Best Practice Catalog

Compressed Air Systems

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Contents

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1.0 Scope and Purpose

This document addresses the technology, condition assessment, operations, and maintenance best practices for compressed air systems with the objective to maximize performance and reliability of generating units. Compressed air systems are used in powerhouses for operation and to facilitate maintenance and repair. Station service air, brake air, and governor air comprise the three sub-systems that are required in all powerhouses. Some powerhouses will also require a draft tube water depression system. [1]

Generally, each of the sub-systems is dedicated except for the brake air system, which is usually supplied by station service air. Figure 1 shows typical process and instrumentation diagrams of compressed air systems at hydropower facilities.

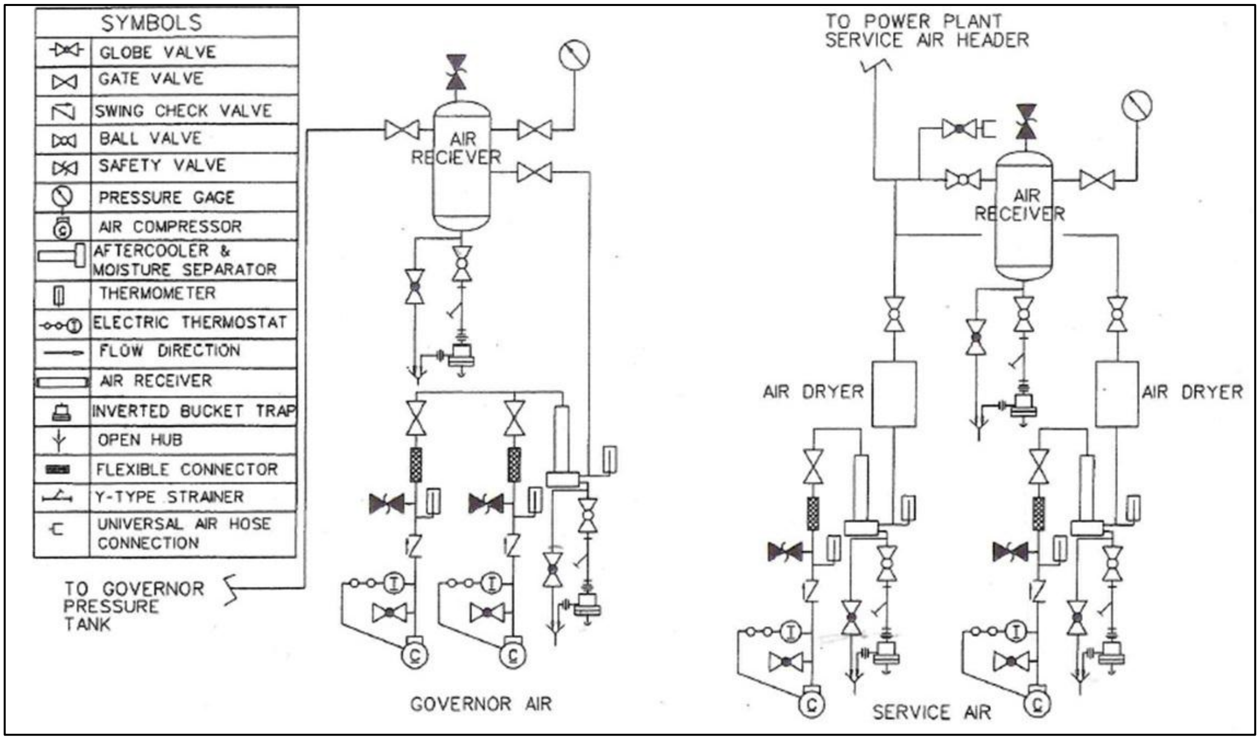

Figure 1: Typical Service and Governor Compressed Air Systems P&ID [1]

1.1 Hydropower Taxonomy Position

Hydropower Facility → Powerhouse → Balance of Plant/Auxiliary Systems → Compressed Air System

1.1.1 Compressed Air System Components

Compressed air is widely regarded as “the fourth utility” after electricity, gas, and water; and is commonly used in hydroelectric generating plants. The main reliability components of compressed air systems include compressors, after-coolers, air dryer/moisture separators, air receiver/tanks, piping (distribution), and control/instrumentation (Figure 2).

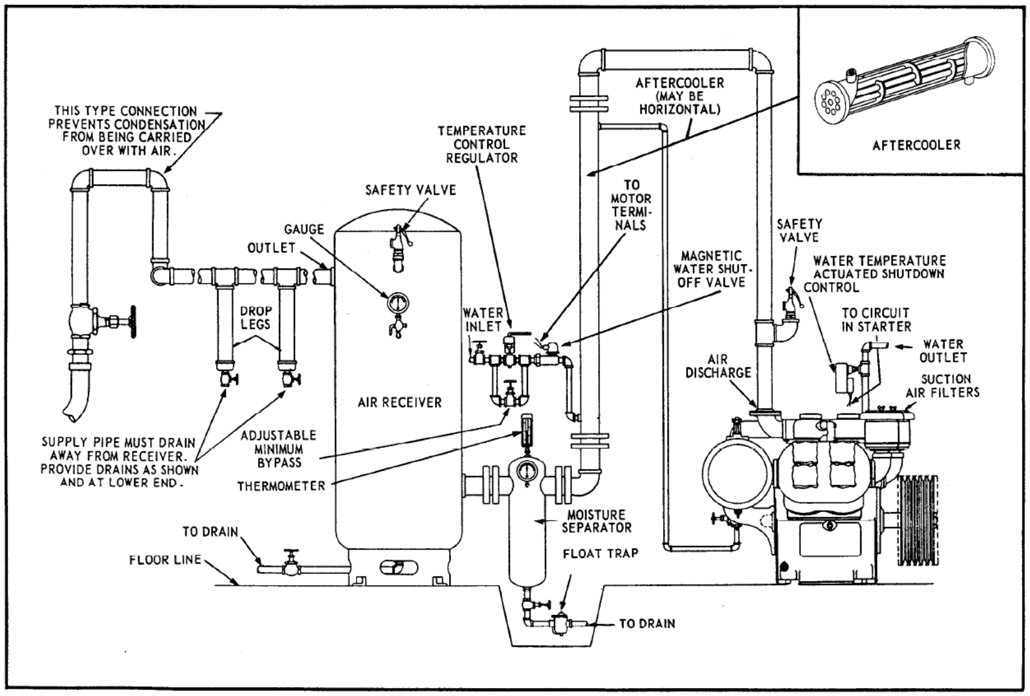

Figure 2: Main Components of a Compressed Air System [2]

