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Nuclear Maintenance Applications Center: Condenser Air Removal Equipment Maintenance Guide

Plant Maintenance Support

Reduced Cost

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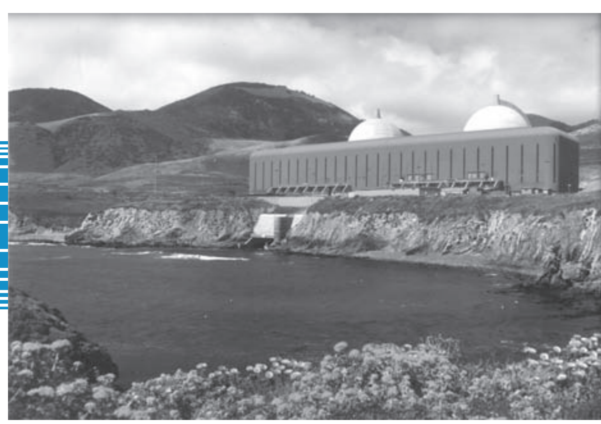

Nuclear Maintenance Applications Center: Condenser Air Removal Equipment Maintenance Guide

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Final Report, December 2007

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REPORT SUMMARY

The *Condenser Air Removal Equipment Maintenance Guide* provides power plant maintenance personnel with current maintenance information on this system. This guide will assist the plant maintenance personnel in improving reliability and reducing maintenance costs for the condenser air removal (CAR) equipment.

Background

Most NMAC member plants use either steam jet air ejectors (SJAEs) or vacuum pumps to remove air and noncondensible gases from the condenser. This equipment is vital for good plant performance because if noncondensible gases are allowed to build up in the condenser, vacuum will decrease and the saturation temperature of the condensate will increase, reducing overall plant efficiency. These undesirable gases can also blanket the tubes of the condenser, which effectively reduces the heat transfer capability of the condenser. For most plants, air-removal equipment also serves to establish an initial condenser vacuum during plant startup.

Objectives

- To describe typical CAR equipment
- To provide guidance on preventive maintenance (PM), repair and replacement, and troubleshooting recommendations for CAR equipment

Approach

The intent of the *Condenser Air Removal Equipment Maintenance Guide* is to address various engineering, maintenance, and operations issues regarding equipment maintenance. Key suppliers of air-removal equipment were solicited for assistance to ensure that the guidance reflected the latest technologies available in the industry. A technical advisory group was formed that consisted of EPRI NMAC utility members and equipment suppliers. Input was solicited regarding current maintenance issues for the equipment. Experience-proven practices and techniques were identified during this effort and are compiled in this report.

Results

This technical report provides an overview of system design parameters and familiarizes maintenance and engineering personnel at power plants with the components used for removing air from condensers and for maintaining vacuum. The focus of the report is to provide guidance for performing PM on the equipment. The report also provides guidance regarding the repair and/or replacement of components and which components are typically repaired or refurbished on site. Troubleshooting guidance is also provided for those components for which it is applicable.

EPRI Perspective

The information contained in this guideline represents a significant collection of technical and human performance information, including techniques and good practices related to CAR equipment that is present at most power plants. This information provides a single point of reference for plant engineering and maintenance personnel, both in the present and in the future. Through the use of these guidelines, EPRI members should be able to significantly improve and consistently implement the processes associated with the reliable operation of their CAR equipment.

Keywords

Vacuum pumps
Air ejectors
Condensers
Maintenance
Preventive maintenance
Troubleshooting

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Name	Company Name
Paul Benard	Gardner Denver Nash
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1
INTRODUCTION

Most Nuclear Maintenance Applications Center (NMAC) member plants use either steam jet air ejectors (SJAEs) or mechanical vacuum pumps (MVPs) to remove air and noncondensible gases from the condenser. This equipment is vital for good plant performance because if noncondensible gases are allowed to build up in the condenser, condenser vacuum will decrease, causing turbine backpressure to increase and reducing overall plant efficiency. If turbine backpressure increases significantly, the plants cannot be operated. The noncondensible gases also blanket the condenser tubes, effectively reducing the heat transfer capability of the condenser. For most plants, air removal equipment is used to establish condenser vacuum during plant startup.

1.1 Purpose

This guide provides information on condenser air removal (CAR) system equipment for boiling water reactor (BWR) and pressurized water reactor (PWR) nuclear power plants. System description and theory of operation on a system level is provided for both BWRs and PWRs, highlighting some of the different CAR equipment configurations. Specific information on the functional description and application at a component level is provided for the SJAEs and MVPs to assist nuclear power plant maintenance personnel in troubleshooting and maintaining SJAEs and MVPs. A discussion of SJAE and MVP characteristics and components that serves as a reference for understanding the basics of their performance and mechanical construction is also provided. Preventive maintenance (PM) guidance is provided to assist in improving the component reliability. Component failure data and failure modes are also included to assist in improving reliability and troubleshooting. A troubleshooting guide is provided to assist in diagnosing problems. Data for this guide were obtained from experience in nuclear plants, review of industry surveys and industry failure reports, and vendor input.

1.2 Organization

The organization of this guide is as follows:

- Section 1 provides an introduction and discussion of the guide’s purpose and organization.
- Section 2 provides a glossary of acronyms and definitions used in the guide.

- Section 3 provides a system description and the theory of operation on a system level for the CAR systems of BWRs and PWRs, highlighting the different possible configurations. To provide a more complete understanding of the process for removing and treating noncondensible gases in BWR condensers, a brief description of the effect of the BWR off-gas treatment system on condenser vacuum is also provided.
- Section 4 provides specific information on the functional description and application at a component level for the SJAEs and MVPs.
- Section 5 provides failure data and failure modes. All available sources, such as Institute of Nuclear Power Operations (INPO), Equipment Performance and Information Exchange (EPIX), NRC, vendor notices, and member records were used to identify failure modes of concern to power plants.
- Section 6 provides guidance for troubleshooting and corrective actions.
- Section 7 provides a discussion of condition monitoring.
- Section 8 provides guidance for PM.
- Section 9 provides a list of references.
- Appendix A provides an industry CAR equipment failure history.
- Appendix B provides a list of all the key points indicated in the guide.
- Appendix C provides an explanation of SJAE terminology.
- Appendix D provides a training overview of this guide and its contents.

1.3 Key Points

Throughout this guide, key information is summarized in “key points.” Key points are bold lettered boxes that succinctly restate information covered in detail in the surrounding text, making the key points easier to locate.

The primary intent of a key point is to emphasize information that will allow individuals to take action for the benefit of their plant. NMAC personnel, the consultants, and the utility personnel that prepared this guide selected the information included in these key points.

The key points are organized according to three categories: operation and maintenance (O&M) cost, technical, and human performance. Each category has an identifying icon, shown as follows, to draw attention to it quickly when reviewing this guide.

Key O&M Cost Point

Emphasizes information that will result in reduced purchase, operating, or maintenance costs.

Key Technical Point

Targets information that will lead to improved equipment reliability.

Key Human Performance Point

Denotes information that requires personnel action or consideration in order to prevent injury or damage or ease completion of the task.

Appendix B contains a listing of all of the key points in each category. The listing restates each key point and provides reference to its location in the body of the report. By reviewing this listing, users of this guide can determine whether they have taken advantage of key information that the writers of the guide believe would benefit their plants.

2
GLOSSARY OF TERMS

2.1 Acronyms

ASTM	American Society for Testing and Materials
BWR	boiling water reactor power plant
cfm	cubic feet per minute
cmm	cubic meters per minute
CAR	condenser air removal
EPRI	Electric Power Research Institute
fpm	feet per minute
Hg	chemical symbol for the element mercury, used as a unit of pressure
HP	horsepower
HEI	Heat Exchange Institute
kPa	kilopascal, a unit of pressure equivalent to one thousand newtons per square meter
MK	speed of sound
MVP	mechanical vacuum pump
NMAC	Nuclear Maintenance Applications Center
O&M	operations and maintenance
PCV	pressure control valve
PM	preventive maintenance
psi	pound(s) per square inch

psig pound(s) per square inch, gauge

psia pound(s) per square inch, absolute

PWR pressurized water reactor power plant

SOV solenoid-operated valve, or solenoid valve

2.1 Definitions

2.2.1 Air Binding

Air binding is the displacement of steam in the condenser with excess air that hinders the heat-transfer process.

2.2.2 Condition Monitoring

Condition monitoring is used to describe any task that allows collection of data (periodically or continuously) on the condition of equipment. The purpose of condition monitoring is to discover whether the condition of the equipment has changed and how it has changed. Although the term *predictive maintenance* is commonly used as synonymous with condition monitoring, it is viewed as a subset of condition-monitoring activities for which the task/technology has the capability to support decisions about how long equipment can continue to provide its function before corrective action is needed.

2.2.3 Hydrogen Water Chemistry

The *hydrogen water chemistry* injection system injects hydrogen into the reactor feed pump suctions. Its purpose is to suppress the dissolved oxygen in the reactor water to a sufficient level so that susceptibility of the reactor internals to intergranular stress corrosion cracking (IGSCC) is reduced. Because of radiolytic decomposition of water that occurs in the core, the level of dissolved oxygen in the reactor coolant rises to 100 to 300 ppb. Dissolved oxygen concentrations at these levels increase the potential for IGSCC of highly stressed, sensitized stainless steel. Testing has shown that the injected hydrogen combines with the oxygen and decreases the potential for IGSCC.

2.2.4 Partial Pressure

In a mixture of ideal gases, each gas has a partial pressure. *Partial pressure* is the pressure that the gas would have exerted if it alone occupied the entire volume. Actual real-world gases come very close to this ideal. The total pressure of a gas mixture is the sum of the partial pressures of each individual gas in the mixture. The partial pressure of a gas is a measure of the thermodynamic activity of the gas's molecules. Gases will always flow from a region of higher partial pressure to one of lower pressure, and the larger this difference, the faster the flow.

2.2.5 Standard Cubic Feet (Meter) per Minute

Standard cubic feet (meter) per minute (SCFM or SCMM) is a volumetric flow rate that has been corrected to a standardized pressure, temperature, and relative humidity. The standard ambient conditions are defined by 14.7 psia (101.35 kPa) atmospheric pressure, some temperature (for example, 68°F or 20°C) depending on the standard used, and some relative humidity (for example, 36%, 0%) depending on the standard used.

2.2.6 Vacuum

Vacuum can be viewed as the relative emptiness of a given volume. It is impossible to obtain a perfect vacuum, but it is possible to obtain some level of vacuum, which is defined as a pressure in a system that is below barometric pressure. For convenience, in vacuum engineering design, the term absolute pressure is used. *Absolute pressure* is a pressure above absolute zero pressure (a perfect vacuum). Condenser absolute pressure is also referred to as *backpressure* because it is a pressure exerted onto the turbine exhaust. Another convenient term is *gauge pressure*, which is a pressure measured above barometric pressure. The relationship between the various pressure and vacuum parameters is shown in Figure 2-1.

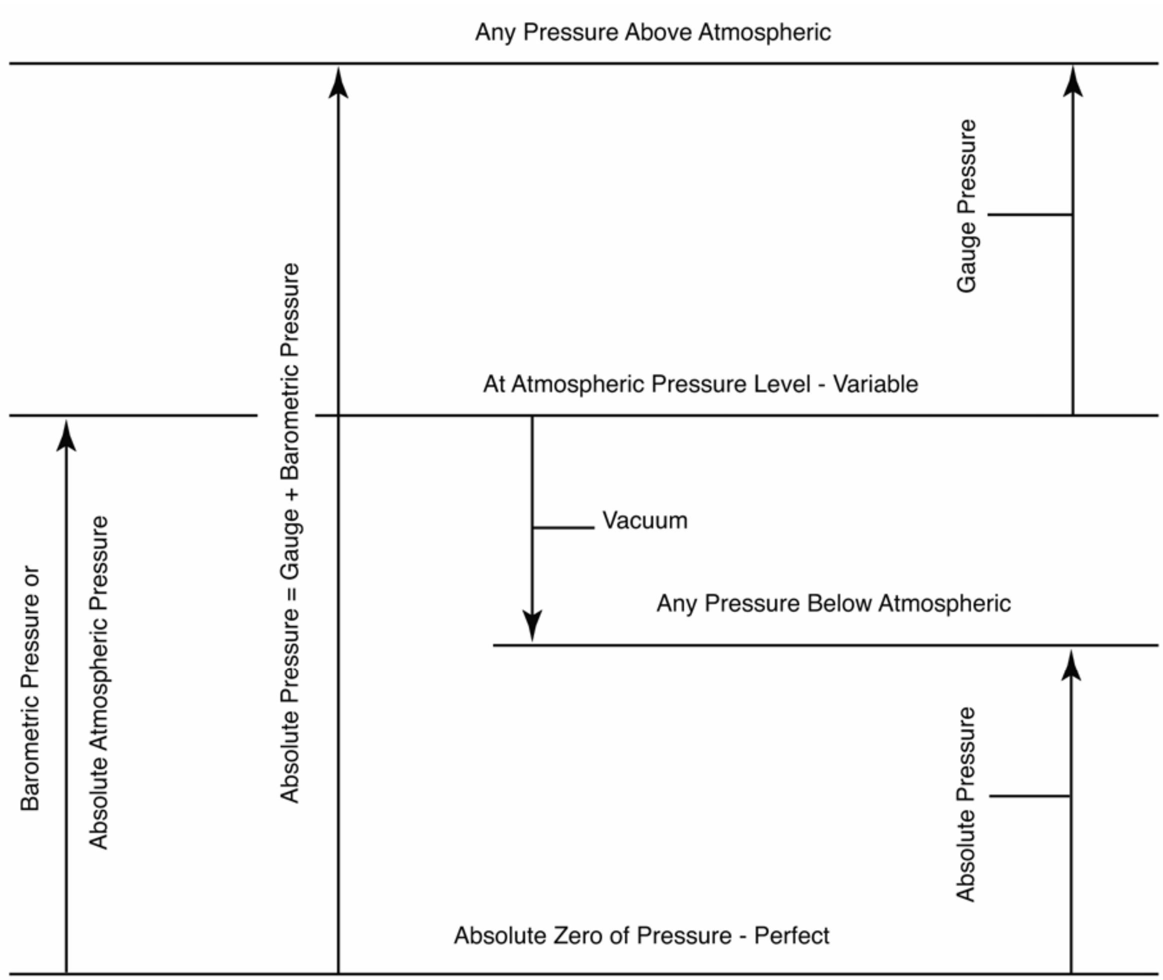


Figure 2-1
Vacuum/Absolute Pressure/Gauge Pressure Relationships
Source: Heat Exchange Institute

3
TECHNICAL DESCRIPTION/TUTORIAL

3.1 Introduction

The CAR system is designed to remove and process noncondensible gases from the main condenser during startup and normal operation. For PWRs, noncondensible gases include in-leakage of air and injected gases, such as nitrogen. For BWRs, noncondensible gases include in-leakage of air and reactor gases, such as hydrogen, oxygen, fission product gases, and nitrogen-16. A *condenser* is a large heat exchanger of the shell and tube type. A typical steam surface condenser is shown in Figure 3-1. Cooling water enters through the waterbox and then travels through the tube sheet and into the tubes. The shell side of the condenser receives steam from the low-pressure turbine exhaust. The steam is cooled to a liquid as it passes over the tubes where the cooling water is circulated and heat is transferred from the steam to the cooling water. For a complete discussion of the condenser components and their functions, refer to EPRI 1003088, *Condenser Application and Maintenance Guide*.

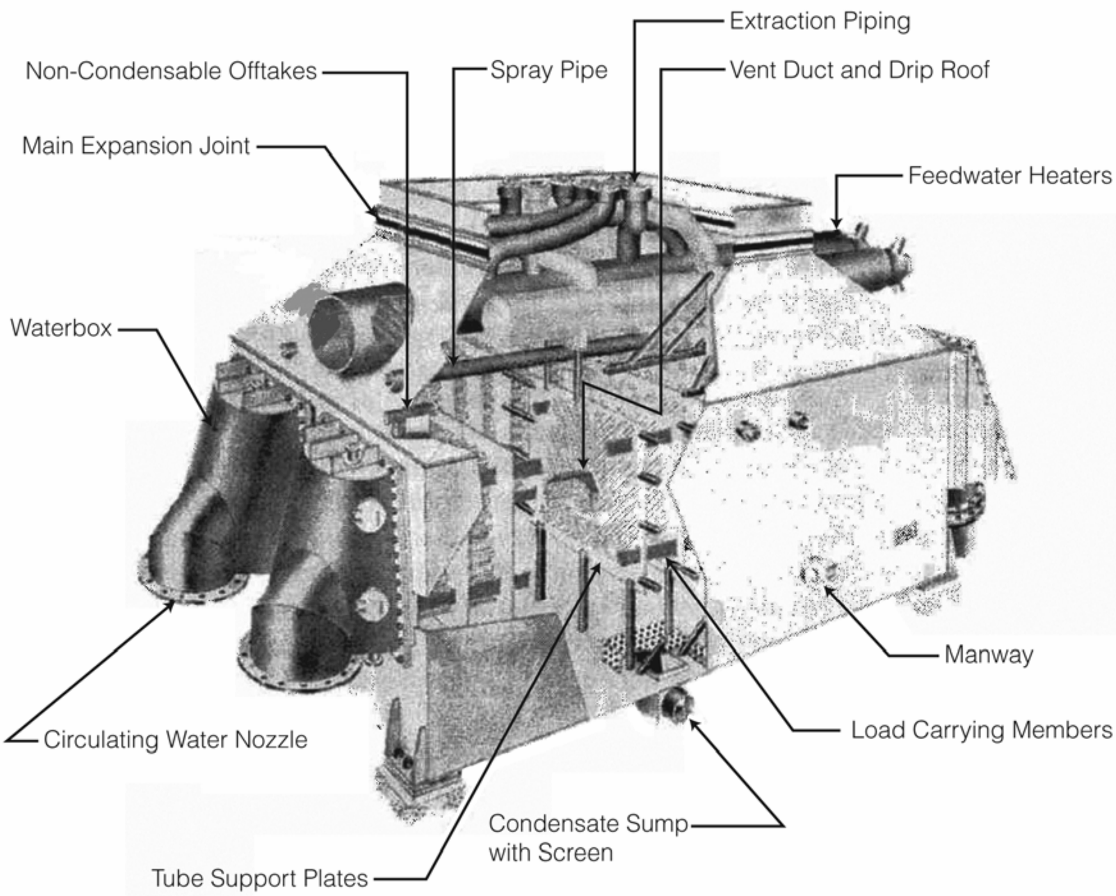


Figure 3-1
Typical Steam Surface Condenser
Source: Senior Engineering Company

Vacuum is produced in the condenser by the condensation of steam to liquid, which causes its specific volume to change. The higher the condenser vacuum, the lower the turbine backpressure. The total work done by the steam flowing through the turbine increases as the difference between the pressure of steam entering the turbine and the backpressure increases. Therefore, the lower the condenser pressure, the more energy that is converted to power in the turbine. The more power produced in the turbine, the greater the output of the turbine and the greater the thermal efficiency. The backpressure is typically between 1 and 3.5 inches Hg (2.5 and 9 cm Hg) absolute.

