for the minimum or average demand, while a reciprocating air compressor then can handle the swings in load from minimum or average to the peaks. The anticipated load swings also will be a determining factor in the selection of a single compressor and its type of capacity control or multiple compressors with sequential controls.

*Note: Advantages and disadvantages of any compressor are based on its characteristics and application. Advantages and disadvantages listed previously are for a typical compressed air system in an industrial plant. In addition, by taking the estimated full load brake horsepower (bhp) requirement of each compressor type at 100 psig discharge pressure at the compressor, a main drive motor typical efficiency of 92% and 0.746 kW/bhp, the approximate operating costs of operation are obtained.
# Compressor Types

**Directions:** Match the compressor type with the correct table of advantages and disadvantages.

- **Lubricant Injected Rotary Screw**
- **Lubricant Free Rotary Screw**
- **Centrifugal**
- **Single Acting Reciprocating**
- **Double Acting Reciprocating**

## A

**Advantages include:**
- Completely packaged for plant or instrument air up through 1000 hp.
- Relative first cost improves as size increases.
- Designed to deliver lubricant free air.
- Do not require any special foundations.

**Disadvantages include:**
- Limited capacity control modulation, requiring unloading for reduced capacities.
- High rotational speeds require special bearings, sophisticated monitoring of vibrations and clearances.
- Specialized maintenance considerations.

## B

**Advantages include:**
- Completely packaged.
- Designed to deliver lubricant free air.
- Do not require any special foundations.

**Disadvantages include:**
- Cost premium.
- Less efficient.
- Limited to Load/unload type capacity control.
- Higher maintenance costs.

## C

**Advantages include:**
- Compact size and complete package.
- Economic first cost.
- Vibration free operation does not require special foundation.
- Part load capacity control systems can match system demand.
- Routine maintenance includes lubricant and filter changes.

**Disadvantages include:**
- Less efficient at full and part load than the highest efficiency compressor types.
- Lubricant carry-over into delivered air requires proper maintenance of air/lubricant separator and the lubricant itself.
### Compressor Types (Continued)

#### D

<table>
<thead>
<tr>
<th>Advantages include:</th>
<th>Disadvantages include:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Efficient compression, particularly with multi-stage compressors.</td>
<td>• Relatively high first cost compared with most common-type of mid-sized industrial compressors.</td>
</tr>
<tr>
<td>• Three-step (0-50-100%) or Five-step(0-25-50-75-100%) capacity controls, allowing efficient part load operation.</td>
<td>• Relatively high space requirements.</td>
</tr>
<tr>
<td>• Relatively routine type maintenance procedures.</td>
<td>• Relatively high vibrations require high foundation costs.</td>
</tr>
<tr>
<td></td>
<td>• Lubricant carry-over on lubricant cooled units.</td>
</tr>
<tr>
<td></td>
<td>• Seldom sold as complete independent packages.</td>
</tr>
<tr>
<td></td>
<td>• Require flywheel mass to overcome torque and current pulsations in motor driver.</td>
</tr>
<tr>
<td></td>
<td>• Repair procedures require some training and skills.</td>
</tr>
</tbody>
</table>

#### E

<table>
<thead>
<tr>
<th>Advantages include:</th>
<th>Disadvantages include:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Small size and weight.</td>
<td>• Lubricant carry-over, which should be avoided.</td>
</tr>
<tr>
<td>• Generally can be located close to point of use, avoiding lengthy piping runs and pressure drops.</td>
<td>• Relatively high noise.</td>
</tr>
<tr>
<td>• Do not require separate cooling systems.</td>
<td>• Relatively high cost of compression.</td>
</tr>
<tr>
<td>• Simple maintenance procedures.</td>
<td>• Generally are designed to run not more than 50% of the time, although some industrial designs have higher duty cycles.</td>
</tr>
<tr>
<td></td>
<td>• Generally compress and store the air in a receiver at a pressure higher than required at the point of use. The pressure then is reduced to the required operating pressure but without recovery of the energy used to compress to the higher pressure.</td>
</tr>
</tbody>
</table>
Compressor Control Types

Compressor controls are designed to match compressor delivery with compressed air demand, by maintaining the compressor discharge pressure within a specified range. This discharge pressure should be set as low as possible to minimize energy use. Control strategies need to be developed using a systems approach, taking into account system dynamics and storage. There are six basic types of individual compressor controls:

1. **Start/Stop**
   
   Turns the motor driving the compressor on or off in response to a pressure signal (reciprocating and rotary screw).

2. **Load/Unload**
   
   Allows the motor to run continuously, but unloads the compressor when a predetermined pressure is reached. The compressor reloads at a predetermined lower discharge pressure. Also known as constant speed or constant run control (reciprocating, rotary screw, and centrifugal).

3. **Modulating**
   
   Restricts inlet air to the compressor to progressively reduce compressor output to a specified minimum, when the compressor is unloaded. Also known as throttling or capacity control (rotary screw and centrifugal).

4. **Dual/Auto Dual**
   
   For small reciprocating compressors, allows the selection of either Start/Stop or Load/Unload. For lubricant injected rotary screw compressors, provides modulation to a pre-set reduced capacity followed by unloading with the addition of an overrun timer to stop the compressor after running unloaded for a pre-set time.

5. **Variable Displacement**
   
   Allows progressive reduction of the compressor displacement without reducing the inlet pressure. (reciprocating {multi-step} and rotary screw {turn, spiral, or poppet valves}).

6. **Variable Speed**
   
   Adjusts the compressor capacity by varying the speed of the electric motor driving the compressor in response to system signals.
Multiple Compressor Controls

Systems with multiple compressors use more sophisticated controls to orchestrate compressor operation and air delivery to the system. Sequencing controls may use a single master controller to shut down compressors that are not needed, while network controls (multi-master) use the individual compressor controls, with one acting as the master controller. Most new compressors incorporate microprocessor controls that allow greater flexibility.

Single Master (Sequencing) Controls

These devices are used to regulate systems by sequencing or staging individual compressor capacity to meet system demand. Sequencers are referred to as single master control units because all compressor operating decisions are made and directed from the master unit. Sequencers take individual compressor capacity on- and off-line in response to monitored system pressure (demand). These controls typically offer a higher efficiency because the control of system target pressures is tighter. This tighter range allows for a reduction in average system pressure. Again, caution needs to be taken when lowering average system header pressure because large, sudden changes in demand can cause the pressure to drop below minimum requirements, leading to improper functioning of equipment. With careful matching of system controls and storage capacity, these problems can be avoided (see also flow/pressure controller).

Multi-Master (Network) Controls

Network controls offer the latest in system control, used to shut down any compressors running unnecessarily and allowing the operating compressors to function in a more efficient mode. Combination controllers are used to provide individual compressor control as well as system control functions. The term multi-master refers to the system control capability within each individual compressor controller. These individual controllers are linked or networked together, thereby sharing all operating information and status. One of the networked controllers is designated as the leader. Because these controllers share information, compressor operating decisions with respect to changing air demand can be made more quickly and accurately. The effect is a tight pressure control range that allows a further reduction in the air system target pressure. Initial costs for system controls are often high, but they are becoming more common because of reductions in operating costs.
Flow/Pressure Controllers

Flow/pressure controllers are optional system pressure controls used in conjunction with the individual compressor or system controls described previously. A flow/pressure controller does not directly control a compressor and is generally not included as part of a compressor package. A flow/pressure controller is a device that serves to separate the supply side of a compressor system from the demand side. This may require compressors to be operated at an elevated pressure and therefore, increased horsepower, while pressure on the demand side can be reduced to a stable level to minimize actual compressed air consumption.

Storage, sized to meet anticipated fluctuations in demand, is an essential part of the control strategy. Higher pressure supply air enters the primary storage tanks from the air compressors and is available to reliably meet fluctuations in demand at a constant lower pressure level.

A well designed and managed system needs to include some or all of the following: overall control strategy, demand control, good signal locations, compressor controls, and storage. The goal is to deliver compressed air at the lowest stable pressure to the main plant distribution system and to support transient events as much as possible with stored higher pressure compressed air. Primary storage replacement should utilize the minimum compressor horsepower to restore the primary pressure to the required level.

Each compressed air system differs in supply, distribution and demand aspects which require proper evaluation of the benefits to the system of a flow/pressure controller. Additional primary and/or secondary air receivers may also address intermittent loads, which can affect system pressure and reliability, and may allow operating the compressor at the lowest possible discharge pressure and input power.

Flow/pressure controllers, as used in compressed air systems, should be distinguished from simple pressure regulators as used in FRLs (Filter/Regulator/Lubricators). While flow/pressure controllers also sense and control downstream pressure, their rate of response and control characteristics are more sophisticated and precise, allowing control of system-wide downstream pressure, usually within +/- 1 psi. Regulators in the traditional sense are applied at the point of use for specific applications.
Other Major Supply System Components

Other major subsystems in a compressed air system include the prime mover, aftercoolers, separators, dryers, filters, and condensate drains.

Compressor Prime Movers

The prime mover is the main power source providing energy to drive the compressor. The prime mover must provide enough power to start the compressor, accelerate it to full speed, and keep the unit operating under various design conditions. This power can be provided by any one of the following sources: electric motors, diesel or natural gas engines, or steam engines or turbines. Electric motors are by far the most common type of prime mover. It is important to consider prime mover efficiency when applying compressors.

Aftercoolers/Separators

As mechanical energy is applied to a gas for compression, the temperature of the gas increases. Aftercoolers are installed after the final stage of compression to reduce the air temperature. As the air temperature is reduced, water vapor in the air is condensed, separated, collected, and drained from the system. A separator generally is installed following each intercooler or aftercooler to remove the condensed moisture. This involves changes in direction and velocity and may include impingement baffles.

Air/Lubricant Separators

Lubricant-injected rotary compressors have an air/lubricant coalescing separator immediately after the compressor discharge to separate the injected lubricant before it is cooled and recirculated to the compressor. This separation must take place before cooling to prevent condensed moisture from being entrained in the lubricant.
When air leaves an aftercooler and moisture separator, it is typically saturated. Atmospheric air contains moisture. The higher the air temperature, the more moisture the air is capable of holding.

When air is cooled, it will reach a temperature at which the amount of moisture present can no longer be contained and some of the moisture will condense and drop out. This temperature is called the dewpoint. In general, reducing the temperature of saturated compressed air by 20°F will reduce the moisture content by approximately 50%. There is a difference between the dewpoint at atmospheric conditions and the dewpoint at higher pressures. Drying compressed air beyond the required pressure dewpoint will result in unnecessary energy and costs.

Dryer ratings usually are expressed at standard dryer inlet conditions, commonly referred to as the three 100s. That is, 100 psig, 100°F inlet air temperature, and 100°F ambient temperature. Deviations from these conditions will affect the capability of a dryer. An increase in inlet temperature or a decrease in inlet pressure will reduce the dryer rating. Most manufacturers provide correction factors for this.
These dryers cool the air to 35-40°F and then remove the condensed moisture before the air is reheated and discharged. To avoid freezing of the condensate, the compressed air passing through the dryer is cooled to around 35°F. The pressure dew point of this type of dryer, therefore, is 35°F.

The approximate operating cost, including the effect of pressure drop through the dryer, is 0.80 kW/100 cfm.
These dryers use a porous desiccant that adsorbs the moisture by collecting it in its myriad pores, allowing large quantities of water to be retained by a relatively small quantity of desiccant. Normally the desiccant is contained in two separate towers. Compressed air to be dried flows through one tower, while the desiccant in the other is being regenerated. Dryers of this type normally have a built-in regeneration cycle, which can be based upon time, dew point, or a combination of the two. Most standard regenerative desiccant type compressed air dryers provide a pressure dewpoint of -40°F. Purge air for regeneration is taken from the air already dried, with no heat added (heatless type), or with heat added externally or internally to reduce the amount of purge air required (heat activated). The amount of purge air required can vary from 10–15% of the air flow passing through the dryer, reducing the air flow available to the system from the compressor by this amount.

Approximate operating cost, including pressure drop through the dryer, is 2.0–3.0 kW/100 cfm.
These are regenerative desiccant dryers that use the heat generated during compression to accomplish desiccant regeneration. The cooled air stream, saturated with moisture, passes through the drying section of the desiccant bed, where it is dried and it exits from the dryer.
Heat of Compression Type Dryers (continued)

A portion of the hot air taken directly from the air compressor at its discharge, prior to the aftercooler, flows through the opposite side of the dryer to regenerate the desiccant bed. The hot air, after being used for regeneration, passes through a regeneration cooler before being combined with the main air stream by means of an ejector nozzle before entering the dryer. This means that there is no loss of purge air. This type of dryer requires air from the compressor at sufficiently high temperature to accomplish regeneration.

The total power requirement, including pressure drop and compressor operating cost, is approximately 0.80 kW/100 cfm.
Deliquescent Type Dryers

Deliquescent type dryers use a drying medium that absorbs, rather than adsorbs, the moisture in the compressed air. This means that the desiccant medium is used up as it changes from solid to liquid and cannot be regenerated.

Deliquescent dryers normally have a design dew point suppression of 20–36°F below an inlet temperature of 100°F, providing a pressure dew point at 100 psig, of 80–64°F. They also are limited to a maximum inlet temperature of 100°F. Because the drying medium is consumed and not regenerated, there is no requirement for purge air.

A filter is recommended after a deliquescent type dryer to remove desiccant fines from the air stream.

The approximate operating cost, including pressure drop through the dryer and any associated filtration, but excluding the cost of replacement desiccant, is approximately 0.20 kW/100 cfm.

Dryer Selection

Typically, the pressure drop through a compressed air dryer is 3–5 psi and should be taken into account in system requirements. Compressed air should be dried only where necessary and only to the pressure dewpoint required.
Dryer Types

Directions: Please match the dryer type with the correct set of characteristics.

Refrigerant-type  
Regenerative-desiccant type  
Deli9uescent-type  
Heat of Compression

A
Description
- Uses a porous material that adsorbs the moisture and is regenerated with compressed air.

Cost to operate
- The approximate operating cost, including the effect of pressure drop through the dryer is 2.0-3.0 kW/100 cfm.

B
Description
- Cools the air to remove the condensed moisture before the air is reheated and discharged.

Cost to operate
- The approximate operating cost, including the effect of pressure drop through the dryer, is 0.80 kW/100 cfm.

C
Description
- Uses the heat generated during compression to regenerate the dryer materials.

Cost to operate
- The total power requirement, including pressure drop and compressor operating cost is approximately 0.80 kW/100 cfm.

D
Description
- Uses a drying medium that absorbs the moisture in the compressed air.
- The medium is used up as it changes from solid to liquid and cannot be regenerated.

Cost to operate
- The approximate operating cost, including pressure drop through the dryer and any associated filtration, but excluding the cost of replacement material, is approximately 0.20 kW/100 cfm.
Compressed air filters downstream of the air compressor are generally required for the removal of contaminants, such as particulates, condensate, and lubricant. Filtration only to the level required by each compressed air application will minimize pressure drop and resultant energy consumption. Elements should also be replaced as indicated by pressure differential, and at least annually, to minimize pressure drop and energy consumption.

A refrigerant-type dryer may not require a filter before or after it, but a desiccant- or deliquescent-type dryer requires a prefilter to protect the drying medium or desiccant from contamination and from being rendered ineffective. An after-filter also is required to catch desiccant fines from being carried downstream to sensitive equipment.
Particulate Filters

Particulate filter designs use different filtering mechanisms to achieve the desired degree of contaminant removal. The higher the degree of contaminant removal, the higher the pressure drop across the filter, the higher pressure required from the air compressor and the higher the energy costs.

Coalescing Filters

Pressure drop increase in a coalescing filter is normally due to particulate matter fouling the element. The coalescing filter should be preceded by a particulate filter.

The rated pressure drop should be the "wet" pressure drop after the element has become saturated. A coalescing filter is recommended before any dryer whose drying medium may be damaged by lubricant. Materials should be compatible with the type of lubricant being used.

Adsorption Filters

Particulate and coalescing filters are capable of removing particles down to 0.01 microns but not lubricant vapors or odors. Adsorption involves the attraction and adhesion of gaseous and liquid molecules to the surface of the medium.
Float type traps use a float connected by linkage to a drain valve that opens when an upper level setting is reached and closes when the drain is emptied. An adequately sized drain valve is essential for satisfactory operation and to prevent blockage. A float that sticks in the closed position does not allow condensate to be drained, while a float that sticks in the open position allows the costly loss of compressed air. The mechanical nature of float-type devices, combined with the contaminants present in condensate, makes these devices, which often are neglected, an ongoing maintenance item. New air-operated reservoir-type float actuated drains overcome many of the problems found in the non-reservoir units.
Electrically Operated Solenoid Valves

These are also called “time cycle blowdown” valves. A solenoid-operated drain valve has a timing device that can be set to open for a specified time and at specified intervals. The period during which the valve is open may not be long enough for adequate drainage of the amount of accumulated condensate, since no reservoir is built in. On the other hand, the valve can operate even when little or no condensate is present, resulting in the expensive loss of compressed air through the drain valve.

Some electrically operated reservoir drain valves use a magnetic reed switch or a capacitance device to detect the level of condensate present in a reservoir and operate only when drainage is called for.
# Compressed Air System Component Functions

**Directions:** Please describe the function of each pictured component:

<table>
<thead>
<tr>
<th>Component</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor Package Enclosure</td>
<td></td>
</tr>
<tr>
<td>Compressor Control Panel</td>
<td></td>
</tr>
<tr>
<td>Inlet Air Filter</td>
<td></td>
</tr>
<tr>
<td>Compressor Air End</td>
<td></td>
</tr>
</tbody>
</table>
Compressed Air System Component Functions (Continued)

**Directions:** Please describe the function of each pictured component:

<table>
<thead>
<tr>
<th>Component</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor</td>
<td></td>
</tr>
<tr>
<td>Air/Lubricant Separator</td>
<td></td>
</tr>
<tr>
<td>Aftercooler and Moisture Separator</td>
<td></td>
</tr>
</tbody>
</table>
### Compressed Air System Component Functions (Continued)

**Directions:** Please describe the function of each pictured component:

<table>
<thead>
<tr>
<th>Component</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lubricant Cooler</td>
<td></td>
</tr>
<tr>
<td>Air Line Filter</td>
<td></td>
</tr>
<tr>
<td>Regenerative Dryer</td>
<td></td>
</tr>
</tbody>
</table>
### Compressed Air System Component Functions (Continued)

**Directions:** Please describe the function of each pictured component:

<table>
<thead>
<tr>
<th>Component</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver</td>
<td></td>
</tr>
<tr>
<td>Flow/Pressure Controller</td>
<td></td>
</tr>
<tr>
<td>Condensate Drains</td>
<td></td>
</tr>
</tbody>
</table>
Key Points

If you want to cut cost, correctly select and integrate:

✓ Compressors and controls

✓ Dryers

✓ Filters

✓ Condensate drains

Applicable Reference Handouts

Basic Types of Compressor and Major System Components (H1)
What is the Demand Side?

A typical modern industrial compressed air system is composed of several major subsystems and many components. The entire system is usually divided into two major subsystems: the supply side and the demand side.

The demand side is all components after the flow/pressure controller (or after the primary receiver in systems without a flow/pressure controller). The supply side consists of components prior to and including the flow/pressure controller (or prior to and including the primary receiver for systems without a flow/pressure controller).

The following diagram shows the demand side and its components.
Compressed Air Versus Other Energy Sources

Compressed air is a necessary part of most plant operations, but is probably the most inefficient source of energy in a plant.

To operate a 1 hp air motor, you need 7-8 horsepower of electrical power. At higher than typical pressures, even more power is needed.

- 30 scfm @ 90 psig is required by the 1 hp air motor
- 6-7 bhp at compressor shaft is required for 30 scfm
- 7-8 hp electrical power is required for 6-7 bhp at shaft

The overall efficiency of a typical compressed air system can be as low as 10-15 percent.

Annual energy costs for a 1 hp air motor vs. a 1 hp electric motor, 5-day per week, 2 shift operation, $0.05/kWh.

$1,164 (compressed air) vs. $194 (electric)
Demand for compressed air goes beyond what is needed to do work. It includes inappropriate uses, leaks, and increased demand due to excessive system pressure. To effectively cut costs in a compressed air system, these demands need to be minimized.

The unproductive demands are defined as follows:

1. Inappropriate uses - any application that can be done more effectively or more efficiently by a method other than compressed air

2. Leaks - an unintended loss of compressed air to ambient conditions

3. Increased demand due to excessive system pressure - additional compressed air usage due to pressure levels higher than what is necessary to keep equipment operating properly.

This section will explore ideas to cut costs due to inappropriate uses and leaks. The Stay Under Control section will address excessive system pressure.
**Inappropriate Uses of Compressed Air**

*Directions:* Break into groups and list as many inappropriate and potentially inappropriate uses of compressed air as you can using the following form. Refer back to your block diagram from the pre-workshop exercises and circle any applications (on this page) you have in your plant.

1. **Air Hoses**

2. **Excessive air Pressure**

3. **Many air motors**

4. 

5. 

6. 

7. 

8. 

9. 

10. 

11. 

12. 

13. 

14. 

15. 

16.
Leaks and How Demand is Affected by Pressure

Leaks are a function of the supply pressure in an uncontrolled system.

- Higher pressure = greater leak flow
- Lower pressure = less leak flow

<table>
<thead>
<tr>
<th>Pressure (psi)</th>
<th>1/64&quot;</th>
<th>1/32&quot;</th>
<th>1/16&quot;</th>
<th>1/8&quot;</th>
<th>1/4&quot;</th>
<th>3/8&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>.300</td>
<td>1.20</td>
<td>4.79</td>
<td>19.2</td>
<td>76.7</td>
<td>173</td>
</tr>
<tr>
<td>80</td>
<td>.335</td>
<td>1.34</td>
<td>5.36</td>
<td>21.4</td>
<td>85.7</td>
<td>193</td>
</tr>
<tr>
<td>90</td>
<td>.370</td>
<td>1.48</td>
<td>5.92</td>
<td>23.8</td>
<td>94.8</td>
<td>213</td>
</tr>
<tr>
<td>100</td>
<td>.406</td>
<td>1.62</td>
<td>6.49</td>
<td>26.0</td>
<td>104</td>
<td>234</td>
</tr>
<tr>
<td>125</td>
<td>.494</td>
<td>1.98</td>
<td>7.90</td>
<td>31.6</td>
<td>126</td>
<td>284</td>
</tr>
</tbody>
</table>

Control the waste due to leaks by minimizing the supply pressure.

All unregulated end uses will use more air when pressure increases.
Common Leak Locations

Directions: On the diagram below, indicate common locations for leaks.
Leaks are a Source of Waste

Leaks can be a significant source of wasted energy in a compressed air system, sometimes wasting 20-30% of a compressor's output.

A typical plant that has not been well maintained will likely have a leak rate equal to 20% of total compressed air production capacity or more. On the other hand, proactive leak detection and repair can reduce leaks to less than 10% of compressor output.

In addition to being a source of wasted energy, leaks can also contribute to other operating losses. Leaks:

- Cause a drop in system pressure, which can make air tools function less efficiently, adversely affecting production;

- Shorten the life of almost all supply system equipment (including the compressor package itself) by forcing the equipment to cycle more frequently;

- Cause increased running time, which can also lead to additional maintenance requirements and increased unscheduled downtime; and

- Can lead to adding unnecessary compressor capacity.
How Do You Find Leaks?

- A $100/year leak can not be felt or heard
- A $400/year leak can be felt but not heard
- A $700/year leak can be felt and heard

Since air leaks are almost impossible to see, other methods must be used to locate them. The best way to detect leaks is to use an ultrasonic acoustic detector, which can recognize the high frequency hissing sounds associated with air leaks. These portable units consist of directional microphones, amplifiers, and audio filters, and usually have either visual indicators or earphones to detect leaks. A simpler method is to apply soapy water with a paint brush to suspect areas. Although reliable, this method can be time consuming. Other methods include smoke sticks, candles, foam, manometers, and stethoscopes.

Ultrasonic detectors can find mid- to large-sized leaks. The advantages of ultrasonic leak detection include versatility, speed, ease of use, the ability to perform tests while equipment is running, and the ability to find a wide variety of leaks. They require a minimum of training; operators often become competent after 15 minutes of training.

Since ultrasound is directional in transmission, the signal is loudest at its source. By generally scanning around a test area, it is possible to very quickly locate a leak site and find its location. For this reason, ultrasonic leak detection is not only fast, it is also very accurate.
Key Points

If you want to cut costs, reduce unproductive demands:

✓ Inappropriate uses

✓ Leaks

✓ Increased demand due to excessive system pressure

Applicable Reference Handouts

Basic Types of Compressor and Major System Components (H1)
Inappropriate Uses of Compressed Air (H2)
Compressed Air System Leaks (H3)
Process of Baselining

Baselining involves taking measurements that determine the effectiveness of your compressed air system in meeting loads efficiently.

Measurements of power, energy, pressure, leak load, flow, and temperature are required to establish the baseline, and are required before and after making changes to the system to determine the effect of these changes (i.e., the revised baseline).
Power and Energy

The initial step of baselining involves measuring power. With power measured, the energy consumption and cost of operating a compressed air system can be estimated.

Power = The rate at which work is done, expressed as the amount of work per unit time and commonly measured in units such as the kilowatt (kW) and horsepower (hp). Power is the time rate of energy transfer.

Energy = The ability to do work, usually measured in kilowatt-hours (kWh).

1. Tools required:
   - Basic: Hook-on ammeter with volt meter
   - Better: kW meter
   - Best: kWh meter with data logger

2. Calculate/measure input power using:

   \[ kW = \frac{(\text{full-load amps}) \times (\text{line-to-line voltage}) \times (1.732) \times (\text{pf})}{1000} \]

   Where:
   - full-load amps = average of three phases measured in amps
   - line-to-line voltage = voltage measured in volts
   - pf = power factor (assumed to be 0.85)

   Note: full-load amps and line-to-line voltage are measured values

3. Estimate operating hours

4. Calculate annual energy consumption (as demonstrated previously in Why Care About Air?). If the system runs at part-load or unloaded during some periods, use the formulas provided in the following section entitled Unloaded and Part-Load Operation.
Unloaded and Part-Load Operation

Most compressors run at part-load or unloaded during some periods. In general this should be avoided, and systems with multiple compressors should have one compressor with good part load efficiency running at part load and the other compressor(s) running at full-load. In order to estimate energy costs for an unloaded or part-loaded compressor:

1. Estimate the percentage of time the compressor is running at full-load, different levels of part load, and unloaded.

2. The fully unloaded bhp and part load bhp and efficiency of the motor at the unloaded/part load bhps will vary by compressor type. For estimating purposes for compressors operating on load/unload capacity control, the following estimates of unloaded bhp as a percentage of full load may be used, unless the manufacturer provides actual data:

   - Lubricant Injected Rotary Screw: 20-30% (after sump has bled down)
   - Lubricant Free Rotary Screw: 20-30%
   - Reciprocating: 10-15%
   - Centrifugal (no blowoff): 15-20%

3. If the compressor operates some of the time at part load, you must use the part load power estimates for different levels of part-load operation. Figures in the Handout titled Compressed Air System Storage provide part load efficiencies for rotary screw compressors using a variety of control types. For other combinations of compressors and controls, consult with your system specialist or manufacturer to obtain typical performance curves. Motor efficiency will drop at low loads.
4. Calculate annual electricity costs for each level of operation, and then sum. Use the following equation for each operation level (full load, part load(s), and unloaded).

\[(\text{bhp}) \times (0.746) \times (\text{hours}) \times (\text{cost}) \times (\% \text{ time}) \times (\% \text{ full load bhp})\]

\[\frac{\text{motor efficiency}}{1}\]

Where:

- \(\text{bhp}\) = motor full-load horsepower
- 0.746 = kW/hp
- \(\text{hours}\) = annual hours of operation
- \(\text{cost}\) = electricity cost in $/kWh
- \(\% \text{ time}\) = percentage of time running a this operation level
- \(\% \text{ full load bhp}\) = bhp as percentage of full load bhp at this operation level
- \(\text{motor efficiency}\) = motor nameplate efficiency

Use the table below to estimate full load efficiencies for motors. Part-load efficiencies typically drop significantly lower than full-load efficiencies at 25% of full load and below. Consult manufacturer's specifications for efficiencies at loads less than 25% of full load.

<table>
<thead>
<tr>
<th>Hp</th>
<th>Energy Efficient</th>
<th>Standard</th>
<th>Rewound</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.93</td>
<td>0.92</td>
<td>0.90</td>
</tr>
<tr>
<td>100</td>
<td>0.94</td>
<td>0.93</td>
<td>0.91</td>
</tr>
<tr>
<td>150</td>
<td>0.945</td>
<td>0.93</td>
<td>0.91</td>
</tr>
<tr>
<td>200</td>
<td>0.95</td>
<td>0.94</td>
<td>0.92</td>
</tr>
<tr>
<td>300</td>
<td>0.96</td>
<td>0.95</td>
<td>0.93</td>
</tr>
</tbody>
</table>
Unloaded and Part-Load Operation (Continued)

Example: (operation at full load and unloaded)

- 200 bhp compressor, 4,160 hours per year of operation, $0.05/kWh electricity price
- 85% of the time fully-loaded, motor 95% efficient at full-load
- 15% of the time unloaded, motor 90% efficient at 25% of full load power

\[
\frac{(200 \text{ bhp}) \times (0.746) \times (4,160 \text{ hrs}) \times (0.85) \times (1.0) \times ($0.05/\text{kWh})}{0.95} = $27,767
\]

\[
+ \frac{(200 \text{ bhp}) \times (0.746) \times (4,160 \text{ hrs}) \times (0.15) \times (0.25) \times ($0.05/\text{kWh})}{0.90} = $1,293
\]

Total annual electricity costs = $29,060

(versus $32,667 compensating for part-load operation)

Factors that can affect the calculation:

- Motors operating in service factor (many compressor packages are engineered to operate into the service factor to provide the package rated flow)
- Utility rate structures (using average $/kWh)
- Motor efficiency (especially after poor-quality repairs and rewinds)
Energy Costs of Unloaded Operation

Directions: Please estimate the annual energy costs (using the equations provided in Unloaded and Part-Load Operation) for the following system:

- 400 bhp lubricant free rotary screw compressor using load/unload controls
- 8,000 hours per year of operation
- $0.05/kWh electricity price
- 60% of the time fully-loaded
- 40% of the time unloaded (where it consumes 25% of full load power)
- Motor 90% efficient at full-load, 80% efficient at 25% of full load power

Calculations:

\[ 400 \times 7.46 \times 8000 \times 0.5 \times 0.6 \times 0.9 = 34829 \]

\[ 79572 \]

\[ 3315 \]

\[ 46417 \]

\[ 0.25 \]

\[ 0.8 \]

\[ 596797 \]
Pressure

Pressure measurements need to be taken to give feedback for control adjustments, determine pressure drops across components, and determine system operating pressures.