<u>Compressors:</u> Ambient air is drawn into compressor intake pipes/ducts and is usually filtered prior to entering the air compressor. Once compressed, the application will determine the components installed in the discharge and distribution network for each system.

Industrial air compressors can be divided into two main groups with positive displacement and dynamic characteristics (Figure 3). Positive displacement compressors draw air into a fixed volume and gradually reduce the volume, increasing the pressure of the air. Once the design pressure is reached, the air is released to the system. Positive displacement compressors include the reciprocating, rotary screw, rotary sliding vane, liquid ring, and rotary blowers.

Positive displacement – dynamic pump comparison

	Positive displacement	Dynamic
Definition	Increases pressure by operating on fixed volume in a confined space	Increases pressure by using rotary blades to increase fluid velocity
Types	Screw, gear, reciprocating	Centrifugal, axial
Characteristics	■ Constant volume ■ Variable differential head ■ Relatively insensitive to liquid properties ■ Relatively insensitive to system changes ■ Not self-limiting	■ Variable volume ■ Constant differential head ■ Sensitive to liquid properties ■ Sensitive to system changes ■ Self-limiting
Characteristic flow vs. differential head curves		

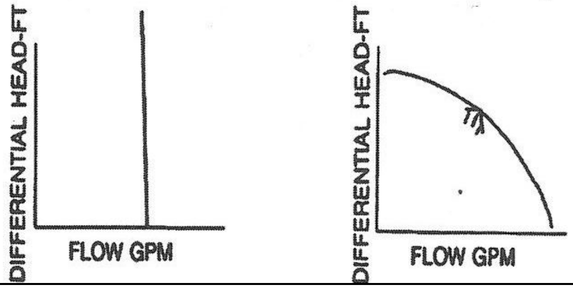

Figure 3: Positive Displacement and Dynamic Characteristics [8]

Dynamic compressors draw air between blades rotating on a rapidly moving impeller accelerating the air to a high velocity. The air is then discharged through a diffuser where the kinetic energy is transformed into static pressure [3]. Dynamic compressors include centrifugal and axial types.

Positive displacement and dynamic compressors are illustrated in Figure 4. Hydroelectric plants generally employ positive displacement compressors, specifically reciprocating and rotary screw, to satisfy their compressed air needs. For this reason this compressed air best practice will focus on positive displacement compressors.

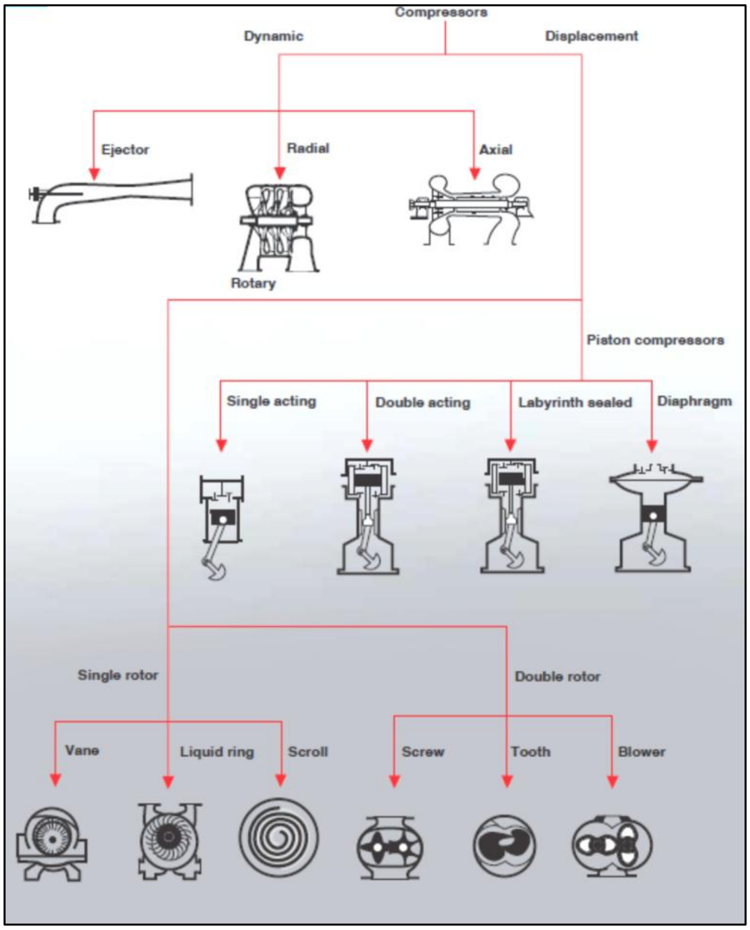

Figure 4: Air Compressor Types [6]

Reciprocating: A reciprocating air compressor functions much like a standard automobile engine (Figure 5). A piston is driven inside a cylinder by a crankshaft. As the piston is drawn towards the crankshaft, an intake valve opens in the cylinder head. The cylinder fills with air until the piston reaches the bottom of the cylinder. As the piston begins to travel away from the crankshaft, the intake valve closes and the air inside the cylinder is compressed. When the compressed air reaches a high enough pressure, an exhaust valve opens in the cylinder head and pushes compressed air into the compressed air system.