Key Technical Point

It is the steam condensation process and the specific volume change from steam to liquid that produces the condenser vacuum. The lower the backpressure, the more work that is done by the steam in the turbine.

In addition, a buildup of noncondensible gases around the tubes prevents heat transfer from the steam to the cooling water and, therefore, prevents complete condensation of the steam. Condensers must continually vent noncondensible gases to prevent air binding and the loss of heat-transfer capability. Figure 3-2 shows how noncondensible gas flows within and out of a condenser.

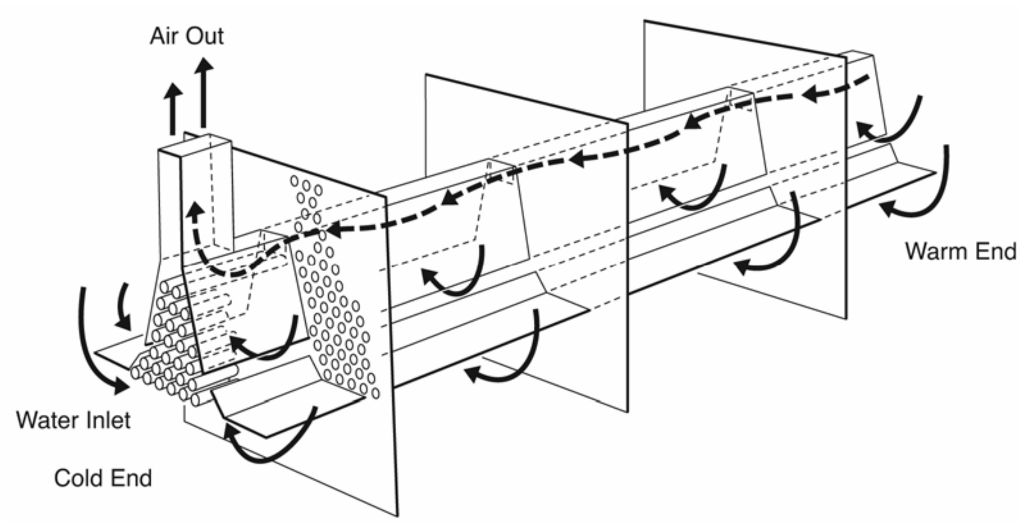


Figure 3-2
Removal of Noncondensible Gas
Source: EPRI TR-107422-V2

Noncondensible gases tend to flow toward the coldest area of the condenser, which is typically the circulating water inlet region of the condenser. This occurs because the partial pressure of the condensing steam is lowest in the cold region. However, having the air outlet at the circulating water inlet might not be possible with all condenser bundle designs.

SJAEs and/or vacuum pumps are used to establish a vacuum in the condenser before startup, and to pull noncondensible gases from the condenser during operation. Along with the noncondensible gases, some water vapor or steam is also removed during operation.

Air-removal equipment must operate in two modes: hogging and holding. Prior to admitting exhaust steam to a condenser, the noncondensible gases must be vented from the condenser. In the hogging mode, large volumes of air are quickly removed from the condenser in order to reduce the condenser pressure from atmospheric pressure to a predetermined level. Once the desired pressure is achieved, the air removal system can be operated in the holding mode to maintain condenser vacuum.

3.2 BWR Off-Gas System

In BWRs, the steam is produced directly in the reactor. As a result, the noncondensible gases that enter a BWR condenser include gases generated in the reactor. The volume of the reactor-generated gases is dependent on power levels in the reactor but is typically an order of magnitude larger than the volume of condenser in-leakage. As an example, in a 1000 MWe BWR power plant condenser, air in-leakage may be on the order of 20 scfm (0.57 scmm), and the gases generated in the reactor may be on the order of 200 scfm (5.66 scmm). Therefore, the equipment used in the holding mode of a BWR is usually an order of magnitude larger in capacity than that used in the holding mode for a PWR.

Reactor-generated gases entering the condenser include:

- Hydrogen and oxygen produced from the radiolysis of water
- Radioactive nitrogen-16 (with a half-life of 7 seconds), nitrogen-13 (with a half-life of 10 minutes), and oxygen-19 (with a half-life of 27 seconds), all produced from the neutron activation of oxygen isotopes
- Fission product gases (primarily radioactive isotopes of xenon and krypton) released as a result of fuel cladding leaks

The BWR off-gas system consists of the CAR system and the off-gas treatment system. Figure 3-3 is a typical schematic of a BWR off-gas system. Typically, two 100% capacity trains are provided. At most BWR facilities, the off-gas treatment system was added later to reduce off-site radiation exposures.

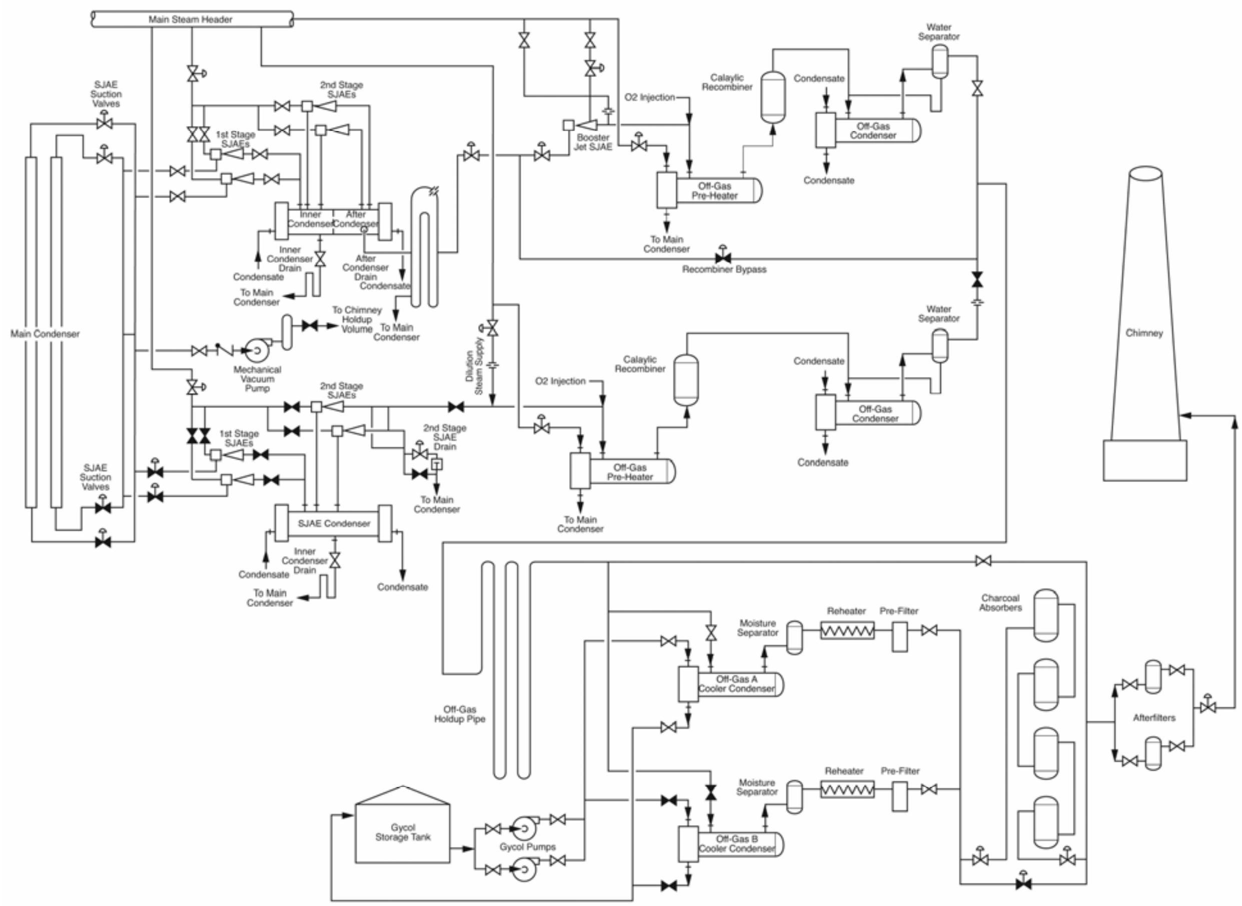


Figure 3-3
Typical BWR Off-Gas System
Source: Sargent & Lundy, LLC

3.2.1 BWR CAR System

The BWR CAR system is designed to remove and process noncondensible gases from the main condenser during startup and normal operation. Typically, the BWR CAR system consists of a first stage SJAE, an inter-condenser, a second stage SJAE, an after-condenser, and a third stage (booster) SJAE. At some BWRs, off-gas pre-coolers, cooled by station service water, are provided upstream of the suction to each first stage SJAE.

As a result of problems with the operation of the BWR off-gas system, many plants have modified the configuration of the second stage SJAE and removed the third stage SJAE altogether. Figure 3-3 shows a BWR plant in which the third stage SJAE was removed in only one of the two 100% trains. Figures 3-4 and 3-5 show expanded views of the CAR portion of the off-gas system for the same plant, for the train with and without the third SJAE. A discussion of each configuration is provided in Section 3.2.1.2.

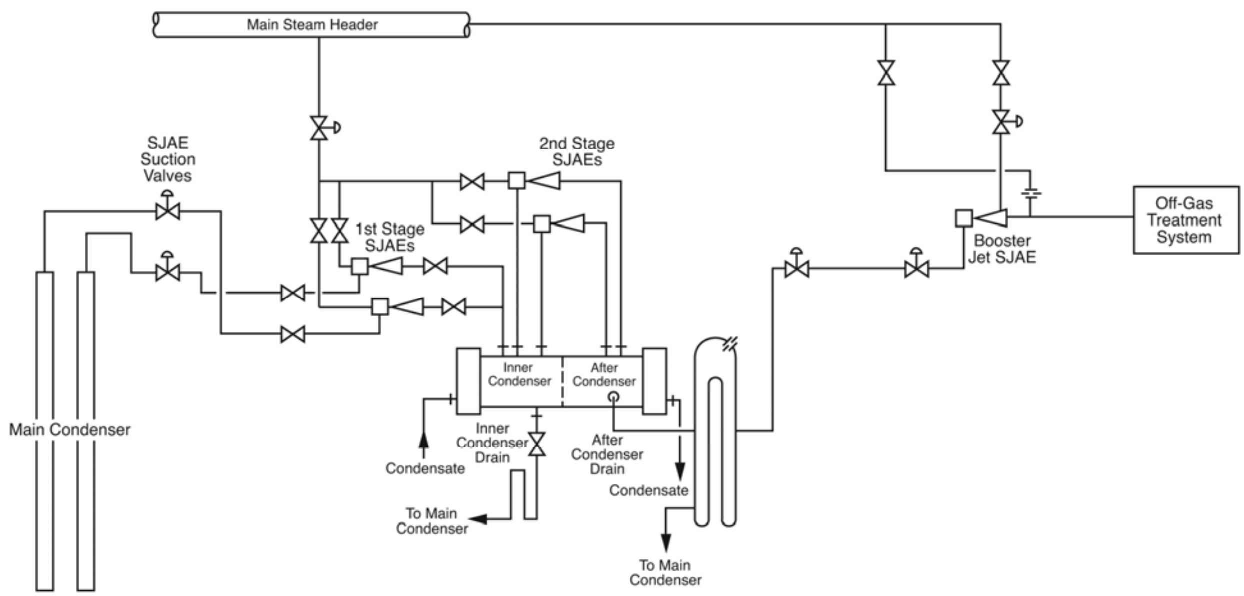


Figure 3-4
BWR CAR System with Booster SJAE
Source: Sargent & Lundy, LLC

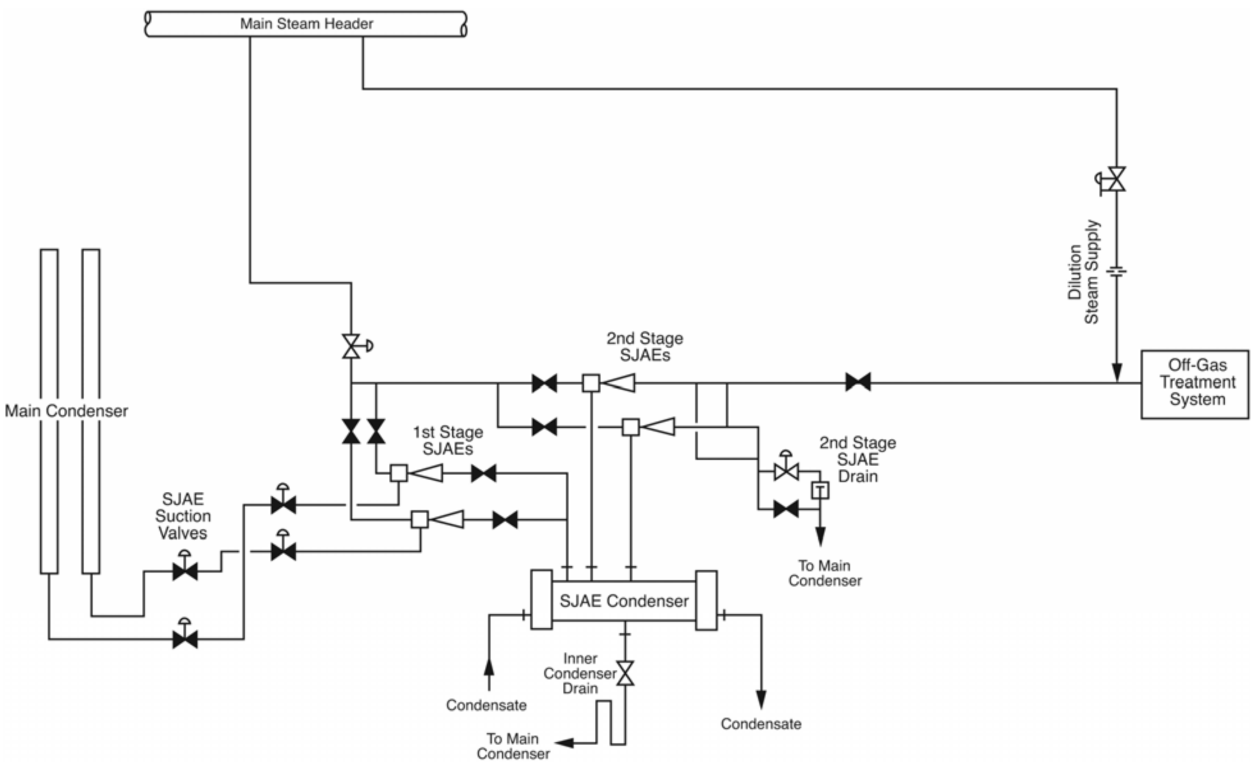


Figure 3-5
BWR CAR Systems Without Booster SJAE
Source: Sargent & Lundy, LLC

3.2.1.1 BWR Initial System Air Removal (Hogging) Mode

As shown in Figure 3-3, an MVP is provided for each condenser to evacuate air from the turbine and the main condenser volumes and to establish a sufficient vacuum during plant startup. One vacuum pump suction line services each main condenser shell.

The MVP takes suction on the common suction line to the SJAEs between the SJAEs and the SJAE suction valves. It is used to draw an initial vacuum in the main condenser, as a result of its much larger capacity than the SJAEs. The MVP discharges to the base of the main chimney.

The BWR MVP is typically a single stage, spiral rotor pump and is designed for a flow rate of about 2300 scfm (65.13 scmm) at 15 inches Hg (38.1 cm) vacuum. Above 15 inches Hg (38.1 cm) vacuum, the MVP flow decreases, and the discharge temperature increases. The MVP will increase the main condenser vacuum to 23–24 inches (58.42–60.96 cm) Hg before it stalls. If left operating, the flow will drop to near zero, and the discharge temperature will rise rapidly to the trip point. The operator should stop the MVP before this trip occurs. The SJAEs should be started and already be drawing off-gas flow before the vacuum pump is tripped.