1. Tools required – matched, calibrated pressure gauges or differential pressure gauges.

2. The following pressure measurements should be taken:
   - Inlet to compressor (to monitor inlet air filter) vs. atmospheric pressure
   - Differential across air/lubricant separator (if applicable)
   - Interstage on multistage compressors
   - Pressure differentials, including,
     - Aftercooler
     - Treatment equipment (dryers, filters, etc.)
     - Various points of the distribution system
     - Check pressure differentials against manufacturers’ specifications, if available (high pressure drops indicate service is required)

The figure below shows the pressure drops through an example system.
Pressure Measurement Locations

Directions: On the diagram below, indicate where pressure measurements should be taken to determine pressure drop across key components:
Estimating Pressure Drop

Directions: Given the following measured pressure drops, please complete the pressure profile below and determine the lowest pressure seen by the end-uses (note: these are in random order):

| Compressor operating range: | 115-105 psig |
| FRL | 7 psid |
| Aftercooler | 3 psid |
| Filter | 3 psid |
| Air/Lubricant Separator | 5 psid |
| Hose and Disconnects | 4 psid |
| Dryer | 4 psid |
| Distribution System | 3 psid |

Supply

115 psig
Operating Range of Compressors
105 psig
Pressure Drop From Separator, Aftercooler, Dryer, and Filter
80 psig

Demand

Distribution System Pressure Drop
3 psig
Unregulated End-Uses
FRL, Valve, Hose, and Disconnect Pressure Drop
Regulated End-Uses
Leak Load

Leak load should be estimated periodically. On a well-maintained system, leakage should be less than 10% of full system flow. Tests should be undertaken quarterly as part of a leak detection and repair program. A simple methodology estimating leak load is described below.

Estimating Leak Load for Systems with Load/Unload Controls

For compressors that use load/unload controls, there is an easy way to roughly estimate the amount of leakage in the system. This method involves starting the compressor when there are no demands on the system and bringing the system to normal operating pressure. All air-operated end-use equipment should have the supply valves and/or solenoids open with the equipment electronics off to account for internal leaks. Open blowing applications should be isolated through shutoff valves. A number of measurements are taken to determine the average time it takes to load and unload the compressor.

The compressor will load and unload because the air leaks will require the compressor to cycle on as the pressure drops from air escaping through the leaks. Total leakage (percentage) can be calculated as follows:

\[
\text{Leakage (\%)} = \left[\frac{(T \times 100)}{(T+t)}\right]
\]

where:

- \( T \) = loaded time (minutes)
- \( t \) = unloaded time (minutes)

Leakage will be expressed in terms of the percentage of compressor capacity lost. The percentage lost to leakage should be less than 10% in a well-maintained system. Poorly maintained systems can have losses as high as 20-40% of air capacity and power.
Estimating Leak Load

Directions: Using the data provided below, please estimate the percentage of compressor capacity lost to leaks for the following system. Measurements were taken using the method described previously that involves starting the compressor when there are no demands on the system. A number of measurements were taken to determine the time it takes to load and unload the compressor. The compressor will load and unload because the air leaks will require the compressor to cycle on as the pressure drops from air escaping through the leaks. The following table shows the measurements that were taken:

<table>
<thead>
<tr>
<th>Time loaded</th>
<th>2 min 10 sec</th>
<th>2 min 5 sec</th>
<th>2 min 15 sec</th>
<th>2 min 10 sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time unloaded</td>
<td>5 min 20 sec</td>
<td>5 min 10 sec</td>
<td>5 min 15 sec</td>
<td>5 min 5 sec</td>
</tr>
</tbody>
</table>

Use the following equation:

Total leakage (percentage) can be calculated as follows:

\[
\text{Leakage (\%)} = \left[ \frac{T \times 100}{T + t} \right]
\]

where: \( T \) = total loaded time (minutes)

\( t \) = total unloaded time (minutes)

Calculations:

\[
\frac{520 \times 100}{520 + 1250} = \frac{52000}{1770} = 29.3
\]
Are You on Base?

Leak Load for Systems with Other Controls

Leakage can be estimated in systems with other control strategies if there is a pressure gauge downstream of the receiver. This method requires an estimate of total system volume, including any downstream secondary air receivers, air mains, and piping (V, in cubic feet). The system is then started and brought to the normal operating pressure (P1) and the compressor is turned off.

Measurements should then be taken of the time (T) it takes for the system to drop to a lower pressure (P2), which should be a point equal to about one-half the operating pressure. Leakage can be calculated as follows:

$$\text{Leakage (cfm free air)} = \left[ V \times \frac{(P1-P2)}{T} \times 14.7 \times 1.25 \right]$$

where:  
- V is in cubic feet  
- P1 and P2 are in psig  
- T is in minutes

The 1.25 multiplier corrects leakage to normal system pressure, allowing for reduced leakage with falling system pressure to 50% of the initial reading. Again, leakage of greater than 10% indicates that the system can likely be improved. These tests should be carried out once a month as part of a regular leak detection and repair program.
When to Baseline

Data should be collected by measuring: (1) under normal operating conditions, (2) other significant conditions (different production levels, seasonal variations, etc.), and (3) after changes to system operation. For maintenance purposes, testing should also be performed at full-load rated conditions. In addition to power and pressure measurements, flow and temperature data can be vital.

To ensure that performance actually improves and to re-establish the baseline, be sure to re-measure after performance enhancements are made. Remember to always correlate to production levels. The expectation is that energy use will go down, assuming of course that production did not rise with a corresponding increase in the compressed air loads. If production did not rise, and the pressure went up, adjust controls appropriately.

For more detailed baselining of your compressed air system, consult with your compressed air system specialist or contact an instrumentation expert if you are going to invest money in measuring equipment.
Additional Measurements

Flow

Performed to measure total flow and to determine air consumption

Tools required – flow meter of the mass flow designed to compensate for pressure and temperature variations

Flow should be measured:
- During various shifts
- After energy savings measures are implemented
- If flow is reduced, sometimes a compressor can be turned off

Temperature

Helps determine if equipment is operating at peak performance

Tools required – infrared gun and thermometer

The following temperature measurements should be taken:

- Aftercooler and intercooler cold temperature difference or difference between approach temperature of cold water inlet (or inlet air for air cooled units) and cooled compressed air outlet. Since dryers are normally designed for 100°F max inlet air temperature, some remedial action may be required if aftercooler outlet temperatures exceed 100°F.

- For lubricant injected rotary screw compressors, the air discharge temperatures must be maintained for reliable compressor performance. Excessive temperatures indicate maintenance is required.

- Inlet air temperature. On reciprocating and lubricant free rotary screw compressors, colder inlet air temperature is generally desirable. On centrifugal compressors, lower temperatures will increase mass flow, which will require corresponding increases in horsepower.

Unless the inlet air is drawn from outside the plant, inlet air temperature may differ considerably from the ambient temperature. High humidity will also have a negative effect on compressor performance, especially centrifugals.
Key Points

If you want to cut costs, baseline your system:

✓ Measure power, pressure, and leak load

✓ Estimate energy consumption and correlate to production levels

✓ Maintain system pressure at the lowest possible levels

✓ Avoid part load operation, which is usually inefficient

✓ Measurements of flow and temperature can help you optimize your system

Applicable Reference Handouts

Baselining Your Compressed Air System (H4)
Controls Discussion Questions

Directions: Please answer the following questions.

1. Would you describe a compressed air system as static or dynamic?

2. How do controls help the system deal with changing conditions?

3. What are the three additional objectives of a compressed air control system?
Compressor Control Pros and Cons

Under *Study Your Supply Side*, controls designed to match compressor delivery with compressed air demand were discussed, each with a unique set of pros and cons which affects how the system can be controlled.

<table>
<thead>
<tr>
<th>Control</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start/Stop</td>
<td>• Simple control using only a pressure switch</td>
<td>• Frequent, full load starting wears down motor and compressor</td>
</tr>
<tr>
<td></td>
<td>• Motor and compressor operate only when needed, saving energy</td>
<td>• Requires higher than normal compression to build storage, increasing energy use</td>
</tr>
<tr>
<td></td>
<td>• Good for small compressors (10hp or less)</td>
<td>• Relatively “loose” pressure control, ranging as high as 35 psi</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Limited to small units</td>
</tr>
<tr>
<td>Load/Unload</td>
<td>• Motor and compressor run continuously, reducing wear</td>
<td>• Improperly applied, “short cycles” cause premature wear and failure, and minimal or no power savings</td>
</tr>
<tr>
<td></td>
<td>• Tighter range of pressure control (approximately 10psi)</td>
<td>• Proper bleed down time and storage capacity required for lubricant injected rotary units to achieve energy savings and prevent lubricant foaming</td>
</tr>
<tr>
<td></td>
<td>• Provided adequate storage, offers energy efficient control of both rotary screw and double acting reciprocating compressors</td>
<td></td>
</tr>
<tr>
<td>Modulating</td>
<td>• Motor and compressor run continuously, reducing wear</td>
<td>• Inefficient at lower loads (lubricant injected rotary units limited to 40-60% capacity, centrifugal units limited by potential surge and can require discharge blow-off)</td>
</tr>
<tr>
<td></td>
<td>• Tighter range of pressure control (10psi)</td>
<td>• Pressure ratios increase as inlet pressure is throttled</td>
</tr>
<tr>
<td></td>
<td>• Steadily progressive capacity control to match demand</td>
<td></td>
</tr>
</tbody>
</table>
## Compressor Control Pros and Cons (Continued)

<table>
<thead>
<tr>
<th>Control</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dual/Auto Dual</strong></td>
<td>• Combines features of modulating, load/unload, and start/stop</td>
<td>• Adds complexity to control</td>
</tr>
<tr>
<td></td>
<td>• Shuts down lubricant injected rotary units when unloaded for pre-set duration</td>
<td>• Over-run timer must be set to limit premature starting and wasted energy</td>
</tr>
<tr>
<td></td>
<td>• Better selects operating mode for small reciprocating units</td>
<td></td>
</tr>
<tr>
<td><strong>Variable Displacement (Turn/ Spiral or Poppet Valve)</strong></td>
<td>• Energy-efficient control scheme</td>
<td>• Adds complexity to control</td>
</tr>
<tr>
<td></td>
<td>• Matches displacement to demand without reducing inlet pressure or increasing ratios of compression</td>
<td>• Relatively high initial cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Generally available only for 50 hp or larger units</td>
</tr>
<tr>
<td><strong>Variable Speed</strong></td>
<td>• Energy-efficient and precise control</td>
<td>• Adds complexity to control</td>
</tr>
<tr>
<td></td>
<td>• Varies rotating speed of compressor, since displacement is directly proportional to speed of rotation</td>
<td>• Relatively high initial cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Reduced full load efficiency</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Efficiency of rotary screw units drops at lower speed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Unsuitable for centrifugals</td>
</tr>
<tr>
<td><strong>Multiple Compressor Control</strong></td>
<td>• Saves energy by allowing systems to shut down individual units that are not needed</td>
<td>• Use is generally limited to compressor type and make produced by manufacturer of controls</td>
</tr>
<tr>
<td></td>
<td>• Saves compressor wear by alternating units to be shut down</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Microprocessor type sequencers limit modulating control to one unit, optimizing efficiency</td>
<td></td>
</tr>
</tbody>
</table>
Controls, Part-Load Efficiency, and Storage

- Most oil injected rotary screw compressors are equipped with capacity control by inlet valve modulation designed to match the output from the air compressor with the demand from the points of use.

- An air receiver near the discharge of a rotary screw compressor will shield the compressor control system from pressure fluctuations from the demand side downstream of the receiver, and can allow the compressor to be unloaded for a longer period of time, during periods of light demand.

- The addition of an over-run timer (Automatic Dual Control) can stop the compressor if it runs unloaded for a pre-set time, saving additional energy.

- Some oil injected rotary screw compressors are sold with load/unload capacity control. An adequate receiver volume is essential to obtain any real savings in energy. A comparison of different capacity control types is shown in the figure on the next page (Power vs. Capacity).

- The top line shows what would happen if inlet valve throttling was used without unloading the compressor. Approximately 70% of full load power would still be used when throttling had reduced compressor output to zero.

- The second line shows inlet valve throttling to 40% capacity and unloading at that point.

- The third line shows variable displacement (slide/turn/spiral/poppet valve) capacity reduction to 50% capacity followed by throttling to 40% capacity and unloading at that point.

- Optimal load/unload and the ideal control, where power and capacity exactly match, also is shown.
A solution sometimes proposed is to eliminate modulation and operate in a load/unload mode. The following factors need to be considered: 1) at standard full capacity and full load pressure, the compressor is often running at around 110% of motor nameplate rating; 2) the remaining 5% is meant to cover tolerances and items such as possible increased pressure drop through the air/lubricant separator; and 3) if the discharge pressure rises by an additional 10 psi without the capacity reduction by inlet valve modulation, bhp will increase by 5% and the motor will overload and a reduction in discharge pressure may be needed.

It is falsely assumed that a straight line, from full load bhp to unloaded bhp, represents the actual power requirement in this mode of operation. This is shown as the ideal compressor in the figure above. This presumes that if the average capacity is 50%, the compressor would run fully loaded 50% of the time and fully unloaded 50% of the time. The compressor is not fully unloaded 50% of the time. When the compressor discharge pressure reaches the unload set point, the inlet valve is closed to reduce the mass flow through the compressor. Simultaneously, the lubricant sump/separator vessel pressure begins to lower gradually. Typically, this takes about 40 seconds, to prevent foaming of the lubricant with the potential of excessive lubricant carry-over. The rate at which blow-down occurs gradually slows as the pressure is reduced. The fully unloaded power is not realized until the pressure in the lubricant sump/separator is fully relieved. In addition, a period of about 3 seconds is required to re-pressurize the air/lubricant sump/separator vessel when the system calls for the compressor to re-load.
In many cases, the system pressure will fall and the compressor will re-load before the fully unloaded power is realized. To overcome this, an adequately sized air receiver and/or system volume is essential. Taking the above factors into account, the figure above (Average Power vs. Capacity – Load/Unload Capacity Control) shows the effect of different sizes of air receiver/system volume. It will be seen that some rules of thumb established many years ago for reciprocating air compressors are not adequate for an oil injected rotary screw compressor.

Note: The gal/cfm curves shown above are based on cfm of compressor capacity. Receiver size and location should take into account:
- the number of compressors;
- their sizes, types, and controls; and
- the dynamic nature and variability of the demand.
The figure above (Average Power vs. Capacity – Load/Unload and Inlet Valve Capacity Control Systems) compares modes of capacity control with 3 and 5 gallons per cfm of compressor capacity. The control mode chosen should take into account the receiver/system volume relative to compressor capacity, the range of flow rate normally experienced, and the mean flow rate during 24 hours.
Controls, Part-Load Efficiency, and Storage (Continued)

- In systems with multiple compressors and sequencing controls, it is possible to have most of the compressors running fully loaded with one compressor modulating, providing the most efficient mode for the system. It also is not necessary to have the air receiver/system storage capacity based upon the total capacity of all the compressors, provided they are not all on the same load and unload pressure settings.

- A primary air receiver allows the compressor(s) to operate in a given discharge pressure range (usually 10 psi) from load to unload. Multiple compressors also can be sequenced as needed with all but one operating in the most efficient, fully loaded mode. The capacity of the one compressor is modulated to match system demand.

- In many plants, there will be one or more applications with an intermittent demand of relatively high volume. This can cause dynamic pressure fluctuations in the whole system, with some essential points of use being starved impacting the quality of the end product. Usually, this can be relieved by the correct sizing and location of a secondary air receiver close to the point of high intermittent demand. Such demand often is of short duration and the time between the demand events is such that there is ample time to replenish the secondary receiver pressure without adding compressor capacity. A check valve before the secondary air receiver will prevent back flow to the rest of the system and ensure that the required volume is stored to meet the anticipated event(s).

- Additional pressure/flow controls can be added after the primary receiver to maintain a reduced and relatively constant system pressure and at points of use, while allowing the compressor controls to function in the most efficient control mode and discharge pressure range, with significant energy savings.
The mineral processing facility is served by three lubricant injected rotary screw compressors, with a total of 668 horsepower installed. The largest compressor, a 364 hp unit, is baseloaded. The remaining two 152 hp units use modulating controls and are intended to trim as required by demand. Each compressor has a refrigerated dryer and coalescing filter, with a total pressure drop of 12 psi before the header. The system is served by 400 gallons of primary storage.

The two smaller units have inlet valve modulation, which progressively closes the inlet valve, causing a pressure drop. This reduces the pressure at the inlet to the compressor, reducing mass flow of air entering the compressor. However, this also increases the compression ratio of the compressor, resulting in reduced efficiency.

The figures below demonstrate inlet valve operation.
The next two figures demonstrate two problems which result from not understanding the pressure profiles in a system. They depict the pressure drop slightly differently from the graphic presented in the Baseline section, but also convey the differences in pressures from the compressor to the end-use.

At first glance, the compressors appear to be in a reasonable cascade of pressure ranges. As the demand increases, the system pressure starts to drop and the trim compressors are loaded. As the flow increases, the differential pressures on the filters and dryers increase and push the signal pressures up into the control bands on the compressors, causing them to modulate. All of the compressors can not be fully loaded until header pressure drops below 82 psi. At that point, critical demand pressure drops below 65 psi even though the compressor set points are all above 90 psi.
The Mineral Processing Facility (Continued)

As demand decreases, the header pressure increases, and the two smaller compressors continue to modulate (at lower output levels to meet demand). At the same time, the differential pressures from the dryer/filters decrease.

One of the modulating compressors is running at about 50% capacity, and the other is running at about 40%. The total demand being served by these two smaller compressors is less than the capacity of one of the units, and could be much more efficiently served by one trim compressor. Because the compressors do not share a common signal point, neither of the modulation compressors reaches its unload pressure where they could begin a time out sequence for shut down. Thus, this facility operates one compressor more than necessary during the periods of low demand.

Low Demand Period

Note: Caution needs to be taken when using a common signal point located after treatment equipment. Improper engineering and/or poor maintenance practices can result in compressors becoming overloaded. Work with your compressed air system specialist when relocating signal points.
The Mineral Processing Facility (Continued)

If the modulating compressors were simply switched to load/unload control, they would rapid cycle due to the high pressure differential and low storage capability.

The appropriate solution, once the problem was understood, was to add a 4,000 gallon receiver to provide increased primary storage volume at the compressor room. In addition, the individual coalescing filters were replaced by a single filter having a much lower differential pressure. These changes improved the supply response time and allowed time for the compressors to react to increases in demand. One of the modulating compressors was able to fully unload and then time out during periods of low demand. The other modulating compressor was reconfigured to operate in a load/unload mode. The load/unload setpoints were also adjusted.
While the low differential filter and additional control storage corrected the inefficient operation of the compressors, an additional problem existed downstream. The facility had baghouses and dust collectors that were operating inefficiently and required excessive bag changes.

The plant operators found that the baghouses required 80 psi to operate properly, much higher than the design pressure requirement of 60 psi. This higher pressure was due to the high back pulse created (30-50 psi) when the operators reverse flow in the baghouse to "slough off the cake", or clean the filters from accumulated dust. Cake deposits actually help improve the filtering efficiency as additional cake does much of the filtering.

To create enough pressure to slough off the cake, the operators had cranked open the regulators (normally set at 60 psi). When this was ineffective, the pulse control timer was set to minimize time between pulses to keep the bags clean. Baghouse efficiency was decreased due to reduced cake accumulation, and the bags suffered from the shock of too frequent pulses.

As a solution to this problem, local storage was added to ride through the back pulse, allowing the baghouse to operate at 60 psi. The filters then allowed cake buildup as intended, and back pulse was based on the pressure differential across the bag via a pressure differential switch rather than a timer. This improved the baghouse performance as well as reduced compressed air consumption. The pressure dip in the header, previously caused by back pulsing, is now metered by a needle valve. The recovery of pressure need only occur prior to the next pulse. This makes the back pulse pressure requirement be seen as a steady but relatively small demand.
**Using Controls**

**Directions:** Working with your small group, please: (1) analyze your assigned problem situation, and (2) recommend solutions using better control strategies (taking into account storage solutions) to improve the performance of the system.

**Problem #1:**

A facility has three 100 hp rotary screw compressors. During their normal two-shift operation, two compressors (#1 and #2) are baseloaded (operated at full-load almost all of the time), and the third (#3) uses load/unload controls. During the third shift, compressed air demand is only about ½ of the normal demand. During this shift, compressor #1 operates baseloaded (with load/unload controls and a high enough pressure setting to ensure that it does not unload), compressor #2 uses modulating controls, and #3 operates unloaded.

**Recommended Control Strategy:**

---

---

---

---

---

---

---
Problem #2:

A facility has a variety of end-use applications that require 70 psig air (measured after the FRL, valves, hoses, disconnects, and fittings). The average demand from these applications is about 600 scfm with a peak demand of 700 scfm. The facility also has a single large end-use that requires about 300 scfm (continuous) of 95 psig air (measured at the point of use). Currently the controls are set to keep the entire system pressure high enough so that end-use pressure stays above 95 psig.

Recommended Control Strategy:

700 CFM @ 70

300 CFM @ 95

Dirt line to 95 PSI first, then 70 PSI.
Problem #3:

A manufacturing facility just completed an internal audit of their compressed air system. They have a system with two identical rotary screw compressors, with one unit baseloaded and the other acting as a trim unit. Load/unload controls are used on each. During the audit, a substantial amount of leaks were repaired, inappropriate uses were discontinued, and pressure drop was reduced through maintenance actions. No changes were made to the supply-side, and energy savings were not as high as expected.

Recommended Control Strategy:
Problem #4:

A manufacturing facility just completed an internal audit of their compressed air system. They have a system with four identical centrifugal air compressors. During most of the day, one compressor is baseloaded, one compressor is in modulation, a third compressor is operating mostly unloaded, and a fourth compressor is shut down in stand-by mode. During the audit, a substantial amount of leaks were repaired, inappropriate uses were discontinued, and pressure drop was reduced through maintenance actions. No change was made to the supply side, and energy savings were not as high as expected.

Recommended Control Strategy:
Controlling Your Own System

Directions: Refer back to the information gathered in the pre-workshop exercises, and develop ideas for better controlling your compressed air system. Pay special attention to the operating schedule information (page 5), compressor system control information (page 8), and system storage. If you don't have the information, think about how well the system matches supply to demand.
Key Points

✓ If you want to cut costs, create a control strategy:

✓ Know how your controls work

✓ Realize the pros and cons of different controls

✓ Recognize how controls affect part load efficiency

✓ Understand how storage affects the effectiveness of control strategies

Applicable Reference Handouts

Compressed Air Storage (H5)
Compressed Air System Control Basics (H6)
Do You Want to Cut Costs?

If you want to cut costs, you're going to have to
Stay Calm (STA-COLM)

ST orage
A ppropriate Uses
CO ntrols
L eaks
Maintenance
## Checklist for STA-COLM

<table>
<thead>
<tr>
<th>STorage</th>
<th>✓ Make sure your primary storage is adequate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>✓ Consider strategic secondary storage for some applications</td>
</tr>
<tr>
<td>Appropriate Uses</td>
<td>✓ Evaluate each major class of compressed air end-use</td>
</tr>
<tr>
<td></td>
<td>✓ Check end-uses against list of inappropriate uses</td>
</tr>
<tr>
<td>Controls</td>
<td>✓ Periodically work with your equipment service provider to adjust individual compressor controls</td>
</tr>
<tr>
<td></td>
<td>✓ For systems with multiple compressors, use controls to orchestrate the compressors (multiple compressor sequencing)</td>
</tr>
<tr>
<td></td>
<td>✓ Consider flow/pressure controllers</td>
</tr>
<tr>
<td>Leaks</td>
<td>✓ Get the equipment to find the leaks</td>
</tr>
<tr>
<td></td>
<td>✓ Start looking in the right place</td>
</tr>
<tr>
<td></td>
<td>✓ Learn how to repair the leaks</td>
</tr>
<tr>
<td></td>
<td>✓ Establish a leak prevention program</td>
</tr>
<tr>
<td>Maintenance</td>
<td>✓ Follow the maintenance guidelines for your compressor</td>
</tr>
<tr>
<td></td>
<td>✓ Follow the maintenance guidelines for your other compressed air system components</td>
</tr>
<tr>
<td></td>
<td>✓ Develop a maintenance program</td>
</tr>
</tbody>
</table>
Case Study: The Auto Parts Manufacturer

Compressed Air Uses

- **Air hoists**
  - 200 cfm peak, operating about 5 minutes per hour at this level
  - 80 psig

- **Open hand held blow guns**
  - 100 cfm continuous

- **Vacuum generation (venturi cups)**
  - 100 cfm continuous

- **Automated assembly stations**
  - 200 continuous
  - 80 psig
  - Critical application that will not operate properly if pressure fluctuates (has been a problem area)

- **Miscellaneous uses**
  - 200 cfm combined peak
  - 160 cfm average requirement
  - 70 psig available and acceptable at point of use
  - FRLs, valves, hoses, disconnects, and fittings poorly installed and maintained. Personnel cooling and cabinet coolers are also in use.

- **Large pneumatic clamps**
  - 200 cfm peak
  - Operate 10 minutes each hour, on cycle time 10 sec, off cycle time 10 sec
  - 85 psig

- **Pneumatic actuators**
  - 100 cfm peak
  - 50 cfm average requirement
  - 80 psig
  - This application requires both high speed and torque
Other System Information

- Two 150 hp air cooled lubricant injected rotary screw machines. (Note: name plate of 150 hp actually uses 173 bhp (150 hp*1.10 + 8 bhp for cooling fan. For the calculations in this section, 173 hp will be used as the power required by the compressor. Partial load calculations do not reduce the 8 bhp of the fan. The fan horsepower is added in after derating the drive motor power.)

- Combined full-load output of 1500 scfm

- No multiple compressor or flow controls

- Aging single dryer serving both compressors

- Receiver was originally sized for smaller system with only one 150 hp compressor

- The system has only been maintained at a level to keep it running

- 3 shift operation

- Leaks have been estimated at 300 cfm
Steps for Solving Case Study

The following steps will enable you to solve the case study, as well as to realize opportunities within your own facility:

1. Review/Develop Block Diagram.

2. Review/Develop System Pressure Profile. Remember "Name Plate" hp will not always reflect true power consumption. Also, pressure drops across equipment (e.g. dryers) are important and need to be considered.

3. Review/Develop System Demand Profile. If possible, flows should be measured. If this is not economically or physically feasible, use the manufacturer's equipment rating, or a "best estimate" using compressor loading when equipment is in service. Cycling can be timed with a stopwatch if line data is not available.

4. Use STA-COLM method/checklist for identifying opportunities.

5. Identify savings and costs associated with opportunities.

6. Take steps to convert opportunities into actions and save money and energy.
System Pressure Profile

Supply

110 psig
- Operating Range of Compressors

100 psig
- Pressure Drop From Aftercooler, Separator, Dryer, and Filter

90 psig

Demand

85 psig
- Distribution System Pressure Drop

70 psig
- Unregulated End-Uses
- FRL, Valve, Hose, and Disconnect Pressure Drop

Regulated End-Uses
## System Demand Profile

<table>
<thead>
<tr>
<th>Operation</th>
<th>Pressure (psi)</th>
<th>Continuous</th>
<th>Average</th>
<th>Peak</th>
<th>Cycle Time</th>
<th>On</th>
<th>Off</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR HOISTS</td>
<td>80</td>
<td>N/A</td>
<td>16.6</td>
<td>200</td>
<td>5 min</td>
<td>55 min</td>
<td></td>
</tr>
<tr>
<td>OPEN HAND HELD BLOWGUNS</td>
<td>90</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>N/A</td>
<td>Non-Prod.</td>
<td></td>
</tr>
<tr>
<td>VACUUM GENERATION (VENTURI CUPS)</td>
<td>80</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>N/A</td>
<td>Non-Prod.</td>
<td></td>
</tr>
<tr>
<td>AUTOMATED ASSEMBLY</td>
<td>80</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>Prod.</td>
<td>Non-Prod.</td>
<td></td>
</tr>
<tr>
<td>MISCELLANEOUS USES</td>
<td>70</td>
<td>N/A</td>
<td>160</td>
<td>200</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>LARGE PNEUMATIC CLAMPS (10 min each hr)</td>
<td>85</td>
<td>N/A</td>
<td>16.6</td>
<td>200</td>
<td>10 sec</td>
<td>10 sec</td>
<td></td>
</tr>
<tr>
<td>PNEUMATIC ACTUATORS</td>
<td>80</td>
<td>50</td>
<td>50</td>
<td>100</td>
<td>Prod.</td>
<td>Non-Prod.</td>
<td></td>
</tr>
<tr>
<td>AIR LEAKS</td>
<td>90- 70</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td>750</td>
<td>943</td>
<td></td>
<td>1400</td>
<td></td>
</tr>
</tbody>
</table>
Simple, Quick Cost Cutting Measures

Directions: For each of the following cost cutting measures, discuss the potential fix as it applies to the case study.

**STorage**

1. Add more capacity to the primary receiver.

2. Look for applications that could benefit from strategic secondary storage.

3. Add secondary receivers to the system.
Appropriate Uses

1. Replace inappropriate end-uses with another source of power, such as electric motors, hydraulic power, fans, blows, brushes, or vacuum systems.

2. Use nozzles for blowing.
**CO ntrols**

1. Add automatic shut-off devices to compressors.

2. Set unloading controls properly so that compressors are unloading when appropriate instead of modulating.

3. Use sequencing controls for multiple compressor systems.

4. Set sequencing controls to maximize performance and minimize energy consumption.

5. Apply flow/pressure controllers to reduce artificial demand, improve performance, and reduce energy consumption.
6. Reduce system pressure.

7. Add a small compressor.

8. Add a booster compressor
Leaks

1. Fix leaks in the distribution system.

2. Make sure traps are operating properly.

3. Fix leaks at points of use.

4. Repair leaks at air tools.
Maintenance

1. Check that the compressor manufacturer's maintenance requirements are being met or exceeded.

2. Check compressor ventilation openings to the compressor room to make sure that they are large enough and free of obstructions.

3. Clean/change inlet filters.

4. Lubricate compressor/change lubricant filter.

5. Remove all debris from radiators, fans, heat exchanges, etc.

7. Replace clogged air line filters.

8. Repair poorly functioning condensate drain traps.

9. Inspect other system components.
System Demand Profile – Flow Reduction Potential

Using calculations provided in Simple, Quick Cost Cutting Measures, the flow reduction potential can be calculated, as shown in the table below.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Peak Flow</th>
<th>Cycle Time</th>
<th>Action</th>
<th>Potential Peak Decrease</th>
<th>Revised Peak Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR HOISTS</td>
<td>200</td>
<td>5</td>
<td>55</td>
<td>Add storage</td>
<td>183</td>
</tr>
<tr>
<td>OPEN HAND HELD BLOWGUNS</td>
<td>100</td>
<td>N/A</td>
<td>N/A</td>
<td>Install nozzles</td>
<td>75</td>
</tr>
<tr>
<td>VACUUM GENERATION (VENTURI CUPS)</td>
<td>100</td>
<td>Prod.</td>
<td>Non-Prod.</td>
<td>Vacuum pump or lower usage cups</td>
<td>75</td>
</tr>
<tr>
<td>AUTOMATED ASSEMBLY</td>
<td>200</td>
<td>Prod.</td>
<td>Non-Prod.</td>
<td>Add storage to protect</td>
<td>0</td>
</tr>
<tr>
<td>MISCELLANEOUS USES</td>
<td>200</td>
<td>N/A</td>
<td>N/A</td>
<td>Install fans</td>
<td>50</td>
</tr>
<tr>
<td>LARGE PNEUMATIC CLAMPS</td>
<td>200</td>
<td>10sec</td>
<td>10sec</td>
<td>Add storage</td>
<td>183</td>
</tr>
<tr>
<td>PNEUMATIC ACTUATORS</td>
<td>100</td>
<td>Prod.</td>
<td>Non-Prod.</td>
<td>Replace with electric</td>
<td>100</td>
</tr>
<tr>
<td>AIR LEAKS</td>
<td>300</td>
<td>N/A</td>
<td>N/A</td>
<td>Repair</td>
<td>150</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>1400</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>816</strong></td>
</tr>
</tbody>
</table>

Completing the chart by filling in the cost cutting actions shows that it is possible to shut down one of the compressors. Based on the system demand profile, two compressors are running, on average, at 63% of full load capacity (943/1500 cfm).
Since both compressors were running on suction throttle (modulating) control, the figure below, from Stay Under Control shows that they were consuming 86% of the full load power. On this basis, the annual cost, using the equation introduced earlier, is:

\[
\left( (165 \text{ bhp} \times 2 \times 0.86) + (8 \text{ bhp} \times 2) \right) \times (0.746 \text{ kW/hp}) \times (8,760 \text{ hrs}) \times (\$0.05/\text{kWh})
\]

\[
= \frac{103,115}{0.95}
\]

= $103,115
System Demand Profile – Flow Reduction Potential
(Continued)

With the change, we now have one compressor at a 584 cfm peak, or approximately 78% of full load capacity. The controls are adjusted to operate on load/unload capacity control. The primary receiver volume is about 1 gal/cfm of compressor capacity (based on the capacity of one compressor). Referring to the figure below, an average power of 98% would result.