A single-acting reciprocating air compressor uses valves on only one end of the cylinder. To increase efficiency, two cylinders may be operated with the same piston by placing an intake and exhaust valve at either end of the cylinder. With this arrangement, the piston compresses air in each direction. This is called a double-acting reciprocating air compressor. Single-acting reciprocating compressors are cheap and weigh relatively little. They are generally used in applications with smaller power requirements and are usually air-cooled. Due to their smaller size, they do not require substantial base pad sizes. The downside of these compressors is their lower efficiency.

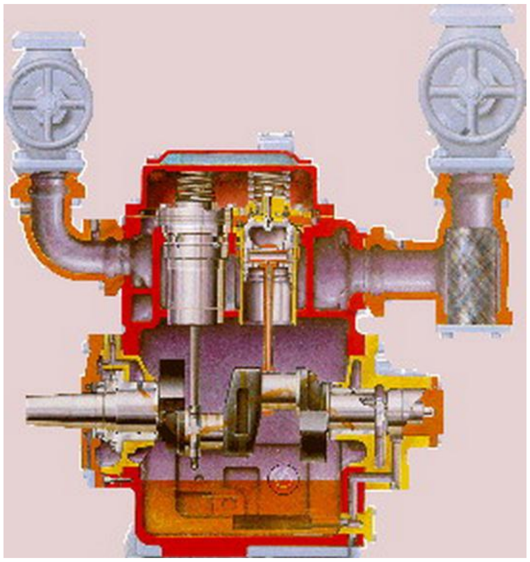

Figure 5: Reciprocating Air Compressor

Double-acting reciprocating compressors are the most efficient type of compressor. They are usually used in applications with higher power requirements and are usually water-cooled. These have become the most common design of the two types. However, these compressors are quite heavy and require substantial pads. They are also more expensive to purchase than single-acting reciprocating compressors and cost more to install and maintain [3].

Rotary Screw: Rotary screw air compressors come in two drive configurations for the same basic design. The basic design is two rotors (one male and one female) meshed together and turning in opposite directions (Figure 6). One end of the rotors is exposed to the intake air and the other is exposed to the compressed air system. The compression begins with air filling the channels of the female rotor. The air fills the channels all the way around the rotor until the male rotor seals the channel. As the rotors turn, the air is driven into the compressed air system by action of the male and female rotors pushing the air along the channel. Another form of drive is to have one rotor turn the other.

Rotary positive displacement compressors are smaller and quieter than reciprocating compressors. They also have smaller footprints than equally sized reciprocating models and may be installed directly on the floor. They do not produce pulsations typically found in reciprocating compressors due to continuous flow. Two-stage rotary compressors are more efficient than single-stage reciprocating, but not as efficient as two-stage, double-acting reciprocating units. Another drawback of rotary units is that their efficiency significantly decreases at partial load. Lubricant-free rotary compressors are less efficient than compressors that use lubricant, but have the added benefit of no oil entrainment in the compressed air [3].

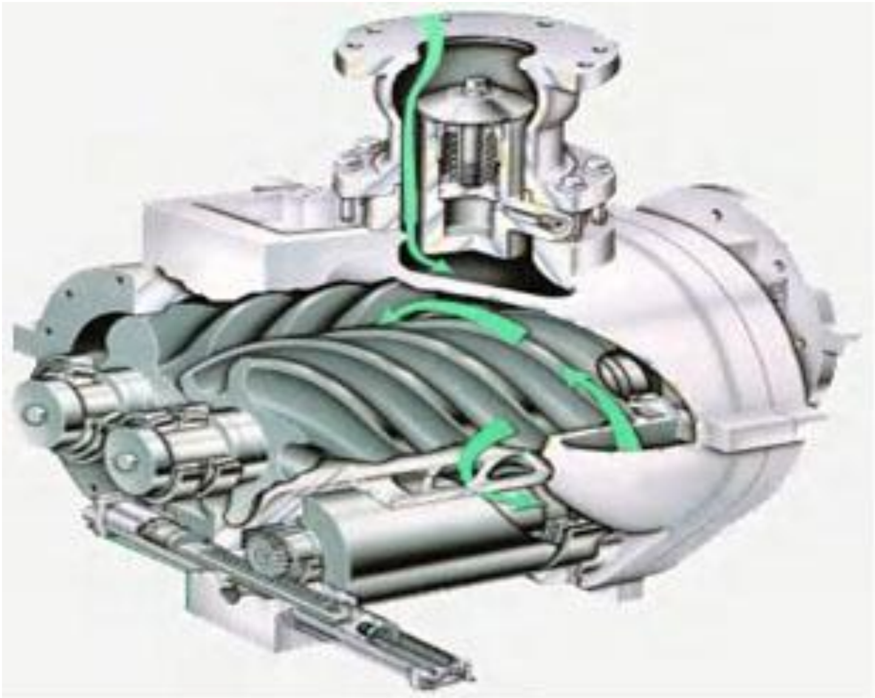

Figure 6: Rotary Screw Compressor

<u>Air Receivers/Tanks:</u> The function of an air receiver is to provide a reservoir of clean dry air to meet fluctuating system demands. The benefit of this item is that, when properly sized and installed, a receiver can minimize air line pressure fluctuations. This also prevents short term capacity requirements from overloading clean-up equipment. Each air receiver should conform to design, construction and testing requirements of the ASME Boiler and Pressure Vessel Code Section VIII Div. 1 and have a “U” or “UM” stamp [10] (Figure 7).

Figure 7: Vertical and Horizontal Air Receivers

After-cooler: The compressed air discharged from an air compressor is hot. Compressed air at these temperatures contains large quantities of water in vapor form. As the compressed air cools this water vapor condenses into a liquid form. As an example if an aftercooler is not used, a 200 scfm compressor operating at 100 psig introduces 45 gallons of water into the compressed air system each day.