3.2.1.2 BWR CAR (Holding) Mode

3.2.1.2.1 BWR CAR System with the Booster SJAE

Main condenser suction lines to the first stage SJAEs are connected together into a common suction line. The driving steam flow for the first and second stage SJAEs is a result of the main turbine throttle equalizing header through a pressure control valve (PCV) that maintains steam inlet pressure at ≈125 psig (861.84 kPa).

The first stage SJAEs discharge to the SJAE inter-condenser shell side where the steam is condensed. The *inter-condenser* is a heat exchanger that uses the main condensate on the tube side as the cooling medium. By condensing the steam out of the off-gas flow, the second stage SJAEs do not have to be as large because they have only noncondensible gases to exhaust from the inter-condenser. The condensate created in the inter-condenser shell side as a result of condensing steam drains to the main condenser via a loop seal.

If enough cooling water is not circulated through the SJAE inter-condenser, the cooling water will not be able to condense the steam content of the gas-vapor mixture entering the inter-condenser. The second stage SJAEs then become overloaded because, instead of handling only air, they must also handle the steam that was not condensed. A loss of vacuum will result.

The second stage SJAEs takes suction on the inter-condenser shell side and discharges to the after-condenser shell side, where steam is again condensed and drains back to the main condenser through a level-sensing loop and a level-control valve. Main condensate provides tube-side cooling water for the SJAE after-condenser.

The third stage SJAE (the booster SJAE) takes suction on the after-condenser and discharges to the off-gas pre-heater in the off-gas treatment system. The steam supply for the third stage is the same as for the first and second stages—via two additional stop valves and a different PCV to maintain steam inlet pressure at ≈125 psig (861.84 kPa). This steam is supplied to both the inlet of the SJAE as the driving steam, and to the off-gas line via an orifice as dilution steam to reduce the hydrogen concentration to less than 4% by volume.

Hydrogen is injected into the feedwater as part of the hydrogen water chemistry control process, and some of this excess hydrogen remains in the off-gas. Therefore, oxygen is injected upstream of the catalytic recombiner to ensure that sufficient oxygen is available to completely combine with the excess hydrogen in the off-gas system.

3.2.1.2.2 BWR CAR System Without the Booster SJAE

Off-gas fires upstream of the catalytic recombiners have continued to plague the industry. Dislocated fines of the recombiner catalyst cause these fires. The catalyst fines, in a combustible mixture of hydrogen and oxygen, heat up to the point of gas ignition. The hydrogen and oxygen then burn back to the point where a combustible mixture begins to exist after the second stage SJAE, which is in the after-condenser. The fire then continues to burn there until extinguished.

To resolve this issue, modifications have been installed to eliminate the booster SJAE and to use larger second stage SJAEs. These modifications eliminated the recurring off-gas fires by keeping the gas stream diluted with steam.

As a result of this modification, the discharge of the second stage SJAE releases directly to the off-gas preheater in the off-gas treatment system. A steam trap has been installed on the second stage discharge to return moisture to the main condenser because the after-condenser is bypassed.

3.2.2 BWR Off-Gas Treatment System

The BWR off-gas treatment system is a non-safety-related system that is designed to reduce the off-site exposures at the nearest site boundary to less than the established maximum limit in an effort to minimize the release of radioactive gases by suitable short-term decay and to minimize the release of radioactive particles to the atmosphere. This is achieved by a controlled recombination of the hydrogen and oxygen in the catalytic recombiners and a holdup and filtering process that allows radioactive gases to decay. Figure 3-3 shows the schematic for a typical BWR off-gas system.

Catalytic recombination of hydrogen and oxygen requires that gases be heated above 240°F (115.56°C). Therefore, steam from the line supplying the booster SJAE PCV is injected into the preheaters to heat the steam/gas mixture.

The catalytic recombiner recombines (burns) the hydrogen and oxygen gases into a water vapor. The off-gas condensers cool and condense the superheated steam to water on the shell side. The condenser is a U-tube-type heat exchanger with the off-gas process stream passing through the shell side while main condensate as the cooling water flows through the tube side.

The water separator coalesces entrained water into droplets that drain back to the off-gas condenser. The water separator contains a basket with shredded metal strips, through which all the gas flows. The coalescing takes place on the metal strips.

A physical volume that requires a specific amount of time to transit accomplishes the holdup phase. This volume was sized so that off-gas, with the design flow rates prior to the installation of the off-gas treatment system, would take 30 minutes to traverse the volume. The recombination of the hydrogen and oxygen reduces the off-gas flow rates and transforms the same hold-up volume from 30 minutes without recombination to about 4–6 hours with recombination.

In order for the charcoal adsorbers to operate, the gas must be dry. If too much moisture reaches the charcoal, it will overheat and catch fire. Therefore, the off-gas stream is cooled to approximately 45°F (7.22°C) in the glycol-cooled cooler/condensers, and the condensate is removed by the moisture separator. Then, the gases are reheated by the reheaters to reduce the relative humidity to an extremely low value.

The off-gas leaving the reheater passes through the prefilter for the removal of particulate daughter products in the off-gas stream. Each of the two 100% capacity prefilters consists of a filter assembly holding a removable, high efficiency, water resistant filter element. The filter element is designed to remove 99.97% of the particles that are 0.3 microns or larger in size.

Charcoal adsorbers delay the noble gases (xenon and krypton) by adsorption, allowing greater decay time for longer-lived radionuclides. Particulate daughters of these noble gases are retained in the charcoal beds, and the effluent gases from the absorber beds are discharged to the after-filters. The expected holdup time for xenon is > 30 days, while for krypton it is > 40 hours.

The after-filters receive flow from the charcoal adsorbers and filter out any carbon fines that contain radioactive material and/or particulate daughter products of the off-gas prior to release through the off-gas chimney. Typically, there are two 100% capacity filters installed.

3.3 PWR Off-Gas System

The PWR off-gas system consists of the CAR system and the off-gas filter system. The CAR system is designed to remove air and to establish a condenser vacuum during unit startup and to remove noncondensible gases during normal operation to maintain the condenser vacuum within established limits over the range of condenser circulating water inlet temperatures.

Air and noncondensible gases discharged from the CAR system are sent to the unit vent stack via the off-gas exhaust header. Exhaust gases from the CAR system are monitored by the process radiation monitoring system prior to discharge. A high radiation condition might exist in the event of a primary to secondary leak in the steam generator, along with a high degree of fuel cladding failure. Some PWRs provide only an alarm to alert the operator that a high radiation condition exists. This allows the operator to take manual action to place the off-gas filter in service. Other PWRs are designed with an off-gas filter system that is automatically put into service upon a high radiation signal.

3.3.1 PWR CAR System

The PWR CAR system may be operated in either the hogging mode or the holding mode. Different equipment is used for each mode, but the flow path is similar in either mode. The air-removal equipment takes suction from the main condenser and discharges the air and the noncondensible gases that are removed from the condenser to the plant ventilation stack. In the hogging mode, high capacity air-removal equipment is required. Hogging mode equipment is normally used during start up when the condenser and turbine volumes need to be evacuated. However, the hogging equipment is sometimes put into service during off-normal plant operating conditions when condenser vacuum is rapidly deteriorating as a result of condenser air in-leakage rates beyond the capacity of the holding mode equipment.

In PWRs, MVPs are often used for hogging mode equipment and SJAEs are often used for holding mode equipment. In some PWRs, MVPs are used for both the hogging and holding modes, and in some other PWRs, SJAEs are used for both the hogging and holding modes. The following sections describe the existing combinations of equipment used in the CAR hogging modes and holding modes of PWRs.

3.3.1.1 Combination 1: MVP (Hogging Mode) – SJAE (Holding Mode)

The CAR system removes noncondensible gases from the main condenser during startup, shutdown, and normal operation. MVPs and SJAEs are used to draw noncondensible gases from the condenser and discharge them to the unit vent stack via the off-gas exhaust header. SJAE exhaust gases are monitored by the process radiation monitoring system prior to their release.

Vacuum is drawn by the MVP during startup (hogging mode). For dual-unit plants, there is typically one MVP for each unit and one shared MVP. The MVP takes suction from the condenser through a pneumatically operated suction valve that would fail open on a loss of instrument air and discharges to an air separator tank. A compressant heat exchanger uses non-essential service water to cool the compressant water that is recirculated back to the MVP. The makeup compressant water is supplied from the demineralized water system. The MVP discharges to the off-gas exhaust header and from there to the unit vent stack.

During normal operation (holding mode), one of the two sets of holding SJAEs is operating, and one set is on standby. Air and noncondensible gases are drawn from the condenser by the first stage SJAE via a pneumatically operated suction valve that would also fail open on a loss of instrument air.

In a typical arrangement, the SJAEs are twin element, two stage units with separate inter-condensers and after-condensers. Two first-stage elements are mounted on each side of the inter-condenser, and two second-stage elements are mounted slightly above and on each side of the after-condenser. High velocity steam is used to entrain noncondensible gases to remove them from the condenser. The motive steam is supplied from the main steam crossover header.

The first stage takes suction on the main condenser and discharges to the inter-condenser. The second stage takes suction on the inter-condenser and discharges to the after-condenser. Noncondensible gases leave the after-condenser and go to the off-gas exhaust header.

Cooling for the inter-condenser and after-condenser is supplied by the condensate system. Using condensate as the cooling medium results in increasing plant efficiency by regaining heat which would otherwise be lost. The air ejector inter-condenser drains to its sump, and the air-ejector after-condenser drains to the inter-condenser sump, which drains to the main condenser via a loop seal. When steam pressure is insufficient for air ejector operation, such as during unit startup or shutdown, the MVPs are used to remove noncondensible gases from the condenser. SJAE exhaust gas from the condenser is monitored by the process radiation monitoring system prior to discharge.

3.3.1.2 Combination 2: SJAE (Hogging Mode) – SJAE (Holding Mode)

The PWR CAR process for this combination of equipment functions the same as for combination 1 except that, in place of an MVP for use during startup (hogging mode), a high capacity, single stage hogging SJAE is provided to evacuate the condenser and turbine volumes. The hogging SJAE uses the same suction piping as the first stage SJAEs but discharges directly to the atmosphere through a separate turbine building roof vent. After-condensers are not used with this type of SJAE.

The typical hogging SJAE has a steam consumption of 7,000 lb/hr (3175 kg/hr) and has an air removal capacity of 4,300 lb/hr (1940 kg/hr) at a suction pressure of 10 inches (25.4 cm) Hg absolute. This is in comparison to the typical two-stage holding SJAE, which has a steam consumption of 2,600 lb/hr (1179 kg/hr) and an air-removal capacity of 180 lb/hr or 40 scfm (81.67 kg/hr or 1.13 scmm) at a suction pressure of one inch (2.54 cm) Hg absolute.

The holding SJAEs function is as described in Section 3.3.1.1.

3.3.1.3 Combination 3: MVP (Hogging Mode) – MVP (Holding Mode)

For those plants that use strictly MVPs for both startup (hogging mode) and normal operation (holding mode), there is no differentiation between the equipment used for the hogging mode and that used for the holding mode. In a typical arrangement utilizing only MVPs to remove air and noncondensible gases from the condenser, three, two-stage, motor-driven pumps are provided. The pump suctions and discharges are connected to headers so that one, two, or three pumps can be run as required.

The typical system design is to remove air and establish a condenser vacuum of 25 inches (63.5 cm) Hg during startup and to remove noncondensible gases and water vapor during normal operation to maintain a condenser vacuum between 26.5 and 29 inches (67.3 and 73.7 cm) Hg over the range of circulating water inlet temperatures.

The typical system design capacity is 75 scfm (2.12 scmm), divided equally between the three MVPs. During startup, all three MVPs may be operated to initially evacuate the condenser and turbine volumes. During normal operation, one or two MVPs are operated, depending upon the level of air in-leakage, and the remaining one or two MVPs are placed in standby operation. In the event of excessive in-leakage into the condenser, the MVPs selected for standby operation start automatically when condenser vacuum falls below the MVP starting setpoint.

MVP exhaust gas from the condenser is monitored by the process radiation monitoring system prior to discharge.

3.3.2 PWR Off-Gas Filter System

PWR condenser exhaust gases are normally free of radioactive particles or iodine but could potentially contain these materials in the event of primary-to-secondary steam generator tube leakage. Therefore, these gases are monitored by the process radiation monitoring system. In some cases, there are radiation monitors dedicated to monitoring the condenser exhaust prior to its discharge at the plant vent stack, and, in other cases, the exhaust is routed to the plant vent stack via the controlled access exhaust units, which contain radiation monitors.

There is an off-gas filter system, either one that is dedicated to the condenser exhaust or one that is part of the controlled access exhaust units. This filter system typically consists of a moisture separator, prefilters, an electrical heating coil, HEPA filters, charcoal adsorbers, and centrifugal fans. In dual-unit plants, the off-gas filter system is typically a system common to both units and is capable of filtering the exhaust gases from either unit. During normal operation, the off-gas filter system is typically bypassed, although, at some plants, only the charcoal adsorbers are bypassed.

For those plants with dedicated filter systems for the condenser exhaust gases, the system is typically designed to operate only if high radiation in the exhaust gases is detected by the process radiation monitoring system. The system is designed to operate following the event of a primary-to-secondary steam generator tube leakage in order to filter the potential radioactive particulates and iodine from the exhaust gases.

A water deluge system is provided for the charcoal adsorbers for fire protection purposes. A deluge valve is locally mounted to permit an operator to deluge after performing a visual inspection. The charcoal adsorbers are provided with a temperature switch that senses temperature of air leaving the charcoal adsorbers. When the air temperature exceeds the switch setpoint, it is annunciated in the main control room and at the local panel. Upon manual operation of the deluge valve, the fan is tripped, and the outlet valves are closed. A flow sensor is provided at the fan exhaust to monitor the air flow.

4
APPLICATIONS

Specific information on the functional description and application at a component level for the SJAEs and MVPs is provided in this section to assist nuclear power plant system engineers and maintenance personnel by providing a deeper understanding the equipment and how it functions. A discussion of SJAE and MVP fundamentals of operation that serves as a reference for understanding the basics of their performance and mechanical construction is also included.

Manufacturers provide CAR units or condenser exhaust units (CEUs), which are comprised of SJAEs, atmospheric jet air ejectors (ejectors using air rather than steam as the motive fluid), or MVPs packaged together or separately, along with the necessary supporting components, such as moisture separators, level control valves, steam supply valves, and associated instrumentation. Several of these packaged units, along with the latest hybrid design, are also discussed.

4.1 SJAEs

4.1.1 SJAE Fundamentals

Figures 4-1 and 4-2 show typical SJAEs. Appendix D provides a discussion on SJAE terminology. There are two separate fluid flows involved in the operation of an SJAE. The first fluid is the high-pressure motive steam (other motive fluids, such as air, are sometimes used), which is introduced into the nozzle (Item 3 of Figure 4-1). By expansion in the diverging part of the nozzle, steam pressure is converted into velocity in the supersonic range (3000–4000 ft/sec) (914–1219 m/sec). The second fluid involved is the load (from a vessel or process) and is introduced into the suction of the SJAE (Item 6). The load can be from the main condenser directly or from a preceding SJAE stage or inter-condenser.

In the suction chamber (Item 2), the high-velocity steam exiting from the nozzle continually entrains the load, resulting in reduced pressure at the suction. The resulting mixture, at the resulting velocity, enters the diffuser section where this velocity energy is converted to pressure energy. As a result, the pressure of the mixture at the SJAE discharge is substantially higher than the pressure in the suction chamber.

An SJAE stage has operating limitations on the attainable compression and will operate efficiently only up to a limited ratio of compression. The ratio of compression is the absolute discharge pressure divided by the absolute suction pressure. If greater ratios of compression are required than can be attained in a single ejector stage, two or more stages can be arranged in series. This assembly constitutes a multi-stage ejector.

An SJAE stage is a constant-capacity device. The physical proportions of the diffuser determine the capacity. To obtain increases in capacity, two or more SJAEs, either single or multi-stage, are arranged to operate in parallel, with each series constituting an element of a multiple-element ejector. This arrangement permits the operation of the number of elements needed for the required capacity, as each element is capable of completely compressing a portion of the total capacity.