The new annual cost, using only one compressor, becomes:

\[
\frac{(165 \text{ bhp} \times 0.98) + 8 \text{ bhp}}{0.95} \times (0.746 \text{ kW/hp}) \times (8,760 \text{ hrs}) \times ($0.05/\text{kWh})
\]

= $58,368

The annual savings is $103,115 - $58,368 = $44,747 or a reduction of 43% (cost of electricity for electric vacuum pumps, fans and hoists not included).
Key Points

If you want to cut costs, stay calm (STA-COLM):

✓ Storage
✓ Appropriate uses
✓ Controls
✓ Leaks
✓ Maintenance

Applicable Reference Handouts

Compressed Air System Leaks (H3)
Compressed Air Storage (H5)
Compressed Air System Maintenance (H7)
Seven Step Action Plan

1. Develop a basic block diagram.

2. Measure your baseline (kW, pressures, and leak load) and calculate energy use and costs, with tools available.

3. Work with your compressed air system specialist to implement an appropriate compressor control strategy.

4. Once controls are adjusted, re-measure to get more accurate readings of kW and pressures, and to determine leak load. Recalculate energy use and costs.

5. Walk through to check for obvious preventive maintenance items and other opportunities to reduce costs and improve performance.

6. Identify and fix leaks and correct inappropriate uses – know costs, re-measure, and adjust controls as above.

7. Evaluate Steps 1-6, begin implementation of awareness and continuous improvements programs, and report results to management.
### Personal Action Plan

<table>
<thead>
<tr>
<th>Action Step</th>
<th>Completion Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Develop a basic block diagram.</td>
<td></td>
</tr>
<tr>
<td>2. Measure my baseline – (kW, pressures, and leak load) and calculate energy use and costs.</td>
<td></td>
</tr>
<tr>
<td>3. Work with my compressed air system specialist to implement an appropriate compressor control strategy.</td>
<td></td>
</tr>
<tr>
<td>4. Once controls are adjusted, re-measure to get more accurate readings of kW and pressures, and to determine leak load. Recalculate energy use and costs.</td>
<td></td>
</tr>
<tr>
<td>5. Walk through to check for obvious preventative maintenance items and other opportunities to reduce costs and improve performance.</td>
<td></td>
</tr>
<tr>
<td>6. Identify and fix leaks and correct inappropriate uses – know costs, re-measure, and adjust controls as above; determine probable cost savings.</td>
<td></td>
</tr>
<tr>
<td>7. Begin awareness/improvement programs, and report results to management.</td>
<td></td>
</tr>
</tbody>
</table>
Implementing Step 7

The seventh step in the Seven Step Action Plan requires that you: evaluate Steps 1-6, begin implementation of awareness and continuous improvements programs, and report results to management.

As you plan to implement this step, keep in mind these six key points:

- It is important to create a partnership with production (and management) so that they understand and support actions taken.

- Begin with something small and non-threatening to production, but involve them in the entire process, so that they have a sense of control and ownership.

- Always document everything that you do.

- Maintain ongoing communication with production and management, so that there are no surprises.

- Involve the line workers and skilled trades people who operate and maintain the equipment.

- Measure and report the impact of the system changes in terms that are important to management and production, including increased productivity and decreased costs.

The process outlined below will ensure the most effective implementation of Step 7:

1. **Work closely with production (and management)** as you begin to identify actions to take in Steps 1-6, so that they understand, accept, and can support the changes that are made to the system:
   
   a. Identify a change that is simple and non-threatening to production.

   b. Explain what you want to do, and why, to production.

   c. Discuss what the impact will be on production, if any.
Implementing Step 7 (Continued)

d. Identify and address any concerns that production has.

e. Explain what you want to do, and why, to the hourly workers who are responsible for operating and maintaining the equipment, in order to gain their support and involvement.

f. Involve production in the implementation and monitoring of the impact of the change—either directly or through ongoing communication.

g. Ask them to document any production benefits or problems that can be attributed to the system change.

h. Promise to immediately address any problems to their satisfaction.

i. Ask them to report the production benefits that result from the system change to management.

j. As you build their confidence with each small success, move on to making a change that will have a direct and tangible benefit to production.

k. Follow steps b. through i. for each system change.

2. Document everything that you do in Steps 1-6, including where appropriate:

a. What you did.

b. Why you did it, in terms of better meeting production’s needs and management’s interests.

c. How you involved production staff in this process.

d. The positive impact on system performance.

e. How you involved hourly workers in this process.
Implementing Step 7 (Continued)

f. The positive impact on the supply side.

g. The cost involved in taking the action.

h. The probable or actual cost savings resulting from the action.

3. **Build a documented history** of compressed air system improvements, resulting cost savings, and production support.

4. **Ask production to document the benefits and cost savings** that they attribute to the changes in the system that you have made.

5. **Submit a written report to management**, listing the system improvements, resulting cost savings for each, production’s documented benefits, and the total cost savings.

6. **Work with production to identify additional actions** to improve the system that will require an initial capital investment.

7. **Create a “marketing plan”** that identifies:

   a. What you want to do.

   b. Why you want to do it, in terms of better meeting production’s needs and management’s interests.

   c. The anticipated positive impact on system performance.

   d. The anticipated positive impact on the supply side.

   e. The cost involved in taking the action.

   f. The probable cost savings resulting from the action, phrased in a way that shows how soon a return on the investment will be achieved.

   g. Production’s support of the actions.

8. **Present the marketing plan to management as a joint effort with production.**
Implementing Step 7 (Continued)

9. As you implement approved actions, repeat items 2-5 above.

10. Continue the process, starting with item 6 above.
Key Points

If you want to cut costs, follow the plan:

✓ Create a partnership with production and management

✓ Find out what they consider important

✓ Begin with something small and involve production

✓ Always document everything that you do

✓ Maintain ongoing communication with production and management

✓ Measure and report the impact of system changes in terms that are important to management and production
Action Plan Questionnaire

Directions: Please select the correct answer(s) to complete each statement.

1. Compressed air is:
   a. efficient
   b. a resource that should be carefully managed
   c. free
   d. always the best solution

2. A compressed air system:
   a. has hundreds of components
   b. should be carefully managed
   c. is a fancy phrase for supply side
   d. can be very inefficient

3. Doing work with compressed air ______ than doing work with electricity.
   a. can cost up to 10 times more
   b. is much more efficient
   c. is much faster
   d. ensures better quality

4. Over 10 years, electricity costs are about x% of the original cost of a compressor:
   a. 10
   b. 50
   c. 100
   d. 1000

5. Baselining involves taking measurements:
   a. of pressure, flow, and temperature
   b. only under normal operating conditions
   c. to determine the system's effectiveness
   d. every day

6. Compressed air system leaks:
   a. are not a big problem
   b. are hard to fix
   c. affect the performance of the entire system
   d. can always be heard

7. The best way to correct inadequate plant pressure is to:
   a. add a compressor
   b. take a systems approach
   c. increase compressor discharge pressure
   d. bypass the compressor controls
8. For facilities with varying demand, the biggest impacts on efficiency result from (pick two of the four):

- a. compressor full load efficiency
- b. how storage is used
- c. the control strategy
- d. the efficiency of the compressor motor

9. Pressure drop is caused by:

- a. dirty filters
- b. undersized equipment
- c. poorly designed distribution systems
- d. poor maintenance

10. Compressed air storage:

- a. helps stabilize system pressure
- b. is not required for most applications
- c. makes the system easier to control
- d. is always placed at the compressor

11. Compressed air system maintenance:

- a. should only be reactive
- b. should only be done annually
- c. can increase system efficiency
- d. can improve system reliability

12. If you want to cut the cost of compressed air:

- a. review your system pressure profile
- b. eliminate inappropriate uses of air
- c. fix leaks
- d. add storage
Action Plan Questionnaire

Directions: Please select the correct answer(s) to complete each statement.

1. Compressed air is:
   a. efficient
   b. a resource that should be carefully managed
   c. free
   d. always the best solution

2. A compressed air system:
   a. has hundreds of components
   b. should be carefully managed
   c. is a fancy phrase for supply side
   d. can be very inefficient

3. Doing work with compressed air _______ than doing work with electricity.
   a. can cost up to 10 times more
   b. is much more efficient
   c. is much faster
   d. ensures better quality

4. Over 10 years, electricity costs are about _x_% of the original cost of a compressor:
   a. 10
   b. 50
   c. 100
   d. 1000

5. Baselining involves taking measurements:
   a. of pressure, flow, and temperature
   b. only under normal operating conditions
   c. to determine the system's effectiveness
   d. every day

6. Compressed air system leaks:
   a. are not a big problem
   b. are hard to fix
   c. affect the performance of the entire system
   d. can always be heard

7. The best way to correct inadequate plant pressure is to:
   a. add a compressor
   b. take a systems approach
   c. increase compressor discharge
   d. bypass the compressor controls
Action Plan Questionnaire (Continued)

8. For facilities with varying demand, the biggest impacts on efficiency results from (pick two of the four):
   a. compressor efficiency
   b. how storage is used
   c. the control strategy
   d. the efficiency of the compressor motor

9. Pressure drop is caused by:
   a. dirty filters
   b. undersized equipment
   c. poorly designed distribution systems
   d. poor maintenance

10. Compressed air storage:
    a. helps stabilize system pressure
    b. is not required for most applications
    c. makes the system easier to control
    d. Is always placed at the compressor

11. Compressed air system maintenance:
    a. should only be reactive
    b. should be done annually
    c. can increase system efficiency
    d. can improve system reliability

12. If you want to cut the cost of compressed air:
    a. review your system pressure profile
    b. eliminate inappropriate uses of air
    c. fix leaks
    d. add storage
Summary

1. Compressed air is important.
Under Why Care About Air?, we discussed some examples of how a number of facilities have saved real dollars by managing their compressed air system. We also provided a method to calculated costs at your facility. It is important!

2. Compressed air systems start with the supply side.
Under Study Your Supply Side, we introduced over a dozen components common to the supply side of compressed air systems. All of these components must be properly integrated into the compressed air system and should be operating properly for a compressed air system to be efficient.

3. Compressed air systems go beyond the compressor room.
Under Understand Your Demands, we showed that a compressed air system includes productive uses as well as unproductive uses such as leaks, excessive system pressure, and inappropriate uses. These wasteful components of demand can double the amount of air needed!

4. Baselining is essential to manage a compressed air system.
Under Are You on Base?, we presented the steps for baselining your compressed air system. This is an essential step in the Seven Step Action Plan to manage your compressed air system.

5. Compressed air systems can be controlled.
Under Stay Under Control, we discussed how a compressed air system is controlled. One of the Seven Steps in the Action Plan is to work with your compressed air system specialist to develop and implement an appropriate compressor control strategy.

6. The efficiency of a compressed air system can be maintained.
Under Maintaining System Efficiency, we tried to STA-COLM. Remember these quick fixes and you can keep your system running efficiently and cost effectively.

7. By developing a plan, you can ensure that your compressed air system is efficient and cost-effective.
Under Get With the Plan, we discussed the Seven Step Action Plan. By following this plan, you can make sure that your facility will save money and continually maintain your compressed air system.
### How Much Can You Save?

**Directions:** Refer to page 21 in the *Why Care About Air?* section. Copy the your estimated annual energy cost into the blank below. Estimate the range of energy savings that can be easily realized by multiplying this number by 10% and 30%.

<table>
<thead>
<tr>
<th>Your Annual Energy Consumption ($/yr)</th>
<th>10% Savings ($/yr)</th>
<th>30% Savings ($/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

If you implement the steps in your action plan, you should be able to realize savings in this range, and perhaps even more.
Compressed Air Challenge Training

Fundamentals of Compressed Air Systems

Worksheets
Compressor Annual Energy Cost Estimation

Directions: Please complete this form using information from the Compressor Information form and the Electricity Cost form you completed prior to the workshop.

Data Needed:

Motor Horsepower _______ hp
Annual Days of Operation _______ days
Number of Hours per Day _______ hours
Average Cost of Electricity _______ $/kWh

Calculation (repeat for each compressor):

annual electricity costs =

\[ \text{bhp} \times 0.746 \times \text{hours} \times \text{cost} \times \text{motor efficiency} \]

Where:

- \( \text{bhp} \) = motor full-load horsepower
- 0.746 = kW/hp
- \( \text{hours} \) = annual hours of operation (days x hours/day)
- \( \text{cost} \) = electricity cost in $/kWh
- \( \text{motor efficiency} \) = motor nameplate full load efficiency

Calculations:

<table>
<thead>
<tr>
<th>Motor Efficiency Estimates</th>
<th>Energy Efficient</th>
<th>Standard</th>
<th>Rewound</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.93</td>
<td>0.92</td>
<td>0.9</td>
</tr>
<tr>
<td>100</td>
<td>0.94</td>
<td>0.93</td>
<td>0.91</td>
</tr>
<tr>
<td>150</td>
<td>0.945</td>
<td>0.93</td>
<td>0.91</td>
</tr>
<tr>
<td>200</td>
<td>0.95</td>
<td>0.94</td>
<td>0.92</td>
</tr>
<tr>
<td>300</td>
<td>0.96</td>
<td>0.95</td>
<td>0.93</td>
</tr>
</tbody>
</table>
# Checklist for STA-COLM

| Storage | ☐ Make sure your primary storage is adequate  
☐ Consider strategic secondary storage for some applications |
|---|---|
| Appropriate Uses | ☐ Evaluate each major class of compressed air end-use  
☐ Check end-uses against list of inappropriate uses |
| Controls | ☐ Periodically work with your equipment service provider to adjust individual compressor controls  
☐ For systems with multiple compressors, use controls to orchestrate the compressors (multiple compressor sequencing)  
☐ Consider flow/pressure controllers |
| Leaks | ☐ Get the equipment to find the leaks  
☐ Start looking in the right place  
☐ Learn how to repair the leaks  
☐ Establish a leak prevention program |
| Maintenance | ☐ Follow the maintenance guidelines for your compressor  
☐ Follow the maintenance guidelines for your other compressed air system components  
☐ Develop a maintenance program |
# Original System Demand Profile

<table>
<thead>
<tr>
<th>Operation</th>
<th>Pressure (psi)</th>
<th>Continuous</th>
<th>Average</th>
<th>Peak</th>
<th>Cycle Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>On</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Off</td>
</tr>
</tbody>
</table>

| TOTAL     |               |            |         |      |            |
## Revised System Demand Profile

<table>
<thead>
<tr>
<th>Operation</th>
<th>Action</th>
<th>Original Flow (cfm)</th>
<th>Revised Flow (cfm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Continuous</td>
<td>Average</td>
</tr>
</tbody>
</table>

| TOTAL     |        |                     |                    |                   |


Compressed Air Challenge

Fundamentals of Compressed Air Systems

Pre-Workshop Exercises
Pre-Workshop Assignment

In order to ensure that the Compressed Air Challenge Fundamentals of Compressed Air Systems Training is most useful to you, it will be important for you to bring information about your plant’s compressed air system to the workshop.

Please complete the four enclosed worksheets:

1. **Compressed Air System Block Diagram**, which asks you to draw a block diagram of your plant’s compressed air system.

2. **Compressor Information**, which asks you to identify the type, size, and operation of each air compressor in your plant.

3. **Compressed Air System Control Information**, which asks you to identify how your plant’s compressors are controlled (optional).

4. **Electricity Cost Information**, which asks you to identify the electricity costs of your plant.

A compressed air systems terminology refresher has also been included. These terms will be used during the workshop. The better you understand them, the easier it will be for you to participate in the workshop exercises.

We will use all of this information during the workshop, so please be sure to **bring the four completed worksheets to the workshop**.

You will also need to bring a **calculator**.

Thank you.
Sample Block Diagram
Compressed Air System Block Diagram

Directions: Please (1) review the Sample Block Diagram, and then (2) complete a block diagram of your plant’s compressed air system using the shapes shown below.

Name: ___________________________  Date: ______________________

Plant: ___________________________________________________________________

[Diagram with shapes: Compressor, Dryer, Receiver, Filter, Pipe, End Use]

Your System
Compressor Types and Nameplate Information

Five Types of Industrial Air Compressors

1. **Single-acting Reciprocating**
   - Uses a piston(s) with compression on the top side. Usually air cooled, most are less than 30 hp, but can be as large as 100 hp.

2. **Double-acting Reciprocating**
   - Uses a piston(s) with compression on both sides. Usually water cooled and greater than 10 hp.

3. **Lubricant-injected Rotary Screw**
   - Male and female screw rotors mesh, trap air, and reduce the volume along the length of the rotors to the discharge point. Lubricant is injected into the compression chamber. Usually 5-600 hp and air cooled in smaller sizes. Most common industrial air compressor over 10 hp.

4. **Lubricant-free rotary screw**
   - Like lubricant injected, except either water injected or multistage dry. Air or water cooled and typically 30-600 hp.

5. **Centrifugal**
   - Uses a continuously flowing air stream which has kinetic energy imparted to it by high speed rotating impellers, and is further converted to pressure in a diffuser. Usually multi-stage, water cooled, and greater than 200 hp.

**Nameplate Information**

- The compressor manufacturer, model information, rated cfm, and maximum full load discharge pressure can be found on the compressor nameplate or the documentation furnished with the compressor.

- The motor horsepower can be found on the motor nameplate or the documentation furnished with the compressor (or replacement motor).

- The compressor discharge pressure is dependent on how the controls are set and where the signal locations are. Discharge pressure can be determined from control set points or readouts. Record compressor discharge pressure during typical operation.
Compressor Information

Directions: Please (1) review the fact sheet titled Compressor Types and Nameplate Information, and (2) complete this form for each of your plant's compressors larger than 30 hp.

Name: ___________________________ Date: __________

Plant: ____________________________

<table>
<thead>
<tr>
<th>Compressor #</th>
<th>(from block diagram)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>______________________</td>
</tr>
<tr>
<td>Model</td>
<td>______________________</td>
</tr>
<tr>
<td>Compressor Type</td>
<td>______________________</td>
</tr>
<tr>
<td>Motor Nameplate Horsepower</td>
<td>_____ hp</td>
</tr>
<tr>
<td>Rated CFM</td>
<td>_____ cfm</td>
</tr>
<tr>
<td>Maximum Design Full Load Pressure</td>
<td>_____ psig</td>
</tr>
<tr>
<td>Age/Comments:</td>
<td>______________________</td>
</tr>
</tbody>
</table>

Operating Schedule Information

Number of Days of Operation Annually: ______________________

Number of Hours per Day: ______________________

Compressor Discharge Pressure: _____ psig

Notes on Load Profile, Part-load/Unloaded Operation:

_________________________________________________
Compressed Air System Control Information

Compressor controls are designed to match compressor delivery with compressed air demand, by maintaining the compressor discharge pressure within a specified range. This discharge pressure should be set as low as possible to minimize energy use. Control strategies need to be developed using a systems approach, taking into account system dynamics and storage. There are six basic types of individual compressor controls:

1. **Start/Stop**
   - Turns the motor driving the compressor on or off in response to a pressure signal (reciprocating and rotary screw).

2. **Load/Unload**
   - Allows the motor to run continuously, but unloads the compressor when a predetermined pressure is reached. The compressor reloads at a predetermined lower discharge pressure. Also known as constant speed or constant run control (reciprocating, rotary screw, and centrifugal).

3. **Modulating**
   - Restricts inlet air to the compressor to progressively reduce compressor output to a specified minimum, when the compressor is unloaded. Also known as throttling or capacity control (rotary screw and centrifugal).

4. **Dual/Auto Dual**
   - For small reciprocating compressors, allows the selection of either start/stop or load/unload. For lubricant injected rotary screw compressors, provides modulation to a pre-set reduced capacity followed by unloading with the addition of an over-run timer to stop the compressor after running unloaded for a pre-set time.

5. **Variable Displacement**
   - Allows progressive reduction of the compressor displacement without reducing the inlet pressure. (reciprocating {multi-step} and rotary screw {turn, spiral, or poppet valves}).

6. **Variable Speed**
   - Adjusts the compressor capacity by varying the speed of the electric motor driving the compressor in response to system signals.
Compressed Air System Control Information (Continued)

In addition, systems with multiple compressors use more sophisticated controls to orchestrate compressor operation and air delivery to the system. Sequencing controls may use a single master controller to shut down compressors that are not needed, while network controls (multi-master) use the individual compressor controls, with one acting as the master controller. Most new compressors incorporate microprocessor controls which allow greater flexibility.

Some systems use flow/pressure controllers to separate the supply side of a compressor system from the demand side.
Compressor System Control Information (Optional)

Directions: Please (1) review the fact sheet titled Compressed Air System Control Information, and then (2) complete this form for each of your plant's compressors that are larger than 30 hp. Note: This worksheet is optional.

Name: ___________________________ Date: ____________

Plant: ___________________________________________

Individual Compressor Control

Compressor #1 Compressor #2 Compressor #3
☐ Start/Stop ☐ Start/Stop ☐ Start/Stop
☐ Load/Unload ☐ Load/Unload ☐ Load/Unload
☐ Modulating ☐ Modulating ☐ Modulating
☐ Dual ☐ Dual ☐ Dual
☐ Variable Displacement ☐ Variable Displacement ☐ Variable Displacement
☐ Variable Speed ☐ Variable Speed ☐ Variable Speed
☐ Unknown ☐ Unknown ☐ Unknown

System Control for Multiple Compressors

☐ Single Master (Sequencing) Control
☐ Multi-Master (Network) Control
☐ None
☐ Unknown

System Pressure Control

☐ Flow/Pressure Controller
☐ None
☐ Unknown
Understanding Your Electric Bill

Electricity costs are often the largest component of your compressed air costs. When adding a new compressor or fixing problems with your old system, you can significantly increase or decrease your electric bill. As a result, it is important to understand certain features of your monthly electric bill.

1. Two components of your electric bill are demand and energy charges. Demand charge is based on the maximum level of power you use during that month (measured in kilowatts or kW), and is expressed in dollars per kW. Energy charge is based on the amount of energy consumed (measured in kilowatt-hours or kWh), and is expressed in dollars per kWh.

2. These demand and energy charges usually make up the main components of the electricity rate (or price) you are on. Sometimes there is a customer charge that is also added, and other charges such as fuel adjustment clauses can be incorporated.

3. Rates usually vary by season, particularly the demand charges. This is usually based on the fact that, during periods where the need for power is high, the cost to generate or purchase power goes up.

4. Rates are usually tiered by levels of use. Typically, the more you use, the cheaper the cost per kWh. However, if you use more during peak periods, you may increase the price you pay.

5. When estimating the cost impact of compressed air system changes, it is important to consider changes in both energy and demand. If you add a compressor to handle just periods of peak air demand, it may add significantly to your electricity demand and not much to your energy use. As a result, your price of electricity may go up considerably. Conversely, if you fix leaks in your system, it may save both energy and demand, since it could allow you to shut down compressors or run them less frequently.

6. For the purpose of the Fundamentals training, the average cost of electricity will be used to simplify calculations. In Level II training, you will learn more about the demand and energy charges by using the marginal cost of electricity.

7. Consult your local electric utility representative for more information.
Electricity Cost Information

Directions: Please (1) review the fact sheet titled Understanding Your Electricity Bill, and then (2) complete this form for each of the past twelve months. If you cannot locate bills from each of the past twelve months, use as many as possible, since seasonal variations can significantly affect your cost information.

Name: ___________________________ Date: _________________

Plant: ________________________________

<table>
<thead>
<tr>
<th>Month</th>
<th>Total Bill ($)</th>
<th>Usage (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Totals (a) ___________ (b) ______________

Average Electricity Cost [divide (a) by (b)] = ___________ Dollars per kWh
Compressed Air System Terminology

The following terms will be used in the workshop. The better you understand them, the easier it will be for you to participate in the workshop exercises.

**Absorption** - The chemical process by which a hygroscopic desiccant, having a high affinity with water, melts and becomes a liquid by absorbing the condensed moisture.

**Adsorption** - The process by which a desiccant with a highly porous surface attracts and removes the moisture from compressed air. The desiccant is capable of being regenerated.

**Capacity** - The amount of air flow delivered under specific conditions, usually expressed in cubic feet per minute (cfm).

- **Capacity, Actual** - The actual volume flow rate of air or gas compressed and delivered from a compressor running at its rated operating conditions of speed, pressure, and temperature. Actual capacity is generally expressed in actual cubic feet per minute (acfm) at conditions prevailing at the compressor inlet. Also called Free Air Delivered (FAD).

- **Rated Capacity** - Volume rate of air flow at rated pressure at a specific point.

- **Required Capacity** - Cubic feet per minute (cfm) of air required at the inlet to the distribution system.

**Cubic Feet Per Minute (cfm)** - Volumetric air flow rate.

- **Cfm, Free Air (or Free Air Delivered {FAD})** - Cfm of air delivered to a certain point at a certain condition, converted back to ambient conditions. This term sometimes is used for the capacity of an air compressor. This is the same as acfm, being the delivered flow rate measured at prevailing ambient conditions.

- **Actual Cfm (acfm)** - Flow rate of air at a certain point at a certain condition at that point. When used for the capacity of an air compressor, it is the delivered rate of flow, measured at prevailing ambient conditions of pressure, temperature and relative humidity.
**Inlet Cfm** - Cfm flowing through the compressor inlet filter or inlet valve under rated conditions. Also used to describe the rate of flow of a centrifugal type air compressor. **Acfm** and **icfm** should be the same for displacement type air compressors, but may not be the same in some designs of centrifugal air compressors. There may be air losses through shaft seals of each stage, so that the delivered rate of flow in **acfm** may be up to 5% less than the **icfm** entering the compressor.

**Standard Cfm** - Flow of free air measured and converted to a standard set of reference conditions. There may be confusion with this term since all standards are not the same. The Compressed Air Challenge and The Compressed Air & Gas Institute have adopted the International Standards Organization (ISO) definition of standard air as: 14.5 psia (1 bar); 68°F (20°C); dry (0% relative humidity).

Other standards include:
14.7 psia; 68°F; 36% relative humidity and 14.7 psia; 60°F; dry.
When the term scfm is used, the applicable standard should be stated.

**Deliquescent** - Melting and becoming a liquid by absorbing moisture.

**Desiccant** - A material having a large proportion of surface pores, capable of attracting and removing water vapor from the air.

**Demand** - Flow of air at specific conditions required at a point or by the overall facility.

**Humidity, Relative** - The relative humidity of a gas (or air) vapor mixture is the ratio of the partial pressure of the vapor to the vapor saturation pressure at the dry bulb temperature of the mixture.

**Dew Point** - The temperature at which moisture in the air will begin to condense if the air is cooled at constant pressure. At this point the relative humidity is 100%.

**Pressure Dew Point** - For a given pressure, the temperature at which water will begin to condense out of air.

**Specific Humidity** - The weight of water vapor in an air-vapor mixture per pound of dry air.
Power – The rate at which work is done.

Brake Horsepower (bhp) - Horsepower delivered to the output shaft of a motor or engine, or the horsepower required at the compressor shaft to perform work.

Load Factor - Ratio of average compressor load to the maximum rated compressor load over a given period of time.

Full-Load - Air compressor operation at full speed with a fully open inlet and discharge delivering maximum air flow.

Specific Power - A measure of air compressor efficiency, usually in the form of bhp/100 acfm or acfm/bhp.

Total Package Input Power - The total electrical power input to a compressor, including drive motor, cooling fan, motors, controls, etc.

Pressure - Force per unit area, measured in pounds per square inch (psi).

Gauge Pressure - The pressure determined by most instruments and gauges, usually expressed in psig. Barometric pressure must be considered to obtain true or absolute pressure.

Pressure Drop - Loss of pressure in a compressed air system or component due to friction or restriction.

Pressure Range - Difference between minimum and maximum pressures for an air compressor. Also called cut in-cut out or load-no load pressure range.

Rated Pressure - The operating pressure at which compressor performance is measured.

Receiver - A vessel or tank used for storage of gas under pressure. In a large compressed air system there may be primary and secondary receivers.

Surge - A phenomenon in centrifugal compressors where a reduced flow rate results in a flow reversal and unstable operation.
# Fundamentals of Compressed Air Systems

## References

### Table of Contents

<table>
<thead>
<tr>
<th>Page Number</th>
<th>Reference</th>
<th>Applicable Training Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1-1</td>
<td>Handout: Basic Types of Compressors and Major System Components</td>
<td>Study Your Supply Side Understand Your Demands</td>
</tr>
<tr>
<td>H2-1</td>
<td>Handout: Inappropriate Uses of Compressed Air</td>
<td>Understand Your Demands</td>
</tr>
<tr>
<td>H3-1</td>
<td>Handout: Compressed Air System Leaks</td>
<td>Understand Your Demands</td>
</tr>
<tr>
<td>H4-1</td>
<td>Handout: Baselining Your Compressed Air System</td>
<td>Are You on Base?</td>
</tr>
<tr>
<td>H5-1</td>
<td>Handout: Compressed Air Storage</td>
<td>Stay Under Control</td>
</tr>
<tr>
<td>H6-1</td>
<td>Handout: Compressed Air Control Basics</td>
<td>Stay Under Control</td>
</tr>
<tr>
<td>H7-1</td>
<td>Handout: Compressed Air System Maintenance</td>
<td>Maintain System Efficiency Throughout</td>
</tr>
<tr>
<td>H8-1</td>
<td>Handout: Compressed Air System Terminology</td>
<td></td>
</tr>
<tr>
<td>H9-1</td>
<td>Ford Monroe Case Study</td>
<td></td>
</tr>
</tbody>
</table>
Handout: Basic Types of Compressors and Major System Components

A typical modern industrial compressed air system is composed of several major subsystems and many sub-components. Major subsystems include the compressor, prime mover, controls, treatment equipment and accessories, and the distribution system. The compressor is the mechanical device that takes in ambient air and increases its pressure. The prime mover powers the compressor. Controls serve to regulate the amount of compressed air being produced. The treatment equipment removes contaminants from the compressed air and accessories keep the system operating properly. Distribution systems are analogous to wiring in the electrical world - they transport compressed air to where it is needed. Compressed air storage can also serve to improve system performance and efficiency. The following diagram shows a typical compressed air system.
Compressor Types
Many modern industrial air compressors are sold "packaged" with the compressor, drive motor, and many of the accessories mounted on a frame for ease of installation. Provision for movement by forklift is common. Larger packages may require the use of an overhead crane. An enclosure may be included for sound attenuation and aesthetics.