Type of Compressor	Average Outlet Air Temperature (°F)
Oil Flooded Rotary	200
Oil Free Rotary	350
2-St. Reciprocating	300

Additionally, by reducing the air temperature, condensate forms. Most air aftercoolers are sized to cool the air to within 5°F to 20°F of ambient air temperature. As the compressed air cools, up to 75% of the water vapor present condenses to a liquid and can be removed from the system. [7]

Air Dryer: A moisture separator/air-dryer installed at the discharge of the after-cooler removes most of the liquid moisture and solids from the compressed air. Utilizing centrifugal force, moisture and solids collect at the bottom of the moisture separator. An automatic drain should be used to remove the moisture and solids. Aftercoolers are either water or air-cooled. Depending upon the quality of air required, driers may be placed on either the supply or discharge side of the air receiver tank. For example, brake air tapped off the discharge of the station service air receiver may have a smaller individual air dryer.

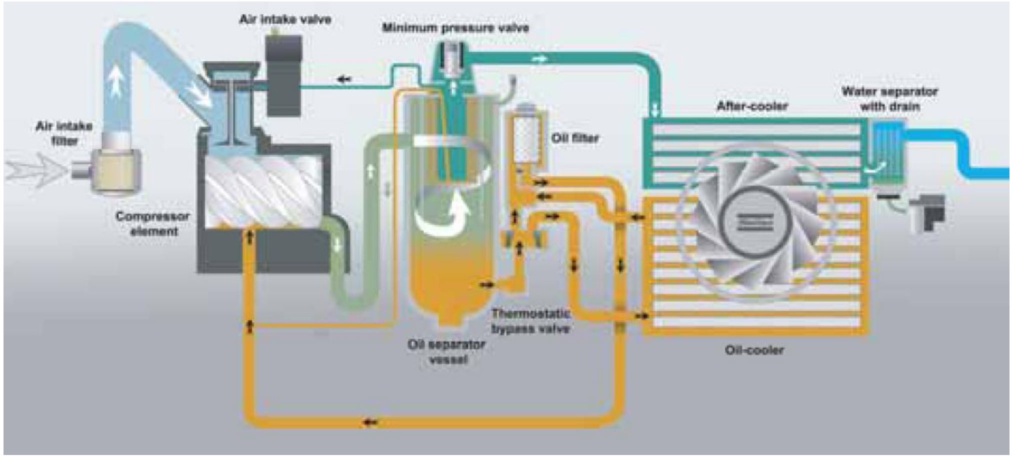

Figure 8: Oil Lubricated Screw Compressor and After-cooler Arrangement [6]

Piping: The function of the piping is to direct ambient air from the source to the compressor and from the compressor through installed system components to the end users in the distribution system. The piping distribution system is the link between supply, storage, and demand. Ideally, the distribution system will be sized to allow the required air to flow with minimum pressure drop. It will supply an adequate amount of compressed air at the required pressure to all of the locations where compressed air is needed.

Control/Instrumentation: Control systems for air compressors vary from the relatively simple to the extremely sophisticated. The simpler control systems, through the use of sensors, monitor the performance of the equipment and alert the operator through the use of lights and/or audible sounds when a set variable is beyond the normal operating range. Most systems automatically initiate a shutdown procedure under certain conditions to prevent equipment damage. With increasing use of remote unattended compressor installations, the demand for the highest degree of protection and reliability has brought much advancement and lessened the need for operator involvement.

Many control systems provide a completely automatic sequence for starting, operating, and shutdown of compressors. The advanced control systems are able to optimize equipment efficiency by controlling one or more variables (flow, pressure, and temperature) to obtain a specified level of performance. Pressure indicators, flow meters, temperature indicators, and differential pressure indicators are examples of key instruments.

1.2 Summary of Best Practices

1.2.1 Performance/Efficiency & Capability-Oriented Best Practices

- There are no best practices directly associated with the efficiency and capacity of compressed air systems.

1.2.2 Reliability/Operations & Maintenance-Oriented Best Practices

- Measure for performance and gather baseline data by using instruments and methods set out in ISO 1217 International Standard [9].
- Compare actual air compressor run time to the expected run time as an indicator of compressor performance and system integrity.
- Restrict reciprocating compressor pulsation limits to +/- 2% of line pressure for safe and reliable operation.
- Do not use medium to high speed reciprocating compressors (i.e., greater than 400 rpm) for hydro plant duty.
- Size generator brake air system capacity to stop all turbine-generator units simultaneously without adding air to the system and without reducing system pressure below 75 psi.
- Supply governor air system by dedicated air compressors. The operating pressure should be approximately 10% above the rated governor system pressure. Compressor capacity should be sufficient to completely pressurize the governor tank with the proper oil level in 4 to 6 hours.
- Size air receiver capacity for governor air system to provide 5 minute compressor running time to raise receiver pressure from atmospheric to system pressure.
- Draft tube water depression system capacity should be sized sufficient to displace the draft tube water to clear the turbine runner in approximately 10 seconds and to 3 feet below the runner in approximately 60 seconds.
- Ensure total pressure drop does not exceed 15 psi across all compressed air system components including piping.
- Develop a formal program to monitor and repair leaks.

- Use a header pipe size at least one size larger than calculated. This will provide additional air storage capacity and allow for future expansion.
- Schedule compressors for weekly running inspection and a yearly major inspection.
- Establish a lubrication schedule for air compressors and establish specific responsibilities for carrying out periodic lubrication.
- Slope all piping in a loop system with accessible drain points. Air outlets should be taken from the top of the main line and install drip legs or drain valves at all low points.

1.3 Best Practice Cross-references

- I&C - Automation
- Mechanical – Lubrication Systems
- Mechanical – Governor
- Electrical – Generator

2.0 Technology Design Summary

2.1 Material and Design Technology Evolution

The idea of using compressed air to transmit energy became popular in the early 1800's as metal manufacturing plants grew and emphasized the limitation of steam power. A plant powered by water and compressed air was built in Wales in the 1820s, and despite a few air leaks, new uses for compressed air began to emerge.