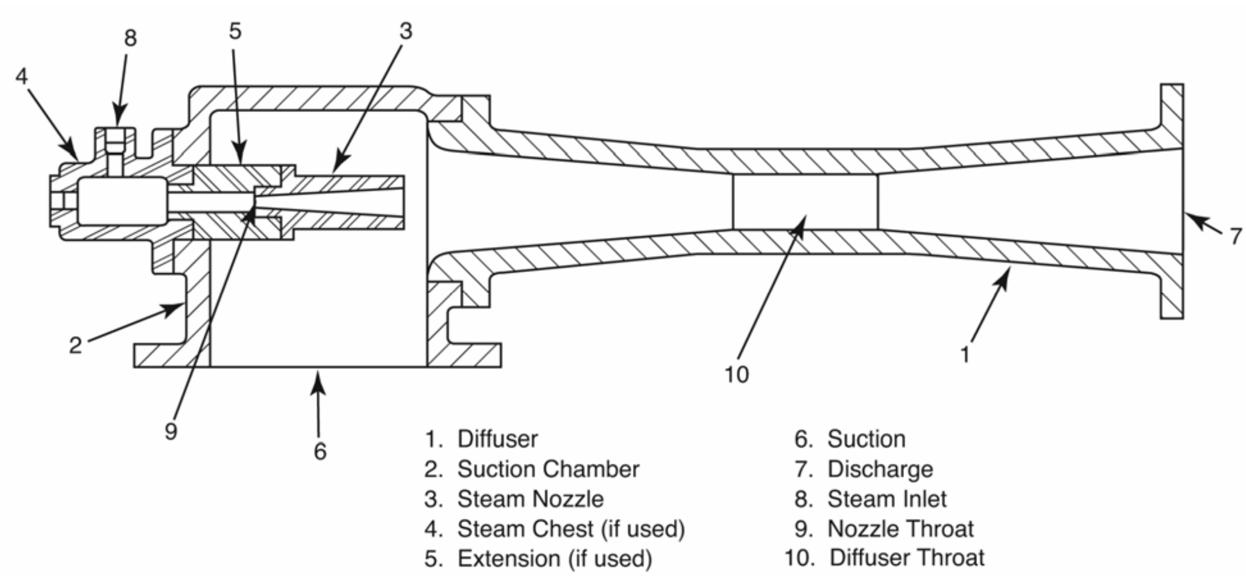


Figure 4-1
Typical SJAE Stage
Source: Heat Exchange Institute

4.1.2 SJAE System Types

Some of the various types of SJAE systems commonly used are illustrated in Figure 4-2a through 4-2h.

4.1.2.1 Single-Stage, Single-Element SJAEs (see Figure 4-2[a])

These consist of one basic assembly that is designed to operate at a suction pressure below atmospheric pressure and to discharge at atmospheric pressure or higher.

4.1.2.2 Single-Stage, Multiple-Element SJAEs (see Figure 4-2[b])

These consist of two or more basic assemblies that are designed to operate at a suction pressure below atmospheric pressure and to discharge at atmospheric pressure or higher. In these combinations, each basic assembly is termed an *element*. The complete unit is termed a single-stage, twin-element SJAE, a single-stage, triple-element SJAE, and so on, depending on the number of elements provided.

4.1.2.3 Multi-Stage, Single-Element SJAEs (see Figure 4-2[c], [d], [f], [g], and [h])

These are two or more basic assemblies arranged in series. The first and any intermediate assemblies of the series are designed to operate at suction and discharge pressures below atmospheric pressure. The final assembly of the series is designed to discharge at atmospheric pressure or higher.

The discharge pressure of the first stage and the suction and discharge pressures of the intermediate stages are selected to best subdivide the total compression among the several stages, according to the particular operating conditions.

A complete series of stages, composed of one basic assembly per stage, is termed a two-stage, single-element ejector, a three-stage, single-element ejector, and so on,, depending upon the number of basic assemblies arranged in series.

4.1.2.4 Multi-Stage, Multiple-Element SJAEs (see Figure 4-2[e])

These consist of two or more multi-stage, single element SJAEs assembled in parallel and arranged to permit the operation of any multi-stage element independently or in combination with others. These SJAEs use common condensers with isolating inter-stage valves or subdivided surface condensers.

4.1.2.5 Condensing and Noncondensing Types

Condensing multi-stage SJAEs have inter-condensers between some or all of the various stages (see Figure 4-2[d] through [h]) for the purpose of condensing as much of the vapor discharged from the preceding stage or stages as possible, in order to reduce the weight of gas to be compressed by the next succeeding stage or stages. Noncondensing multi-stage ejectors have no inter-condensers between stages (see Figure 4-2[c]).

4.1.2.6 Inter-Condensers

Inter-condensers can be of the surface (see Figures 4-2[e] and [g]) or direct contact (Figure 4-2[d], [f], and [h]) type. Surface condensers are typically shell-and-tube type.

Multistage SJAE systems can have more than one inter-condenser. The inter-condenser operating at the lowest absolute pressure is the first inter-condenser and that following the next stage, the second inter-condenser, and so on.

4.1.2.7 After-Condensers

Condensers arranged to condense the vapors discharged from one or more single-stage SJAEs or from the final stage or stages of a combination of' SJAEs at approximately atmospheric pressure are termed *after-condensers*. These may be of the surface or direct-contact type.

4.1.2.8 Surface Inter-Condensers and After-Condensers

Surface inter-condensers and alter-condensers can be arranged in separate shells (as in Figure 4-2[g]) or can be combined in a common shell suitably subdivided (as in Figure 4-2[e]).

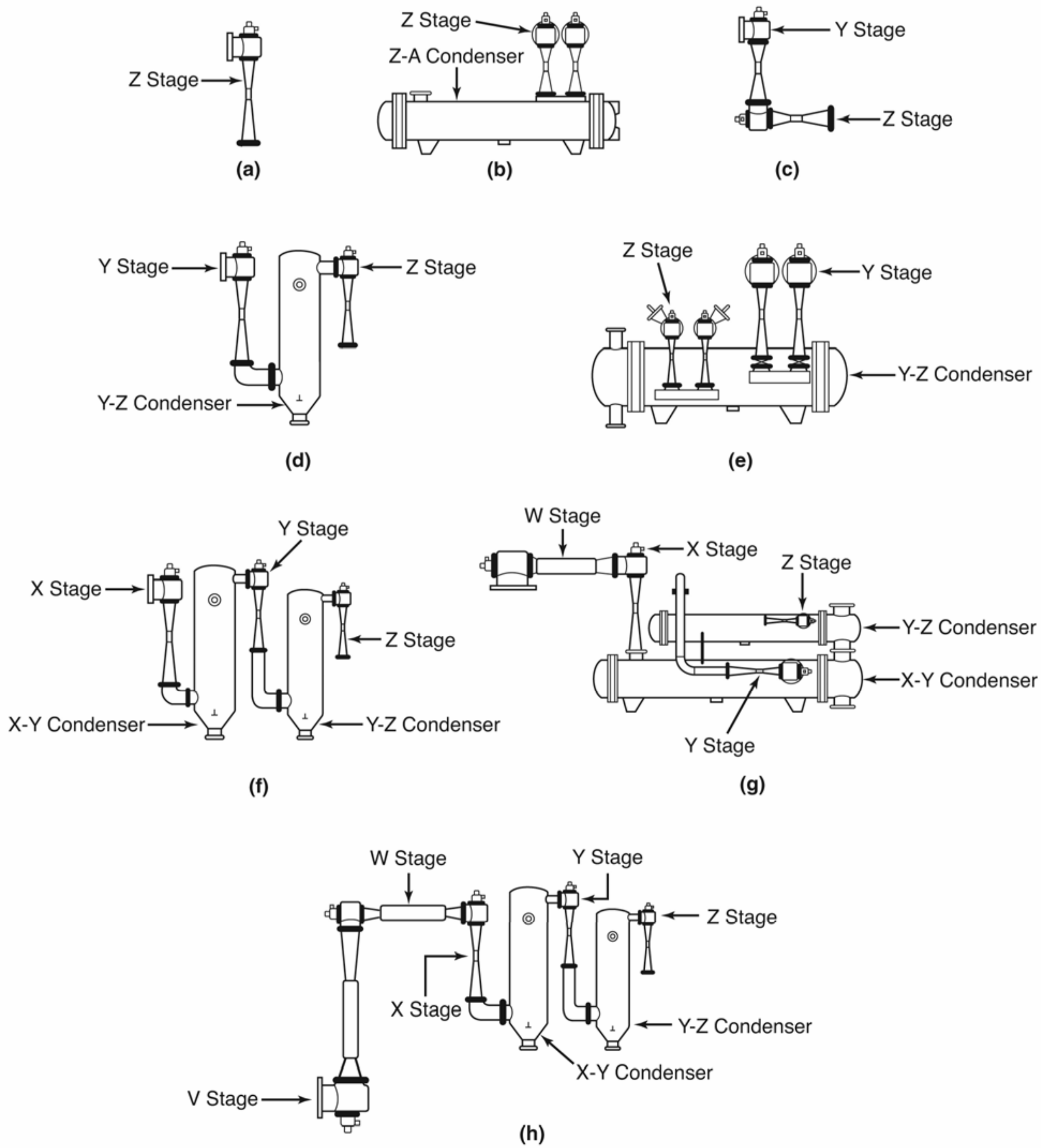


Figure 4-2
Common Types of Ejector Units
Source: Heat Exchange Institute

4.1.3 SJAE Applications

4.1.3.1 Boiling Water Reactors

Figure 3-4 shows typical BWR CAR system configurations. BWRs use SJAE systems for the holding mode of CAR because the large volumes of gases generated in the reactor (see Section 3.2) make the use of MPVs impractical. For those plants that have maintained the booster SJAE, there are typically two trains of equipment. Each train is comprised of a two-element, two-stage SJAE with an inter-condenser and an after-condenser. The booster SJAE is downstream of the main SJAE and is a single-stage, single-element, noncondensing SJAE. The discharge of the booster SJAE is not condensed because, as discussed in Section 3.2.1.2, dilution steam is needed to reduce the off-gas hydrogen concentration to < 4% by volume.

For those plants that have removed the booster SJAE, there are typically two trains of equipment. Each train is comprised of a two-element, two-stage SJAE with an inter-condenser but no after-condenser. The discharge of the second-stage SJAE is not condensed because dilution steam is needed to reduce the off-gas hydrogen concentration to < 4% by volume.

4.1.3.2 Pressurized Water Reactors

For those PWRs that use an SJAE in the hogging mode, there is typically one high capacity, single-element, and single-stage noncondensing SJAE that takes suction from the main condenser and discharges directly to the atmosphere.

For those PWRs that use SJAEs in the holding mode, there are typically either two or three elements of a two-stage SJAE with both an inter-condenser and after-condenser. The first stage takes suction from the main condenser, and the after-condenser discharges to the atmosphere. The SJAE condensers drain back to the main condenser via a loop seal and SJAE condenser hotwell level control arrangement.

Also, as will be discussed in more detail later, there are some PWRs that have CAR units that are designed with a single-stage, noncondensing atmospheric jet air ejector that takes suction from the main condenser and discharges into the suction of a single-stage, liquid ring vacuum pump.

4.2 Rotary Screw MVP

The rotary screw MVP is comprised of spiral rotor MVPs and helical rotor MVPs. The theories of compression between the two are similar except that the spiral rotor is a single-stage, low-pressure pump, and the helical rotor is a two-stage, high-pressure pump. Rotors for these two designs are different. For the spiral rotor MVP, the main rotor has two lobes, and the gate rotor has four matching grooves. For the helical rotor MVP, the main rotor has four lobes, and the gate rotor has six matching grooves.

4.2.1 Spiral Rotor MVP

4.2.1.1 Theory of Operation

As shown in Figures 4-3 and 4-4, the spiral rotor MVP consists essentially of just two moving parts: a four-grooved gate rotor (at the top) and a mating two-lobed main rotor mounted directly below it.

The shaft of the main rotor extends outside of the housing and is driven at high speed by an external driver. The gate rotor is driven from the main rotor shaft by helical timing gears. The gate rotor operates at half the speed of the driving main rotor.

The intake connection is located on one side of the housing at the timing-gear end, and the discharge opening is located on the opposite side, at the drive-shaft end. Therefore, the flow of air through the compressor is both rotary and axial.

During rotation and throughout the meshing cycle, the rotors do not come into contact, as timing gears preserve the 2 to 1 rotor speed ratio and the predetermined rotor clearance relationship. Each rotor shaft is supported and held by means of anti-friction bearings.

The compression cycle starts as the rotors unmesh at the inlet port. As rotation proceeds, the fluid to be compressed is drawn into the cavity between the main rotor lobes and into the grooves of the gate rotor, such as the suction stroke of a reciprocating compressor. The fluid is trapped in these pockets and follows the rotational direction of each rotor. As soon as the inlet port is closed, the compression cycle begins as the fluid is directed to the opposite, or discharge, side of the compressor. The rotors mesh, reducing the normal free volume, thus increasing the pressure. The reduction in volume continues, resulting in an increase in pressure until the closing pocket reaches the discharge port.

Leakage loss of compressed fluid is held to a minimum by maintaining safe minimum clearances between the meshing rotors, housing, and end walls. These clearances restrict fluid flow from the discharge to the inlet. Because there is no contact between the rotor lobes, housing, or end walls, no internal lubrication is required.

Each rotor shaft is equipped with anti-friction bearings. Self-aligning spherical roller bearings are used at the discharge end of the compressor, while single-row ball bearings are used at the inlet end of the compressor. All bearings are mounted in bearing cartridges fitted in bearing carriers, thus permanently locating the rotors within the housing. Thermal expansion of the rotors causes axial movement of the rotor shafts. The ball bearings allow this axial movement on the inlet end of the rotor shafts, while the spherical roller bearings restrain the axial movement on the discharge end of the rotor shafts.

The MVP is equipped with standard labyrinth seals with water slingers. The addition of a water slinger prevents any water from entering the bearing cavity and mixing with the lubricating oil. The standard labyrinth seal with water slinger consists of a stationary, Babbitt-lined seal bushing and a rotating grooved seal sleeve. The seal sleeve is held in position on the rotor shaft by the stack-up of water slinger, oil slinger, and bearing. The heat of compression causes the rotor shaft and seal sleeve to expand, thereby displacing the seal bushing Babbitt lining and creating an effective seal.

The MVP is equipped with an internal, self-contained, forced-feed lubrication system. An oil reservoir is provided in the inlet end-bearing carrier to supply oil to the gear-driven oil pump. Oil from the pump is filtered and distributed to each bearing and the timing gears. The MVP is provided with pump trip switches for high discharge temperature and low oil pressure.