As shown in the figure, there are two basic compressor types: positive-displacement and dynamic. In the positive-displacement type, a given quantity of air or gas is trapped in a compression chamber and the volume which it occupies is mechanically reduced, causing a corresponding rise in pressure prior to discharge. At constant speed, the air flow remains essentially constant with variations in discharge pressure. Dynamic compressors impart velocity energy to continuously flowing air or gas by means of impellers rotating at very high speeds. The velocity energy is changed into pressure energy both by the impellers and the discharge volutes or diffusers. In the centrifugal-type dynamic compressors, the shape of the impeller blades determines the relationship between air flow and the pressure (or head) generated.

Positive-Displacement Compressors
These compressors are available in two types: reciprocating and rotary. Reciprocating compressors work like bicycle pumps. A piston, driven through a crankshaft and connecting rod by an electric motor reduces the volume in the cylinder occupied by the air or gas, compressing it to a higher pressure. Single-acting compressors have a compression stroke in only one direction, while double-acting units provide a compression stroke as the piston moves in each direction. Large industrial reciprocating air compressors are double-acting and water-cooled. Multi-stage double-acting compressors are the most efficient compressors available, and are typically larger, noisier, and more costly than comparable rotary units. Reciprocating compressors are available in sizes from less than 1 hp to more than 600 hp.

Rotary compressors have gained popularity and are now the "workhorse" of American industry. They are most commonly used in sizes from about 30-200 hp. The most common type of rotary compressor is the helical twin screw-type (also known as rotary screw or helical lobe). Male and female screw-rotors mesh, trapping air, and reducing the volume of the air along the rotors to the air discharge point. Rotary screw compressors have low initial cost, compact size, low weight, and are easy to maintain. Rotary screw compressors are available in sizes from 3-600 hp and may be air- or water-
Basic Types of Compressors and Major System Components

Page H1-3

cooled. Less common rotary compressors include sliding-vane, liquid-ring, and scroll-type.

**Single Acting Reciprocating Air Compressors**

This type of compressor is characterized by its “automotive” type piston driven through a connecting rod from the crankshaft. Compression takes place on the top side of the piston on each revolution of the crankshaft.

Single acting reciprocating air compressors may be air cooled or liquid cooled. These may be single stage, usually rated at discharge pressures from 25 to 125 psig, two-stage, usually rated at discharge pressures from 125 psig to 175 psig, or multi-stage for pressures above 175 psig.

The most common air compressor in the fractional and single digit hp sizes is the air cooled reciprocating air compressor. In larger sizes, single acting reciprocating compressors are available up to 150 hp, but above 25 hp are much less common.

Two-stage and multi-stage designs include inter-stage cooling to reduce discharge air temperatures for improved efficiency and durability.

Pistons used in single-acting compressors are of the “automotive” or “full skirt” design, the underside of the piston being exposed to the crankcase. Lubricated versions have a combination of compression and lubricant control piston rings which seal the compression chamber, control the lubricant to the compression chamber, and act (in some designs) as support for piston movement on the cylinder walls. Lubricant-free, or non-lube, designs do not allow lubricant in the compression chamber and use pistons of self lubricating materials or use heat resistant, non-metallic guides and piston rings which are self lubricating. Some designs incorporate a distance piece or crosshead to isolate the crankcase from the compression chamber.

Lubricant-less designs have piston arrangements similar to lubricant-free versions but do not have lubricant in the crankcase. Generally these have grease pre-packed crankshaft and connecting rod bearings.

**Cooling.** Single acting air compressors have different arrangements for removing the heat of compression. Air cooled versions have external finning for heat dissipation on the cylinder, cylinder head and, in some cases, the external heat exchanger. Air is drawn or blown across the fins and the compressor crankcase by a fan, which may be the spokes of the drive pulley/flywheel.

Liquid cooled compressors have jacketed cylinders, heads and heat exchangers, through which liquid coolant is circulated to dissipate the heat of compression. Water, or an ethylene glycol mixture to prevent freezing, may be employed.

**Drives.** The most common drive arrangement is belt drive from an electric motor. The compressor sheave also acts as a flywheel to limit torque pulsations and its spokes often
are used for cooling air circulation. Belt drive allows a great degree of flexibility in obtaining the desired speed of rotation.

Flange mounted, or direct coupled motor drives provide compactness and minimum drive maintenance. Belts and couplings must be properly shielded for safety and to meet OSHA requirements in industrial plants.

**Double Acting Reciprocating Air Compressors**
These use both sides of the piston for air compression, doubling the capacity for a given cylinder size. A piston rod is attached to the piston at one end and to a crosshead at the other end. The crosshead ensures that the piston rod travels concentrically with the piston. These compressors may be single or multi-stage, depending on discharge pressure and hp size. These can range upwards from 10 hp and with pressures upwards from 50 psig.

**Cooling.** Double acting air compressors generally have cooling water jackets around the cylinder body and in the cylinder head. This combined with their relatively slow speed of operation and water cooled intercooling, results in excellent compression efficiency.

**Lubrication.** Cylinder lubrication generally is by means of a forced feed cylinder lubricator, with a feed rate of several drops per minute, depending on cylinder size and piston speed and as specified by the manufacturer. Lubricant free versions also are available with PTFE or similar materials for piston and glide, or rider, rings and a distance piece between the crankcase and the cylinder(s) to ensure that no part of the piston rod, which enters the lubricated crankcase, can enter the lubricant free cylinder area.

**Balance.** Single and two cylinder compressors of this type generally require a substantial foundation due to unbalanced reciprocating forces.

**Drives.** Below 200 hp, belt drives often are used or flange mounted induction motors. Direct drive synchronous motors sometimes are used with 1.0 power factor or 0.8 power factor to provide power factor correction to off-set other induction type electrical loads.

**Lubricant Injected Rotary Screw Compressors**
The lubricant injected rotary screw compressor, with electric motor driver, has become a dominant type for a wide variety of applications. It is characterized by low vibration, requiring only a simple load bearing foundation and providing long life with minimal maintenance in broad ranges of capacity and pressure.

**Compression Principle.** The lubricant injected rotary screw compressor consists of two intermeshing rotors in a stator housing having an inlet port at one end and a discharge port at the other. The male rotor has lobes formed helically along its length while the female rotor has corresponding helical grooves or flutes. The number of helical lobes and grooves may vary in otherwise similar designs.
Air flowing in through the inlet port fills the spaces between the lobes on each rotor. Rotation then causes the air to be trapped between the lobes and the stator as the inter-lobe spaces pass beyond the inlet port. As rotation continues, a lobe on one rotor rolls into a groove on the other rotor and the point of intermeshing moves progressively along the axial length of the rotors, reducing the space occupied by the air, resulting in increased pressure. Compression continues until the inter-lobe spaces are exposed to the discharge port when the compressed air is discharged.

Lubricant is injected into the compression chamber during compression and serves three basic functions: 1) it lubricates the intermeshing rotors and associated bearings, 2) it takes away most of the heat caused by compression, and 3) it acts as a seal in the clearances between the meshing rotors and between rotors and stator.

**Lubrication.** The generic term lubricant has been used. This may be a hydrocarbon product but most compressors now use cleaner and longer life synthetic lubricants, including diesters; polyglycols; polyalphaolefins, polyol esters and silicon based lubricants. These newer products are suitable for a wider range of temperatures and have higher flash points.

A mixture of compressed air and injected lubricant leaves the air end and is passed to a sump/separator where the lubricant is removed from the compressed air. Directional and velocity changes are used to separate most of the liquid. The remaining aerosols in the compressed air then are separated by means of a coalescing filter, resulting in only a few parts per million of lubricant carry-over (usually in the range 2-5 ppm). A minimum pressure device, often combined with a discharge check valve, prevents excessive velocities through the separator element until a normal system pressure is achieved at start-up. Most lubricant injected rotary screw compressor packages use the air pressure in the lubricant sump/separator, after the discharge of the air end, to circulate the lubricant through a filter and cooler prior to re-injection to the compression chamber. Some designs may use a lubricant pump.

**Multi-stage compressors.** Multi-stage compressors may have the individual stages mounted side by side, either in separate stators or within a common, multi-bore stator housing. Alternatively, the stages may be mounted in tandem with the second stage driven directly from the rear of the first stage. Multiple stages are used either for improved efficiency at a given pressure or to achieve higher pressures.

**Cooling.** The temperature of the lubricant injected into the compression chamber generally is controlled directly to approximately 140°F, or indirectly by controlling the discharge temperature. A thermostatic bypass valve allows some or all of the lubricant being circulated to bypass the lubricant cooler to maintain the desired temperature over a wide range of ambient temperatures.

Generally, a suitable temperature and viscosity of the lubricant are required for proper lubrication, sealing and to avoid condensation in the lubricant sump. It also is necessary
to avoid excessive temperatures, which could result in breakdown of the lubricant and reduced life.

In addition to lubricant cooling, an air aftercooler is used to cool the discharged air and to remove excess moisture. In the majority of applications, radiator type lubricant and air coolers are employed and provide the opportunity of heat recovery from the compression process for facility heating. Water cooled heat exchangers, with water control valves, also are available on most rotary screw compressor packages.

In multi-stage designs, lubricant may be removed and the air cooled between the stages in an intercooler, or the air/lubricant mixture may pass through a curtain of lubricant as it enters the next stage.

Single stage lubricant injected rotary screw compressor packages are available from 3-900 hp, or 8-5000 cubic feet per minute, with discharge pressures from 50-250 psig. Two stage versions can reduce specific power up to 15% and some can achieve discharge pressures up to 500 psig. Lubricant injected rotary screw vacuum pumps also are available from 80-3100 inlet cfm and vacuum to 29.7 in. Hg.

Most compressor packages now incorporate microprocessors for controls and safety devices.

**Lubricant Free Rotary Screw Compressors**

The principle of compression is similar to that of the lubricant injected rotary screw compressor but without lubricant being introduced into the compression chamber. Two distinct types are available - the dry type and the water injected type.

In the dry type, the intermeshing rotors are not allowed to touch and their relative positions are maintained by means of lubricated timing gears external to the compression chamber. Since there is no injected fluid to remove the heat of compression, most designs use two stages of compression with an intercooler between the stages and an aftercooler after the second stage.

The lack of a sealing fluid also requires higher rotation speeds than for the lubricant injected type.

Dry type lubricant free rotary screw compressors have a range from 25-4000 hp or 90-20,000 cubic feet per minute. Single stage units can operate up to 50 psig while two-stage generally can achieve up to 150 psig.

In the water injected type, similar timing gear construction is used but water is injected into the compression chamber to act as a seal in internal clearances and to remove the heat of compression. This allows pressures in the 100-150 psig range to be accomplished with only one stage. The injected water, together with condensed moisture from the atmosphere, is removed from the discharged compressed air by a conventional moisture separation device.
Similar to the lubricant injected type, lubricant free rotary screw compressors generally are packaged with all necessary accessories.

**Lubrication.** Lubricant free rotary screw compressors utilize lubricant for lubrication of bearings and gears, which are isolated from the compression chamber. The lubricant also may be used for stator jacket cooling in lieu of water, to eliminate the effects of fouling.

Typically, a lubricant pump is directly driven from a shaft in the gearbox, assuring lubricant flow immediately at start-up and during run-down in the event of power failure. A lubricant filter, typically with 10 micron rating, protects bearings, gears and the lubricant pump from damage. Lubricant temperature typically is maintained through the use of a thermostatic mixing valve, sensing supply temperature and bypassing the lubricant cooler as necessary.

**Cooling.** The cooling system for the dry type lubricant free rotary screw compressor, normally consist of an air cooler after each stage and a lubricant cooler. These may be water cooled or air cooled radiator type. Some two-stage designs also employ an additional heat exchanger to cool a small portion of the compressed air for recycling to the compressor inlet during the unloaded period.

**Dynamic Compressors**
These compressors raise the pressure of air or gas by imparting velocity energy and converting it to pressure energy. Dynamic compressors include centrifugal and axial types. The centrifugal-type is the most common and is widely used for industrial compressed air. Each impeller, rotating at high speed, imparts primarily radial flow to the air or gas which then passes through a volute or diffuser to convert the residual velocity energy to pressure energy. Some large manufacturing plants use centrifugal compressors for general plant air, and, in some cases, plants use other compressor types to accommodate demand load swings while the centrifugal compressors handle the base load.

Axial compressors consist of a rotor with multiple rows of blades and a matching stator with rows of stationary vanes. The rotating blades impart velocity energy, primarily in an axial plane. The stationary vanes then act as a diffuser to convert the residual velocity energy into pressure energy. This type of compressor is restricted to very high flow capacities and generally has a relatively high compression efficiency.

Mixed flow compressors have impellers and rotors which combine the characteristics of both axial and centrifugal compressors.

**Centrifugal Type Air Compressors**
A centrifugal air compressor has a continuously flowing air stream which has velocity energy, or kinetic energy, imparted to it by an impeller, or impellers, which rotate at speeds which may exceed 50,000 rpm. Approximately half of the pressure energy is developed in the impeller with the other half achieved by converting the velocity energy to pressure energy as the air speed is reduced in a diffuser and volute. The most common
is the centrifugal air compressor with from two to four stages for pressures in the 100-150 psig range. A water cooled intercooler and separator between each stage returns the air temperature to approximately ambient temperature and removes condensed moisture before entering the next stage. An aftercooler and separator cools the air from the final stage and removes more moisture prior to air delivery to distribution.

The inherent characteristic of the centrifugal air compressor is that as system pressure decreases, the compressor's capacity increases. The steepness of the pressure head/capacity curve is dependent upon the impeller design. The more the impeller blades lean backwards from the true radial position, the steeper the curve.

Most standard centrifugal air compressor packages are designed for an ambient temperature of 90°F and near sea level barometer pressure. The dynamic nature of the centrifugal compressor results in the pressure head generated by each impeller increasing as the air density increases. The compressor mass flow and actual cfm capacity at a given discharge pressure increases as the ambient temperature decreases. Typically, a capacity control system is provided with the compressor to maintain the desired capacity and to operate within the motor horsepower limits. The control system regulates the air flow by means of an inlet throttle valve or inlet guide vanes. The amount of reduction in the flow rate is limited by a minimum point flow reversal phenomenon known as surge. Control systems normally unload the compressor to avoid this occurrence which could result in excessive vibration and potential damage to the compressor.

Centrifugal air compressors range from around 500 to over 100,000 acfm but the more common air compressors are from 1,000 to 5,000 acfm and with discharge pressures up to 125 psig. These may have several impellers in line on a single shaft or with separate impellers integrally geared.

Centrifugal air compressors provide lubricant free air delivery as there is no lubricant in the compression chambers. Lubrication, for speed increasing gears and the special high speed shaft bearings, is kept away from the compression chambers by means of shaft seals which may also have air purge and vent connections.

Centrifugal air compressors are high speed rotating machines and as such, shaft vibration monitoring is mandated to record operational trends and protect the equipment. Automatic control of the compressors is typical and has been greatly improved by the use of microprocessors, which monitor the pressure/capacity/temperature characteristics as well as main drive motor current draw. It is important that the manufacturer's recommended maintenance procedures be followed and that certain maintenance procedures be carried out by factory qualified staff. This is particularly true of attempts to remove an impeller from its shaft, since special procedures and tools may be involved.

**Lubrication and Lubrication Systems.** Centrifugal compressors use a pressure lubrication system for bearings and drive gears. The main lubricant pump may be driven from the gearbox input shaft with an electric motor driven auxiliary lubricant pump for
pre-lubrication prior to start-up and for post lubrication during a cool down period. A water cooled lubricant cooler also is included.

Because of the high rotation speeds, some designs use a high pressure lubricant supply to the special bearings involved. The manufacturer’s recommended lubricant should be used and changed at the specified intervals.

Advantages and Disadvantages of Each Compressor Type
Advantages and disadvantages of any compressor are based on its characteristics and application. Advantages and disadvantages listed below are for a typical compressed air system in an industrial plant. The estimated full load brake horsepower (bhp) requirement of each compressor type at 100 psig discharge pressure at the compressor, a main drive motor typical efficiency of 92% and 0.746 kW/bhp, the approximate operating costs of operation are obtained.

Single Acting Air Cooled Reciprocating Air Compressors
Advantages include:
- Small size and weight.
- Generally can be located close to point of use, avoiding lengthy piping runs and pressure drops.
- Do not require separate cooling systems.
- Simple maintenance procedures.

Disadvantages include:
- Lubricant carry-over, which should be avoided.
- Relatively high noise.
- Relatively high cost of compression.
- Generally are designed to run not more than 50% of the time.
- Generally compress and store the air in a receiver at a pressure higher than required at the point of use. The pressure then is reduced to the required operating pressure but without recovery of the energy used to compress to the higher pressure.

Operating Cost: 22-24 kW/100 cfm*

Double Acting Water Cooled Reciprocating Air Compressors
Advantages include:
- Efficient compression, particularly with multi-stage compressors.
- Three-step (0-50-100%) or five-step (0-25-50-75-100%) capacity controls, allowing efficient part load operation.
- Relatively routine type maintenance procedures.

Disadvantages include:
- Relatively high first cost compared with equivalent rotary air compressors.
- Relatively high space requirements.
• Lubricant carry-over on lubricant cooled units.
• Relatively high vibrations require high foundation costs.
• Lubricant carry-over on lubricant cooled units.
• Seldom sold as complete independent packages.
• Require flywheel mass to overcome torque and current pulsations in motor driver.
• Repair procedures require some training and skills.

Operating cost: 15-16 kW/100 cfm*

**Lubricant Injected Rotary Screw Compressors.**

*Advantages include:*
• Compact size and complete package.
• Economic first cost.
• Vibration free operation does not require special foundation.
• Part load capacity control systems can match system demand.
• Routine maintenance includes lubricant and filter changes.

*Disadvantages include:*
• Less efficient full and part load operation compared with water cooled reciprocating air compressors.
• Lubricant carry-over into delivered air requires proper maintenance of air/lubricant separator and the lubricant itself.

Operating cost: 18-19 kW/100 cfm single stage*
16-17 kW/100 cfm two stage*

**Lubricant Free Rotary Screw Air Compressors**

*Advantages include:*
• Completely packaged.
• Designed to deliver lubricant free air.
• Do not require any special foundations.

*Disadvantages include:*
• Significant premium over lubricant injected type.
• Less efficient than lubricant injected type.
• Limited to Load/Unload type capacity control.
• Higher maintenance costs than lubricant injected type.

Operating Cost: 20-22 kW/100 cfm*

**Centrifugal Air Compressors**

*Advantages include:*
• Completely packaged for plant or instrument air up through 500 hp.
• Relative first cost improves as size increases.
• Designed to deliver lubricant free air.
Basic Types of Compressors and Major System Components

- Do not require any special foundations.
  Disadvantages include:
- Limited capacity control modulation, requiring unloading for reduced capacities.
- High rotational speeds require special bearings, sophisticated monitoring of vibrations and clearances.
- Specialized maintenance considerations.

Operating Cost: 16-20 kW/100 cfm*

* By taking the estimated full load brake horsepower (bhp) requirement of each compressor type at 100 psig discharge pressure at the compressor, a main drive motor typical efficiency of 92% and 0.746 kW/bhp, the approximate operating costs of operation are obtained.

Compressor Selection
Selection of air compressors must take into account the requirements of the different points of use, the air capacity for each when fully loaded, and the frequency of these requirements. Demands often are intermittent but the “worst case scenario” also must be considered. Standby compressor capacity also must be considered, taking into account the essential nature of an application and the cost of downtime compared with the cost of a spare compressor.

The capacity required will be a major factor in determining the type of compressor chosen. A general rule is that centrifugal and rotary air compressors are better suited to continuous base-load type of service. Reciprocating air compressors are better suited to swings in loads. This means that a centrifugal or rotary air compressor may be sized for the minimum or average demand while a reciprocating air compressor then can handle the swings in load from minimum or average to the peaks. The anticipated load swings also will be a determining factor in the selection of a single compressor and its type of capacity control or multiple compressors with sequential controls.

Other Major System Components
Other major subsystems in a compressed air system include the prime mover, controls, treatment equipment and accessories, and the distribution system. Each is discussed below.

Compressor Prime Movers
The prime mover is the main power source providing energy to drive the compressor. The prime mover must provide enough power to start the compressor, accelerate it to full speed, and keep the unit operating under various design conditions. This power can be provided by any one of the following sources: electric motors, diesel or natural gas engines, or steam engines or turbines. Electric motors are by far the most common type of prime mover. It is important to consider prime mover efficiency when applying compressors.
Electric motors are a widely available and economical means of providing reliable and efficient power to compressors. Most compressors use standard polyphase induction motors. In many cases either a standard or energy-efficient motor can be specified when purchasing a compressor or replacement motor. When replacing a standard motor with an energy-efficient one, careful attention needs to be paid to performance parameters such as full-load speed and torque. A replacement motor with performance as close as possible to the original motor should be used.

Diesel or natural gas engines are a common compressor power source in the oil and gas industries. Considerations such as convenience, cost, and the availability of liquid fuel and natural gas play a role in selecting an engine to power a compressor. Although the majority of industrial compressed air systems use electric motors for prime movers, in recent years there has been renewed interest in using non-electric drives such as reciprocating engines powered by natural gas, especially in regions with high electricity rates. Standby or emergency compressors may also be engine-driven to allow operation in the event of a loss of electrical power. Maintenance costs for engine-driven systems are significantly higher than those that use electric motors.

The oldest method of driving compressors is through the use of a steam engine or turbine. In general, however, it is not economical to use a steam engine or turbine unless the steam is readily available within the plant for use as a power source.

Compressed Air System Controls
Compressed air system controls serve to match compressor supply with system demand. Proper compressor control is essential to efficient operation and high performance. Since compressor systems are typically sized to meet a system's maximum demand, a control system is almost always needed to reduce the output of the compressor during times of lower demand. Compressor controls are typically included in the compressor package, and many manufacturers offer more than one type of control technology. For systems with multiple compressors, sequencing controllers can be used to bring individual compressors on and off line as needed. Other system controllers, such as network controllers and demand controllers, can substantially improve performance for many systems.

The type of control system specified for a given system is largely determined by the type of compressor being used and the facility's demand profile. If a system has a single compressor with a very steady demand, a simple control system may be appropriate. On the other hand, a complex system with multiple compressors, varying demand, and many types of end-uses will require a more sophisticated control strategy. In any case, careful consideration should be given to compressor system control selection because it can be the most important single factor affecting system performance and efficiency. For information about efficiency and compressor controls, see the Handout titled “Compressed Air System Controls Basics.”
Accessories
Accessories are the various types of equipment used to treat compressed air by removing contaminants such as dirt, lubricant, and water; to keep compressed air systems running smoothly; and to deliver the proper pressure and quantity of air throughout the system. Accessories include: compressor aftercoolers, filters, separators, dryers, heat recovery equipment, lubricators, pressure regulators, air receivers, traps, and automatic drains.

Air Inlet Filters. An air inlet filter protects the compressor from atmospheric airborne particles. Further filtration is needed, however, to protect equipment downstream of the compressor.

Compressor Cooling. Air or gas compression generates heat. As a result, industrial air compressors that operate continuously generate substantial amounts of heat. Compressor units are cooled with air, water, and/or lubricant. Reciprocating compressors of less than 100 hp are typically air-cooled using a fan, which is an integral part of the belt drive flywheel. Cooling air blows across finned surfaces on the outside of the compressor cylinder's cooler tubes. Larger, water-cooled reciprocating air compressors have built-in cooling water jackets around the cylinders and in the cylinder heads. The temperature of the inlet water and the design and cleanliness of the cooler can affect overall system performance and efficiency.

Lubricant-injected rotary compressors use the injected lubricant to remove most of the heat of compression. In air-cooled compressors, a radiator-type lubricant cooler is used to cool the lubricant before it is re-injected. The cooling fan may be driven from the main motor drive shaft or by a small auxiliary electric motor. In plants where good quality water is available, shell and tube heat exchangers generally are used.

Intercooling. Most multi-stage compressors use intercoolers, which are heat exchangers that remove the heat of compression between the stages of compression. Intercooling affects the overall efficiency of the machine.

Aftercoolers. As mechanical energy is applied to a gas for compression, the temperature of the gas increases. Aftercoolers are installed after the final stage of compression to reduce the air temperature. As the air temperature is reduced, water vapor in the air is condensed, separated, collected, and drained from the system. Most of the condensate from a compressor with intercooling is removed in the intercooler(s), and the remainder in the aftercooler. Almost all industrial systems, except those that supply process air to heat-indifferent operations such as forges and foundries, require aftercooling. In some systems, aftercoolers are an integral part of the compressor package, while in other systems the aftercooler is a separate piece of equipment. Some systems have both.

Separators. Compressor filters and separators remove contamination (e.g., dirt, water, and lubricant) from the air before it enters and as it exits, the compressor. Depending on the level of air purity required, different levels of filtration and types of filters are used. Separators are devices which separate liquids entrained in the air or gas. A separator generally is installed following each intercooler or aftercooler to remove the condensed...
moisture. This involves changes in direction and velocity and may include impingement baffles.

Lubricant-injected rotary compressors have an air/lubricant coalescing separator immediately after the compressor discharge to separate the injected lubricant before it is cooled and recirculated to the compressor. This separation must take place before cooling to prevent condensed moisture from being entrained in the lubricant.

**Dryers.** When air leaves an aftercooler and moisture separator, it is typically saturated. Any further radiant cooling as it passes through the distribution piping, which may be exposed to colder temperatures, will cause further condensation of moisture with detrimental effects such as corrosion and contamination of point-of-use processes. This problem can be avoided by the proper use of compressed air dryers.

Atmospheric air contains moisture. The higher the air temperature, the more moisture the air is capable of holding. The term "Relative Humidity" commonly is used to describe the moisture content although technically, the correct term is "Relative Vapor Pressure", the air and the water vapor being considered as gases. When the air contains all the moisture possible under the prevailing conditions, it is called "saturated". Air at 80% R.H. would contain 80% of the maximum possible.

When air is cooled, it will reach a temperature at which the amount of moisture present can no longer be contained and some of the moisture will condense and drop out. This is called the dewpoint. In general, reducing the temperature of saturated compressed air by 20°F will reduce the moisture content by approximately 50%.

When air is compressed and occupies a smaller volume, it no longer can contain all of the moisture it could at atmospheric conditions. Again, some of the moisture will drop out as liquid condensate.

The result of both of these is that there is a difference between the dewpoint at atmospheric conditions and the dewpoint at higher pressures. Drying compressed air beyond the required pressure dewpoint will result in unnecessary energy and costs.

Different types of compressed air dryers have different operating characteristics and degrees of dew point suppression. Dryer ratings usually are expressed at standard dryer inlet conditions, commonly referred to as the three 100s. That is, 100 psig, 100°F, and 100°F ambient temperature. Deviations from these conditions will affect the capability of a dryer. An increase in inlet temperature or a decrease in inlet pressure will reduce the dryer rating. Most manufacturers provide correction factors for this.

The most common types of dryers are discussed below.

- Refrigerant-type dryers cool the air to 35-40°F and then remove the condensed moisture before the air is reheated and discharged. Refrigerant-type dryers remove moisture from the compressed air by cooling the air in a heat exchanger that uses the
evaporation of a liquid refrigerant, causing condensate to form and to be drained off by means of a separator and trap. To avoid freezing of the condensate, the compressed air passing through the dryer is cooled to around 35°F. Most dryers use the incoming air to reheat the outgoing dried air in another heat exchanger, also reducing the incoming air temperature and reducing the heat load on the refrigeration system. The pressure dew point of this type of dryer, therefore, is 35°F. This is equivalent to a dew point of -10°F at atmospheric conditions. The approximate operating cost, including the effect of pressure drop through the dryer, is 0.79 kW/100 cfm.

- Regenerative-desiccant type dryers use a porous desiccant which adsorbs the moisture by collecting it in its myriad pores, allowing large quantities of water to be retained by a relatively small quantity of desiccant. Desiccant types include silica gel, activated alumina, and molecular sieves. Use only the type specified by the manufacturer. In some cases, more than one desiccant type can be used for special drying applications. In most of these cases, a larger particle size (1/4” or more) is used as a buffer zone at the inlet, while a smaller particle size desiccant (1/8” to 1/4”) is used for final drying. Where very low dewpoints are required, molecular sieve desiccant is added as the final drying agent.

Normally the desiccant is contained in two separate towers. Compressed air to be dried flows through one tower, while the desiccant in the other is being regenerated. Regeneration is accomplished by reducing the pressure in the tower and passing previously dried purge air through the desiccant bed. The purge air may also be heated, either within the dryer or externally, to reduce the amount of purge air required. Purge air may also be supplied by a blower. Dryers of this type normally have a built-in regeneration cycle, which can be based upon time, dew point, or a combination of the two.

Most standard regenerative desiccant type compressed air dryers provide a pressure dewpoint of -40°F, which is equivalent to -72°F at atmospheric conditions. For heatless dryers, purge air for regeneration is taken from the air already dried. The amount of purge air required can vary from 10–15% of the air flow passing through the dryer, reducing the air flow available to the system from the compressor by this amount. Approximate operating cost, including pressure drop through the dryer, is 2.0–3.0 kW/100 cfm.

- Deliquescent type dryers, use a drying medium that absorbs, rather than adsorbs, the moisture in the compressed air. This means that the desiccant medium is used up as it changes from solid to liquid and cannot be regenerated. The most common deliquescent chemicals for compressed air drying are salts of sodium, potassium, calcium, and those with a urea base. Various compounds of these have been developed and sold under a variety of trade names. Deliquescent dryers normally have a design dew point suppression of 20–36°F below an inlet temperature of 100°F, providing a pressure dew point at 100 psig, of 80–64°F. Deliquescent dryers are sensitive to the saturated air inlet temperature; the lower the inlet temperature, the
lesser the dew point suppression. They also are limited to a maximum inlet temperature of 100°F. Because the drying medium is consumed and not regenerated, there is no requirement for purge air. The approximate operating cost, including pressure drop through the dryer and any associated filtration, but excluding the cost of replacement desiccant, is approximately 0.2 kW/100 cfm.

- Heat of compression type dryers are regenerative desiccant dryers, which use the heat generated during compression to accomplish desiccant regeneration. A common type has a rotating desiccant drum in a single pressure vessel divided into two separate air streams. Most of the air discharged from the air compressor passes through an air aftercooler, where the air is cooled and condensed moisture is separated and drained. The cooled air stream, saturated with moisture, passes through the drying section of the desiccant bed, where it is dried and where it exits from the dryer. A portion of the hot air taken directly from the air compressor at its discharge, prior to the aftercooler, flows through the opposite side of the dryer to regenerate the desiccant bed. The hot air, after being used for regeneration, passes through a regeneration cooler before being combined with the main air stream by means of an ejector nozzle before entering the dryer. This means that there is no loss of purge air. Drying and regeneration cycles are continuous as long as the air compressor is in operation. This type of dryer requires air from the compressor at sufficiently high temperature to accomplish regeneration. For this reason, it is used almost exclusively with centrifugal or lubricant-free rotary screw compressors. Technically, there is no reduction of air capacity with this type of dryer. However, an inefficient entrainment-type nozzle has to be used for the purge air. The total power requirement, including pressure drop and compressor operating cost is approximately 0.8 kW/100 cfm.

**Dryer Selection.** The selection of a compressed air dryer should be based upon the required pressure dew point and the estimated cost of operation. Where a pressure dew point of less than 35°F is required, a refrigerant-type dryer cannot be used. The required pressure dew point for the application at each point of use eliminates certain types of dryers. Because dryer ratings are based upon saturated air at inlet, the geographical location is not a concern. The dryer has a lower load in areas of lower relative humidity, but the pressure dew point is not affected. Typically, the pressure drop through a compressed air dryer is 3–5 psi and should be taken into account in system requirements. Compressed air should be dried only where necessary and only to the pressure dewpoint required.