The novelty of many compressed air services started a backlash against electricity by many engineers who saw compressed air as the energy distribution system of the future. However, electricity advocates held strong to their belief that pneumatic plants were inefficient and would eventually be trumped by electricity.

As both energy systems developed, compressed air became an important complement to electricity. Pneumatic tools are lightweight and safe, and compressed air is used for monitoring, control, and regulation frequently in combination with hydraulics and electricity. The electricity and pneumatic systems working together have given the world new ways to use power [7].

2.2 State of the Art Technology

There are two main types of modern compressed air systems: oil-free and lubricated. Depending on the air purification and system requirements, each design is suitable for plant applications. Air purification requirements include general purity, instrument quality, breathing air, and clean dry air. Hydropower facilities generally utilize lubricated compressors producing cool compressed air with minimal treatment. It is also current practice to use instrument quality air for brakes to reduce corrosion and maintenance on pistons for modernized units.

The lubricant is used to alleviate friction between moving parts. In rotary screw compressors, the lubricant also seals clearances and removes heat of compression. The viscosity of the lubricant used depends largely on the operating ambient temperature range. It must offer adequate lubrication for bearings and rotors at operating temperature. In addition, it must have a pour point low enough to provide fluidity at low starting temperature.

A modern lubricated rotary screw compressor and high-efficiency purification system can produce compressed air with very high purity. These systems are very similar to the oil-free system consisting of a wet receiver, an air dryer, and a coalescing filter. These are integrated inside of a sound reduction enclosure (Figure 10). This type of system should be considered when air compressors are replaced/upgraded or when a major modernization to a plant is proposed. A variable-speed drive (VSD) air compressor is also a state of the art technology. This type of compressor uses a variable-frequency drive to control the speed of the unit which in turn saves energy compared to a fixed speed equivalent.

Figure 10: Lubricated Air Cooled Compressor

Downstream from the compressor, an air receiver stabilizes system pressure, serves as a demand reservoir, and holds some moisture. Downstream from the receiver, an air dryer, which will provide the correct pressure dew point, traps the remaining moisture. If either fails, there is a coalescing filter consecutive to the dryer to provide protection. A dry receiver can also be installed after the coalescing filter to stabilize pressure and serve as a reservoir for times of high demand.

Moisture in the form of liquid and vapor is in compressed air as it leaves the system. The system can lose productivity and require significant maintenance if the moisture and other contaminants are not removed properly. Purification devices have been developed to help remove some of the contaminants from the system. As pneumatic applications and compressed air systems become more sophisticated, the proper selection of these devices is crucial. The most critical devices for condensate control are the coalescing filter, drain valve, air dryer, and after filter.

3.0 Operation and Maintenance Practices

3.1 Condition Assessment

Determining the condition of a compressed air system is an essential step in analyzing the risk of failure. There are a number of best practices for assessing the condition of the compressed air system.

Compressor performance testing is intended to assess how well the compressor is working. Measurements usually require special test equipment that will vary depending on the type of equipment. Compressor air flow measurements indicate the functionality of the compressor while it is running and exclude the effects from other system components that will bias the run time data. Compressor air temperature tests measure the effectiveness of the after coolers and/or excessive output temperatures while running. Compressor motor current and megger-resistance to ground tests provide information about the motor condition and input shaft power requirements. ISO 1217 International Standard [9] sets out the instruments and methods for the measurement of performance and gathering of baseline data.

Compressed air system problems can often be detected during the course of physical inspections. Problems that may be observed include substantial air, oil, and water leaks, excessive vibrations, abnormal noise while operating, corrosion, warping, belt tension, or failures on control panels. The known physical condition of the compressed air system is a major indicator of overall system reliability.

A comparison of actual air compressor run time to the expected run time is an indicator of compressor performance and system integrity. An increase in run time indicates a reduction in performance due to worn compressor components (i.e., cylinder wear, ring wear, check valve leakage, or similar wear related effects) [4].

3.2 Operations

<u>Service Air System:</u> The service air system is usually a nominal 100 psi system providing air for maintenance and repair, control air, hydropneumatic tank air, charging air for the brake air system, air via a pressure reducing regulator for wicket gate shear pin alarm systems, and in some cases air for ice control bubblers. This system is supplied by dedicated air compressors. Typical plant service air requirements vary from 75 cfm to 125 cfm with major maintenance requirements supplied by portable sources.

When using a reciprocating compressor, the action of the piston is non-continuous and pressure pulsations will be generated. Depending upon the piping arrangement, these pulsations can be magnified to destructive levels. It is a best practice to restrict reciprocating compressor pulsation limits to +/- 2% of line pressure for safe reliable operation. This can be achieved with the use of pulsation dampers. Installation of orifices or pipe modification may be necessary.

Station service air is typically passed through an aftercooler. The aftercooler is equipped with a moisture separator following compression to lower the air discharge temperature to essentially ambient temperature and remove any entrained moisture that would ultimately condense in the distribution piping system. Aftercoolers are incorporated into virtually all modern compressor installations as an integral part of the compressor.

It is a best practice not to use medium to high speed reciprocating compressors (i.e., greater than 400 rpm) for plant duty. Maintenance costs, excessive pulsation, and associated safety and mechanical issues have resulted in an aversion to the use of lubricated compressors operating above 400 rpm. Typical component mean time between failures (MTBF) for high speed (greater than 100 rpm) for packing, piston ring, and valves is less than 12 months and is less than 6 months for shutdown to repair pulsation related issues [8].

Compressors should be heavy duty, water-cooled, flood lubricated, and cooled rotary screw type rated for continuous duty. Normally, aside from major maintenance, service air should be supplied by two identical compressors each of which is capable of supplying approximately 75% of the requirement [5].

Brake Air System: The brake air system is comprised of one or more semi-independent storage and distribution installations for providing a reliable supply to actuate the generator brake systems. Compressed air is supplied from the service air system, stored in air receivers, and distributed through the governor actuator cabinets to the generator brake systems.