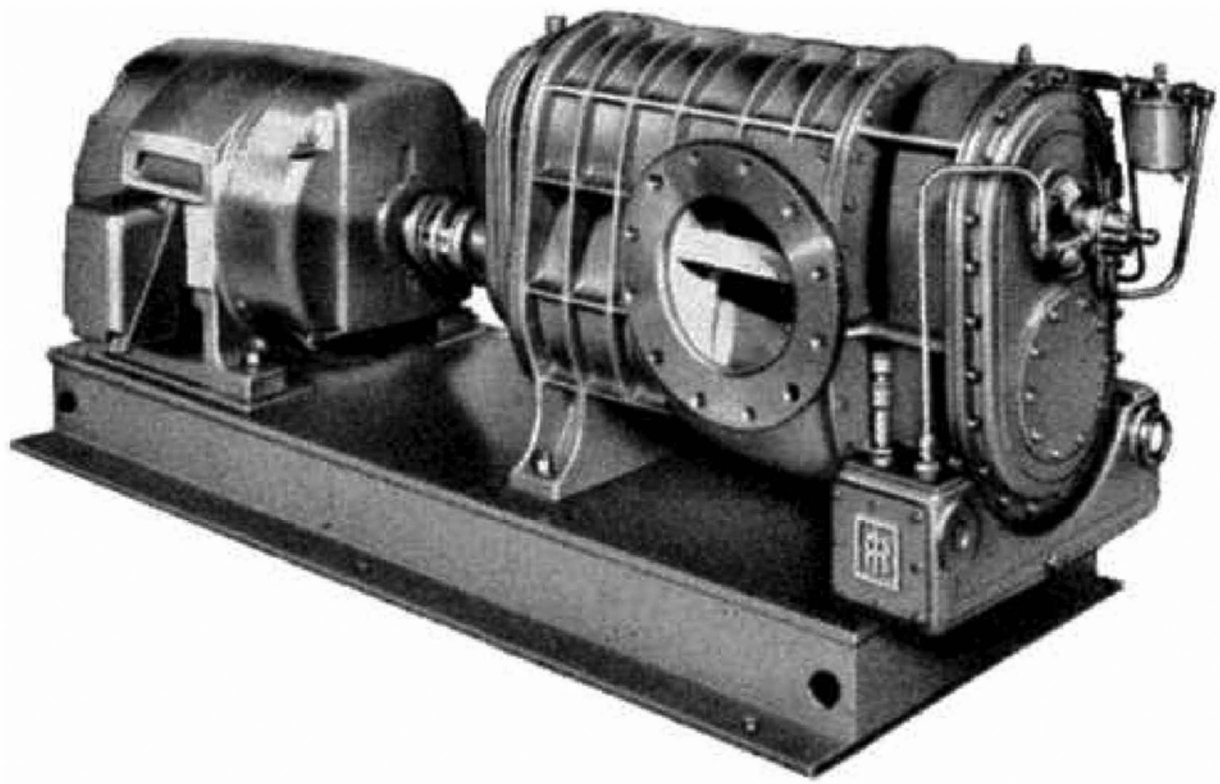


Figure 4-3
Spiral Rotor MVP
Source: Dresser-Rand Company

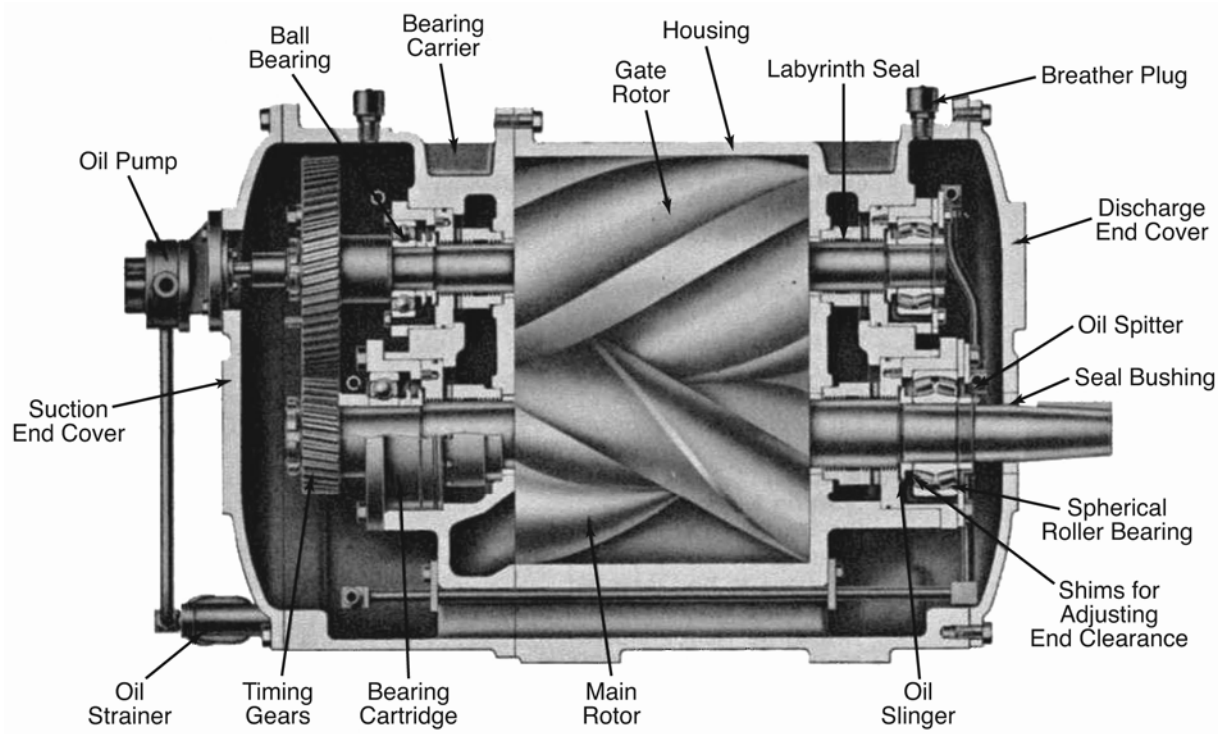


Figure 4-4
Cross-Section Spiral Rotor MVP
Source: Dresser-Rand Company

4.2.1.2 Application

Single-stage spiral rotor MVPs are used in the hogging mode by some BWRs, while SJAEs are used for the holding mode. In this capacity, the pumps take suction on the common suction line to the SJAEs between the SJAEs and the SJAE suction valves and discharge to the base of the main chimney.

The condenser off-gas enters the vacuum pump saturated with water vapor. Water is also injected into the inlet port to keep the inlet stream of gas saturated. This partly seals the clearance between the rotors as well as the clearance between the rotors and the housing, and also prevents excess discharge temperature. The additional amount of water that is added after the gas becomes saturated seals the clearance and, thus, increases the delivery and the efficiency of the vacuum pump. An injection of approximately one gallon (3.8 liters) of water per one thousand cubic feet (28 cubic meters) per minute of inlet capacity is normally required to effect a slip reduction, saturate the inlet, and control the discharge temperature.

A sufficient amount of water should be injected to maintain a discharge temperature of approximately 130°F (54.4°C). When the injected water enters the compression area of the vacuum pump and, as a result of the vacuum flashes into vapor, the heat of compression is removed. As the water flashes, dissolved minerals in the water tend to form deposits on the rotors. The amount of deposit is a function of discharge temperature, injection rate, and the percent of dissolved minerals in the water. By maintaining a discharge temperature of approximately 130°F (54.4°C), the deposits on the rotors will normally remain soft and be washed away. An adjustable water inlet valve with a fixed, maximum flow control valve and water flow indicator is used to control the rate of water injection.

Drain piping is installed in the pump suction, along with a check valve that opens only when the unit is shut down, to allow water that collects in the housing to drain out. At one plant, the drain-flow check valve was initially installed in an improper geometric orientation, and the drain piping was not properly sloped down and away from the machine to keep the water seal from overflowing and filling up the compressor. This resulted in the intrusion of water into the oil.

Key Technical Point

Ensure that the drain-flow check valve is in the right geometric orientation and that the drain piping is sloped down and away from the machine to keep the water seal from overflowing and filling up the compressor such that the water intrudes into the oil.

4.2.2 Helical Rotor MVP

4.2.2.1 Theory of Operation

Figures 4-5 through 4-9 show a typical helical rotor MVP. The helical rotor MVP is a two-stage, rotary, positive-displacement compressor. In the helical rotor MVP, the displacement is obtained through the meshing of two helical rotors on parallel shafts encased in a vertically split housing. Inlet and discharge ports are at opposite ends of the rotor housing with the inlet port being at the drive end.

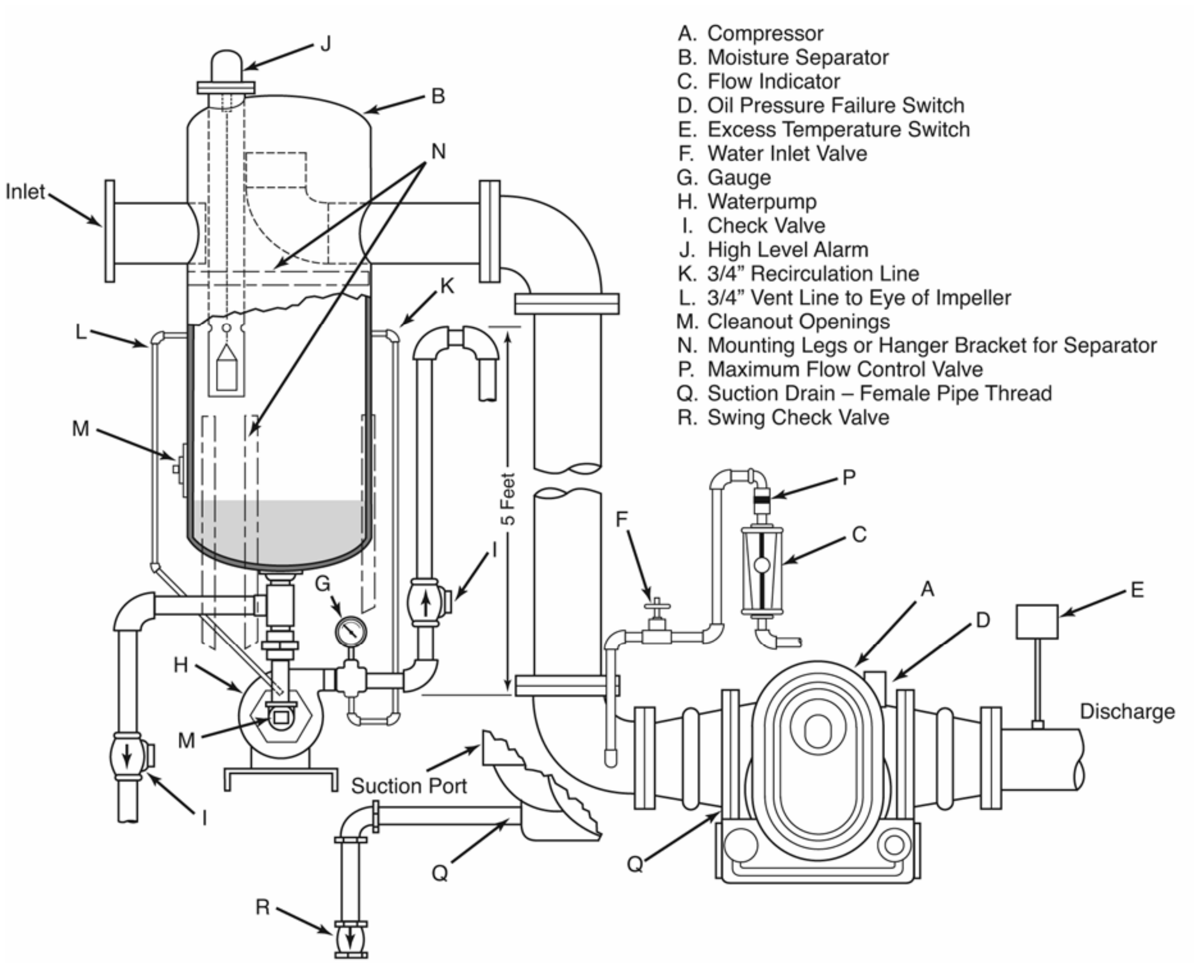


Figure 4-5
Helical Rotor MVP
Source: Dresser-Rand Company

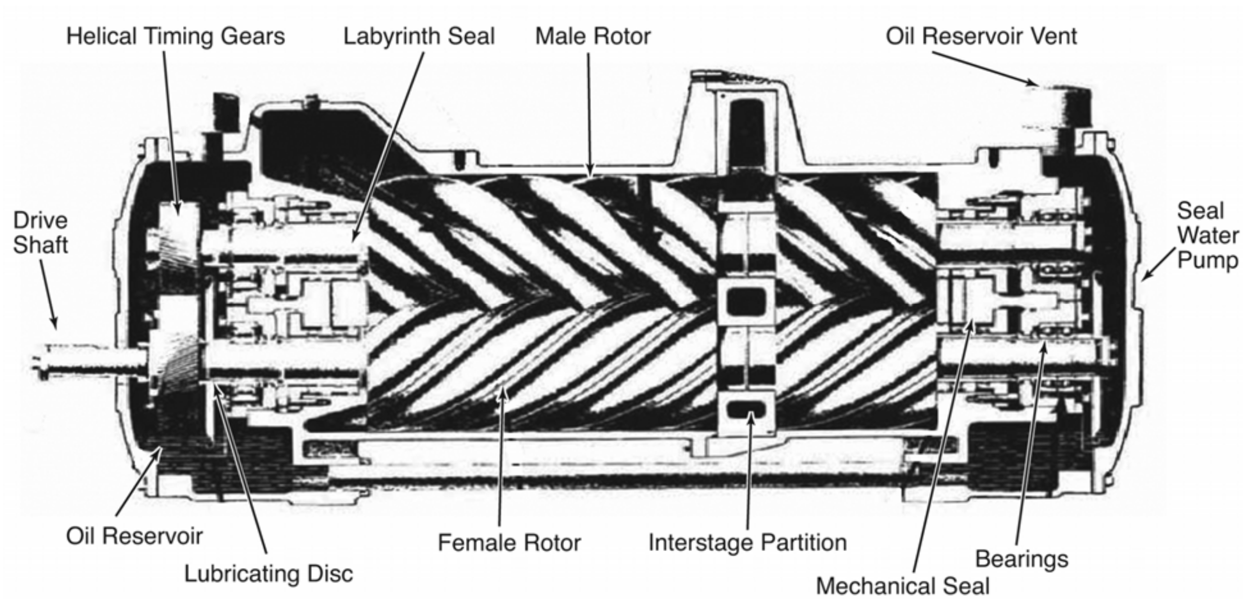


Figure 4-6
Cross-Section Helical Rotor MVP
Source: Dresser-Rand Company

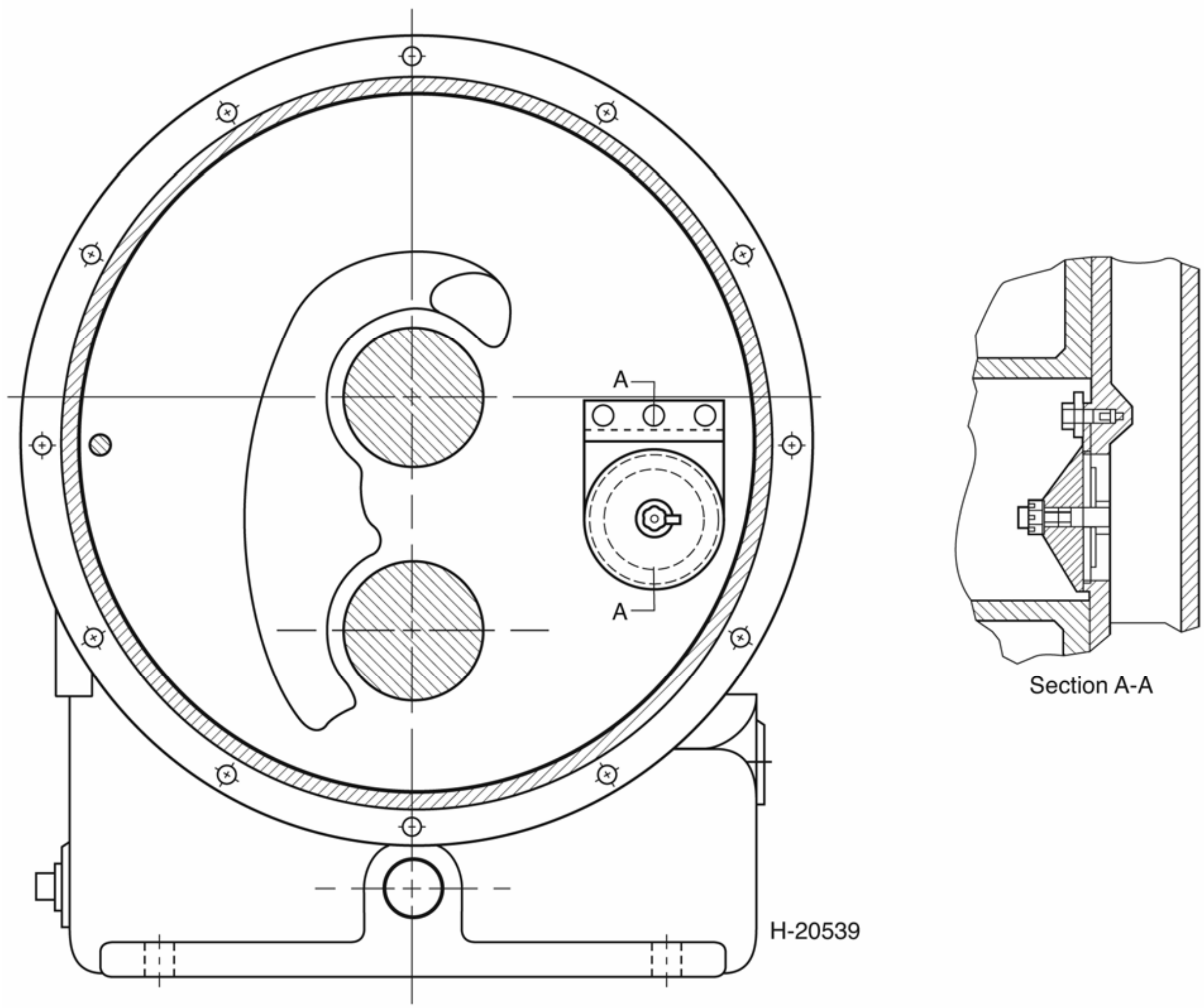


Figure 4-7
Inter-Stage Partition and Relief Valve
Source: Dresser-Rand Company

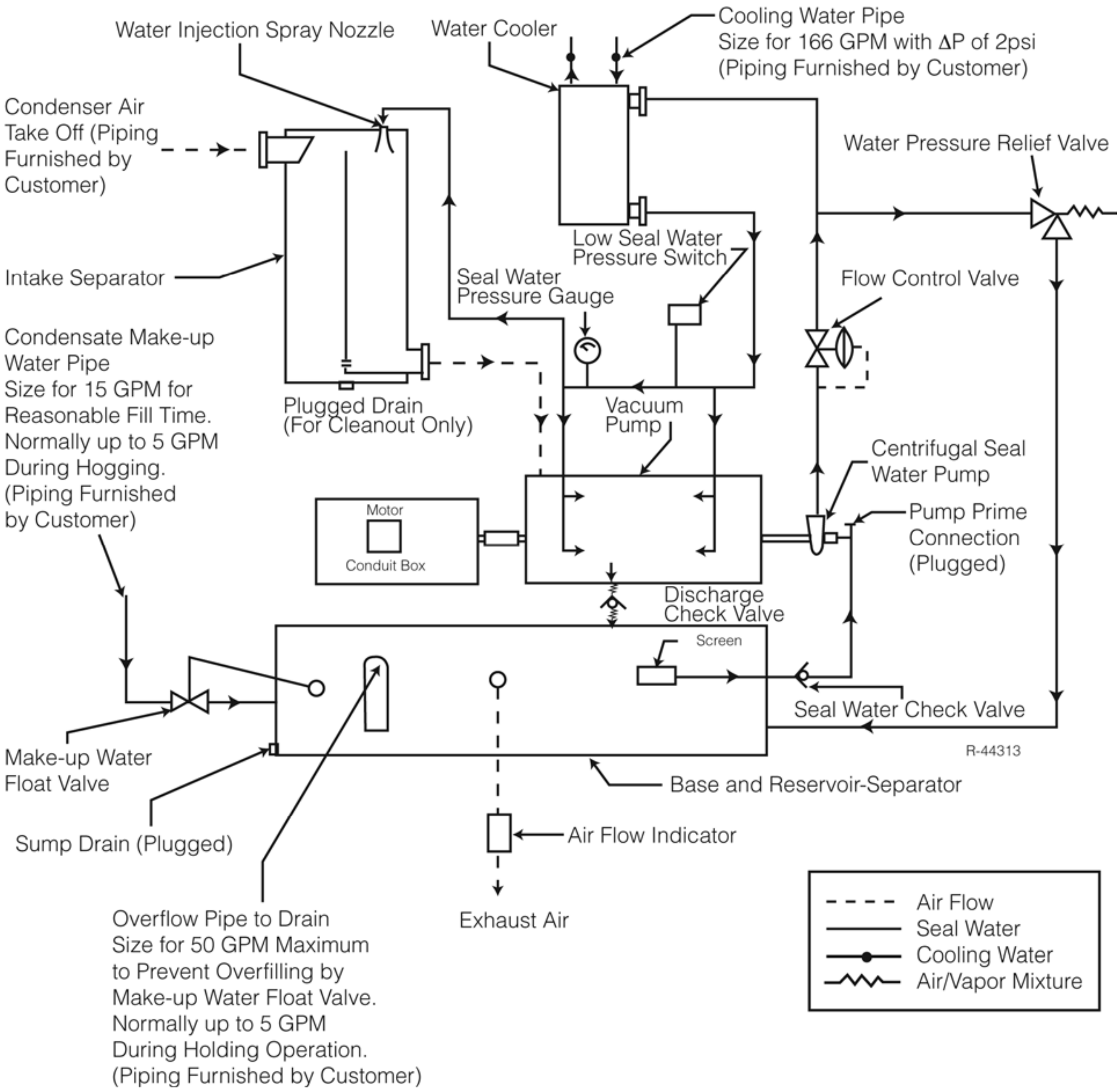


Figure 4-8
Schematic Diagram for Air and Water Flow
Source: Dresser-Rand Company

The circular profile rotors in the MVP are known as *male* and *female rotors*. The male rotor has four helical lobes, while the female rotor has six helical grooves that mesh with the male rotor lobes. The power input is to the female rotor shaft. The power is transmitted to the male rotor through the timing gears. The male and female rotors have the same outside diameter. The male rotors and the male rotor shafts for both stages are made from a single piece of stock. This is also the case for the female rotors and shafts.