**Compressed Air Filters.** These include particulate filters to remove solid particles, coalescing filters to remove lubricant and moisture, and adsorbent filters for very fine contaminants. A particulate filter is recommended after a desiccant-type dryer to remove desiccant "fines". A coalescing-type filter is recommended before a desiccant-type dryer to prevent fouling of the desiccant bed. Additional filtration may also be needed to meet requirements for specific end-uses. Compressed air filters downstream of the air compressor are generally required for the removal of contaminants, such as particulates, condensate, and lubricant. Filtration only
to the level required by each compressed air application will minimize pressure drop and resultant energy consumption. Elements should also be replaced as indicated by pressure differential, and at least annually, to minimize pressure drop and energy consumption.

Air leaving an air compressor is not normally of a quality suitable for the intended use. The air inlet filter for the air compressor is intended to protect the compressor and often is inadequate to protect downstream equipment. The compressor itself may add contaminants, including wear particles, carbon deposits, and lubricant. These require filtration.

A refrigerant-type dryer may not require a filter before or after it, but a desiccant- or deliquescent-type dryer requires a prefilter to protect the drying medium or desiccant from contamination and from being rendered ineffective. An after-filter also is required to catch desiccant fines from being carried downstream to sensitive equipment.

Filtration literature may refer to an “Absolute Rating” or a “Nominal Rating.” The Absolute Rating refers to the diameter, in microns, of the largest particle that will pass through the filter. This is theoretical because it requires a consistent pore size of the filter medium, which is not always practical, and particle sizes are not always spherical.

The Nominal Rating is determined by the filter manufacturer and is an arbitrary value. Usually it is a percentage retention by weight of a specified contaminant of a given size. Glass beads are the normal test contaminant. The Beta Ratio is designed to give a more accurate comparison among filter media. It is the ratio of the number of particles larger than a given micron size upstream of the filter to the number of particles larger than the given size downstream of the filter. The higher the Beta Ratio, the more particles are retained by the filter and, hence, the higher the efficiency.

**Particulate Filters.** Particulate filter designs use different filtering mechanisms to achieve the desired degree of contaminant removal. The higher the degree of contaminant removal, the higher the pressure drop across the filter, the higher pressure required from the air compressor and the higher the energy costs. The maximum allowable pressure drop before the filter element is changed (usually 10 psi), must also be taken into account when determining the pressure required at the air compressor discharge and downstream of the drying and filtration equipment. A differential pressure gauge is recommended for each filter. A particulate filter is recommended downstream of a desiccant type dryer, before any operational equipment or process.

**Coalescing Filters.** Small droplets of moisture or lubricant are caught by the filter medium and coalesce into larger liquid droplets. Air flow from the inside to the larger diameter outside of the element allows a lower exit velocity. An optional anti-re-entrainment barrier prevents droplets from being re-introduced into the air stream. The coalesced liquid runs down by gravity to the bottom of the filter bowl and is drained, usually by an automatic drain. The liquid may contain both lubricant and water.
Pressure drop increase in a coalescing filter is normally due to particulate matter fouling the element. The coalescing filter should be preceded by a particulate filter.

The rated pressure drop should be the “wet” pressure drop after the element has become saturated. A coalescing filter is recommended before any dryer whose drying medium may be damaged by lubricant. Materials should be compatible with the type of lubricant being used.

**Adsorption Filters.** Particulate and coalescing filters are capable of removing particles down to 0.01 microns but not lubricant vapors or odors. Adsorption involves the attraction and adhesion of gaseous and liquid molecules to the surface of the medium. Most filter elements contain activated carbon granules having an extremely high surface area and dwell time. This medium is for the adsorption of vapors only. An adsorption filter must be protected by an upstream coalescing-type filter to prevent liquid lubricant contamination and liquid condensate. For applications, follow the recommendations of the dryer and filter manufacturers.

**Heat Recovery.** As noted earlier, compressing air generates heat. In fact, industrial-sized air compressors generate a substantial amount of heat that can be recovered and put to useful work. More than 80% of the electrical energy going to a compressor becomes heat. Much of this heat can be recovered and used for producing hot water or hot air.

**Lubrication.** Compressor lubricants are designed to cool, seal, and lubricate moving parts for enhanced performance and longer wear. Important considerations for compressor lubricants include proper application and compatibility with downstream equipment, including piping, hoses, and seals. A lubricator may be installed near a point of use to lubricate items such as pneumatic tools. The lubricator may be combined with a filter and a pressure regulator. The lubricant should be that specified by the point-of-use equipment manufacturer.

**Flow Controllers.** Besides regulating pressure, these devices also deliver varying volumes of air in response to changing demand. Various types of regulators are available for a wide range of applications. A regulator should be selected for a specific application, based upon type of equipment, supply and downstream pressure requirements, flow rate, and required pressure accuracy.

**Air Receiver.** Receivers are used to provide compressed air storage capacity to meet peak demand events and help control system pressure. Receivers are especially effective for systems with widely varying compressed air flow requirements. Where peaks are intermittent, a large air receiver may allow a smaller air compressor to be used and can allow the capacity control system to operate more effectively and improve system efficiency. An air receiver after a reciprocating air compressor can provide dampening of pressure pulsations, radiant cooling, and collection of condensate. Demand-side control will optimize the benefit of the air receiver storage volume by stabilizing system header pressure and “flattening” the load peaks.
**Traps and Drains.** Automatic condensate drains or traps are used to prevent the loss of air through open petcocks and valves. Drain valves should allow removal of condensate but not compressed air. Two types of traps are common: mechanical and electrical. Mechanical traps link float devices to open valves when condensate rises to a preset level. Electric solenoid drain valves operate on a preset time cycle, but may open even when condensate is not present. Other electrical devices sense liquid level and open to drain only when condensate is present. Improperly operating or maintained traps can create excessive air usage and waste energy.

Headers should have a slight slope to allow drainage of condensate and drop legs from the bottom side of the header should be provided to allow collection and drainage of the condensate. The direction of the slope should be away from the compressor.

Piping from the header to points of use should connect to the top or side of the header to avoid being filled with condensate for which drainage drop legs from the bottom of the header should be installed.

The location of an air receiver is important and regular draining is essential. The potential of freezing must be considered and provision made for heated drains where necessary. The relatively common practice of leaving a manual drain valve cracked open should not be tolerated because it wastes relatively costly compressed air.

Contaminated condensate requires removal of lubricant before the condensate is discharged to a sewer system. It is recommended that the local sewage authority be consulted for allowable contamination levels.

- **Float-Type Traps.** The traditional float-type drain trap was originally designed for steam applications, to drain off condensate. The amount of condensate will vary with geographic location and atmospheric conditions of temperature and relative humidity. Drain traps should be sized for the anticipated rate of accumulated condensate and chosen for the specific location and anticipated contamination by lubricants being used.

  The float is connected by linkage to a drain valve that opens when an upper level setting is reached and closes when the drain is emptied. The float device varies from a simple ball to an inverted bucket, but the basic principle is the same. An adequately sized drain valve is essential for satisfactory operation and to prevent blockage. A float that sticks in the closed position does not allow condensate to be drained, while a float that sticks in the open position allows the costly loss of compressed air. The mechanical nature of float-type devices, combined with the contaminants present in condensate, makes these devices, which often are neglected, an ongoing maintenance item. New air-operated reservoir-type float actuated drains overcome many of the problems found in the non-reservoir units.

- **Electrically Operated Solenoid Valves.** This type of device sometimes is called “time cycle blowdown.” A solenoid-operated drain valve has a timing device that can
be set to open for a specified time and at specified intervals. Again, the size of the valve and any associated orifices must be adequate to prevent blockage. The potential problem with this type of device, apart from an electrical malfunction, is that the valve is set to operate without reference to the presence of condensate, or lack of it. The period during which the valve is open may not be long enough for adequate drainage of the amount of accumulated condensate. On the other hand, the valve can operate even when little or no condensate is present, resulting in the expensive loss of compressed air through the drain valve.

Some electrically operated drain valves use a magnetic reed switch or a capacitance device to detect the level of condensate present in a reservoir and operate only when drainage is called for.

**Air Distribution Systems.** The air distribution system links the various components of the compressed air system to deliver air to the points of use with minimal pressure loss. The specific configuration of a distribution system depends on the needs of the individual plant, but frequently consists of an extended network of main lines, branch lines, valves, and air hoses. The length of the network should be kept to a minimum to reduce pressure drop. Air distribution piping should be large enough in diameter to minimize pressure drop. A loop system is generally recommended, with all piping sloped to accessible drop legs and drain points.

When designing an air distribution system layout, it is best to place the air compressor and its related accessories where temperature inside the plant is the lowest. A projection of future demands and tie-ins to the existing distribution system should also be considered.
Compressed air is probably the most expensive form of energy available in a plant. Compressed air is also clean, readily-available, and simple-to-use. As a result, compressed air is often chosen for applications in which other energy sources are more economical. Users should always consider more cost-effective forms of power before considering compressed air. Inappropriate uses of compressed air include any application that can be done more effectively or more efficiently by a method other than compressed air. Examples of inappropriate uses of compressed air include:

- Open blowing,
- Sparging,
- Aspirating,
- Atomizing,
- Padding,
- Dilute phase transport,
- Dense phase transport,
- Vacuum generation,
- Personnel cooling,
- Open hand held blowguns or lances,
- Cabinet cooling,
- Vacuum venturis, and
- Diaphragm pumps.

Each is inappropriate use and suggested alternatives are described below.

**Open Blowing**
Open blowing is using compressed air applied with an open, unregulated tube, hose, or pipe for one of these applications:

- Cooling,
- Bearing cooling,
- Drying,
- Clean-up,
- Draining compressed air lines, and
- Clearing jams on conveyors.
The alternatives to open blowing are vast. Some are listed below:

- Brushes,
- Brooms,
- Duct collection systems,
- Non-air loss auto drains,
- Blowers,
- Blowers with knives,
- Electric fans,
- Electric barrel pumps,
- Mixers, and
- Nozzles.

**Sparging**
Sparging is aerating, agitating, oxygenating, or percolating liquid with compressed air. This is a particularly inappropriate application as liquid can be wicked into a dry gas increasing the dew point. The lower the dew point of the compressed air the more severe the wicking effect. This can occur with oil, caustics, water rinse materials, etc. Alternatives to sparging include low-pressure blowers and mixers.

**Aspirating**
Aspirating is using compressed air to induce the flow of another gas with compressed air such as flu gas. An alternative is a low-pressure blower.

**Atomizing**
Atomizing is where compressed air is used to disperse or deliver a liquid to a process as an aerosol. An example is be atomizing fuel into a boiler. Fluctuating pressure can effect combustion efficiency. An alternative is a low-pressure blower.

**Padding**
Padding is using compressed air to transport liquids and light solids. Air is dispensed over the material to be moved. The expansion of the air moves the material. The material is usually only moved short distances. An example is unloading tanks or tank cars. Molecular diffusion and wicking are typical problems with padding. An alternative is low to medium pressure blowers.
Dilute Phase Transport

Dilute Phase Transport is used in transporting solids such as powdery material in a diluted format with compressed air. Molecular diffusion and wicking are typical problems with dilute phase transport. An alternative is a low to high-pressure blowers or a low-pressure air compressor designed for 35 psig. The pressure required depends upon the moisture content and size of the material being transported.

Dense Phase Transport

Dense Phase Transport used to transport solids in a batch format. This usually involves weighing a batch in a transport vessel, padding the vessel with compressed air, forcing the batch into a transport line, and moving it in an initial plug with a boost of compressed air at the beginning of the transport pipe. Once the material is moving in a plug, you may fluidize the material in a semi-dense or moderate dilute phase using fluidizers or booster nozzles along the transport path. The material is typically transported to a holding vessel that dispenses it on an as needed basis using pad air from the secondary transport vessel to move it to the use location. A typical application would be the dense phase transport of carbon black. There are typically four compressed air elements to the transport. They are control air for the equipment, pad air for the initial transporter, transport air to move it in the piping, and fluidizers or booster nozzles along the transport piping. Most dense phase manufacturers specify 80-90 psig with one single line supporting the entire process. The control air and booster nozzles typically use pressures in the 60-70 psig range. The actual article psig required for the pad air and the transport air is typically 30-45 psig. Because of the lack of capacitance in most of these applications and the high volume-short cycle transport times, the original equipment manufacturers request 80-90 psig and uses the entire supply system as the storage tank. As this usually negatively impacts the plant air system, separate compressors, filters, and dryers are applied to this process at the elevated pressure.

Alternatives include supporting the control air, pad air, and boosters with regulated plant air plus metered storage and using a two-stage positive displacement blower (28 psig) or single stage compressor (40-50 psig) for the transport air. Another alternative is to use metered storage for both the pad air and transport cycle. This necessitates providing the entire requirement from storage and metered recovery per cycle, with a metering adjustment to refill the vessel just before the next transport cycle. The storage should be sized to displace the required air first for the pad and then for the transport cycles within an allowable pressure drop to terminate the transport cycle pressure at the required article pressure. This will flatten the volumetric load on the system, eliminate any impact on other users, and reduce the peak energy required to support the process.

Vacuum generation

Vacuum generation is those applications where compressed air is used in conjunction with a venturi, eductor, or ejector to generate a negative pressure mass flow. Typical applications are piabs, hold-downs, or 55-gallon drum mounted compressed air vacuum cleaners. This is by far the most inefficient application in industry with less than 4% total
efficiency, although for very intermittent use (less than 25% load factor), compressed air can be a reasonably efficient solution. An alternative is a vacuum pump. If a compressed air generated vacuum is required, install a solenoid valve on the compressed air supply line to shut this application off when in is not needed.

**Personnel Cooling**
Personnel cooling is operators directing compressed air on themselves to provide ventilation. This is dangerous because it can shoot particulate into the skin. A 1/4" tube blowing air on an operator can consume 15-25 bhp of compressed air. An alternative is fractional horsepower fans of 1/4 bhp or less.

**Open Hand Held Blowguns or Lances**
Unregulated hand held blowing is not only a violation of most health and safety codes, but is also very dangerous. Hand held blowing guns that conform to all occupational health and safety standards should be used. There are different styles of blowguns that deliver various airflow, velocity, and concentrations. Selecting the proper gun for the application. Pipes installed in the end of hose and unregulated non-approved guns must not be used. Blowguns must have no more than 30-psig discharge nozzle pressure. The nozzle should be constructed to relieve backpressure if the nozzle is plugged or blocked. The blowgun must also have a spring-operated throttle mechanism so it shuts off automatically if it is dropped.

**Diaphragm pumps**
A common error is to not size diaphragm pumps to the maximum viscosity, highest-pressure required and highest volume. The result is poor performance and an increased supply pressure requirement. Diaphragm pumps are commonly found installed without regulators and speed control valves. Those diaphragm pumps that are installed with regulators are found with the regulators adjusted higher than necessary. The higher than necessary setting of the regulator increases the demand on the compressed air system and increases the compressed air system operating costs. With higher than necessary pressure settings, the amount of compressed air admitted into the diaphragm chamber is increased above that which is actually required to move the product. The amount of product actually transferred remains the same, but the amount of air required increases with the increased pressure. Diaphragm pumps must have generously sized diaphragm regulators installed in the supply line and generously sized supply piping or hose. The regulator must be adjusted to equal the maximum head that the pump is required to provide. A flow control valve installed up stream of the regulator will accomplish the required speed control. Operating the diaphragm pump without a speed control increases the rate of compressed air consumption by increasing the strokes per minute of the diaphragm pump. The speed control should be adjusted to pump product in the maximum allowable time. As a general rule the regulator and flow control valve are not included with the standard pump package. Also, when the pump has no liquid or slurry to pump it will rapid cycle, wearing out the diaphragm. The pump controls must be configured to turn
the pump off when there is nothing to pump. The following drawing shows the proper installation of a diaphragm pump.

The air operated diaphragm pump is designed to pump a wide variety of liquids. The low initial cost of the pump in conjunction with the ease of installation makes this an "universal pump". While the convenience and safety of these pumps is acknowledged and makes them an obvious choice for a chemical facility, they are extremely expensive to operate. It requires 7 to 9 times the energy to operate a pump with compressed air as it does to operate an electric pump of the same capability. The pumps are usually installed with a combination filter-regulator-lubricator (FRL). From the (FRL) a piece of hose is then connected to the pump. If the operator requires more flow the regulator is adjusted to deliver more pressure. This is an incorrect assumption. When the regulator is completely open -- there is no regulation. Do not confuse pressure with flow. One way to reduce the operating costs is to install the pump as shown above. The regulator setting is directly proportional to the discharge pressure of the pump. If the pump is required to provide 100 gallons per minute at a total dynamic head of 115 feet, the corresponding regulator setting will be: \( \frac{115}{2.31} = 50 \) psig. The needle valve is used to control the rate of flow. Adjust the pressure at the regulator and then set the needle valve to a corresponding rate of flow. The small receiver is used to store air and the check valve insures that the stored air will be available for this dedicated application only.

**Vacuum venturis**

When compressed air is forced through a conical nozzle, its velocity increases and a decrease in pressure occurs. This principle, discovered by 18th century physicist G. B. Venturi, can be used to generate vacuum without a single moving part. Vacuum
generators are used throughout industry. Some applications for vacuum generators are listed below:

- Shop Vacuums,
- Drum Pumps,
- Palletizers,
- Depalletizers,
- Box makers,
- Packaging Equipment, and
- Automatic Die cutting Equipment.

Vacuum generators are selected for safety, ease of installation, physical size of the generator, the fact that no electricity is required, and low first cost. Vacuum generators are not normally selected because they are more economical to operate. As a rule of thumb, in a base load situation, if the vacuum generator is operating less than 25% of the time, it will be more economical to operate than a dedicated vacuum pump. Otherwise, vacuum generators are, in general, less effective in pulling a vacuum and cost as much as five times more to operate than a dedicated vacuum pump. Using vacuum generators to generate the vacuum for shop vacuums and drum pumps, which are typically peak load applications, could cause another compressor to turn and stay on until it times out. Having to operate a second compressor because of the added demand associated with a vacuum generator eliminates any apparent savings associated with a vacuum generator, even if it operates only once a day for a short period of time. In the cases where vacuum generators should be more economical to operate they are installed without an automatic shutoff solenoid or the automatic shutoff solenoid is wired into the stop circuit and not the run circuit. When the machine stops the vacuum generator or the control valve exhausts compressed air because of the position at which the equipment stops. Again, the first cost may be cheaper, but the operating cost is four to five times greater. A dedicated vacuum pump, or the use of central vacuum system will provide more suction force at a fraction of the cost of vacuum produced by compressed air. In this case, it is significantly more cost effective to provide a system that is designed into the machine from the beginning than it is to try to retrofit a piece of equipment. This can accomplished by being proactive at the time the machine specifications are prepared and the purchase orders issued. Vacuum generators must be applied properly and only after taking life cycle costs into consideration. Even then, if there is remaining capacity on a central vacuum system, the additional vacuum requirements may be added to it for such a small additional energy cost that there is no possible economical justification for a vacuum generator.

**Cabinet Cooling**

Cabinet cooling should not be confused with panel purging. The following are typical applications where cabinet cooling is found:

- Programmable controllers,
- Line control cabinets,
• Motor control centers,
• Relay panels,
• NC/CNC systems,
• Modular control centers, and
• Computer cabinets.

When first cost is the driving factor, open tubes, air bars (copper tube with holes drilled long the length of the tube) and vortex tube coolers are used to cool cabinets. When life cycle costs are taken into consideration these choices prove to be expensive. It is not uncommon to find an open tube or air bar consuming 7-1/2 hp of compressed air to cool a cabinet. Vortex tube coolers can be an improvement over open tubes and air bars because they are often cycled with a thermostat control, which reduces air consumption. However, air to air, air to water and refrigerated cabinet cooler are available that only use 1/3 hp to accomplish the same task.

Other Inappropriate Uses
Other improper uses of compressed air are unregulated end-uses and supply air to abandoned equipment, both of which are described below.

Unregulated End-Uses
A pressure regulator is used to limit maximum end-of-use pressure and is placed in the distribution system just prior to the tool. If a tool operates without a regulator, it uses full system pressure. This results in increased system air demand and energy use, since the tool is using air at this higher pressure. High pressure levels can also increase equipment wear, resulting in higher maintenance costs and shorter tool life.

Abandoned Equipment
Many plants undergo numerous equipment configuration changes over time. In some cases, plant equipment is no longer used. Air flow to this unused equipment should be stopped, preferably as far back in the distribution system as possible without affecting operating equipment.

Using Compressed Air
As a general rule, compressed air should only be used if safety enhancements, significant productivity gains, or labor reductions will result. Typical overall efficiency is 10-15%. If compressed air is used for an application, the amount of air used should be of minimum quantity and pressure and used for the shortest possible duration of time. Compressed air use should also be constantly monitored and re-evaluated.
Handout: Finding & Fixing Leaks and Establishing a Leak Prevention Program

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

<table>
<thead>
<tr>
<th>Size</th>
<th>Cost per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/16&quot;</td>
<td>$523</td>
</tr>
<tr>
<td>1/8&quot;</td>
<td>$2,095</td>
</tr>
<tr>
<td>1/4&quot;</td>
<td>$8,382</td>
</tr>
</tbody>
</table>

Costs calculated using electricity rate of $0.05 per kWh, assuming constant operation, and an efficient compressor.

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

There are two types of air leaks, planned and unplanned. The planned air leaks are the ones that have been designed into the system. These leaks are the blowing, drying, sparging etc. used in the production process. Many times these have been installed as a quick fix for a production problem. Some leaks take the form of "coolers", which are used to cool production staff or equipment. The Handout titled “Inappropriate Uses of Compressed Air” has more detail on planned leaks.

The unplanned leaks are the ongoing maintenance issues and can appear in any part of the system. These leaks require an ongoing air leak detection and repair program. While leakage can come from any part of the system, the most common problem areas are:

- Couplings, hoses, tubes, and fittings. Tubes and push-to-lock fittings are common problems.
- Disconnects. O-rings required to complete the seal may be missing.
- Filters, regulators and lubricators (FRLs). Low first-cost improperly installed FRLs often leak.
- Open condensate traps. Improperly operating solenoids and dirty seals are often problem areas.
Compressed Air System Leaks

Page H3-2

- Pipe joints. Missed welds are a common problem.
- Control and shut-off valves. Worn packing through the stem can cause leaks.
- Point of use devices. Old or poorly maintained tools can have internal leaks.
- Flanges. Missed welds are a common problem.
- Cylinder rod packing. Worn packing materials can cause leaks.
- Thread sealants. Incorrect and/or improperly applied thread sealants cause leaks. Use the highest quality materials and apply them per the instructions.

Estimating Amount of Leakage

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

\[
\text{Leakage} \% = \frac{\text{T} \times 100}{\text{T} + \text{t}}
\]

where:
- \( \text{T} \) = on-load time (minutes)
- \( \text{t} \) = off-load time (minutes)

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

Leakage can be estimated in systems with other control strategies if there is a pressure gauge downstream of the receiver. This method requires an estimate of total system volume, including any downstream secondary air receivers, air mains, and piping (\( V, \) in cubic feet). The system is started and brought to the normal operating pressure (\( P_1 \)). Measurements should then be taken of the time (\( T \)) it takes for the system to drop to a lower pressure (\( P_2 \)), which should be a point equal to about one-half the operating pressure.
Leakage can be calculated as follows:

\[
\text{Leakage (cfm free air)} = (V \times (P_1 - P_2)/T \times 14.7) \times 1.25
\]

where: 
- \( V \) is in cubic feet
- \( P_1 \) and \( P_2 \) are in psig
- \( T \) is in minutes

The 1.25 multiplier corrects leakage to normal system pressure, allowing for reduced leakage with falling system pressure. Again, leakage of greater than 10% indicates that the system can likely be improved. These tests should be carried out quarterly as part of a regular leak detection and repair program.

**Leak Detection**

Since air leaks are almost impossible to see, other methods must be used to locate them. The best way to detect leaks is to use an ultrasonic acoustic detector, which can recognize the high frequency hissing sounds associated with air leaks. These portable units consist of directional microphones, amplifiers, and audio filters, and usually have either visual indicators or earphones to detect leaks. A simpler method is to apply soapy water with a paint brush to suspect areas. Although reliable, this method can be time consuming. Other methods include smoke sticks, candles, foam, manometers, and stethoscopes.

**Ultrasonic Leak Detection**

Ultrasonic leak detection is probably the most versatile form of leak detection. Due to its capabilities, it is readily adapted to a variety of leak detection situations. The principle behind ultrasonic leak detection is simple. In a pressure or vacuum leak, the leak flows from a high pressure laminar flow to a low pressure turbulence. The turbulence generates a white noise which contains a broad spectrum of sound ranging from audible to inaudible frequencies. An ultrasonic sensor focuses in on the ultrasonic elements in the noise. Since ultrasound is a short wave signal, the sound level will be loudest at the leak site. Ultrasonic detectors are generally unaffected by background noises in the audible range because these signals are filtered out.

Ultrasonic detectors can find mid- to large-sized leaks. The advantages of ultrasonic leak detection include versatility, speed, ease of use, the ability to perform tests while equipment is running, and the ability to find a wide variety of leaks. They require a minimum of training, and operators often become competent after 15 minutes of training.

Due to the nature of ultrasound, it is directional in transmission. For this reason, the signal is loudest at its source. By generally scanning around a test area, it is possible to very quickly hone it on a leak site and pinpoint its location. For this reason, ultrasonic leak detection is not only fast, it is also very accurate.
How to Fix Leaks
Leaks occur most often at joints and connections. Stopping leaks can be as simple as tightening a connection or as complex as replacing faulty equipment such as couplings, fittings, pipe sections, hoses, joints, drains, and traps. In many cases leaks are caused by bad or improperly applied thread sealant. Select high quality fittings, disconnects, hose, tubing, and install them properly with appropriate thread sealant.

Non-operating equipment can be an additional source of leaks. Equipment no longer in use should be isolated with a valve in the distribution system.

Another way to reduce leaks is to lower the demand air pressure of the system. The lower the pressure differential across an orifice or leak, the lower the rate of flow, so reduced system pressure will result in reduced leakage rates. Stabilizing the system header pressure at its lowest practical range will minimize the leakage rate for the system. Once leaks have been repaired, the compressor control system should be re-evaluated to realize the total savings potential.

Establishing a Leak Prevention Program
There are two basic types of leak repair programs, the Leak Tag program and the Seek and Repair program. The seek and repair is the simplest. As it states, you simply find the leak and repair it immediately. With the leak tag program, the leak is identified with a tag and logged for repair at a later time. The tag is often a two part tag; one part stays on the leak and the other part is turned into the maintenance department, identifying the location, size, and description of the leak to be repaired. The best approach depends on the type, size, and the culture/work practices of the facility. It is more likely that the best solution will be a combination of the two. In any case, there are several key elements required to have a successful leak program, which are:

- **Baseline compressed air usage** - Establish a good grounds for comparison on the effectiveness of the compressed air leak repair program (see the Handout titled "Baselining Your Compressed Air System").

- **Establish leak loss** – See the section on estimating leak loss in this handout.

- **Develop cost of air leaks** - The cost of compressed air leaks is one of the most important aspects of the program. It should be used as a benchmark not only for the effectiveness and promotion of the program, but also to illustrate the amount of resources that can cost effectively be allocate to the program.

- **Identify leaks** - Survey the facility and identify the leaks. Leaks can be identified by many methods, the most common is using an ultrasonic acoustic leak detector. There are many types and price ranges, but for most applications the inexpensive hand held meter will identify leaks and give an indication of the size or intensity.
- **Document the leaks** - Document the location of leak, type of leak, size of leak, and the estimated cost of leak. Any documentation should be compatible with the facility's Predictive Maintenance program. Leak tags can also be used but should not take the place of a master leak list. If you are using the seek and repair method, leaks should still be documented so the number and effectiveness of the program can be tracked.

- **Prioritize leak repair** - Fix the biggest leaks first to get the biggest savings. This will insure a good start to the air leak program.

- **Document repairs** - Showing the fixed leaks and the cost savings shows the effectiveness of the program and strengthens the support. Documenting the repairs and the type of leaks can also indicate equipment that is a reoccurring problem. When this occurs, the process should be looked at for a root cause and permanent solution should be developed to stop the reoccurring air leak.

- **Compare baselines and publish results** - By comparing before and after, the effectiveness of the program and the savings can be determined. Then, tell "the world" about the program and the results that have been achieved. This is very important because showing the saving will solidify support for the program.

- **Start over again** - Air leaks continue to occur so the program has to be ongoing. Periodic reviews should be done on the system, and the process repeated as necessary to maintain system efficiency.

A good compressed air system leak repair program is very important in maintaining the efficiency, reliability, stability and cost effectiveness of any compressed air system.
Handout: Baselining Your Compressed Air System

The purpose of baselining or benchmarking is to establish current performance levels and costs of a compressed air system, and to correlate the results with your plant’s present production levels. As you make improvements to your system, it will be possible to estimate the success by comparing the new measurements with the original baseline.

First, measurements of the system need to be taken. This requires the measurement of power, pressure, flow, and temperature. These measurements will be used in calculations to baseline system performance and energy consumption correlated to the plant production levels. Correlation to plant production levels is required to normalize data and perform an “apples-to-apples” comparison.

Energy saving measures implemented on both the supply and demand sides of the system, combined with proper compressor controls, will result in reduced energy consumption. This should be documented through continued measurements, again correlated to your plant’s production levels.

Some companies will also benchmark their compressed air systems against similar plants in their company, and sometimes even compare individual compressors.

Tools You Will Need
Properly baselining and monitoring a compressed air system requires the right tools. The following tools are required:

- Infrared gun - Infrared guns measure heat radiated from a piece of equipment in order to determine the surface temperature.

- Matched, calibrated pressure gauges or differential pressure gauges

- Hook-on amp/volt meter (or kW meter)

- Data logger - Data loggers are used in conjunction with other measurement devices to record multiple readings over a period of time. Data loggers are used to create plant pressure and energy consumption profiles, and can be important tools in developing a control strategy for a compressed air system. Use of data logging techniques is beyond the scope of this Fundamentals training, but will be discussed the Level 2 training.

- Ultrasonic leak detector - These portable units consist of directional microphones, amplifiers, and audio filters, and usually have either visual indicators or earphones to detect leaks.
Flow meter - Factors to consider in selecting flow meters include type (in-line or insertion), ease of installation, life cycle cost (including possible pressure drop, such as orifice plates, and maintenance), and accuracy (repeatability and turn down range).

What to Measure
Baselining a system requires measurement of power, pressure, flow, and temperature under different operating conditions, and also estimating leak load. Each is discussed below. Please refer to all operation and safety instructions provided with measurement equipment before using it.

Power
Energy is measured in order to estimate the annual electricity consumption of a compressed air system. A hook-on amp/volt meter or a wattmeter will be required. The current and voltage into the compressor should be measured. Full-load and no-load input power to the compressor should be measured.

For three-phase systems, power can be estimated by the following equation.

\[ kW = \frac{1.73 \times \text{volts} \times \text{amps} \times \text{power factor}*}{1000} \]

(*Assume 0.85 power factor at full load)

Using a wattmeter provides a direct reading of kW with no calculation or power factor adjustment.