Air is required in the system to stop all turbine-generator units simultaneously without adding air to the system and without reducing system pressure below 75 psi. Each unit may be assumed to require 1.5 cubic ft at 75 psi. Storage capacity calculations should consider the number of brake applications per stop, the maximum brake cylinder displacement with worn linings, and the volume of all piping downstream from the control valve. Each subsystem should be designed to serve two units and include a receiver, piping from the service air system to the receiver, and piping from the receiver to the governor cabinet to the respective generator brake system. Each receiver should be designed, manufactured, and tested in accordance with the ASME Boiler and Pressure Vessel Code VIII Div. 1 [10] and be isolated from the service air system in case of a loss of service air pressure [5].

Governor Air System: The governor air system provides the air cushion in the governor pressure tanks. When the governor system is to be placed in operation, the pressure tank is filled approximately one-fourth full with oil, and the tank is pressurized to governor operating pressure from the governor air system. The governor air system is supplied by dedicated air compressors. Pressures for various sizes of units currently vary from 300 psi to 1,700 psi. The operating pressure should be approximately 10% above the rated governor system pressure. Compressor capacity should be sufficient to completely pressurize the governor tank with the proper oil level in 4 to 6 hours. To reduce this time range, a best practice is to provide a tie to the station air system (large volume) to quickly add compressed air and reduce the time required for the smaller governor air compressor.

The total governor air supply should be provided by two identical compressors, each rated at not less than 50% of the capacity. The compressors should be heavy duty, reciprocating, water or air-cooled, and rated for continuous duty. Package units are preferred. Each package should include compressor, motor, base, aftercooler, controls, and other accessories. Each compressor should be supplied with manual start-stop and automatic load-unload control.

Since manual-start and automatic-unloading control is used for governor air compressors, receiver capacity is required only to assure reasonable control action. A receiver capacity providing a 5 minute compressor running time to raise receiver pressure from atmospheric to system pressure is adequate. Air receivers should be designed, manufactured, and tested in accordance with the ASME Boiler and Pressure Vessel Code VIII Div 1 [10].

Draft Tube Water Depression System: A draft tube water depression system is required in plants with submerged turbine or pump-turbine runners where planned operations include the operation of one or more units at synchronous condenser mode, motor starting for pumping, or spinning reserve. The system function is to displace and maintain draft tube water to a level below the turbine runner permitting the runner to turn in air. The draft tube water depression air system is normally supplied by dedicated air compressors, although some plants supply station service air from the depression air system. System components, particularly receivers and piping, will generally be of large physical size. The minimum system operating pressure during initial depression should be approximately 15 psi higher than the pressure required to depress the draft tube water 3 feet below the runner. Maximum system pressure depends on required displacement volume and receiver capacity, but a nominal 100 psi system will usually be satisfactory.

The system capacity should be sufficient to displace the draft tube water to clear of the turbine runner in approximately 10 seconds and to 3 feet below the runner in approximately 60 seconds, plus additional volume to cover air losses during initial depression. Air must also be available after initial depression to maintain the water level approximately 3 feet below the runner. This includes a control system with pressure switch solenoid valves for the described blow down procedure. An estimate of this air capacity requirement is dependent upon leakage of air through the shaft gland and water leakage through the wicket gates. A reasonable estimate of this requirement is 2 cfm per foot of unit diameter at the wicket gates. The capacity for initial draft tube water depression must be available in receivers due to the brief, high flow requirement. Receivers should be designed, manufactured, and tested in accordance with the ASME Boiler and Pressure Vessel Code VIII Div. 1 [10].

The total draft tube water depression air supply should be provided by two identical heavy duty, water cooled, reciprocating, or flood-lubricated and cooled rotary screw compressors suitable for continuous duty, each rated at no less than 50 to 60 percent of the required capacity [5].

Air System Control: Most compressors are controlled by line pressure. A drop in pressure normally signifies a demand increase. This is corrected by increased compressor output. A rise in pressure usually indicates a decrease in demand which causes a reduction in compressor output. To accommodate the fluctuating demand, a load/no load or constant speed control can be used to run the compressor at full load or idle. Either a single compressor or a multiple compressor installation, which is either centralized or decentralized, can provide the entire plant supply. There are three other types of compressor control systems:

> Auto-dual control: Most traditional modulating controls throttle the capacity 30%-50% before fully unloading the compressor. This type of modulation is known as auto-dual control. It combines start/stop and constant speed control into a single control system. Auto-dual control automatically selects the most desirable control method and runs the compressor in constant speed control. When the compressor unloads, an unloaded run timer energizes which usually has a time range of 5 to 60 minutes. If the compressor does not reload, the timer will shut the compressor off. The compressor will restart and reload when the pressure switch senses low pressure.

> Sequencing**:** Sequencing is also known as a central controller. This has the advantage of little cost per compressor and is usually available for systems with up to 10 compressors. A sequencer should have a single pressure transducer in the air header. Logic should maintain a target pressure within +/- 5 psi. The sequencer should automatically start and stop compressors, as well as load and unload them.

The control should be set to rotate the order of loading and unloading to optimize compressor combinations for different demand conditions.

Lead/Lag: Lead/lag controls are typically found on reciprocating compressors. When there are two compressors in the system, one compressor can be set as the lead compressor, and the other as the lag compressor. When the pressure drops to a certain point on the lead compressor, the lag compressor will then take over. These can also be switched so that the other compressor is the lead compressor. This periodic switching is to equalize wear.