The theory of compression for the helical rotor MVP is the same as that previously presented for the spiral rotor MVP.

The timing gears maintain a close clearance between the rotors and prevent the rotors from contacting each other, and they also serve as speed-up gears.

The shafts are supported with anti-friction ball bearings at each end of each shaft. Thrust loads are taken up by angular-contact, duplex-mounted ball bearings, located on the discharge end of each shaft. The inlet end radial bearings are ball bearings.

The MVP is equipped with mechanical seals for sealing the rotor chamber from the seal vent area and the lubrication system. Labyrinth seals regulate seal cooling water flow from the seal chamber to the rotor chamber.

Lubrication is comprised of a splash system, utilizing an oil reservoir at each end of the vacuum pump housing. These reservoirs are interconnected, and both are vented to the atmosphere. The lubricating oil is picked up from these reservoirs by lubricating discs located on each end of the female rotor shafts and is thrown from these discs in such a manner that it is distributed to the timing gears and all bearing locations. The lubricating oil is kept from entering the seal cooling water vent area by an oil slinger.

The inter-stage partition contains an inter-stage relief valve (refer to Figure 4-7). On pump down (hogging mode), prior to the first stage reaching its balance ratio, the first stage discharges more gas than the second stage can handle and causes a build-up of inter-stage pressure to a point where it exceeds the discharge pressure. This unbalanced pressure causes the inter-stage relief valve to open, and some of the first stage discharge gas bypasses the second stage. This saves on horsepower by limiting the first stage discharge pressure and allows the second stage to operate unloaded until the first stage reaches its balance ratio. After the first stage reaches its balance ratio, the second stage starts to load, causing the discharge pressure to exceed the inter-stage pressure, thereby closing the inter-stage relief valve. The inter stage relief valve stays closed during the rest of pump down and during the normal operational period (holding mode).

The base is cast iron and is ribbed to provide a rigid mounting for the vacuum pump and all its associated equipment. The cavity within the base provides a condensate reservoir and serves as a receiver-separator for the air and vapor mixture that is discharged from the condenser vacuum pump.

Figure 4-9 shows a cross-section of the base. An air and vapor mixture from the MVP discharge enters the base at “A” where condensation of the vapor occurs. This water leg also acts as a silencer. Additional condensation occurs as the air-vapor mixture moves from left into the cooler area of the base cavity.

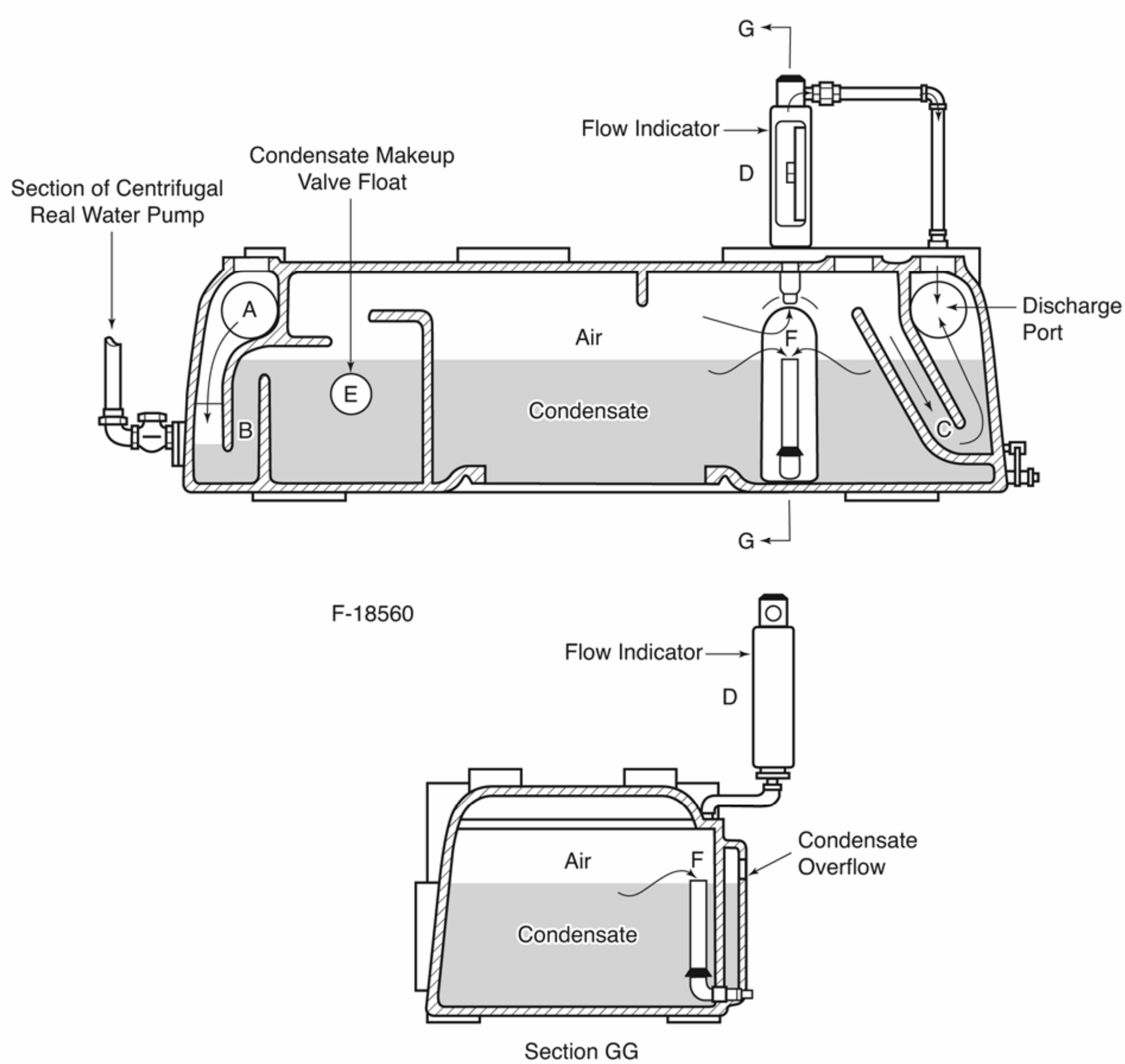


Figure 4-9
Schematic of Base and Reservoir
Source: Dresser-Rand Company

During condenser pump-down (hogging mode), the airflow rate is greater than the airflow indicator can handle, and large volumes of air are forced out through a second water leg “C,” connected to the base discharge. As the condenser pressure approaches design values, airflow through the water leg “C” falls off to where the water leg reseals. All of the air then flows through the flow indicator “D” and on out the discharge.

A condensate makeup float valve “E” keeps the reservoir filled to the proper level, and an overflow “F” is provided in case the condensate level rises.

The MVP is equipped with a low-seal water pressure trip switch that will shut the MVP down on loss of water pressure.

A centrifugal seal water circulating pump is flange mounted on the discharge end cover, directly connected to the female rotor shaft. This pump provides demineralized water from the reservoir in the base to the mechanical type shaft seals, located in the vacuum pump.

A seal water cooler is mounted on the side of the base to maintain the seal water temperature at 7.5°F (4.17°C) above the cooling water inlet temperature. Normally, the cooling water will be condenser circulating water. The use of circulating water in the seal water cooler provides the vacuum pump with seal water that is always cooler than the condenser at its operating pressure. This difference between seal water temperature and saturation temperature provides the most efficient air removal at any condenser vacuum level. The vacuum pump will automatically track the condenser, thereby providing maximum air removal under any condenser load during the whole year.

Key Technical Point

Maintaining the seal water at a temperature cooler than the condenser at its operating pressure provides the most efficient air removal at any condenser vacuum level. The vacuum pump will automatically track the condenser, thereby providing maximum air removal under any condenser load during the whole year.

Inside the intake separator is a vertical baffle that is arranged to separate the liquid from the noncondensible gases. The gas flows over the top of the baffle. The liquid remains behind the baffle and is metered into the gas stream through an orifice. This prevents large slugs of liquid from entering the MVP and allows a uniformly controlled liquid flow that the MVP is capable of handling. A spray nozzle is provided on the gas side of the baffle to facilitate the addition of a cooling spray when required to control the MVP discharge temperatures.

4.2.2.2 Application

Two-stage, helical-rotor MVPs are used as CAR equipment at some PWRs. In this capacity, the pumps function in both the hogging and holding modes. No additional equipment is needed. The full capacity of the MVP is directly used during all levels of condenser vacuum operation without any valve changes or switching of air flow.

The condenser air take-off is piped to the intake separator (Figure 4-5). Internal baffles in the separator allow any water carried over from the system to collect and drain at a controlled rate into the vacuum pump inlet. The air-vapor mixture from the condenser is drawn through the intake separator and enters the first-stage rotor chamber where it is compressed to inter-stage pressure. The air-vapor mixture then enters the second-stage where it is compressed to atmospheric pressure.

As stated earlier, the inter-stage partition is equipped with an inter-stage relief valve. In the hogging mode, the inter-stage relief valve opens, and some of the first-stage discharge gas bypasses the second stage, allowing the second stage to operate unloaded until the first stage reaches its balance ratio. After the first stage reaches its balance ratio, the inter-stage relief valve closes during the rest of pump down and during the normal holding mode operation.

4.3 Liquid Ring MVP

4.3.1 Liquid Ring MVP Fundamentals

The liquid ring MVP is a specific form of rotary positive displacement pump utilizing liquid as the principle element in gas compression. The compression is performed by the liquid ring, as a result of the relative eccentricity between the casing and a rotating multi-bladed impeller.

The eccentricity results in nearly complete filling then partial emptying of each rotor chamber during each revolution. This partial filling and emptying creates a piston action within each set of rotor or impeller blades. Parts are positioned in such a manner as to admit gas when the rotor chamber is emptying of liquid and allow the gas to discharge once compression is completed. Sealing areas between the inlet and discharge ports are provided to close the rotor areas, separating the inlet and discharge flows.

A portion of the liquid in the casing is continuously discharged with the gas, and the cooler service liquid is introduced to remove the heat generated during operation. Figures 4-10 and 4-11 provide typical examples of liquid ring MVPs and describe the gas compression cycle for each. Figure 4-12(a) through (d) shows the four common types of liquid ring MVPs. The four types are:

- Figure 4-12(a) - Single stage, flat port plates
- Figure 4-12(b) - Single stage, conical ports
- Figure 4-12(c) - Two stage, flat port plates
- Figure 4-12(d) - Two stage, conical ports

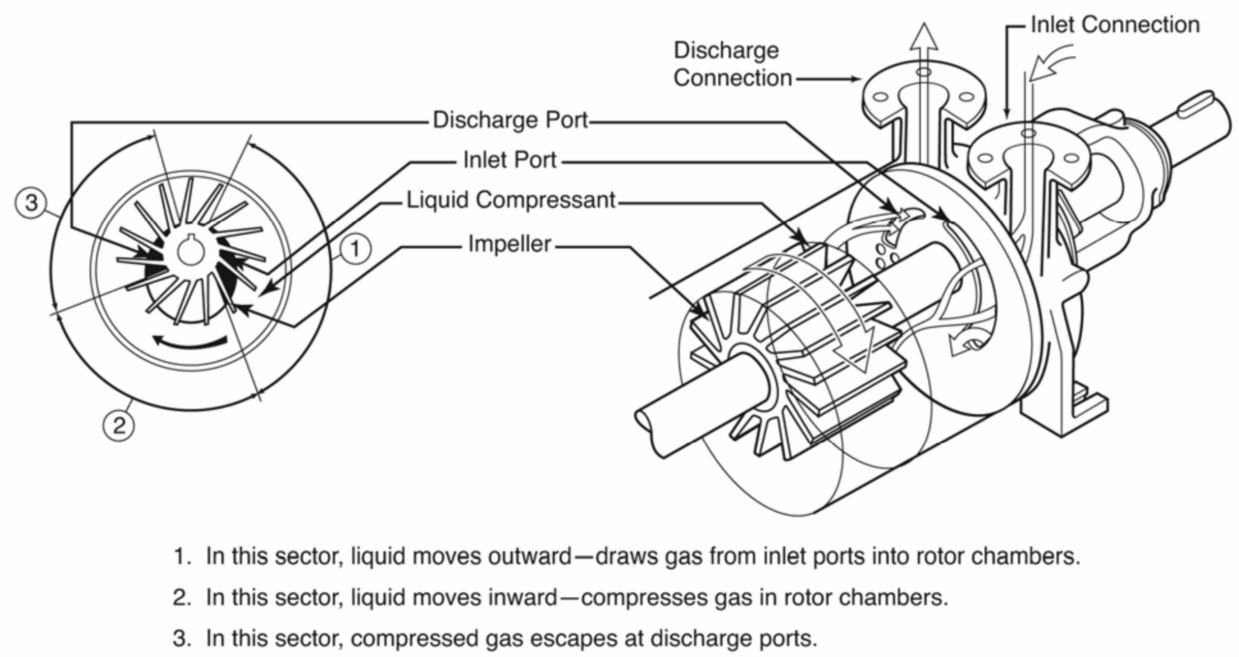


Figure 4-10
Flat Port Plate Liquid Ring Vacuum Pump Gas Compression Cycle
Source: Heat Exchange Institute

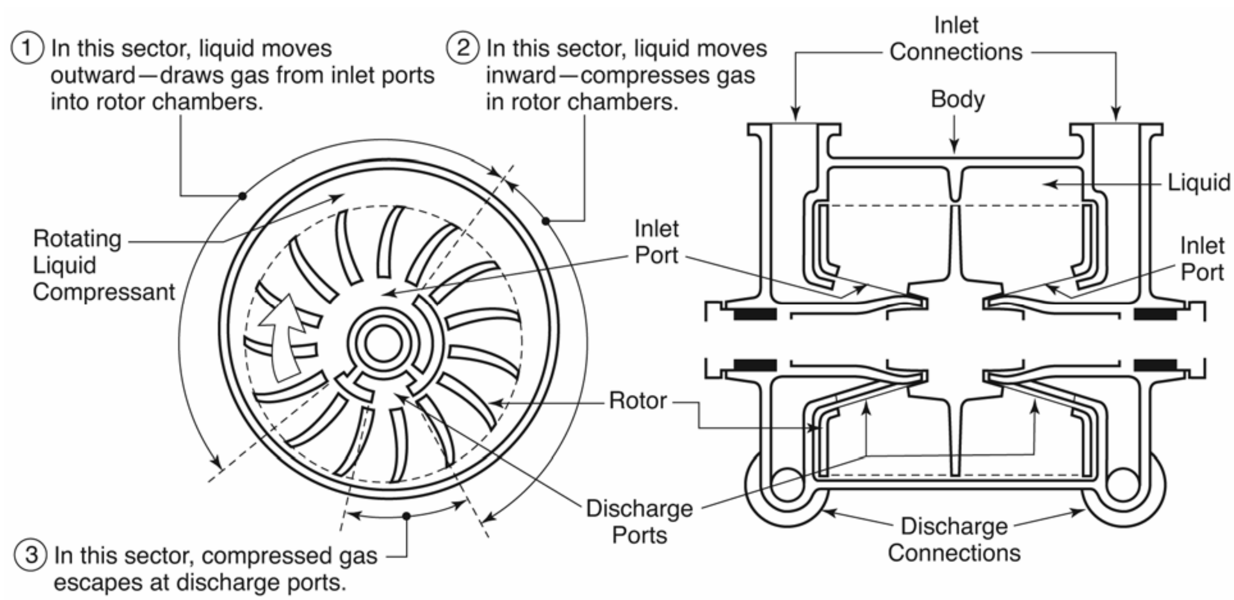


Figure 4-11
Conical Port Liquid Ring Vacuum Pump Gas Compression Cycle
Source: Heat Exchange Institute