Pressure
Pressure is measured to give feedback for control adjustments, and to determine pressure drops across equipment. A calibrated pressure gauge is required. The following pressure measurements should be taken when baselining a system:

- Inlet to compressor (monitor inlet filter),
- Differential across air/lubricant separator for a lubricated rotary compressor,
- Interstage on multistage machines, and
- Pressure differentials, including,
  - Aftercooler,
  - Treatment equipment (dryers, filters, etc.), and
  - Various points in the distribution system.

Flow
Flow meters are necessary to measure total flow and to determine consumption. Flow should be measured:

- during various shifts,
- as energy saving measures are implemented, and
- for leaks during non-production periods.
Flow meters should be of the mass flow design to compensate for pressure and temperature variations and, if practical, should be suitable to measure the output of each individual compressor in the system. The mass flow is based upon standard reference conditions, which should be checked for the specific instrument used.

**Temperature**

Temperature measurements help to indicate if equipment is operating at peak performance. Generally, equipment that runs hotter than specified parameters is not performing at peak efficiency and requires service. The following temperature measurements should be taken when baselining a system:

- Aftercooler and intercoolers cold temperature difference or approach temperature of cold water inlet to cooled air outlet. Since dryers are normally designed at 100°F maximum inlet air temperature, some remedial action may be required if aftercooler outlet temperatures exceed 100°F.

- For rotary lubricated compressors, the air discharge temperatures must be maintained for reliable compressor performance. Normal operation requires temperatures below 200°F.

- Inlet air temperature.

**Using Power, Pressure, and Flow to Baseline System Performance and Energy Consumption**

Using the techniques described previously, determine both cfm @ psig and energy consumption (kW x hours) per unit of production. Always correlate to production levels for a true measure of air compressor system performance.

Other parameters to monitor over time include:

- Cfm @ psig per kW,
- Psig, and
- Pressure drop across various components.

Remember to always correlate to production levels. The expectation is that energy use will go down, assuming of course that production did not rise with a corresponding increase in the compressed air loads. If production did not rise, and the pressure went up, adjust controls appropriately.

**Estimating Leak Load**

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

\[
\text{Leakage (\%) = \left(\frac{T}{T+t}\right) \times 100}
\]

where:  
- \(T\) = on-load time (minutes)  
- \(t\) = off-load time (minutes)

Leakage will be expressed in terms of the percentage of compressor capacity lost. The percentage lost to leakage should be less than 10% in a well-maintained system. Poorly maintained systems can have losses as high as 20-30% of air capacity and power. Leakage can be estimated in systems with other control strategies if there is a pressure gauge downstream of the receiver. This method requires an estimate of total system volume, including any downstream secondary air receivers, air mains, and piping (\(V\), in cubic feet). The system is then started and brought to the normal operating pressure (\(P_1\)). Measurements should then be taken of the time (\(T\)) it takes for the system to drop to a lower pressure (\(P_2\)), which should be a point equal to about one-half the operating pressure.

Leakage can be calculated as follows:

\[
\text{Leakage (cfm free air) =}\]
\[
(V \times \frac{(P_1 - P_2)}{T} \times 14.7) \times 1.25
\]

where:  
- \(V\) is in cubic feet  
- \(P_1\) and \(P_2\) are in psig  
- \(T\) is in minutes

The 1.25 multiplier corrects leakage to normal system pressure, allowing for reduced leakage with falling system pressure. Again, leakage of greater than 10% indicates that the system can likely be improved. These tests should be carried out quarterly as part of a regular leak detection and repair program.
Handout: Compressed Air System Storage

Receivers are used to provide compressed air storage capacity to meet peak demand events and help control system pressure. Receivers are especially effective for systems with widely varying compressed air flow requirements. Where peaks are intermittent, a large air receiver may allow a smaller air compressor to be used and can allow the capacity control system to operate more effectively and improve system efficiency. An air receiver after a reciprocating air compressor can provide dampening of pressure pulsations, radiant cooling, and collection of condensate. Demand-side control will optimize the benefit of the air receiver storage volume by stabilizing system header pressure and "flattening" the load peaks.

Storage can be used to control demand events (peak demand periods) in the system by reducing both the amount of pressure drop and the rate of decay. Storage can be used to protect critical pressure applications from other events in the system. Storage can also be used to control the rate of pressure drop in demand while supporting the speed of transmission response from supply. For some systems, it is important to provide a form of refill control such as a flow control valve. Many systems have a compressor operating in modulation to support demand events, and sometimes strategic storage solutions can allow for this compressor to be turned off.

The basic purpose of an air receiver is to store a volume of compressed air for use when needed. The most common example is a small, air cooled, piston type compressor, mounted on a tank or air receiver. The compressor operates on a start/stop control system, usually controlled by a pressure switch having a fixed differential. Because of automotive applications, the pressure at which the compressor is stopped, normally is 175 psig. The compressor is restarted when the use of the compressed air causes the pressure to fall to about 145 psig (a differential of 30 psi). On larger compressor sizes, the compressor may be loaded and unloaded but continues to run. The tank provides radiant cooling and requires an automatic drain to remove condensate. The problem from an energy standpoint is that all of the air is being compressed to at least 145 psig and most of it to 175 psig, although most applications require a much lower pressure. Pneumatic tools normally are designed for operation at 90 psig, so energy is being expended to compress the air well beyond what is needed. A rule of thumb for a 100 psig system is that each additional 2 psi results in an additional 1% in energy consumption.

In industrial compressed air systems, the supply side generally is considered to be the air compressors, dryers and related filters, and a primary air receiver. There are two differing points of view on the location of a primary air receiver in a plant air system. If the receiver is located soon after the compressor discharge and the compressor(s) is a piston type, the receiver acts as a dampener for pressure pulsations. If the receiver is located before the compressed air dryer, the receiver will provide additional radiant cooling and drop out of some of the condensate and entrained oil, benefiting the dryer. However, the receiver will be filled with saturated air and if there is a sudden demand which exceeds
the capacity rating of the compressor and matching dryer, the dryer can be overloaded, resulting in a higher pressure dew point.

If the air receiver is located after the compressed air dryer, some of the above advantages are lost but the receiver is filled with compressed air which has been dried and a sudden demand in excess of the compressor and dryer capacity rating will be met with dried air. The dryer is not overloaded, since it is seeing only the output of the compressor, so the pressure dew point is not affected.

In either case, it should be recognized that the compressed air dryer and associated filters will add pressure drop, which must be taken into account when determining the compressor discharge pressure to achieve the desired pressure leaving the primary air receiver to the system.

The size of an air receiver can be calculated as follows:

\[
V = T \times C \times \frac{p_a}{p_1 - p_2}
\]

where:
- \(V\) = Receiver volume, ft³
- \(T\) = Time allowed (minutes) for pressure drop to occur.
- \(C\) = Air demand, cfm of free air
- \(p_a\) = Absolute atmospheric pressure, psia
- \(p_1\) = Initial receiver pressure, psig
- \(p_2\) = Final receiver pressure, psig

The formula assumes the receiver volume to be at ambient temperature and that no air is being supplied to the air receiver by the compressor(s). If the compressor(s) is running while air is being drawn from the receiver, the formula should be modified so that \(C\) is replaced by \(C - S\), where \(S\) is the compressor capacity, cfm of free air. The initial formula also can be used with a known receiver size, to determine the time to restore the air receiver pressure. In this case, \(C\) is replaced by \(S\), which is the compressor capacity, cfm of free air.

In the past, mainly with reciprocating compressors, rules of thumb for sizing a primary air receiver, have been from 1 gallon per cfm to 3 gallons per cfm of compressor capacity. This is no longer regarded as good practice and the recommended primary receiver size will vary with the type of compressor capacity control used.

Most oil injected rotary screw compressors are equipped with capacity control by inlet valve modulation designed to match the output from the air compressor with the demand from the points of use. On this basis, it has been stated that an air receiver is not needed. At best, this is misleading. An air receiver near the discharge of a rotary screw compressor will shield the compressor control system from pressure fluctuations from the demand side, downstream of the receiver and can allow the compressor to be unloaded.
for a longer period of time, during periods of light demand. The addition of an over-run timer (Automatic Dual Control) can stop the compressor if it runs unloaded for a pre-set time, saving additional energy.

Some oil injected rotary screw compressors are sold with load/unload capacity control, which is claimed to be the most efficient. This also can be misleading, since an adequate receiver volume is essential to obtain any real savings in energy. A comparison of different capacity control types is shown in the figure below (Power vs. Capacity).

The top line shows what would happen if inlet valve throttling was used without unloading the compressor. Approximately 70% of full load power would still be used when throttling had reduced compressor output to zero. The second line shows inlet valve throttling to 40% capacity and unloading at that point. The third line shows variable displacement (slide/turn/spiral valve) capacity reduction to 50% capacity followed by throttling to 40% capacity and unloading at that point. The ideal control, where power and capacity exactly match, also is shown.

One solution sometimes proposed is to eliminate modulation and have the compressors operate in a load/unload mode. Certain factors must be recognized before making such a change. The standard full capacity, full load pressure, often has the compressor running at around 110% of motor nameplate rating, or using 10% of the available 15% continuous overload service factor. The remaining 5% is meant to cover tolerances and items such as increased pressure drop through the air/oil separator before it is required to be changed.

If the discharge pressure is allowed to rise by an additional 10 psi without the capacity being reduced by inlet valve modulation, the bhp will increase by 5% and the motor could be overloaded. A reduction in discharge pressure may be necessary to operate in this mode.

In addition, it is falsely assumed that a straight line, from full load bhp to unloaded bhp, represents the actual power requirement in this mode of operation. This is shown as the
bottom line in the figure below (Average Power vs. Capacity – Load/Unload Capacity Control). This presumes, for example, that if the average capacity is 50%, the compressor would run fully loaded 50% of the time and fully unloaded 50% of the time. Unfortunately, the compressor is not fully unloaded 50% of the time.

When the compressor discharge pressure reaches the unload set point, the inlet valve is closed to reduce the mass flow through the compressor. Simultaneously, the oil sump/separator vessel pressure begins to be relieved gradually. Typically, this takes about 40 seconds, to prevent foaming of the oil with the potential of excessive oil carry-over. The rate at which blow-down occurs, gradually slows as the pressure is reduced. The fully unloaded power is not realized until the pressure in the oil sump/separator is fully relieved. In addition, a period of about 3 seconds is required to re-pressurize the air/oil sump/separator vessel when the system calls for the compressor to re-load.

In many cases, the system pressure will fall and the compressor will re-load before the fully unloaded power is realized. To overcome this, an adequately sized air receiver and/or system volume is essential. Taking the above factors into account, the figure above (Average Power vs. Capacity – Load/Unload Capacity Control) shows the effect of different sizes of air receiver/system volume. It will be seen that some rules of thumb established many years ago for reciprocating air compressors, are not adequate for an oil injected rotary screw compressor.
The figure below (Average Power vs. Capacity – Load/Unload and Inlet Valve Capacity Control Systems) compares the various modes of capacity control and with 3 and 5 gallons per cfm of compressor capacity. The control mode chosen should take into account the receiver/system volume relative to compressor capacity, the range of flow rate normally experienced, and the mean flow rate during a 24 hour period.

![Graph showing various modes of capacity control.](image)

It should be noted that in systems with multiple compressors and sequencing controls, it is possible to have most of the compressors running full loaded on base load with only one compressor modulating, providing the most efficient mode for the system. It also is not necessary to have the air receiver/system storage capacity based upon the total capacity of all the compressors, provided they are not all on the same load and unload pressure settings.

A primary air receiver allows the compressor(s) to operate in a given discharge pressure range (usually 10 psi) from load to unload. Multiple compressors also can be sequenced as needed and with all but one operating in the most efficient, fully loaded mode. The capacity of the one compressor is modulated to match system demand.

In many industrial plants, there will be one or more applications with an intermittent demand of relatively high volume. This can cause severe dynamic pressure fluctuations in the whole system, with some essential points of use being starved impacting the quality of the end product. Usually, this can be relieved by the correct sizing and location of a secondary air receiver close to the point of high intermittent demand. Such demand often is of short duration and the time between the demand events is such that there is ample time to replenish the secondary receiver pressure without adding compressor capacity. A check valve before the secondary air receiver will prevent back flow to the rest of the system and ensure that the required volume is stored to meet the anticipated event(s).
Correctly sized and located air receivers can provide major advantages in a compressed air system and require little maintenance. They should meet ASME unfired pressure vessel requirements and have appropriate pressure relief valves. An automatic drain device, with manual bypass for service, also should be included. Condensate removed should be decontaminated to meet appropriate Federal, State and Local Codes.

Additional pressure/flow controls can be added after the primary receiver to maintain a reduced and relatively constant system pressure and at points of use, while allowing the compressor controls to function in the most efficient control mode and discharge pressure range, with significant energy savings.
Handout: Compressed Air System Control Basics

Compressed air system controls match the compressed air supply with system demand (although not always in real-time) and are one of the most important determinants of overall system energy efficiency. This Handout discusses both individual compressor control and overall system control of plants with multiple compressors. Proper control is essential to efficient system operation and high performance. The objective of any control strategy is also to shut off unneeded compressors or delay bringing on additional compressors until needed. All units that are operating should be run at full-load, except one unit for trimming.

Compressor systems are typically comprised of multiple compressors delivering air to a common plant air header. The combined capacity of these machines is sized, at a minimum, to meet the maximum plant air demand. System controls are almost always needed to orchestrate a reduction in the output of the individual compressor(s) during times of lower demand. Compressed air systems are usually designed to operate within a fixed pressure range and to deliver a volume of air which varies with system demand. System pressure is monitored and the control system decreases compressor output when the pressure reaches a predetermined level. Compressor output is then increased again when the pressure drops to a lower predetermined level.

The difference between these two pressure levels is called the control range. Depending on air system demand, the control range can be anywhere from 2-20 psi. In the past, individual compressor controls and non-supervised multiple machine systems were slow and imprecise. This resulted in wide control ranges and large pressure swings. As a result of these large swings, individual compressor pressure control set points were established to maintain pressures higher than needed. This ensured that swings would not go below the minimum requirements for the system. Today, faster and more accurate microprocessor-based system controls with tighter control ranges allow for a drop in the system pressure set points. Precise control system are able to maintain lower average pressure without going below minimum system requirements. Every 2 psi of pressure difference is equal to about a 1% change in energy consumption. Narrower variations in pressure not only use less energy, but avoid negative effects on production quality control.

Caution needs to be taken when lowering average system header pressure because large, sudden changes in demand can cause the pressure to drop below minimum requirements, which can lead to improper functioning of equipment. With careful matching of system controls and storage capacity, these problems can be avoided.
Controls and System Performance

Few air systems operate at full-load all of the time. Part-load performance is therefore critical, and is primarily influenced by compressor type and control strategy. The type of control specified for a given system is largely determined by the type of compressor being used and the facility's demand profile. If a system has a single compressor with a very steady demand, a simple control system may be appropriate. On the other hand, a complex system with multiple compressors, varying demand, and many types of end-uses will require a more sophisticated strategy. In any case, careful consideration should be given to both compressor and system control selection because they can be the most important factors affecting system performance and efficiency.

Individual Compressor Control Strategies

Over the years, compressor manufacturers have developed a number of different types of control strategies. Controls such as start/stop and load/unload respond to reductions in air demand, increasing compressor discharge pressure by turning the compressor off or unloading it so that it does not deliver air for periods of time. Modulating inlet and multi-step controls allow the compressor to operate at part-load and deliver a reduced amount of air during periods of reduced demand.

Start/Stop. Start/stop is the simplest control available and can be applied to either reciprocating or rotary screw compressors. The motor driving the compressor is turned on or off in response to the discharge pressure of the machine. Typically, a simple pressure switch provides the motor start/stop signal. This type of control should not be used in an application that has frequent cycling because repeated starts will cause the motor to overheat and other compressor components to require more frequent maintenance. This control scheme is typically only used for applications with very low duty cycles for compressors in the 30 hp and under range. Its advantage is that power is used only while the compressor is running but this is offset by having to compress to a higher receiver pressure to allow air to be drawn from the receiver while the compressor is stopped.

Load/Unload. Load/unload control, also known as constant speed control, allows the motor to run continuously, but unloads the compressor when the discharge pressure is adequate. Compressor manufacturers use different strategies for unloading a compressor, but in most cases, an unloaded rotary screw compressor will consume 15-35% of full-load horsepower while delivering no useful work. As a result, some load/unload control schemes can be inefficient.

Modulating Controls. Modulating (throttling) inlet control allows the output of a compressor to be varied to meet flow requirements. Throttling is usually accomplished by closing down the inlet valve, thereby restricting inlet air to the compressor. This control scheme is applied to centrifugal and rotary screw compressors. This control method, when applied to displacement compressors, is an inefficient means of varying compressor output. When used on centrifugal compressors, more efficient results are obtained, particularly with the use of inlet guide vanes which direct the air in the same
direction as the impeller inlet. The amount of capacity reduction is limited by the potential for surge and minimum throttling capacity.

Inlet valve modulation used on lubricant injected rotary air compressors allows compressor capacity to be adjusted to match demand. A regulating valve senses system or discharge pressure over a prescribed range (usually about 10 psi) and sends a proportional pressure to operate the inlet valve. Closing (or throttling) the inlet valve causes a pressure drop across it, reducing the inlet pressure at the compressor and, hence, the mass flow of air. Since the pressure at the compressor inlet is reduced while discharge pressure is rising slightly, the compression ratios are increased so that energy savings are somewhat limited. Inlet valve modulation normally is limited to the range from 100% to about 40% of rated capacity, at which point the discharge pressure will have reached full load pressure plus 10 psi and it is assumed that demand is insufficient to require continued air discharge to the system. At this point the compressor can unload as previously described in like a compressor using load/unload control.

**Dual Control/Auto Dual.** For small reciprocating compressors, allows the selection of either Start/Stop or Load/Unload. For lubricant injected rotary screw compressors, provides modulation to a pre-set reduced capacity followed by unloading with the addition of an over-run timer to stop the compressor after running unloaded for a pre-set time.

**Variable Displacement.** Some compressors are designed to operate in two or more partially-loaded conditions. With such a control scheme, output pressure can be closely controlled without requiring the compressor to start/stop or load/unload.

Reciprocating compressors are designed as two-step (start/stop or load/unload), three-step (0%, 50%, 100%) or five-step (0%, 25%, 50%, 75%, 100%) control. These control schemes generally exhibit an almost direct relationship between motor power consumption and loaded capacity.

Some rotary screw compressors can vary their compression volumes (ratio) using sliding or turn valves. These are generally applied in conjunction with modulating inlet valves to provide more accurate pressure control with improved part-load efficiency.

**Variable Speed/Variable Frequency Drives.** Historically, the use of variable frequency drives (VFDs) for industrial air compressors has been rare, because the high initial cost of a VFD could not justify the efficiency gain over other control schemes. Cost is no longer a major issue. VFDs may gain acceptance in compressor applications as they become more reliable and efficient at full-load.

Variable Speed Control is gaining acceptance for rotary compressors as the cost for these drives decreases. In a positive displacement rotary compressor the displacement is directly proportional to the rotational speed of the input shaft of the air end. However, it is important to note that with constant discharge pressure, if efficiency remained constant over the speed range, the input torque requirement would remain constant, unlike the
requirement of dynamic compressors, fans or pumps. The actual efficiency also may fall at lower speeds, requiring an increase in torque. Electric motors and controllers currently are available to satisfy these needs but their efficiency and power factor at reduced speeds must be taken into consideration. Steam turbines and engines also are variable speed drivers but rarely are used to power industrial air compressors.

**Capacity Controls for Centrifugal Type Compressors.** Centrifugal compressors have complex characteristics affected by inlet air density and intercooler cooling water temperature. The basic characteristic curve of head (Pressure) vs. flow is determined by the design of the impeller(s). Radial blades produce a very low rise in head as flow decreases. Backward leaning blades produce a steeper curve. The greater the degree of backward leaning, the steeper the curve.

Two potential occurrences must be avoided. The first is surge, caused by a flow reversal, which can occur at low flow rates and can cause damage to the compressor. Surge is avoided by limiting the amount of flow reduction. The second is choke at flow rates above design, when the velocity of the air at the impeller inlet approaches the speed of sound and flow and head cannot be sustained. Choke, or stonewall, normally is avoided by sensing drive motor amps and using this signal to limit the flow rate.

The flow rate can be reduced by an inlet throttle valve, which reduces the pressure at the inlet to the first stage impeller. This reduces the mass flow in direct proportion to the absolute inlet pressure. The inlet air density also is reduced, resulting in reduced pressure head produced by the impeller.

A variation of this uses inlet guide vanes, which also reduce the mass flow and the inlet air density, but cause the air to be directed radially towards the impeller inlet in the same direction as the impeller rotation. This improves the efficiency compared with simple throttling. In some cases, Discharge Bypass or Blow-Off control is used to limit flow delivered to the compressed air system. Compressed air is discharged to atmosphere, through a discharge silencer, or cooled and returned to the compressor inlet. This is a waste of energy and should be used only where necessary.

**Multiple Compressor Control**

Systems with multiple compressors use more sophisticated controls to orchestrate compressor operation and air delivery to the system. Sequencing controls may use a single master controller to shut down compressors that are not needed, while network controls (multi-master) use the individual compressor controls, with one acting as the master controller. Most new compressors incorporate microprocessor controls which allow greater flexibility.

The objective of an effective automatic system control strategy is to match system demand with compressors operated at or near their maximum efficiency levels. This can be accomplished in a number of ways, depending on fluctuations in demand, available
storage, and the characteristics of the equipment supplying and treating the compressed air.

**Single Master (Sequencing) Controls.** Sequencers are, as the name implies, devices used to regulate systems by sequencing or staging individual compressor capacity to meet system demand. Sequencers are referred to as single master control units because all compressor operating decisions are made and directed from the master unit. Sequencers control compressor systems by taking individual compressor capacity on- and off-line in response to monitored system pressure (demand). The control system typically offers a higher efficiency because the control range around the system target pressure is tighter. This tighter range allows for a reduction in average system pressure. Again, caution needs to be taken when lowering average system header pressure because large, sudden changes in demand can cause the pressure to drop below minimum requirements, leading to improper functioning of equipment. With careful matching of system controls and storage capacity, these problems can be avoided (see also flow controller).

**Multi-Master (Network) Controls.** Network controls offer the latest in system control. It is important that these controllers be used to shut down any compressors running unnecessarily. They also allow the operating compressors to function in a more efficient mode. Controllers used in networks are combination controllers. They provide individual compressor control as well as system control functions. The term multi-master refers to the system control capability within each individual compressor controller. These individual controllers are linked or networked together, thereby sharing all operating information and status. One of the networked controllers is designated as the leader. Because these controllers share information, compressor operating decisions with respect to changing air demand can be made more quickly and accurately. The effect is a tight pressure control range which allows a further reduction in the air system target pressure. Although initial costs for system controls are often high, these controls are becoming more common because of the resulting reductions in operating costs.

**Flow Controllers**

Flow controllers are optional system pressure controls used in conjunction with the individual compressor or system controls described previously. A flow controller does not directly control a compressor and is generally not included as part of a compressor package. A flow controller is a device that serves to separate the supply side of a compressor system from the demand side. This may require compressors to be operated at an elevated pressure and therefore, increased horsepower, while pressure on the demand side can be reduced to a stable level to minimize actual compressed air consumption.

Storage, sized to meet anticipated fluctuations in demand, is an essential part of the control strategy. Higher pressure supply air enters the primary storage tanks from the air compressors and is available to reliably meet fluctuations in demand at a constant lower pressure level.
A well designed and managed system needs to include some or all of the following: overall control strategy, demand control, good signal locations, compressor controls, and storage. The goal is to deliver compressed air at the lowest stable pressure to the main plant distribution system and to support transient events as much as possible with stored higher pressure compressed air. Primary storage replacement should utilize the minimum compressor horsepower to restore the primary pressure to the required level.

Each compressed air system differs in supply, distribution and demand aspects which require proper evaluation of the benefits to the system of a flow/pressure controller. Additional primary and/or secondary air receivers may also address intermittent loads, which can affect system pressure and reliability, and may allow operating the compressor at the lowest possible discharge pressure and input power.
Handout: Compressed Air System Maintenance Basics

Like all electro-mechanical equipment, industrial compressed air systems require periodic maintenance to operate at peak efficiency and minimize unscheduled downtime. Inadequate maintenance can have a significant impact on energy consumption via lower compression efficiency, air leakage, or pressure variability. It can also lead to high operating temperatures, poor moisture control, and excessive contamination. Most problems are minor and can be corrected by simple adjustments, cleaning, part replacement, or the elimination of adverse conditions. Compressed air system maintenance is similar to that performed on cars; filters and fluids are replaced, cooling water is inspected, belts are adjusted, and leaks are identified and repaired.

All equipment in the compressed air system should be maintained in accordance with manufacturers' specifications. Manufacturers provide inspection, maintenance, and service schedules that should be followed strictly. In many cases, it makes sense from efficiency and economic standpoints to maintain equipment more frequently than the intervals recommended by manufacturers, which are primarily designed to protect equipment.

One way to tell if a system is being maintained well and is operating properly is to periodically baseline or benchmark the system by tracking power, pressure, flow, and temperature. If power use at a given pressure and flow rate goes up, the system's efficiency is degrading. This baselining will also let you know if the compressor is operating a full capacity, and if the capacity is decreasing over time. On new systems, specifications should be recorded when the system is first set-up and operating properly. See the Handout titled Baselining for more information.

Proper maintenance is essential to compressed air system efficiency and reliability. The key to success requires compressor operators to determine the requirements for each piece of equipment, the necessary resources, and to schedule the maintenance based on the manufacturer's manuals and trend analysis of recorded data. All observations and meter readings should be recorded for compressors, dryers, filters, and any components in the compressor plant. The combination of equipment control panel data, frequent inspections, and log sheets are required to avoid unscheduled system shutdowns, and to utilize the principles of preventive and predictive maintenance. Record the dates of all maintenance and repairs, including a list of all parts which were replaced or services performed.

The maintenance schedules provided in this handout are intended to be used only as a guide. For more exact procedures, always refer to the manufacturer's manuals.
Stopping for Maintenance
The following procedures should be followed when stopping the compressor for maintenance or service:

Step 1
Per O.S.H.A. regulation 1910.147: The Control of Hazardous Energy Source (Lockout/Tagout), disconnect and lockout the main power source. Display a sign in clear view at the main power switch stating that the compressor is being serviced.

WARNING! Never assume a compressor is safe to work on just because it is not operating. It could restart at any time.

Step 2
Isolate the compressor from the compressed air supply by closing a manual shutoff valve downstream (and upstream, if applicable in booster service) from the compressor. Display a sign in clear view at the shutoff valve stating that the compressor is being serviced. Be certain that a pressure relief valve is installed upstream of any isolation valve.

Step 3
Lock open a pressure relief valve within the pressurized system to allow the system to be completely de-pressurized. NEVER remove a plug to relieve the pressure!

Step 4
Shut off the water cooling supply (water cooled compressors).

Step 5
Open all manual drain valves within the area to be serviced.

Step 6
Wait for the unit to cool before starting to service. (Temperatures of 125°F can burn skin. Some surface temperatures exceed 350°F when the compressor is operating, and just after it is shut down).

Step 7
Refer and give preference to the manufacturer’s manuals over these typical maintenance procedures.

Maintenance Schedules
To assure maximum performance and service life of your compressor, a routine maintenance schedule should be developed. Sample schedules have been included here to help you to develop a maintenance schedule designed for your particular application. Time frames may need to be shortened in harsher environments.
The documentation shipped with your compressor should contain a Maintenance Schedule Checklist. Make copies of this checklist and retain the master to make more copies as needed. On each copy of the checklist, enter dates and initials in the appropriate spaces. Keep the checklist and this Handout readily available near the compressor.

**General Maintenance Discussion**

Maintenance issues for specific system components are discussed below.

**Compressor Package**
The main areas of the compressor package in need of maintenance are the compressor, heat exchanger surfaces, air lubricant separator, lubricant, lubricant filter, and air inlet filter.

The compressor and intercooling surfaces need to be kept clean and foul-free. If they are dirty, compressor efficiency will be adversely affected. Fans and water pumps should also be inspected to ensure that they are operating at peak performance.

The air lubricant separator in a lubricant-cooled rotary screw compressor generally starts with a 2-3 psid pressure drop at full-load when new. Maintenance manuals usually suggest changing them when there is about a 10 psid pressure drop across the separator. In many cases it may make sense to make an earlier separator replacement, especially if electricity prices are high.

The compressor lubricant and lubricant filter need to be changed per manufacturer's specification. Lubricant can become corrosive and degrade both the equipment and system efficiency.

For lubricant-injected rotary compressors, the lubricant serves to lubricate bearings, gears, and intermeshing rotor surfaces. The lubricant also acts as a seal and removes most of the heat of compression. Only a lubricant meeting the manufacturer's specifications should be used.

Inlet filters and inlet piping also need to be kept clean. A dirty filter can reduce compressor capacity and efficiency. Filters should be maintained at least per manufacturer's specifications, taking into account the level of contaminants in the facility's air.

**Compressor Drives**

If the electric motor driving a compressor is not properly maintained, it will not only consume more energy, but be apt to fail before its expected lifetime. The two most important aspects of motor maintenance are lubrication and cleaning.

**Lubrication.** Too much lubrication can be just as harmful as too little and is a major cause of premature motor failure. Motors should be lubricated per the manufacturer's specification, which can be anywhere from every 2 months to every 18 months, depending on annual hours of operation and motor speed. On motors with bearing grease
fittings, the first step in lubrication is to clean the grease fitting and remove the drain plug. High quality new grease should be added, and the motor should be run for about an hour before the drain plug is replaced. This allows excess grease to be purged from the motor without dripping on the windings and damaging them.

Cleaning. Since motors need to dissipate heat, it is important to keep all of the air passages clean and free of obstruction. For enclosed motors, it is vital that cooling fins are kept free of debris. Poor motor cooling can increase motor temperature and winding resistance, which shortens motor life and increases energy consumption.

Belts. Motor v-belt drives also require periodic maintenance. Tight belts can lead to excessive bearing wear, and loose belts can slip and waste energy. Under normal operation, belts stretch and wear and, therefore, require adjustment. A good rule-of-thumb is to examine and adjust belts after every 400 hours of operation.

Air Treatment Equipment
Fouled compressed air treatment equipment can result in excessive energy consumption as well as poor-quality air that can damage other equipment. All filters should be kept clean. Dryers, aftercoolers, and separators should all be cleaned and maintained per manufacturer's specifications.

Automatic Drain Traps. Most compressed air systems have numerous moisture traps located throughout the system. Traps need to be inspected periodically to ensure that they are not stuck in either the open or closed position. An automatic drain trap stuck in the open position will leak compressed air; a drain trap stuck in the closed position will cause condensate to backup and be carried downstream where it can damage other system components. Traps stuck in the open position can be a major source of wasted energy in some plants.

End-Use Filters, Regulators, and Lubricators. Point-of-use filters, regulators, and lubricators are needed to ensure that a tool is receiving a clean, lubricated supply of air at the proper pressure. Filters should be inspected periodically because a clogged filter will increase pressure drop, which can either reduce pressure at the point of use or increase the pressure required from the compressor, thereby consuming excessive energy. A filter that is not operating properly will also allow contaminants into a tool, causing it to wear out prematurely. The lubricant level should also be checked often enough to ensure that it does not run dry. Tools that are not properly lubricated will wear prematurely and use excess energy.