Piping Distribution: The compressed air travels through a network of pipelines. The flow creates friction and results in pressure drop. The pressure drop should never exceed 1-2 psi per branch. The longer and smaller diameter the pipe is, the higher the friction loss. To reduce pressure drop effectively, a loop system with two-way flow can be used. Pressure drop caused by corrosion and the system features are important issues. These typically range from 5-25 psi and their control is essential for the efficiency of the system. The control air receiver located after the compressor should be sized for about 1 gallon capacity per CFM of compressor capacity. To ensure an effective demand side control management system, the storage air receiver should be sized for about 2-4 gallon capacity per CFM of compressor capacity. Total pressure drop should not exceed 15 psi across all compressed air system components including piping [7].

3.3 Maintenance

Whole System: Preventive maintenance is crucial. Leaks are one of the biggest maintenance issues and can be very expensive. For example, one ¼" diameter opening equals 100 CFM at 90 psig. This is equivalent to running a 25 horsepower compressor. However, developing a formal program to monitor and repair leaks can help control or prevent leakage. If a leak goes undetected, it can eventually cause the entire system to be shut down.

An air receiver near the compressor should be located to provide a steady source of control air, additional air cooling, and moisture separation. In the distribution system, there may be periodically large volume demands which will rapidly drain the air from surrounding areas and cause pressure levels to fall for surrounding users. However, strategically located receivers in the system can supply these abrupt demands and still provide a consistent air flow and pressure to the affected areas.

It should be selected that piping systems have low pressure drop and provide corrosion free operation. Consideration should be given to the use of 300 series stainless steel piping due to its strength, weight, and corrosion resistant characteristics. The main air header is sized for a maximum pressure drop of 1 to 2 psi (.07 to .14 bar). A good rule is to use a header pipe size at least one size larger than calculated. This will provide additional air storage capacity and allow for future expansion.

It is suggested that all piping in a loop system be sloped to accessible drain points. Air outlets should be taken from the top of the main line to keep possible moisture from entering the outlet. Drip legs or drain valves should be installed at all low points in the system where it is possible for moisture to accumulate [7].

<u>All types of Compressor</u>: A well-maintained compressor, in addition to having less downtime and repairs, will save on electrical power costs as well. The following is the best practice for inspection schedules of compressors:

> <u>Daily Inspection:</u> The operator shall inspect the compressor daily for the following conditions: (a) unusual noise or vibration, (b) abnormal suction or discharge pressure or temperature, (c) abnormal oil pressure when force-fed lubrication is provided, (d) abnormal bearing temperatures, (e) overheating of motor, and (f) oil leaks.
>
> <u>Annual Inspection:</u> Once a year or as required, depending on the severity of service, clean and inspect the compressor for the following conditions: (a) corrosion or erosion of parts, (b) proper clearances, (c) correct alignment, (d) worn or broken timing gears, (e) timing gear setting, (f) operation and setting of safety valves, and (g) wear of shafts at seals.

Establish a lubrication schedule for air compressors and specific responsibilities for carrying out periodic lubrication. Normal oil levels must be maintained at all times. Use only lubricants recommended by the manufacturer. Frequency of oil changes is dependent upon severity of service and atmospheric dust and dirt. The time for oil changes can best be determined by the physical condition of the oil. When changing oil, clean the inside of the crankcase by wiping with clean, lint-free rags. If this is not possible, use a good grade of flushing oil to remove any settled particles.

When replacing fibrous packing, thoroughly clean the stuffing box of old packing and grease. Cover each piece of new packing with the recommended lubricant. Separate the new rings at the split joint to place them over the shaft. Place one ring of packing at a time in the stuffing box and tamp firmly in place. Stagger the joints of each ring so they will not be in line. After the last ring is in place, assemble the gland and tighten the nuts evenly until snug. After a few minutes, loosen the nuts and re-tighten them finger-tight [2].

Reciprocating Type Compressors: Cylinder jackets of water-cooled compressors should be cleaned annually with water. Dirt accumulations interfere with water circulation. Cleaning can be accomplished using a small hose nozzle to get water into the jackets. For compressors fitted with mechanical lubricators, cylinders may be cleaned with a nonflammable cleaning fluid.

Replace all defective valve parts as required. When a valve disk or plate wears to less than one-half its original thickness, it should be replaced. Valve seats may be resurfaced by lapping or regrinding. On some valve designs it is necessary to check the lift after resurfacing. If the lift is found to be more than that recommended by the manufacturer, the bumper must be cut down an equal amount. Failure to do this results in more rapid valve and spring wear. Carbon deposits should be removed and the valve assembly washed in nonflammable cleaning fluid. Before replacing valves, make sure the valve seat and cover plate gaskets are in good condition. If any defects are found, replace the gaskets. Make sure the valve is returned to the same port from which it was removed. Carefully follow the manufacturer's instructions for valve removal and replacement

When replacing worn piston rings, the new rings must be tried in the cylinder for fit. If the cylinder wall is badly scored or out of round, re-bore the cylinder, or if cylinder liners are fitted, replace them. If necessary to file for end clearance, take care to file the ends parallel. Clean the ring grooves and remove any carbon deposits before installing the new rings. Make sure the ring is free by rotating it in its groove. Stagger the ring gaps of succeeding rings so they are not in line. Use a ring clamping device when reinstalling the piston. If this is not available, wire the rings tightly so they enter the bore easily. Consult the manufacturer's instructions for carbon ring replacement.

Always check piston end clearance after replacing pistons or after adjustment or replacement of main, crankpin, wristpin, or crosshead bearings. Consult the manufacturer's instructions for proper clearances and method of clearance adjustment. To measure piston end clearance, insert a length of l/B-inch diameter solder into the cylinder through a valve port and turn the compressor over by hand so that the piston moves to the end of its stroke. Remove the compressed solder and measure its thickness to determine the piston end clearance [2].

Rotary Screw Type Compressors: Timing gears maintain the compressor impellers in proper rotative position and hold impeller clearances. They must be securely locked to their shafts in proper position. Gears or impellers that have been removed for repair must be returned to their original positions. When installing new or repaired parts, carefully follow the manufacturers' instructions for setting clearances. Clearances must be set accurately or damage to the machine may result from impeller rubbing.