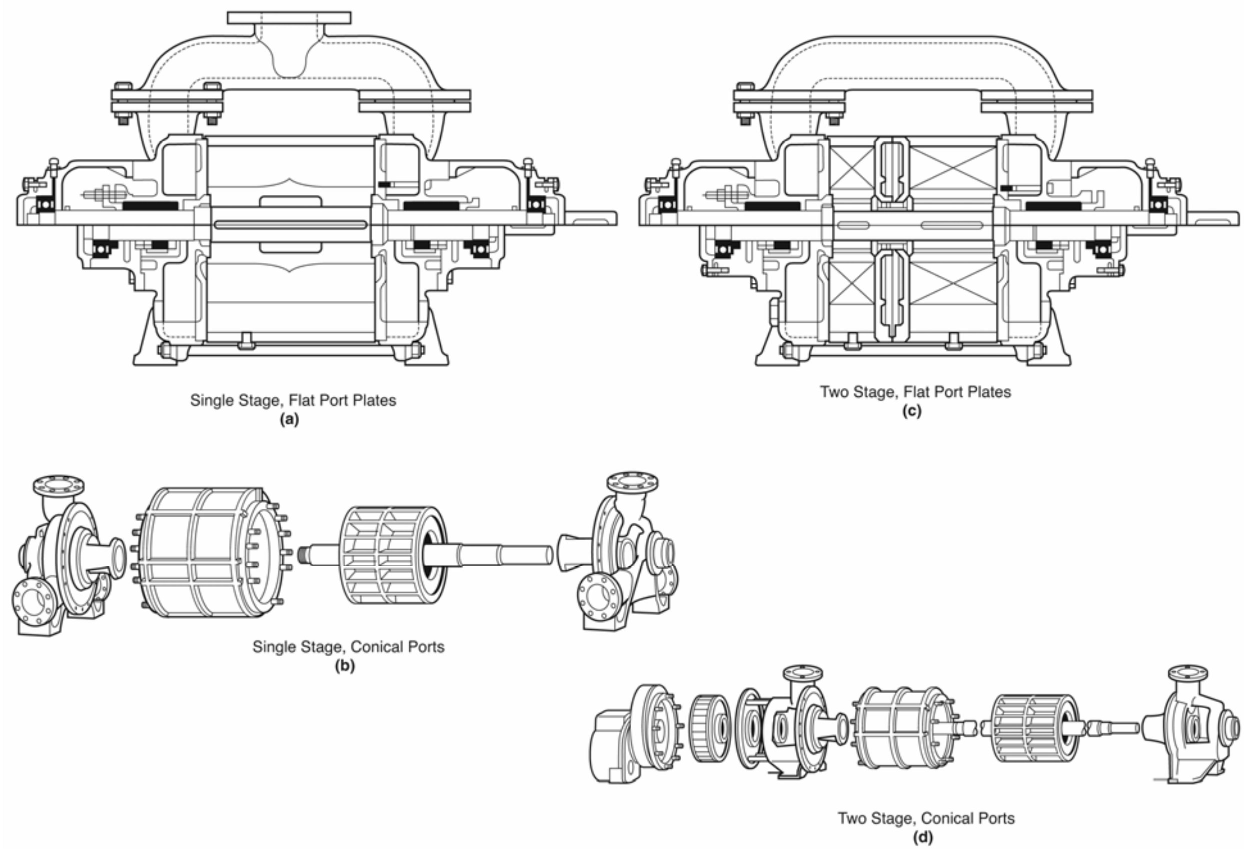


Figure 4-12
Types of Liquid Ring Vacuum Pumps
Source: Heat Exchange Institute

4.3.2 Single-Stage Liquid Ring MVP

Individual single stage liquid ring MVPs are installed in some BWRs and PWRs as hogging mode CAR equipment. Additionally, at some other PWRs the holding mode CAR equipment consists of a combination of an atmospheric jet air ejector and a single stage liquid ring MVP packaged by a vendor into a CEU.

4.3.2.1 Theory of Operation

In addition to being the compressing medium, the liquid ring absorbs the heat generated by compression and friction, absorbs any liquid slugs or vapor entering with the gas stream, and condenses water vapor entering with the gas. Therefore, for CAR service, a closed loop (or total recirculation) seal system is typically used. The seal water temperature will be 3–5°F (1.7–2.8°C) warmer than the cooling water to the MVP heat exchanger, which is normally taken from the same source as the condenser cooling water.

The vacuum attainable by a liquid ring MVP is limited by the vapor pressure of the seal fluid. As the operating vacuum approaches the vapor pressure of the seal, more and more of the seal fluid will “flash” into vapor. The capacity of the liquid ring MVP is reduced as more of the impeller space is occupied by vapor from the seal fluid, leaving less space available to accept the incoming load. If allowed to continue, cavitation will occur inside the pump, resulting in damage to internal surfaces, and preventing the pump from achieving greater vacuum levels.

To prevent cavitation, the operating vacuum of the liquid ring MVP must be limited to approximately 0.25 inch (0.64 cm) Hg above the vapor pressure of the seal liquid. This differential varies somewhat according to pump model and the amount of heat added to the seal water by condensible load, however the importance of vacuum limitations set by seal water temperature should be emphasized. Even if the pump is oversized, it cannot obtain lower pressure levels than those permitted by the vapor pressure of the seal water. This limitation is a disadvantage when the condenser is operated under part load conditions. (See the discussion under hybrid systems.)

Key Technical Point

Even if a liquid ring vacuum pump is oversized, it cannot obtain lower vacuum levels than those permitted by the vapor pressure of the seal water. To prevent cavitation, the operating vacuum of the liquid ring MVP must be limited to approximately 0.25 inch (0.64 cm) Hg above the vapor pressure of the seal liquid.

Liquid ring MVPs are normally supplied completely packaged with controls for fully automatic operation. No separate hogging device for initial evacuation is required, as the pump gains capacity rapidly at higher suction pressures.

4.3.2.2 Hogging Mode Application

Single-stage liquid ring MVPs are used in the hogging mode by some BWRs and PWRs with SJAEs being used for the holding mode. In this capacity, a standard single-stage liquid ring MVP takes suction on the main condenser and discharges to the atmosphere, with the BWRs discharging to the atmosphere via the gland seal holdup volume.

4.3.2.3 Holding Mode Application

The holding mode CAR equipment consists of a combination of a first-stage atmospheric jet air ejector and a second-stage, single-stage liquid ring MVP packaged into a CEU. (See Figure 4-13 and the following discussion.)

4.3.2.3.1 CEU Fundamentals

The atmospheric jet air ejector (Figure 4-14), which constitutes the first stage of the CEU, operates through the use of atmospheric air as the motivating medium. Steam and compressed gas are not used. Instead, air at atmospheric pressure passes through a specially designed acoustical nozzle into the suction chamber or ejector body.

This motive air, because of the pressure differential between inlet and outlet of the air jet, accelerates to a velocity several times that of sound (MK 2.0). This high-velocity air entrains gases entering the ejector body from the main condenser, effectively compressing the gas and the motivating air.

A standard single-stage liquid ring MVP takes suction at the discharge of the atmospheric jet air ejector, completing the evacuation.

Compressant liquid in the MVP is part of a closed loop consisting of heat exchanger, separator, and circulating pump. At the time of initial start-up, the system is filled with condensate. During subsequent operation, vapor is continuously drawn over from the main condenser and condensed by the liquid ring in the MVP. Thus, there is a small amount of makeup being added to the system constantly with a corresponding overflow from the separator.

Cooling water to the heat exchanger should be condenser circulating water whenever possible. Because of the vapor pressure existing within the MVP, the pump will tend to track the main condenser whenever both are fed the same temperature of coolant.

Key Technical Point

Cooling water to the liquid ring MVP heat exchanger should be condenser circulating water whenever possible. Because of the vapor pressure existing within the MVP, the pump will tend to track the main condenser whenever both are fed the same temperature of coolant.

4.3.2.3.2 Theory of Operation

CEU Shut-Down (Figure 4-15). When the exhauster is not operating, the SOVs are de-energized. Atmospheric pressure is on the system diaphragm valve, which causes the valve to be in the closed position. Controlled air is on the inner side of the piston of the bypass valve, causing it to be in the open position. The motive air valve and the balanced check valve are closed.

Hogging Operation (Figure 4-16). Energizing the liquid ring MVP (exhauster) starter also starts the seal water centrifugal pump. Energizing the exhauster starter also energizes the three-way SOV, which forces controlled air to the bottom of the system diaphragm valve, causing it to open. The bypass valve is also open, and, therefore, the flow of the air from the condenser evacuation goes directly from the condenser to the exhauster inlet, bypassing the air jet.

Holding Operation (Figure 4-17). When the pressure in the condenser reaches approximately 25 inches (63.5 cm) Hg. vacuum, or 5 inches (12.7 cm) Hg absolute, the jet vacuum switch makes contact and energizes the four-way SOV, causing the vent to open and bleed the control air from the inner side of the piston of the bypass valve. Control air is supplied to the outer side of the piston through the four-way SOV, causing the bypass valve to close. Control air also goes to the inner side of the piston of the motive air valve, causing the valve to change position and allowing motive air to flow from the atmosphere to the air jet nozzle.

All system air in-leakage must now flow through the air jet, bringing both the jet and exhauster into full operation to evacuate the condenser.