Leaks
Leak detection and repair is an important part of any maintenance program. For more information on finding and fixing leaks, see the Handout on leaks.
Maintenance Schedules
Establishing a regular, well-organized maintenance program and strictly following it is critical to maintaining the performance of a compressed air system. One person should be given the responsibility of ensuring that all maintenance is performed properly, on schedule, and adequately documented.

The following are typical recommended minimum maintenance procedures for air-cooled reciprocating compressors, water-cooler double-acting reciprocating compressors, lubricant-injected rotary compressors, and lubricant-free rotary compressors.
Routine Maintenance for Air-Cooled Reciprocating Compressors

Every 8 Hours (or Daily)
- Maintain lubricant level between high and low level marks on bayonet gauge. (Discoloration or a higher lubricant level reading may indicate the presence of condensed liquids). If lubricant is contaminated, drain and replace.

- Drain receiver tank, drop legs and traps in the distribution system.

- Give compressor an overall visual inspection and be sure safety guards are in place.

- Check for any unusual noise or vibration.

- Check lubricant pressure on pressure lubricated units. Maintain 18 to 20 psig when compressor is at operating pressure and temperature. High pressure rated compressors should maintain 22 to 25 psig of lubricant pressure.

- Check for lubricant leaks.

Every 40 Hours (or Weekly)
- Be certain pressure relief valves are working.

- Clean the cooling surfaces of the intercooler and compressor.

- Check the compressor for air leaks.

- Check the compressed air distribution system for leaks.

- Inspect lubricant for contamination & change if necessary.

- Clean or replace the air intake filter. Check more often under humid or dusty conditions.

Every 160 Hours (or Monthly)
- Check belt tension.

Every 500 Hours (or Every 3 Months)
- Change lubricant (more frequently in harsher environments).

- Check lubricant filter on pressure lubricated units (more frequently in harsher environments).

- Torque pulley clamp screws or jamnut.
Every 1000 Hours (or Every 6 Months)

- When synthetic lubricant is used, lubricant change intervals may be extended to every 1000 hours or every 6 months, whichever occurs first (change more frequently in harsher conditions).

- Inspect compressor valves for leakage and/or carbon build-up. The lubricant sump strainer screen inside the crankcase of pressure lubricated models should be thoroughly cleaned with a safety solvent during every lubricant change. If excessive sludge build-up exists inside the crank-case, clean the inside of the crankcase as well as the screen. Never use a flammable or toxic solvent for cleaning. Always use a safety solvent and follow the directions provided.

Every 2000 Hours (or Every 12 Months)

- Inspect the pressure switch diaphragm and contacts. Inspect the contact points in the motor starter.

Lubrication

Compressors may be shipped without lubricant in the crankcase. Before starting the compressor, add enough lubricant to the crankcase to register between the high and low marks on the dipstick or on bull’s eye sight gauge. Use the specified lubricant or consult the manufacturer for recommendations.

Certain synthetic lubricants have proven under extensive testing to minimize friction and wear, limit lubricant carryover, and reduce carbon and varnish deposits. They will support the performance characteristics and life and are highly recommended. Refer to the manufacturer's specifications to determine the correct amount of lubricant and viscosity to use for your model and application. Use the supplier’s lubricant analysis program.
Routine Maintenance for Water-Cooled Double-Acting Reciprocating Compressors

The following are typical minimum maintenance requirements for this type of compressor.

Daily or every 8 hours*
- Check compressor lubricant level in crankcase and cylinder lubricator and, if necessary, add to level indicated by sight gauge.
- Check cylinder lubrication feed rate and adjust, as necessary.
- Check lubricant pressure and adjust as necessary to meet specified operating pressure.
- Check cylinder jacket cooling water temperatures.
- Check capacity control operation. Observe discharge pressure gauge for proper LOAD and UNLOAD pressures.
- Drain control line strainer.
- Check operation of automatic condensate drain trap (intercooler and aftercooler).
- Drain condensate from discharge piping as applicable (dropleg and receiver).
- Check intercooler pressure on multi-stage machines, and refer to manufacturer's manual if pressure is not as specified.

Monthly or every 360 hours*
- Check piston rod packing for leaks and for blow-by at gland. Repair or replace as necessary per manufacturer's manual.
- Inspect lubricant scraper rings for leakage. Replace as necessary per manufacturer's manual.
- Inspect air intake filter. Clean or replace as necessary.
- Drain lubricant strainer/filter sediment.
- Lubricate unloader mechanism per manufacturer's manual.
- Check motor amps at compressor full capacity and pressure.
Semi-annually or every 3000 hours*
- Perform valve inspection per manufacturer's manual.
- Inspect cylinder or cylinder liner, through valve port, for scoring.
- Change crankcase lubricant, if required.
- Clean crankcase breather (if provided).
- Change lubricant filter element.
- Remove and clean control air filter/strainer element.
- Check all safety devices for proper operation.
- Perform piston ring inspection on non-lubricated design. Replace as necessary per manufacturer's manual.

Annually or every 6000 hours*
- Remove and clean crankcase lubricant strainer.
- Check foundation bolts for tightness. Adjust as necessary.
- Perform piston ring inspection. Replace as necessary per manufacturer’s manual.

* Whichever interval is sooner. Experience gained from a well kept maintenance log may allow the recommended times to be adjusted.
Routine Maintenance for Lubricant Injected Type Rotary Compressor

The following are typical minimum maintenance requirements.

**Periodically/Daily-8 hours maximum**
- Monitor all gauges and indicators for normal operation.
- Check lubricant level.
- Check for lubricant leaks.
- Check for unusual noise or vibration.
- Drain water from air/lubricant reservoir.
- Drain control line filter.

**Weekly**
- Check safety valve operation.

**Monthly**
- Service air filter as needed. (daily or weekly if extremely dusty conditions exist).
- Wipe entire unit down, to maintain appearance.
- Check drive motor amps at compressor full capacity and design pressure.
- Check operation of all controls.
- Check operation of lubricant scavenger/return system. Clean, as necessary.

**6 Months or every 1000 hours**
- Take lubricant sample.
- Change lubricant filter.*

**Periodically/yearly**
- Go over unit and check all bolts for tightness.
- Change air/lubricant separator.
- Change air filter.
- Lubricate motors per manufacturer's instructions.

- Check safety shutdown system. Contact authorized serviceman.

*Manufacturers may recommend changing the lubricant filter within the first week of operation, to rid the system of foreign matter, which may have collected during initial assembly and startup.
Routine Maintenance for Lubricant Free Rotary Screw Compressor

The following are typical minimum requirements for this type of compressor.

Routine maintenance is relatively minimal. The microprocessor control panel monitors the status of the air and oil filters. When maintenance to either device is required, the control panel may display the appropriate maintenance message, and flash the location on the display as a visual remainder.

DO NOT remove caps, plugs, and/or other components when compressor is running or pressurized. Stop compressor and relieve all internal pressure before doing so.

Daily
Following a routine start, observe the various control panel displays and local gauges to check that normal readings are being displayed - previous records are very helpful in determining the normalcy of the measurements. These observations should be made during all expected modes of operation (i.e. full load, no-load, different line pressures, cooling water temperatures, etc.).

After Initial 50 Hours of Operation
Upon completion of the first 50 hours of operation, a few maintenance requirements are needed to rid the system of any foreign materials, which may have accumulated during assembly:

- Change the lubricant filter element.
- Clean the control line filter element.
- Check/replace the sump breather filter element.

Every 3000 Hours of Operation
The following items should be checked every 3000 hours of operation, although service conditions such as relative cleanliness of process air or quality of cooling water may require shorter inspection intervals.

- Check/change oil charge and filter element.
- Check/change air filter element.
- Check/change sump breather filter element.
- Check/clean control line filter element.
- Check/clean condensate drain valve.
- Check condition of shaft coupling element and tightness of fasteners.
- Measure and record vibration signatures on compressor, gearbox and motor (optional).

NOTE: Please refer to the motor manufacturer’s documentation for recommended maintenance. Keep in mind that the specified type and quantity of lubricating grease for motor bearings is crucial.
Every 15,000 Hours of Operation
In addition to those items covered by in the 3000 hour maintenance interval, the following items must also be checked every 15,000 hours of operation, depending upon conditions of service:

- Operate/test all safety devices.
- Check/clean heat exchangers.
- Check/clean blowdown valve.
- Check operation of balancing switch/valve assembly.
- Check/clean water regulating valve.
- Check/clean check valve.
- Check/clean galvanized interstage pipe work.
- Check condition of isolation mounts under compressor unit and motor.
- Check/clean strainer and check valve included in oil pump suction line, inside oil sump.
- Check compressor unit internal clearances.

Please be aware that work on the compressor stages and gearbox must be conducted by manufacturer's personnel only. Any work done by unauthorized personnel can render the manufacturer's equipment warranty null and void.

Parts Replacement and Adjustment Procedures
Familiarize yourself with the safety guidelines offered in the Safety Section of the manufacturer's manual before attempting any maintenance on the package.
Routine Maintenance for Centrifugal Air Compressors

The following are typical maintenance requirements for this type of compressor.

**Daily**
- Record operating air inlet, interstage and discharge pressures and temperatures.
- Record cooling water inlet and outlet pressures and temperatures.
- Record lubricant pressure and temperatures.
- Record all vibration levels.
- Check air inlet filter differential pressure.
- Check proper operation of drain traps.
- Drain control air filter.
- Check for leaks, air, water and lubricant. Repair and clean as necessary.
- Check lubricant sump level and adjust as necessary.
- Check drive motor for smooth operation and record amperes.

**Every 3 months**
- Check lubricant filter differential pressure. Replace element as necessary.
- Check lubricant sump venting system. Replace filter elements as necessary.
- Check operation of capacity control system.
- Check operation of surge control system.
- Check main drive motor amperes at full load operation.
- Check automatic drain traps and strainers. Clean and/or replace as necessary.

**Every 6 months**
- Check air inlet filter and replace element as necessary.
- Take oil sample for analysis. Replace lubricant as necessary.

**Annually**
- Inspect intercooler, aftercooler, and lubricant cooler. Clean and/or replace as necessary.
- Inspect main drive motor for loose mounting bolts, frayed or worn electrical cables, accumulated dirt. Follow manufacturer's recommendations, including lubrication.
- Inspect main drive coupling for alignment and required lubrication.
- Inspect gearbox for loose mounting bolts, vibration, unusual noise or wear and axial clearances per manufacturer's manual.
- Check impeller inlets and diffusers for signs of wear, rubbing or cracking.
- Check control panel for complete and proper operation.
- Check all control valves for proper operation.
- Check all safety devices for proper settings and operation.
- Inspect check valve; replace worn parts.

Keep all components/accessories clean and follow all recommended safety procedures.
Handout: Compressed Air System Terminology

The following are definitions of terms commonly used in the compressed air system industry.

Absolute Pressure - Total pressure measured from zero.

Absolute Temperature - See Temperature, Absolute.

Absorption - The chemical process by which a hygroscopic desiccant, having a high affinity with water, melts and becomes a liquid by absorbing the condensed moisture.

Adsorption - The process by which a desiccant with a highly porous surface attracts and removes the moisture from compressed air. The desiccant is capable of being regenerated.

Actual Capacity – See Capacity, Actual.

Air Receiver - See Receiver.

Aftercooler - A heat exchanger used for cooling air discharged from a compressor. Resulting condensate may be removed by a moisture separator following the aftercooler.

Atmospheric Pressure - The measured ambient pressure for a specific location and altitude.

Automatic Sequencer - A device which operates compressors in sequence according to a programmed schedule.

Brake Horsepower (bhp) - Horsepower delivered to the output shaft of a motor or engine, or the horsepower required at the compressor shaft to perform work.

Capacity - The amount of air flow delivered under specific conditions, usually expressed in cubic feet per minute (cfm).

Capacity, Actual - The actual volume flow rate of air or gas compressed and delivered from a compressor running at its rated operating conditions of speed, pressures, and temperatures. Actual capacity is generally expressed in actual cubic feet per minute (acfm) at conditions prevailing at the compressor inlet. Also called Free Air Delivered (FAD).

Capacity Gauge - A gauge that measures air flow as a percentage of capacity, used in rotary screw compressors as an estimator during modulation controls.
Compression, Adiabatic - Compression in which no heat is transferred to or from the gas during the compression process.

Compression, Isothermal - Compression is which the temperature of the gas remains constant.

Compression Ratio - The ratio of the absolute discharge pressure to the absolute inlet pressure.

Constant Speed Control - A system in which the compressor is run continuously and matches air supply to air demand by varying compressor load.

Cubic Feet Per Minute (cfm) - Volumetric air flow rate.

Cfm, Free Air (or Free Air Delivered {fad}) - Cfm of air delivered to a certain point at a certain condition, converted back to ambient conditions. This term sometimes is used for the capacity of an air compressor. This is the same as acfm, being the delivered flow rate measured at prevailing ambient conditions.

Actual Cfm (acfm) - Flow rate of air at a certain point at a certain condition at that point. When used for the capacity of an air compressor, it is the delivered rate of flow, measured at prevailing ambient conditions of pressure, temperature and relative humidity.

Inlet Cfm (icfm) - Cfm flowing through the compressor inlet filter or inlet valve under rated conditions. Also used to describe the rate of flow of a centrifugal type air compressor. Acfm and icfm should be the same for displacement type air compressors, but may not be the same in some designs of centrifugal air compressors. There may be air losses through shaft seals of each stage, so that the delivered rate of flow in acfm may be up to 5% less than the icfm entering the compressor.

Standard Cfm (scfm) - Flow of free air measured and converted to a standard set of reference conditions. There may be confusion with this term since all standards are not the same. The Compressed Air Challenge and The Compressed Air & Gas Institute have adopted the International Standards Organization (ISO) definition of standard air as: 14.5 psia (1 bar); 68°F (20 C); dry (0% relative humidity).

Other standards include:
14.7 psia; 68°F; 36% relative humidity and 14.7 psia; 60°F; dry.

When the term scfm is used, the applicable standard should be stated.

Cut In/Cut Out Pressure - Respectively, the minimum and maximum discharge pressures at which the compressor will switch from unload to load operation (cut in) or from load to unload (cut out).
Cycle - The series of steps that a compressor with unloading performs; 1) fully loaded, 2) modulating (for compressors with modulating control), 3) unloaded, 4) idle.

Cycle Time - Amount of time for a compressor to complete one cycle.

Degree of Intercooling - Difference in air or gas temperature between the outlet of the intercooler and the inlet of the compressor.

Deliquescent - Melting and becoming a liquid by absorbing moisture.

Desiccant - A material having a large proportion of surface pores, capable of attracting and removing water vapor from the air.

Dew Point - The temperature at which moisture in the air will begin to condense if the air is cooled at constant pressure. At this point the relative humidity is 100%.

Demand - Flow of air at specific conditions required at a point or by the overall facility.

Discharge Pressure - Air pressure produced at a particular point in the system under specific conditions.

Discharge Temperature - The temperature at the discharge flange of the compressor.

Efficiency, Compression - Ratio of theoretical power to power actually imparted to the air or gas delivered by the compressor.

Efficiency, Isothermal - Ratio of the theoretical work (as calculated on a isothermal basis) to the actual work transferred to a gas during compression.

Efficiency, Mechanical - Ratio of power imparted to the air or gas to brake horsepower (bhp).

Efficiency, Volumetric - Ratio of actual capacity to piston displacement.

Free Air - Air at atmospheric conditions at any specified location, unaffected by the compressor.

Full-Load - Air compressor operation at full speed with a fully open inlet and discharge delivering maximum air flow.

Gauge Pressure - The pressure determined by most instruments and gauges, usually expressed in psig. Barometric pressure must be considered to obtain true or absolute pressure.

Horsepower, Brake - See Brake Horsepower.
Horsepower, Theoretical or Ideal - The horsepower required to isothermally compress the air or gas delivered by the compressor at specified conditions.

Humidity, Relative - The relative humidity of a gas (or air) vapor mixture is the ratio of the partial pressure of the vapor to the vapor saturation pressure at the dry bulb temperature of the mixture.

Humidity, Specific - The weight of water vapor in an air vapor mixture per pound of dry air.

Indicated Power - Power as calculated from compressor-indicator diagrams.

Inlet Pressure - The actual pressure at the inlet flange of the compressor.

Intercooling - The removal of heat from air or gas between compressor stages.

Leak - An unintended loss of compressed air to ambient conditions.

Load Factor - Ratio of average compressor load to the maximum rated compressor load over a given period of time.

Load Time - Time period from when a compressor loads until it unloads.

Load/Unload Control - Control method that allows the compressor to run at full-load or at no load while the driver remains at a constant speed.

Modulating Control - System which adapts to varying demand by throttling the compressor inlet proportionally to the demand.

Perfect Intercooling - The condition when the temperature of air leaving the intercooler equals the temperature of air at the compressor intake.

Piston Displacement - The volume swept by the piston; for multistage compressors, the piston displacement of the first stage is the overall piston displacement of the entire unit.

Pneumatic Tools - Tools that operate by air pressure.

Pressure - Force per unit area, measured in pounds per square inch (psi).

Pressure Dew Point - For a given pressure, the temperature at which water will begin to condense out of air.

Pressure Drop - Loss of pressure in a compressed air system or component due to friction or restriction.
Pressure Range - Difference between minimum and maximum pressures for an air compressor. Also called cut in-cut out or load-no load pressure range.

Rated Capacity - Volume rate of air flow at rated pressure at a specific point.

Rated Pressure - The operating pressure at which compressor performance is measured.

Required Capacity - Cubic feet per minute (cfm) of air required at the inlet to the distribution system.

Receiver - A vessel or tank used for storage of gas under pressure. In a large compressed air system there may be primary and secondary receivers.

Relative Humidity - The ratio of the partial pressure of a vapor to the vapor saturation pressure at the dry bulb temperature of a mixture.

Sequence - The order in which compressors are brought online.

Specific Humidity - See Humidity, Specific.

Specific Power - A measure of air compressor efficiency, usually in the form of bhp/100 acfm or acfm/bhp.

Specific Weight - Weight of air or gas per unit volume.

Standard Air - The Compressed Air & Gas Institute and PNEUROP have adopted the definition used in ISO standards. This is air at 14.5 psia (1 bar); 68°F (20 C) and dry (0% relative humidity).

Start/Stop Control - A system in which air supply is matched to demand by the starting and stopping of the unit.

Surge - A phenomenon in centrifugal compressors where a reduced flow rate results in a flow reversal and unstable operation.

Temperature, Absolute - The temperature of air or gas measured from absolute zero. It is the Fahrenheit temperature plus 459.6 and is known as the Rankine temperature. In the metric system, the absolute temperature is the Centigrade temperature plus 273 and is known as the Kelvin temperature.

Temperature, Discharge - The total temperature at the discharge connection of the compressor.

Temperature, Inlet - The total temperature at the inlet connection of the compressor.
Temperature Rise Ratio - The ratio of the computed isentropic temperature rise to the measured total temperature rise during compression. For a perfect gas, this is equal to the ratio of the isentropic enthalpy rise to the actual enthalpy rise.

Temperature, Static - The actual temperature of a moving gas stream. It is the temperature indicated by a thermometer moving in the stream and at the same velocity.

Temperature, Total - The temperature which would be measured at the stagnation point if a gas stream were stopped, with adiabatic compression from the flow condition to the stagnation pressure.

Theoretical Power - The power required to compress a gas isothermally through a specified range of pressures.

Torque - A torsional moment or couple. This term typically refers to the driving couple of a machine or motor.

Total Package Input Power - The total electrical power input to a compressor, including drive motor, cooling fan, motors, controls, etc.

Unload - (No load) Compressor operation in which no air is delivered due to the intake being closed or modified not to allow inlet air to be trapped.
Handout: Ford Monroe Case Study – Implementing an Awareness Program

Although treating compressed air as a system is critical to improving overall performance, there is another factor, the “human element”, that can be just as important. The human element is often overlooked, which is unfortunate, since people design, specify, purchase, build, operate, control, and maintain the complete compressed air process from the compressor to the end uses. People hold the key to effective and efficient compressed air systems, and the best way to start a program is to focus on the people and reach them through awareness building.

It has been said that "lack of knowledge is the root of all evil", and in compressed air systems, no truer words were spoken. People do not intentionally operate compressed air systems poorly and waste money. It happens because of lack of knowledge and awareness.

The best way to start a program is with the proper data. Baselining, as outlined in the Baselining Your Compressed Air System section, shows how to gather the data needed to get started. Baselining must tie compressed air consumption to output metrics or numbers that are meaningful. For production facilities, baseline to usage/cost per unit of production. For non-production, use usage/cost per time (hour, day, month, year) or per area (sq. ft. or meter). While the usage numbers hold the key to efficiency, cost numbers have the biggest awareness impact. Many people can relate to reducing energy, but everyone can relate to saving money.

Once the baseline has been established, one has the ammunition to fight the war against inefficient compressed air systems. Be warned that the size of the weapon may be proportional to the usage/cost. The larger the number, the bigger the weapon. The smaller the number, the harder the battle. Like in any war, the outcome depends on the effectiveness of both the generals as well as the soldiers. For a compressed air awareness program, or any energy awareness program to be effective, it has to have support from not only the top down, but be driven from the bottom up. Unlike war, the program is more effective if it is based on evolution rather than revolution. The best way to start the evolution is to get both top management and the hourly workers involved.

One of the best examples of this process is Ford Monroe Energy Team. This team is made up of volunteers, almost all of whom are hourly UAW employees. The team is lead by an hourly energy coordinator, whose mission is to reduce energy waste. Their first target was air leaks. They gathered the baseline data, both during production and during a holiday shutdown, so they could estimate the cost of compressed air and calculate the loss due to air leaks. The production number gave them the base to measure to, and the shutdown number gave them their potential reduction target. They convinced management to start an air leak program based on the potential savings.
The approach that the Monroe Team developed was unique because it combined the traditional air leak program with innovative implementation and marketing. The program started with a traditional "tag and fix" program that grew into a process which evolved into a cultural change. They knew that the key was not only to have management support, but also to have the involvement of the line workers and the skilled trades. After all, who knows more about the machines than the people who operate and maintain them?

The team started with the traditional tagging of air leaks, which generated a list of leaks and repairs that could be tracked. The results were published weekly and got the plant manager's attention and support. The team then started to "spread the word". This convinced management to buy red energy team jackets for every team member. This made them "stand out" in the plant and gave them their own unique identity. While they developed this identity, they never lost sight that their goal was to make every employee a member of the energy team. They talked to the operators and skilled trades on a one-to-one basis and it became apparent to everyone in the plant that they were there to help, not to criticize.

As for the marketing of the program, the team developed a procedure for all employees to report leaks. They used "give away" items like buttons, hats, tee shirts, key chains, and refrigerator magnets to promote the program and reward employees for helping and becoming part of the team. They posted "leak boards" in several locations in the plant that showed the leaks that were identified and repaired. The black dots on the board became symbols of progress. The Monroe Team also developed posters to illustrate the cost of air leaks, as well as other energy wastes. They took charts from the Compressed Air and Gas Institute, developed fact sheets on the cost of air leaks, and passed them out to the employees. They also used the Ford Communication Network to develop messages that were shown on the monitors throughout the plant. In addition, the team developed stickers and placards for proper shutdown of equipment.

The most important part of this story is that the team used top down support combined with bottom up implementation. They made everyone aware, but concentrated their efforts on the people who have the knowledge of the equipment and can make the changes. The team had immediately successes, and also fostered a permanent cultural change, and the results speak for themselves.

When the program started in 1988, the plant used 17.4 million cubic foot per day, or 3.4 mcf/BWS (Budget Work Standard) hour during production. By 1992, air consumption was reduced to 9.0 million cubic foot per day, or 1.6 mcf/BWS hour. This represents a savings of almost $2,000 per day. Non-production compressed air consumption was reduced from 5400 cfm to less than 600 cfm. The testament to the cultural change is that the compressed air usage has remained at a fairly constant level ever since. The Monroe Energy Team illustrates the effectiveness of an energy awareness team. They have also told their story, and helped build successful teams at other Ford facilities. They are as willing to share as they are to implement ideas from other plants. This is also one of the keys to their success.
The key points to remember are:

- **Baseline the data** (without data your just another person with an opinion)
- **Plan strategy** (with a good map you will not get lost)
- **Implement program** (execution is still the key to success)
- **Track results** (report card for end user and program accountability)
- **Publish results** (remember the old adage "publish or parish")
- **Market and build on success** (perception becomes reality)
**ETERMINE THE WATER VOLUME**

The following chart was created to simplify the procedure necessary to determine the amount of water vapor that is present in a cubic foot of air at various temperature and humidity conditions. The design conditions are based on sea level (14.7 psia), and 35 degree pressure dewpoint.

**Gallons Per Hour per CFM**

<table>
<thead>
<tr>
<th>Temp F.</th>
<th>Percentage of Saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0.0010 0.0012 0.0015 0.0017 0.0020 0.0022 0.0024</td>
</tr>
<tr>
<td>45</td>
<td>0.0014 0.0018 0.0021 0.0025 0.0028 0.0032 0.0035</td>
</tr>
<tr>
<td>50</td>
<td>0.0017 0.0021 0.0025 0.0030 0.0034 0.0038 0.0042</td>
</tr>
<tr>
<td>55</td>
<td>0.0020 0.0025 0.0030 0.0035 0.0040 0.0045 0.0050</td>
</tr>
<tr>
<td>60</td>
<td>0.0024 0.0030 0.0036 0.0042 0.0048 0.0054 0.0060</td>
</tr>
<tr>
<td>65</td>
<td>0.0028 0.0035 0.0042 0.0049 0.0056 0.0063 0.0070</td>
</tr>
<tr>
<td>70</td>
<td>0.0033 0.0041 0.0050 0.0058 0.0066 0.0075 0.0083</td>
</tr>
<tr>
<td>75</td>
<td>0.0039 0.0049 0.0058 0.0068 0.0078 0.0088 0.0097</td>
</tr>
<tr>
<td>80</td>
<td>0.0045 0.0057 0.0068 0.0080 0.0091 0.0102 0.0114</td>
</tr>
<tr>
<td>85</td>
<td>0.0053 0.0066 0.0079 0.0093 0.0106 0.0119 0.0132</td>
</tr>
<tr>
<td>90</td>
<td>0.0061 0.0077 0.0092 0.0108 0.0123 0.0138 0.0154</td>
</tr>
<tr>
<td>95</td>
<td>0.0071 0.0089 0.0107 0.0125 0.0142 0.0160 0.0178</td>
</tr>
<tr>
<td>100</td>
<td>0.0082 0.0103 0.0123 0.0144 0.0164 0.0185 0.0205</td>
</tr>
<tr>
<td>105</td>
<td>0.0095 0.0118 0.0142 0.0166 0.0189 0.0213 0.0236</td>
</tr>
<tr>
<td>110</td>
<td>0.0108 0.0136 0.0163 0.0190 0.0217 0.0244 0.0271</td>
</tr>
<tr>
<td>115</td>
<td>0.0124 0.0155 0.0186 0.0217 0.0248 0.0279 0.0310</td>
</tr>
<tr>
<td>120</td>
<td>0.0142 0.0177 0.0212 0.0248 0.0283 0.0319 0.0354</td>
</tr>
</tbody>
</table>

Use this chart, determine your maximum temperature and humidity condition. (In event you are between ratings please round up to the next number present.) Locate the factor that is at the intersection point of these two conditions. Take the rating of the air compressor system that you intend to dehydrate. Multiply them by the factor at the intersection of the proper conditions. The answer you get is total amount of water in gallons per hour that would be condensed when chilled to 35 degrees F.
Answer Key

Compressed Air Challenge Training
Fundamentals of Compressed Air Systems

Presented by
Compressed Air Challenge
**Compressed Air Challenge Questionnaire**

1. Production staff think that compressed air is free.  
   \[ \checkmark \quad \blacksquare \]
   At many plants, production staff have the attitude that compressed air is free, and that there are no consequences to wasting air, since it is being made anyway. Compressed air is a resource for production. Like any resource, if wasted, it adds unnecessarily to costs and makes your company less competitive and profitable.

2. Compressed air is an efficient source of energy in a plant.  
   \[ \quad \checkmark \]
   Compressed air is probably the most inefficient source of energy in a plant. To operate a 1 hp air motor, you need 7-8 horsepower of electrical power into the motor driving the compressor.

3. Compressed air is often the biggest end-use of electricity in a plant.  
   \[ \checkmark \quad \blacksquare \]
   For many industrial plants, compressed air is the largest single end-use source of electricity consumption. A 500 hp compressor running 3 shifts at full-load consumes 3,630,000 kWh of electricity annually ($182,000 @ 0.05 cents/kWh).

4. I know exactly how much compressed air my plant uses and how much it costs.  
   \[ \quad \checkmark \]
   Most plants do not know their actual air requirements
   Very few plants calculate and maintain records of compressed air costs

5. Acfm, scfm, icfm, and fad are all the same.  
   \[ \checkmark \quad \blacksquare \]
   They are not they same, and the differences will be discussed.
6. Adding horsepower is the best way to increase system pressure. 
   Additional "capacity" can often be achieved by:
   Reducing leaks
   Eliminating inappropriate uses
   Better matching demand to supply
   Implementing storage solutions
   Adding horsepower should be a last resort

7. Compressed air systems that waste air also frequently have reliability problems that affect production.
   An inefficient system is one that is not being managed
   Unmanaged systems typically have problems with maintaining reliable end-use pressure, which can affect production
   Unmanaged systems can typically have problems with unscheduled downtime, which can affect production

8. There are actions that I can take to save more than 20 percent of my current cost of air.
   Most plants waste at least 20 percent of their air
   By examining both supply and demand and the interaction between them (taking a systems approach), you can substantially reduce the cost of compressed air at your plant
## Compressor Types

**Directions:** Match the compressor type with the correct table of advantages and disadvantages.

<table>
<thead>
<tr>
<th>Compressor Type</th>
<th>Letter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lubricant Injected Rotary Screw</td>
<td>C</td>
</tr>
<tr>
<td>Lubricant Free Rotary Screw</td>
<td>B</td>
</tr>
<tr>
<td>Centrifugal</td>
<td>A</td>
</tr>
<tr>
<td>Single Acting Reciprocating</td>
<td>E</td>
</tr>
<tr>
<td>Double Acting Reciprocating</td>
<td>D</td>
</tr>
</tbody>
</table>

### A
**Advantages include:**
- Completely packaged for plant or instrument air up through 1000 hp.
- Relative first cost improves as size increases.
- Designed to deliver lubricant free air.
- Do not require any special foundations.

**Disadvantages include:**
- Limited capacity control modulation, requiring unloading for reduced capacities.
- High rotational speeds require special bearings, sophisticated monitoring of vibrations and clearances.
- Specialized maintenance considerations.

### B
**Advantages include:**
- Completely packaged.
- Designed to deliver lubricant free air.
- Do not require any special foundations.

**Disadvantages include:**
- Cost premium.
- Less efficient.
- Limited to Load/Unload type capacity control.
- Higher maintenance costs.

### C
**Advantages include:**
- Compact size and complete package.
- Economic first cost.
- Vibration free operation does not require special foundation.
- Part load capacity control systems can match system demand.
- Routine maintenance includes lubricant and filter changes.

**Disadvantages include:**
- Less efficient at full and part load than the highest efficiency compressor types.
- Lubricant carry-over into delivered air requires proper maintenance of air/lubricant separator and the lubricant itself.
Compressor Types (Continued)

**D**
Advantages include:

- Efficient compression, particularly with multi-stage compressors.
- Three-step (0-50-100%) or Five-step (0-25-50-75-100%) capacity controls, allowing efficient part load operation.
- Relatively routine type maintenance procedures.