Rotary twin-lobe compressors are normally fitted with mechanical seals. Seals should be kept free of dirt, dust, and foreign matter to ensure long life. Sealing faces are lapped together during manufacturing and the entire assembly must be replaced when defective seals are found. Use extreme care when installing seals to prevent marring of the sealing faces. Be sure that the lapped sealing faces are free of scratches, dust, or finger marks before installation. Carefully follow the manufacturers' instructions when replacing mechanical seals.

Rotary twin-lobe compressors are normally fitted with anti-friction ball or roller bearings. Worn or defective bearings should be replaced. Wear to bearings may allow the impeller shaft to shift position until a cylinder rub develops or the impellers begin rubbing. Carefully follow the manufacturers' instructions when replacing bearings.

Leave sufficient space around the compressor to permit routine maintenance. It is also suggested to provide space for the removal of major components during compressor overhauls. Be sure to provide sufficient ventilation for all equipment that may be installed in the compressor room. All compressor manufacturers publish allowable operating temperatures [2].

4.0 Metrics, Monitoring and Analysis

4.1 Measures of Performance, Condition, and Reliability

Leakage of compressed air is a problem at any installation and, if not corrected, will result in significant monetary losses. Leakage can result from corrosion in underground piping, damaged joints, and defective fittings and valves. A relatively simple test has been devised which rapidly and economically determines whether a distribution line is leaking and if so, the magnitude of the losses.

A common measure for evaluation of losses in compressed air systems is listed below:

In determining the air losses, use the following mass loss formula [2]:

$$Q = \frac{35.852\,V}{(T + 460)(t_f - t_i)}(P_i - P_f)$$

Where: Q = volumetric airflow (scfm)

V = volume of tank, ft^3

T = temperature, °F

P = pressure, psig

t = time, minutes

i = initial

f = final

In standard ISO 1217:2009 [9], a formal displacement compressor test is detailed as well as the measurement equipment and methods are defined. These are utilized in a defined performance test procedure.

4.2 Data Analysis

The following steps must be performed to complete a pressure decay test:

- Obtain scale drawings of the section to be tested. Verify drawings in the field and calculate the volume of the section to be tested.
- Install a pressure gauge at a convenient location.
- Secure all loads the line supplies.

- Isolate the line from the compressed air system.
- Immediately begin taking readings at the pressure gauge but do not commence the data readings the moment the valve is closed. Observe the pressure gauge and begin timing when the pointer passes a convenient mark. Example: On a 100 psig system, wait for the pressure gauge to reach 95 psig before starting the stopwatch.
- Note the time at convenient pressure intervals (5 or 10 psi increments). Continue data recording until 20 psig is reached.
- Using the field data, construct a chart as shown in table (Figure 11). The LOSS column values (Q) are calculated by using the field data in formula above.

Pressure (psig)	Average Pressure (psig)	Time (min:sec)	Time (min)	Loss (scfm)
90-80	85	10:42	10.70	40
80-70	75	23:17	23.28	34
70-60	65	38:34	38.57	28
60-50	55	58:56	58.93	21
50-40	45	87:28	87:47	15
40-30	35	135:01	135.02	9
30-20	25	277:40	277.67	3

Figure 11: Typical Calculation of Losses Table

- On graph paper, plot Q on the Y axis and P on the X axis.
- Using linear regression, calculate the equation for the best fitting straight line (Figure 12) and solve for $Q_{nominal}$. $Q_{nominal}$ is defined as normal operating pressure [2].

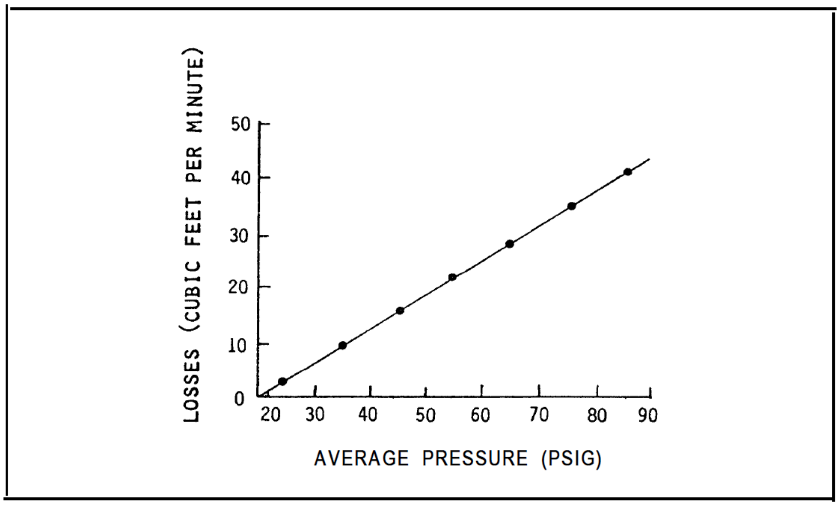

Figure 12: Typical Loss (cfm) vs. Pressure (psig) graph

Analysis of test data (test report) is also defined in standard ISO 1217 [9].

4.3 Integrated Improvements

$Q_{nominal}$ represents the loss in the compressed air system at operating conditions, assuming a constant pressure over the length of pipe in question. This value, taken with the activity's cost to produce compressed air, can be used as justification to develop projects to repair or replace sections of compressed air line.

Interpretation of test data and recommended actions are also defined in ISO 1217:2009 [9].

5.0 Information Sources:

Baseline Knowledge:

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8. Forsthoffer, W., E., *Best Practice Handbook for Rotating Machinery* – 2011

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9. ISO 1217:2009 *Displacement compressors - Acceptance tests - Fourth Edition* – 2009
10. ASME, *Boiler and Pressure Vessel Code VIII Div 1, Rules for construction of pressure vessels* - 2010

It should be noted by the user that this document is intended only as a guide. Statements are of a general nature and therefore do not take into account special situations that can differ significantly from those discussed in this document.

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