Disadvantages include:

- Relatively high first cost compared with most common-type of mid-sized industrial compressors.
- Relatively high space requirements.
- Relatively high vibrations require high foundation costs.
- Lubricant carry-over on lubricant cooled units.
- Seldom sold as complete independent packages.
- Require flywheel mass to overcome torque and current pulsations in motor driver.
- Repair procedures require some training and skills.

**E**
Advantages include:

- Small size and weight.
- Generally can be located close to point of use, avoiding lengthy piping runs and pressure drops.
- Do not require separate cooling systems.
- Simple maintenance procedures.

Disadvantages include:

- Lubricant carry-over, which should be avoided.
- Relatively high noise.
- Relatively high cost of compression.
- Generally are designed to run not more than 50% of the time, although some industrial designs have higher duty cycles.
- Generally compress and store the air in a receiver at a pressure higher than required at the point of use. The pressure then is reduced to the required operating pressure but without recovery of the energy used to compress to the higher pressure.
## Dryer Types

**Directions:** Please match the dryer type with the correct table.

<table>
<thead>
<tr>
<th>Refrigerant-type</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regenerative-desiccant type</td>
<td>B</td>
</tr>
<tr>
<td>Deliquescent-type</td>
<td>C</td>
</tr>
<tr>
<td>Heat of Compression</td>
<td>D</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost to operate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uses a porous material that adsorbs the moisture, and is regenerated with compressed air.</td>
<td>The approximate operating cost, including the effect of pressure drop through the dryer is 2.0-3.0 kW/100 cfm.</td>
</tr>
<tr>
<td>Cools the air to remove the condensed moisture before the air is reheated and discharged.</td>
<td>The approximate operating cost, including the effect of pressure drop through the dryer, is 0.80 kW/100 cfm.</td>
</tr>
<tr>
<td>Uses the heat generated during compression to regenerate the dryer materials.</td>
<td>The total power requirement, including pressure drop and compressor operating cost is approximately 0.80 kW/100 cfm.</td>
</tr>
<tr>
<td>Use a drying medium that absorbs the moisture in the compressed air. The medium is used up as it changes from solid to liquid and cannot be regenerated.</td>
<td>The approximate operating cost, including pressure drop through the dryer and any associated filtration, but excluding the cost of replacement material, is approximately 0.20 kW/100 cfm.</td>
</tr>
</tbody>
</table>
## Compressed Air System Component Functions

**Compressor Package Enclosure**

Function:
Many modern industrial air compressors are sold "packaged" with the compressor, drive motor, and many of the accessories mounted on a frame for ease of installation. Provision for movement by forklift is common. Larger packages may require the use of an overhead crane. An enclosure may be included for sound attenuation and aesthetics.

**Compressor Control Panel**

Function:
The control panel allows the user to adjust the control settings and check the status of the compressor.

**Inlet Air Filter**

Function:
An air inlet filter protects the compressor from atmospheric airborne particles. Further filtration is needed, however, to protect equipment downstream of the compressor.

**Compressor Air End**

Function:
The compressor air end is the actual mechanical compressor. There are two basic compressor types: positive-displacement and dynamic. In the positive-displacement type, a given quantity of air or gas is trapped in a compression chamber and the volume which it occupies is mechanically reduced, causing a corresponding rise in pressure prior to discharge (reciprocating and rotary screw). Dynamic compressors impart velocity energy to continuously flowing air or gas by means of impellers rotating at very high speeds. The velocity energy is changed into pressure energy both by the impellers and the discharge volutes or diffusers (centrifugal).
Compressed Air System Component Functions (Continued)

**Directions:** Please describe the function of each pictured component:

<table>
<thead>
<tr>
<th>Component</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Motor</strong></td>
<td>The motor provides the torque to turn the compressor air end. Electric motors are a widely available and economical means of providing reliable and efficient power to compressors. Most compressors use standard polyphase induction motors. In many cases either a standard or energy-efficient motor can be specified when purchasing a compressor or replacement motor. The incremental cost of the energy-efficient motor is typically recovered in a very short time from the resulting energy savings. When replacing a standard motor with an energy-efficient one, careful attention needs to be paid to performance parameters such as full-load speed and torque. A replacement motor with performance as close as possible to the original motor should be used.</td>
</tr>
<tr>
<td><strong>Air/Lubricant Separator</strong></td>
<td>Separators are devices that separate liquids entrained in the air or gas. A separator generally is installed following each intercooler or aftercooler to remove the condensed moisture. This involves changes in direction and velocity and may include impingement baffles. Lubricant-injected rotary compressors have an air/lubricant coalescing separator immediately after the compressor discharge to separate the injected lubricant before it is cooled and recirculated to the compressor. This separation must take place before cooling to prevent condensed moisture from being entrained in the lubricant.</td>
</tr>
<tr>
<td><strong>Aftercooler and Moisture Separator</strong></td>
<td>Air or gas compression generates heat. As a result, industrial air compressors that operate continuously generate substantial amounts of heat. Compressor units are cooled with air, water, and/or lubricant. Reciprocating compressors of less than 50 hp are typically air-cooled using a fan, which is an integral part of the belt drive flywheel. Cooling air blows across finned surfaces on the outside of the compressor cylinder's cooler tubes. Larger, water-cooled reciprocating air compressors have built-in cooling water jackets around the cylinders and in the cylinder heads. In plants where good quality water is available, shell and tube heat exchangers generally are used. The moisture separator removes liquids from the air.</td>
</tr>
</tbody>
</table>
Compressed Air System Component Functions (Continued)

**Directions:** Please describe the function of each pictured component:

<table>
<thead>
<tr>
<th>Component</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lubricant Cooler</td>
<td>Lubricant-injected rotary compressors use the injected lubricant to remove most of the heat of compression. In air-cooled compressors, a radiator-type lubricant cooler is used to cool the lubricant before it is re-injected. The cooling fan may be driven from the main motor drive shaft or by a small auxiliary electric motor.</td>
</tr>
<tr>
<td>Air Line Filter</td>
<td>These include particulate filters to remove solid particles, coalescing filters to remove lubricant and moisture, and adsorbent filters for vapors. A particulate filter is recommended after a desiccant-type dryer to remove desiccant &quot;fines&quot;. A coalescing-type filter is recommended before a desiccant-type dryer to prevent fouling of the desiccant bed. Additional filtration may also be needed to meet requirements for specific end-uses. Compressed air filters downstream of the air compressor are generally required for the removal of contaminants, such as particulates, condensate, and lubricant. Filtration only to the level required by each compressed air application will minimize pressure drop and resultant energy consumption. Elements should also be replaced as indicated by pressure differential, and at least annually, to minimize pressure drop and energy consumption.</td>
</tr>
<tr>
<td>Dryer</td>
<td>When air leaves an aftercooler and moisture separator, it is typically saturated. Any further radiant cooling as it passes through the distribution piping, which may be exposed to colder temperatures, will cause further condensation of moisture with detrimental effects such as corrosion and contamination of point-of-use processes. This problem can be avoided by the proper use of compressed air dryers. When air is compressed and occupies a smaller volume, it no longer can contain all of the moisture it could at atmospheric conditions. Again, some of the moisture will drop out as liquid condensate. The most common types of dryers are refrigerant-type, regenerative-desiccant type, deliquescent type, and heat of compression type dryers. The selection of a compressed air dryer should be based upon the required pressure dew point and the estimated cost of operation. Where a pressure dew point of less than 35°F is required, such as for instrument air, a refrigerant-type dryer cannot be used. The required pressure dew point for the application at each point of use eliminates certain types of dryers.</td>
</tr>
</tbody>
</table>
Compressed Air System Component Functions
(Continued)

Directions: Please describe the function of each pictured component:

<table>
<thead>
<tr>
<th>Component</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver</td>
<td>Receivers are used to provide compressed air storage capacity to meet peak demand events and help control system pressure. Receivers are especially effective for systems with widely varying compressed air flow requirements. Where peaks are intermittent, a large air receiver may allow a smaller air compressor to be used and can allow the capacity control system to operate more effectively and improve system efficiency. An air receiver after a reciprocating air compressor can provide dampening of pressure pulsations, radiant cooling, and collection of condensate. Demand-side control will optimize the benefit of the air receiver storage volume by stabilizing system header pressure and &quot;flattening&quot; the load peaks.</td>
</tr>
<tr>
<td>Flow/Pressure Controller</td>
<td>Flow/pressure controllers are optional system pressure controls used in conjunction with the individual compressor or system controls described previously. A flow/pressure controller does not directly control a compressor and is generally not included as part of a compressor package. A flow/pressure controller is a device that serves to separate the supply side of a compressor system from the demand side. This may require compressors to be operated at an elevated pressure and therefore, increased horsepower, while pressure on the demand side can be reduced to a stable level to minimize actual compressed air consumption. Storage, sized to meet anticipated fluctuations in demand, is an essential part of the control strategy. Higher pressure supply air enters the primary storage tanks from the air compressors and is available to reliably meet fluctuations in demand at a constant lower pressure level. A well designed and managed system needs to include some or all of the following: overall control strategy, demand control, good signal locations, compressor controls, and storage. The goal is to deliver compressed air at the lowest stable pressure to the main plant distribution system and to support transient events as much as possible with stored higher pressure compressed air. Primary storage replacement should utilize the minimum compressor horsepower to restore the primary pressure to the required level. Each compressed air system differs in supply, distribution and demand aspects which require proper evaluation of the benefits to the system of a flow/pressure controller. Additional primary and/or secondary air receivers may also address intermittent loads, which can affect system pressure and reliability, and may allow operating the compressor at the lowest possible discharge pressure and input power.</td>
</tr>
<tr>
<td>Condensate Drain</td>
<td>Condensate drains should allow removal of condensate but not compressed air. Automatic condensate drains or traps are used to prevent the loss of air through open petcocks and valves. Drain valves should allow removal of condensate but not compressed air. Two types of traps are common: mechanical and electrical. Mechanical traps link float devices to open valves when condensate rises to a preset level. Electric solenoid drain valves operate on a preset time cycle, but may open even when condensate is not present. Other electrical devices sense liquid level and open to drain only when condensate is present. Improperly operating or maintained traps can create excessive air usage and waste energy.</td>
</tr>
</tbody>
</table>
## Inappropriate Uses of Compressed Air

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Open Blowing</strong></td>
<td>Processes such as cooling, bearing cooling, drying, clean-up, draining compressed air lines, and clearing jams on conveyors.</td>
</tr>
<tr>
<td><strong>Sparging</strong></td>
<td>Sparging is aerating, agitating, oxygenating, or percolating liquid with compressed air.</td>
</tr>
<tr>
<td><strong>Aspirating</strong></td>
<td>Aspirating is using compressed air to induce the flow of another gas (such as flue gas) with compressed air.</td>
</tr>
<tr>
<td><strong>Atomizing</strong></td>
<td>Atomizing is where compressed air is used to disperse or deliver a liquid to a process as an aerosol.</td>
</tr>
<tr>
<td><strong>Padding</strong></td>
<td>Padding is using compressed air to transport liquids and light solids.</td>
</tr>
<tr>
<td><strong>Dilute Phase Transport</strong></td>
<td>Dilute Phase Transport is used in transporting solids such as powdery material in a diluted format with compressed air.</td>
</tr>
<tr>
<td><strong>Dense Phase Transport</strong></td>
<td>Dense Phase Transport used to transport solids in a batch format.</td>
</tr>
<tr>
<td><strong>Vacuum Generation</strong></td>
<td>Applications where compressed air is used with a venturi, eductor, or ejector to generate a negative pressure mass flow.</td>
</tr>
<tr>
<td><strong>Personnel Cooling</strong></td>
<td>Personnel cooling is operators directing compressed air on themselves to provide ventilation. (always inappropriate)</td>
</tr>
<tr>
<td><strong>Open hand held blowguns or lances</strong></td>
<td>Open hand help blowguns or lances are any unregulated hand held blowing and are a violation of most health and safety codes, and very dangerous. (always inappropriate)</td>
</tr>
<tr>
<td><strong>Diaphragm pumps</strong></td>
<td>Diaphragm pumps are commonly found installed without regulators and speed control valves. Those diaphragm pumps that are installed with regulators are found with the regulators adjusted higher than necessary.</td>
</tr>
<tr>
<td><strong>Vacuum venturis</strong></td>
<td>When compressed air is forced through a conical nozzle, its velocity increases and a decrease in pressure occurs. Vacuum generators are used throughout industry. Some applications for vacuum generators are shop vacuums, drum pumps, palletizers, depalletizers, box makers, packaging equipment, and automatic die cutting equipment.</td>
</tr>
<tr>
<td><strong>Cabinet cooling</strong></td>
<td>When first cost is the driving factor, open tubes, air bars (copper tube with holes drilled long the length of the tube) and vortex tube coolers are used to cool cabinets. Cabinet cooling should not be confused with panel purging (an explosion proof panel having an inert gas passed through it at positive pressure).</td>
</tr>
</tbody>
</table>
Common Leak Problem Areas

*Couplings, hoses, tubes, and fittings
Tubes and push-to-lock fittings are common problems.

*Disconnects
O-rings required to complete the seal may be missing.

*Filters, regulators and lubricators (FRLs)
Low first-cost improperly installed FRLs often leak.

*Open condensate traps
Improperly operating solenoids and dirty seals are often problem areas.

*Pipe joints
Missed welds are a common problem.

*Control and shut-off valves
Worn packing through the stem can cause leaks (note: no-leak valves are available).

*Point of use devices
Old or poorly maintained tools can have internal leaks.

Flanges
Missed welds are a common problem.

Cylinder rod packing
Worn packing materials can cause leaks.

Thread sealants
Incorrect and/or improperly applied thread sealants cause leaks.

*Problem areas with asterisks should have been indicated on the diagram during the exercise.
Energy Costs of Unloaded Operation

Directions: Please estimate the annual energy costs (using the equations provided in Unloaded and Part-Load Operation) for the following system:

- 400 bhp lubricant free compressor
- 8,000 hours per year of operation
- $0.05/kWh electricity price
- 60% of the time fully-loaded
- 40% of the time unloaded (where it consumes 25% of full load power)
- motor 90% efficient at full-load, 80% efficient at 25% of full load power

Calculations:

\[
\text{(400 bhp) x (0.746 kW/hp) x (8,000 hrs) x (0.60) x (1.0) x ($0.05/kWh) = $79,573}} \frac{0.90}{0.90}
\]

\[
\text{+}
\]

\[
\text{(400 bhp) x (0.746 kW/hp) x (8,000 hrs) x (0.40) x (0.25) x ($0.05/kWh) = $14,920}} \frac{0.80}{0.80}
\]

Total annual electricity costs = $94,493
Pressure Measurement Locations

Directions: On the diagram below, indicate where pressure measurements should be taken to determine pressure drop across key components:

- Air Inlet Filter
- Compressor
- Air/Lubricant Separator
- Aftercooler
- Primary Receiver
- Filter
- Dryer
- Moisture Separator
- Flow/Pressure Controller
- Each End-Use Drop
- Each End-Use FRL
- Each End-Use Hose
- End-Use Drop
- End Use FR
- Secondary Receiver (SR)
- End-Use Hose Supplied by SR

Pressure differential measurements could be taken across any of these components.
Estimating Pressure Drop

Directions: Given the following measured pressure drops, please complete the pressure profile below and determine the lowest pressure seen by the end-uses:

Compressor operating range: 115-105 psig
FRL 7 psid
Aftercooler 3 psid
Filter 3 psid
Separator 5 psid
Hose and Disconnects 4 psid
Dryer 4 psid
Distribution System 3 psid
Estimating Leak Load

Directions: Using the data provided below, please estimate the percentage of compressor capacity lost to leaks for the following system. Measurements were taken using the method describe previously that involves starting the compressor when there are no demands on the system. A number of measurements were taken of determine the time it takes to load and unload the compressor. The compressor will load and unload because the air leaks will require the compressor to cycle on as the pressure drops from air escaping through the leaks. The following table shows the measurements that were taken:

<table>
<thead>
<tr>
<th>Time loaded</th>
<th>2 min 10 sec</th>
<th>2 min 5 sec</th>
<th>2 min 15 sec</th>
<th>2 min 10 sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time unloaded</td>
<td>5 min 20 sec</td>
<td>5 min 10 sec</td>
<td>5 min 15 sec</td>
<td>5 min 5 sec</td>
</tr>
</tbody>
</table>

Use the following equation:
Total leakage (percentage) can be calculated as follows:

\[
\text{Leakage (\%)} = \frac{(T \times 100)}{(T+t)}
\]

where: \( T \) = total on-load time (minutes or seconds)
\( t \) = total off-load time (minutes or seconds)

Calculations:

\[
\left(\frac{520}{(520+1250)}\right)\times100 = 29.4\%
\]
Controls Discussion Questions

Compressor systems are typically comprised of multiple compressors delivering air to a common plant air header. The combined capacity of these compressors is sized, at a minimum, to meet the maximum plant air demand.

1. Would you describe a compressed air system as static or dynamic?

   Answer: Demand for compressed air in most industrial systems is very dynamic, changing constantly over time.

2. How do controls help the system deal with changing conditions?

   Answer: Compressed air system controls attempt to match the compressed air supply with this dynamic demand (taking into account storage) and are one of the most important determinants of overall system energy efficiency.

3. What are the three additional objectives of a compressed air control system?

   Answer: The objective of any control strategy is also to:

   1. Shut off unneeded compressors,

   2. Delay bringing on additional compressors until needed, and

   3. Make sure operating compressors are performing efficiently.
Using Controls

Problem #1:

A facility has three 100 hp rotary screw compressors. During their normal two-shift operation, two compressors (# 1 and #2) are baseloaded (operated at full-load almost all of the time), and the third (#3) uses load/unload controls. During the third shift, compressed air demand is only about ½ of the normal demand. During this shift, compressor # 1 operates baseloaded (with load/unload controls and a high enough pressure setting to ensure that it does not unload), compressor #2 uses modulating controls, and #3 operates unloaded.

Recommended Control Strategy:

One of the compressors should be baseloaded all the time, with the other two used as trim units. One of the two trim units should then be shut down during the third shift either manually or by installing auto-dual controls on both trim compressors for automatic shutdown.
Using Controls (Continued)

Problem #2:

A facility has a variety of end-use applications that require 70 psig air (measured after the FRL, valves, hoses, disconnects, and fittings). The average demand from these applications is about 600 scfm with a peak demand of 700 scfm. The facility also has a single large end-use that requires about 300 scfm (continuous) of 95 psig air (measured at the point of use). Currently the controls are set to keep the entire system pressure high enough so that end-use pressure stays above 95 psig.

Recommended Control Strategy:

The entire system should not be kept at a pressure level to satisfy the 95 psig application. A number of solutions are possible:

- The compressed air system could be split into two systems, each operating at a different pressure level.
- A booster compressor could be used to supply higher pressure air to the 95 psig application if budget permits.
- Modify or replace the large end use components to operate at 70 psig, and adjust system pressure accordingly.
Using Controls (Continued)

Problem #3:

A manufacturing facility just completed an internal audit of their compressed air system. They have a system with two identical rotary screw compressors, with one unit baseloaded and the other acting as a trim unit. Load/unload controls are used on each. During the audit, a substantial amount of leaks were repaired, inappropriate uses were discontinued, and pressure drop was reduced through maintenance actions. No changes were made to the supply-side, and energy savings were not as high as expected.

Recommended Control Strategy:

The user should work with their compressed air system specialist to re-adjust the compressor control setpoints and overall control strategy. Both overall demand and pressure drops will likely be reduced, and it may be possible to turn compressors off.
Problem #4:

A manufacturing facility just completed an internal audit of their compressed air system. They have a system with four identical centrifugal air compressors. During most of the day, one compressor is baseloaded, one compressor is in modulation, a third compressor is operating mostly unloaded, and a fourth compressor is shut down in stand-by mode. During the audit, a substantial amount of leaks were repaired, inappropriate uses were discontinued, and pressure drop was reduced through maintenance actions. No change was made to the supply side, and energy savings were not as high as expected.

Recommended Control Strategy:

The user should work with their compressed air system specialist to re-adjust the compressor control setpoints and overall control strategy. Both overall demand and pressure drops will likely be reduced, and it may be possible to turn compressors off. The major differences in analyzing centrifugal compressors versus rotary screw or reciprocating compressors are larger motor sizes, longer time to start from a cold start condition, and performance variations for different ambient and system conditions.
Simple, Quick Cost Cutting Measures

Directions: For each of the following cost cutting measures, discuss the potential fix as it applies to the case study.

**Storage**

1. Add more capacity to the primary receiver.

   The receiver is likely undersized, because it used to serve a smaller system. It is best to reduce the demand as much as possible and determine the need and size of additional primary storage. If it is required, work with equipment service provider to determine the proper size to enhance system performance.

2. Look for applications that could benefit from strategic secondary storage.

   In determining the use of secondary storage (receivers), loads that have cycle times should be considered, because with proper storage, they can reduce the peak demand on the compressors. Critical loads may also benefit from secondary storage if pressure stabilization is necessary. Three applications may benefit from secondary storage. The air hoists and pneumatic clamps are a large, intermittent demand on the system that could be better served by a dedicated secondary receiver that is filled slowly. This would help to smooth the system demand profile. The automated assembly stations may be protected from pressure fluctuations with a secondary receiver. Caution must be taken because the system profile indicates that it is a continuous operation, thus, recovery time may not be available. The variation in the system pressure can also be caused by the operation being downstream of the previous cyclical loads, lowering the system pressure. Correcting them may solve the pressure variation critical to this operation.

3. Add secondary receivers to the system.

   Calculating the size of the receivers for these applications is beyond the scope of this training on fundamentals. The estimation of peak flow reduction from using properly sized secondary storage for two of the applications can be easily calculated and provides some insights into how costs can be cut.
For the air hoists the average demand = \( \frac{200 \text{ cfm} \times 5 \text{ min}}{60 \text{ min}} = 17 \text{ cfm} \). By adding appropriately sized storage, we can lower the demand from a peak of 200 cfm to a continuous flow of 17 cfm, resulting in a peak reduction to the air compressor load of 183 cfm.

For the pneumatic clamps the average demand = \( \frac{200 \text{ cfm} \times (10 \text{ min}/60 \text{ min}) \times (10 \text{ sec}/20 \text{ sec})}{60 \text{ min}} \approx 17 \text{ cfm} \). By adding appropriately sized storage, we can lower the demand from a peak of 200 cfm to a continuous flow of 17 cfm, resulting in a peak reduction to the air compressor load of 183 cfm.
A ppropriate Uses

1. Replaced inappropriate end-uses with another source of power, such as electric motors, hydraulic power, fans, blows, brushes, or vacuum systems.

- The air hoists could possibly be replaced with electric hoists, depending on the life cycle cost justification.

- Open hand held blowguns and open blowing are one of the biggest misused and misapplied compressed air applications. They are often used as a "quick fix" to a production problem. The root cause of the problem or the application should be examined to determine the best solution to apply. For example, if the blowguns are being used for parts drying, a low pressure blower/fan can be used at a fraction of the cost (see personnel cooling fan example). Other examples are chip removal, dust/dirt removal, parts cooling, etc. Force applied to move parts or product, or free up a "sticking area", can be done mechanically or the process can be improved to remove the problem "sticking area". If the blowgun is absolutely necessary for production, then the application should be reviewed to run at a lower pressure, thus reducing usage, and solenoid valves should be installed to shut off blowguns during non-production. Nozzles should also be installed to reduce usage (see item # 2). Any use or application of blowguns needs to conform to all occupational health and safety standards.

- Vacuum Generation (Venturi Cups) is generally an inefficient use of compressed air. It should be replaced with an efficient vacuum pump or lower usage vortex venturi cups. These will reduce the usage by a factor of 4 to 10, depending on the application. This will save at least 75 cfm of compressor load in this example.

- Personnel coolers and cabinet coolers should be replaced. Personnel coolers are very inefficient and dangerous. A ¾” personnel cooler can consume 15-25 hp of compressed air and can be replaced with a ¼ hp fan of or less. The savings are

\[
15\text{hp} - \frac{1}{4}\text{hp} = 14\ \frac{3}{4}\text{hp}
\]

and annually are

\[
(14\ \frac{3}{4}\text{hp} \times .746\ kW/\text{hp} \times 8760\ \text{hrs.} \times .05/\text{kwh})/0.95 = 5100/\text{year}.
\]

Buying a $200 fan would offer a payback of less than two weeks.
- Similarly, a cabinet cooler can use 7 ½ hp worth of compressed air and can be replaced by air to air, air to water, or refrigerated cabinet coolers using 1/3hp to accomplish the same task. This would result in savings of over 7 hp. The annual savings are (7hp * .746 kW/hp * 8760 hrs. * $.05/kwh)/.95 = $2400/year. At a cost of $300, this project yields a 1 ½ month payback.

- Large pneumatic clamps can possibly be replaced with hydraulic units, depending on the application, or can be designed with larger cylinders to use lower pressure compressed air. If it is cost prohibitive to retrofit this application during normal production, alternatives should be considered when replacing the unit or during production process changes.

- Pneumatic actuators, depending on the application and cost, can be converted to electric-powered units, or have larger cylinders installed to reduce the pressure required. Another common problem with air tools is the hose sizing is often too small and causes the operating pressure to be increased to obtain proper flow. Verify proper line size with tool manufacturer’s data.

2. Use nozzles for blowing.

Open hand held blowguns, as previously stated, should be avoided, but if absolutely needed, nozzles should be used. Vortex nozzles can reduce the amount of air required by using ambient air to "assist" in supplying air to accomplish the task. These nozzles can reduce the usage by a factor of 4 to 6. This would result in a reduction of at least 75 cfm.

On this system, 173 bhp/750 scfm = .23 bhp/cfm. An estimate of the annual savings would be ((75cfm * .23 bhp/cfm) * .746 kW/hp * 8760 hrs. * $.05/kwh)/.95 = $5900/year. With a cost of $10-$20 per nozzle and estimating 100 nozzles, the approximate payback is 2 to 4 months.
**Controls**

1. Add automatic shut-off devices to compressors.

   After other measures are implemented, the system could benefit from using automatic dual control (i.e. automatic start and time-delayed stop). It may be possible to turn off one compressor for the majority of the time (maybe permanently).

2. Set unloading controls properly so that compressors are unloading when appropriate instead of modulating.

   If compressors must be run in load/unload, switch to lead lag machine so that one machine can be fully loaded and only one run load/unload, as needed to meet demand.

3. Use sequencing controls for multiple compressor systems.

   A control strategy that sequences compressors to run only when needed can be utilized to maximize system efficiency.

4. Set sequencing controls to maximize performance and minimize energy consumption.

   As stated above, proper sequencing of compressor will maximize performance and minimize energy consumption.

   In items 1-4, the important point is to shut off the compressors as much as possible. The ultimate goal to shut down one of the compressors all the time by minimizing the usage.

5. Apply flow/pressure controllers to reduce artificial demand, improve performance, and reduce energy consumption.

   A flow/pressure controller can be used to separate the supply side of a compressor system from the demand side. In this case study, some of the benefits of the flow/pressure controller will be achieved by the use of additional primary and secondary storage and compressor controls.
6. Reduce system pressure.

Reducing system pressure will result in further efficiency gains. The rule of thumb is 1% efficiency gain for every 2 psi reduction in compressor discharge pressure. Based on just one compressor fully loaded, the annual savings per 2 psi drop would be: \(((173 \text{ bhp} \times .746 \text{ kW/hp}) \times 8760 \text{ hrs.} \times .05/\text{kwh}) \times .95) \times .01 = $600/\text{year}.

7. Add a small compressor.

If non-production loads were much less than the capacity of one compressor or if the production loads was just greater than one compressor, a smaller compressor could be added. This allows for a larger compressor to be shut off instead of run partially loaded.

8. Add a booster compressor. (If you have end-uses with different pressure requirements, consider separating end-uses and using a booster to supply higher pressure air to some applications.)

Booster compressors, or intensifiers, can be added, allowing a reduction in the system pressure by eliminating loads that may require higher pressure than the rest of the system loads. In the case study, the only potential for a booster compressor would be the pneumatic clamps. This may not be a good example, because the pressure difference between the clamps and the other end uses is not great. A better example would be a tire fill application in an automotive plant requiring 120 psi. If this were the case, the 173hp would be running at 130 - 140 to supply the load. At the $600/2psi calculated earlier, 130 - 100 = 30psi \times 600/2 = $9000. A 15hp booster compressor would require; \((15 \text{ hp} \times .746 \text{ kW/hp} \times 8760 \text{ hrs.} \times .05/\text{kwh}) \times .95 = $5160/\text{year}.

A booster compressor of this size has an installed cost of about $3000, yielding a payback of less than a year. Inline booster compressors and intensifiers can also be used but caution must be taken in applying any of these solutions. A booster compressor and an intensifier serve the same purpose (to raise pressure from one level to another) but with different construction. In some cases, it may be appropriate to have a separate compressor to go from atmospheric to the higher pressure, rather than drawing from the main system at around 100 psig and taking it up to the required pressure.
Leaks

1. Fix leaks in the distribution system.

A good air leak repair program is important in maintaining system efficiency and reducing pressure loss in the system. Currently the system leak rate is 300 cfm (20% of compressor system capacity and about 30% of average flow). This should be reduced to 150 cfm or less. An estimation of annual cost of the system leaks in the case study are as follows: 

\[
((300 \text{ cfm} \times .23 \text{ bhp/cfm}) \times .746 \text{ kW/hp} \times 8760 \text{ hrs.} \times .05 \text{ kwh}) / .95 = 23,700 \text{ /year.}
\]

Dollars savings are not directly proportional to leak reduction, but this is a good estimate. Remember, an ¼ " air leak will cost over $8,000 per year.

2. Make sure traps are operating properly.

Traps stuck open can "leak" system pressure.

3. Fix leaks at points of use.

Leaks often occur at couplings, cracked/pitted hoses, tubes, fittings, and the FRLs.

4. Repair leaks at air tools.

Watch out for sticking air valves and worn out cylinder packing.
Maintain System Efficiency

M aintenance

1. Check that the compressor manufacturer's maintenance requirements are being met or exceeded.

   Monitor temperatures, pressure differentials, motor current, and investigate unusual changes.

2. Check compressor ventilation openings to the compressor room to make sure that they are large enough and free of obstructions.

   Small or obstructed openings can decrease compressor efficiency.

3. Clean/change inlet filters.

   Dirty inlet filters can decrease system efficiency. A rule of thumb is 1% efficiency for every 4" of water column, which could be expected from replacing a dirty filter. From the calculation on pressure drop, 1% efficiency is equal to $600 per year. With $100 cost for a filter change, the payback would be than a two months.

4. Lubricate compressor/change lubricant filter.

   Poorly lubricated compressors or dirty lubricant filters can decrease efficiency and damage compressor.

5. Remove all debris from radiators, fans, heat exchanges, etc.

   Dirt and debris can get deposited on these components from many sources, and can decrease efficiency.

   A neglected separator can increase pressure drop, and should be changed per manufacturer specification or when the pressure drop becomes excessive. Same rule of thumb of 1% efficiency gain per 2 psi drop applies.

7. Replace clogged air line filters.

   Air line filters require regular changing per manufacturer specifications or when pressure drop becomes excessive. Same rule of thumb of 1% efficiency gain per 2 psi drop applies.

8. Repair or replace poorly functioning condensate drain traps.

   Empty and clean condensate drain traps and check for proper operation. Traps are often found leaking or bypassed.

9. Inspect other system components.

   Refer to Reference Handout on maintenance for other system equipment.