(a) View 1

(b) View 2

(c) Liquid Ring Rotor

Figure 4-13
Single-Stage Liquid Ring CEU
Source: Robinson Nuclear Plant

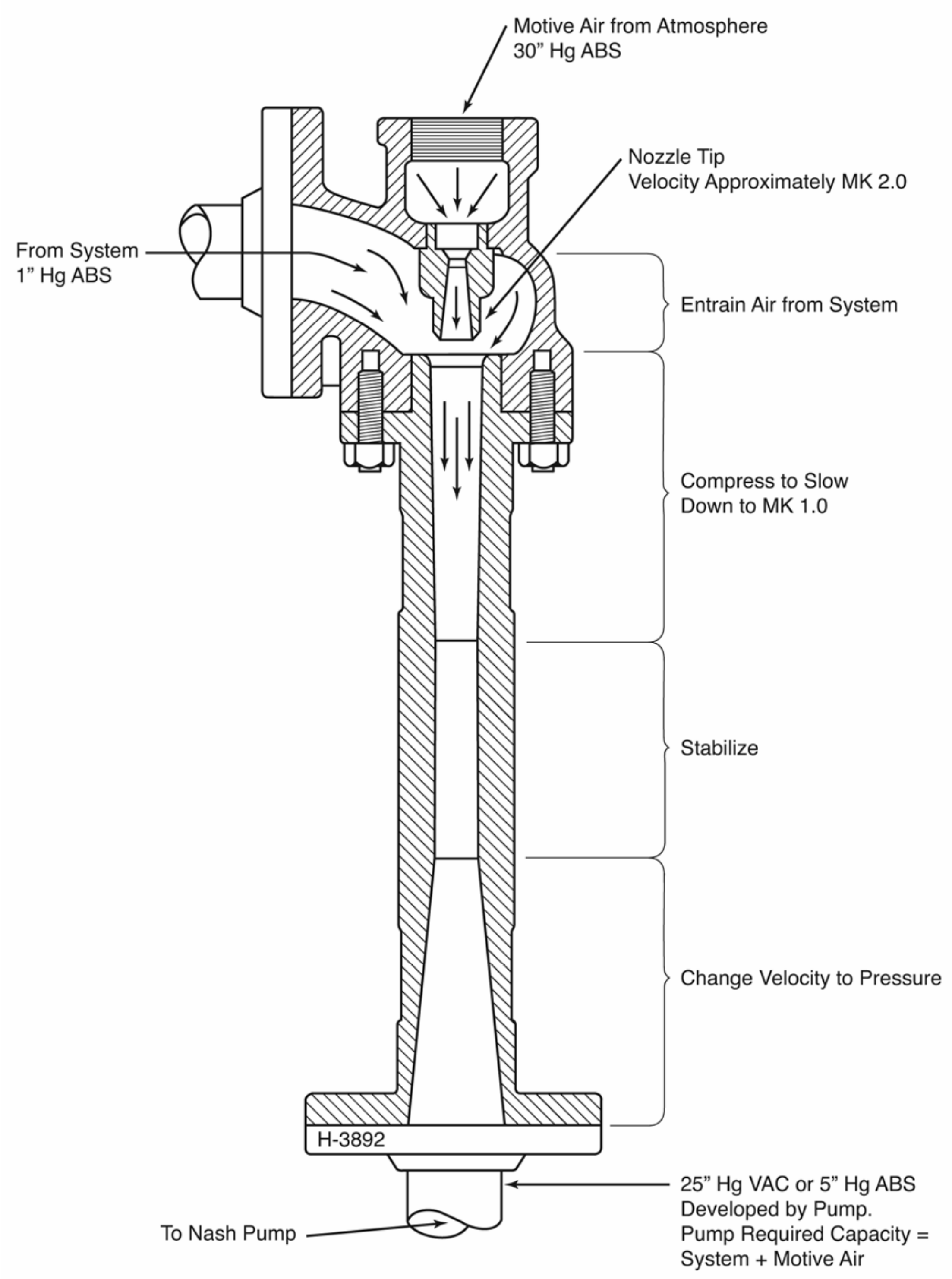


Figure 4-14
Nash Atmospheric Jet Air Ejector
Source: Nash Gardner Denver

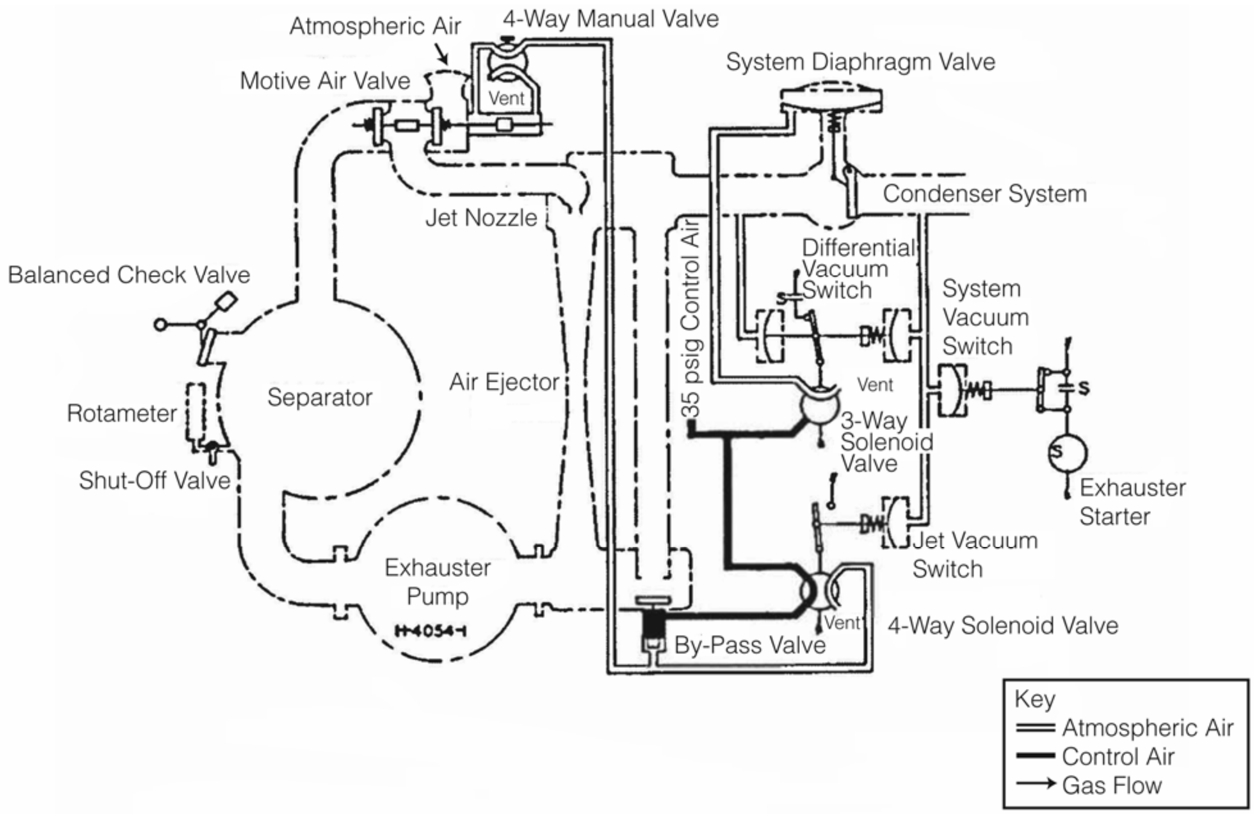


Figure 4-15
Nash CEU (Before Start)
Source: Nash Gardner Denver

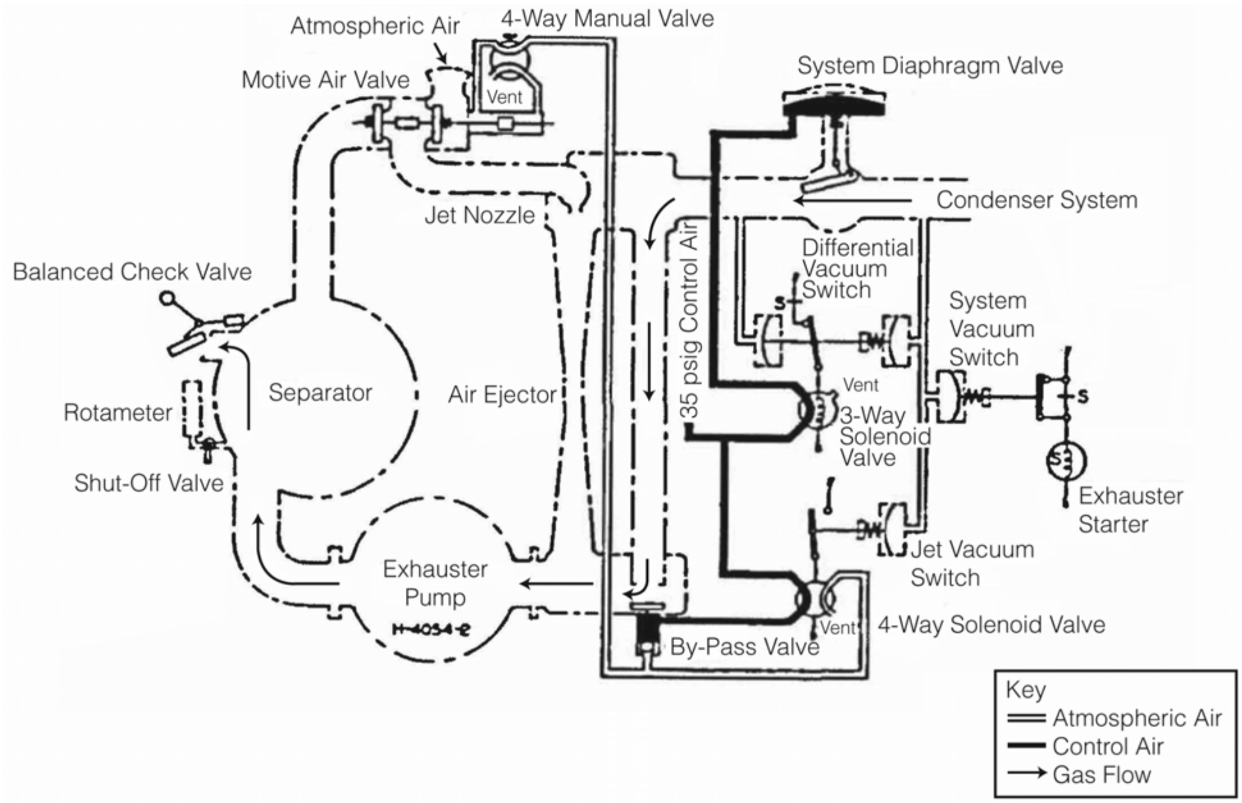


Figure 4-16
Nash CEU (Hogging)
Source: Nash Gardner Denver

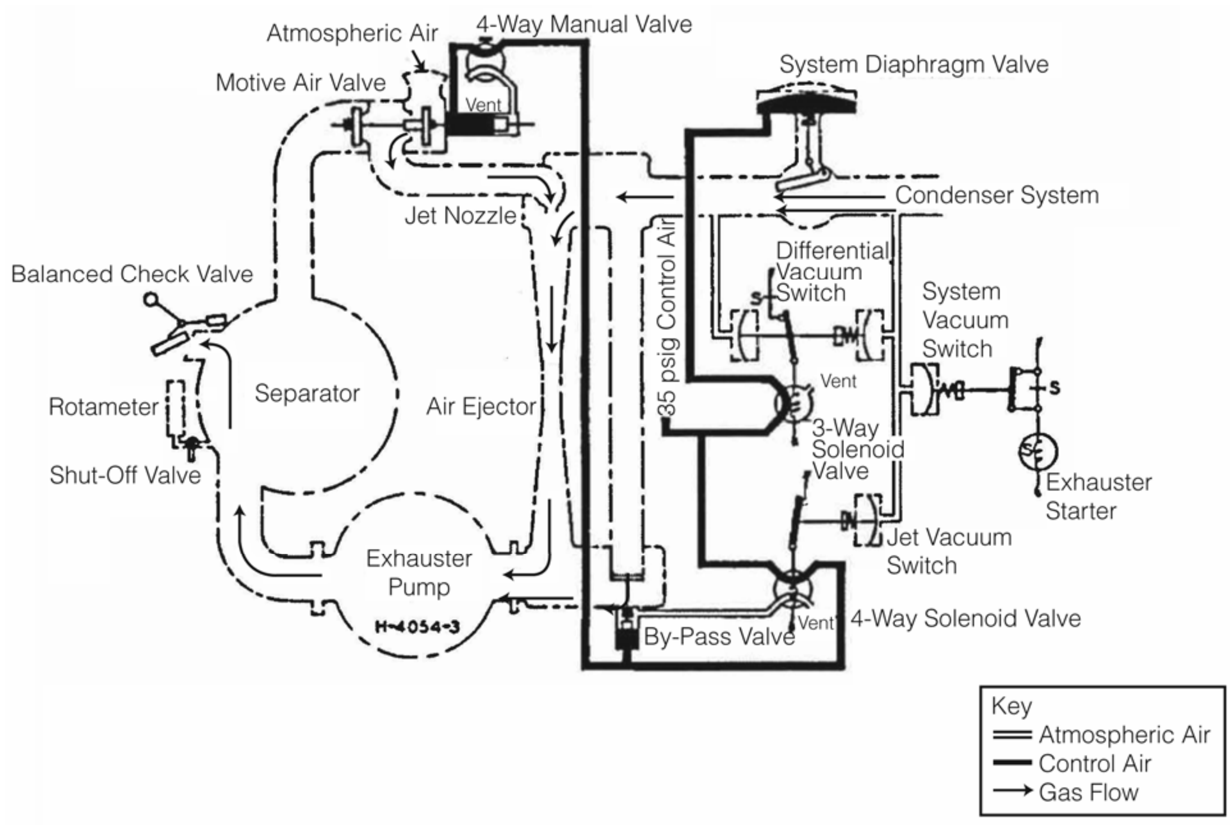


Figure 4-17
Nash CEU (Holding)
Source: Nash Gardner Denver

4.3.3 CEU with Two-Stage Liquid Ring MVP

The main assemblies of the two-stage liquid ring (MVP) are shown in Figure 4-18. An electric drive motor is directly coupled to the pump drive shaft that is common to both stages of the MVP. Rotors in each stage are rigidly mounted on the shaft and rotate at the same speed as the shaft.

4.3.3.1 Two Stage Liquid Ring MVP Operation

The operating principle of this MVP is the same as was described in Section 4.3.1 for the single stage. Evacuated gas and water are discharged by the first stage of the MVP into the second stage discharge manifold. During low-vacuum operation, a check valve in the second-stage manifold is open, allowing the first-stage discharge to flow directly to an externally located atmospheric discharge separator. Thus, at low vacuum, only the first stage of the vacuum pump performs an evacuation function. During high-vacuum operation, the check valve is automatically closed. The first stage discharge is then routed to the inlet of the second stage and through the second stage before being discharged through the second stage manifold to the separator. Operation under low- and high-vacuum conditions is shown in Figure 4-19.

Liquid compressant (seal water) is applied to the vacuum pump to provide the makeup for the liquid in the pump and to seal the clearances between the cone and rotor. The liquid compressant enters the vacuum pump at the first-stage heads, where it then flows through a passage in the heads to the cones and through the clearance between the cones and rotor into the rotor chamber. Liquid compressant is discharged with the evacuated gas into the second-stage manifold. From the second-stage manifold, it passes directly into the atmospheric discharge separator (low vacuum operation) or flows into the second-stage inlet (high vacuum operation) before being discharged with the evacuated gas into the separator.

Stuffing boxes on the vacuum pump contain packing rings and, in the first stage stuffing boxes only, lantern gland seals. These stuffing boxes are lubricated by the liquid compressant. Liquid compressant is applied to the lantern glands under a pressure of 2–5 psig (13.8 to 34.5 kPa) from the second stage shroud, preventing atmospheric air from entering the vacuum pump through the stuffing boxes.

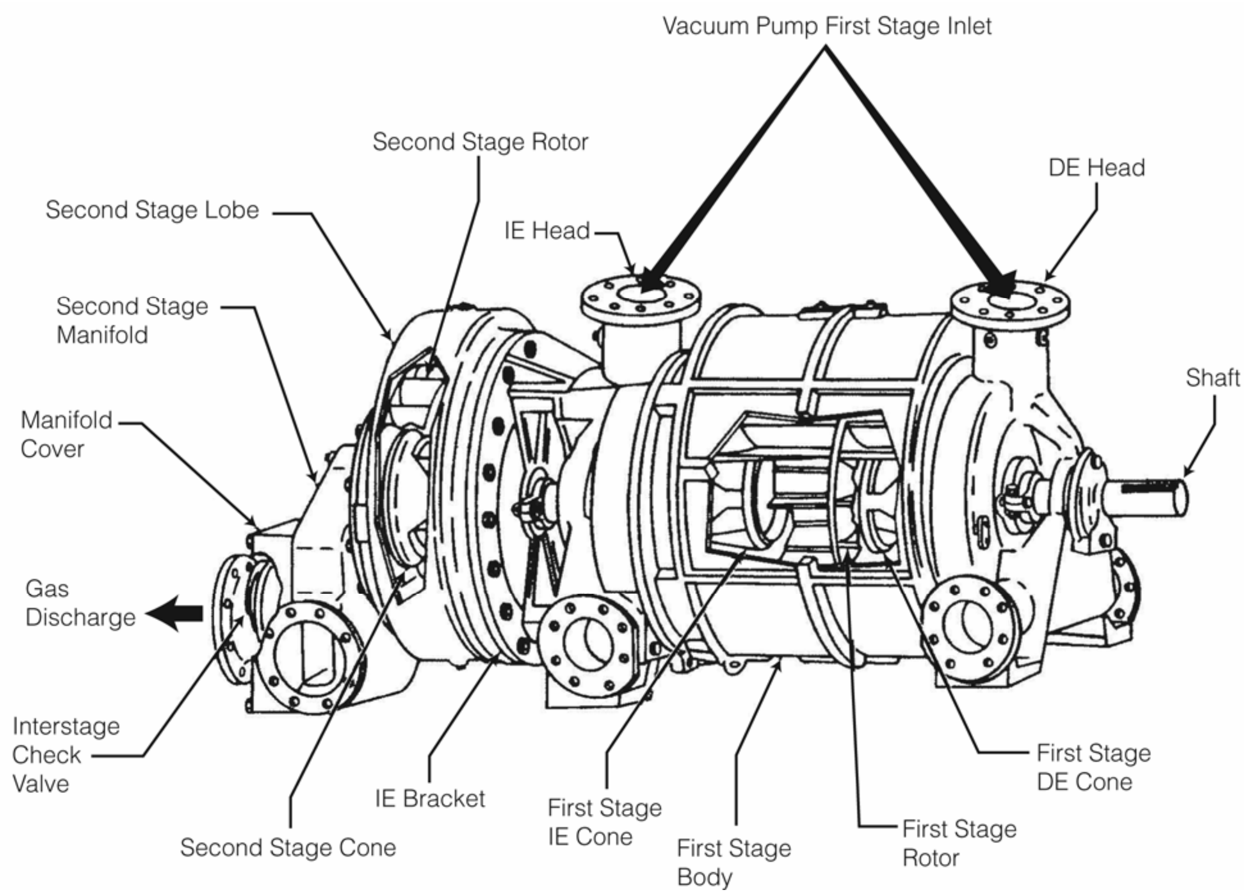


Figure 4-18
Major Components of a Two-Stage Vacuum Pump
Source: Nash Gardner Denver

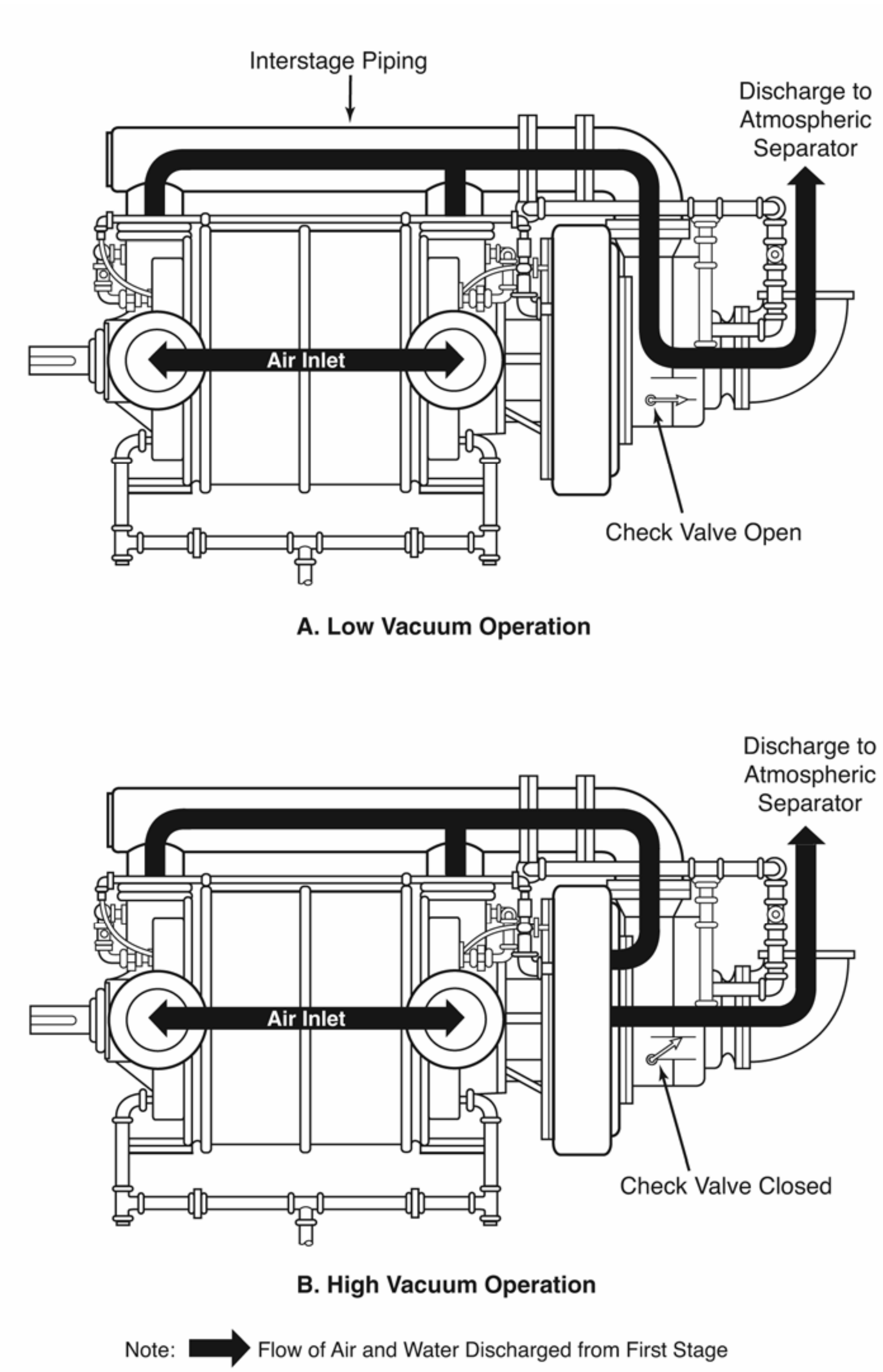


Figure 4-19
Vacuum Pump Low and High Vacuum Operation
Source: Nash Gardner Denver

4.3.3.2 CEU Operation

4.3.3.2.1 Overall CEU Operation

Liquid compressant (seal water) in the CEU is circulated through a closed loop that consists of a two-stage vacuum pump, a separator, a centrifugal pump, and a heat exchanger. Seal water is pumped by the centrifugal pump from the separator through the heat exchanger to the vacuum pump. As the seal water flows through the heat exchanger, it is cooled to a temperature approximately 2 to 4°F (1.1 to 2.2°C) above the inlet temperature of the cooling water that flows through the heat exchanger. Seal water from the heat exchanger outlet flows to the vacuum pump where it is fed to the inlet manifold and the first-stage heads of the vacuum pump.

Seal water entering the inlet manifold directly is applied through two spray nozzles that are threaded into the inlet manifold. Horsepower requirements are kept to a minimum during low vacuum operation by means of a spray water vacuum switch in the control panel, a water pilot SOV, and a spray water control pneumatic valve which shuts off the supply of liquid sealant to the spray nozzles at a vacuum of 23 inch (58.4 cm) Hg and below. The supply of liquid sealant to the spray nozzles opens at a rising vacuum of 25 inch (63.5 cm) Hg. The spray nozzles form the seal water into a spray pattern through which the system air-water vapor mixture must pass. As the system air-water vapor mixture contacts the seal water spray, most of the water vapor in the mixture is condensed. The condensed water vapor, the balance of the air-water vapor mixture and seal water spray flow through inlet passages in the first-stage heads into the vacuum pump.

At the same time, the seal water fed directly to the vacuum pump from the heat exchanger flows through the passages in the first-stage heads into the first stage pump to seal clearances in the vacuum pump. Within the pump, the seal water contacts the mixture flowing from the inlet manifold. Water vapor in this mixture is thereby condensed, reducing the volume of air that has to be removed by the two-stage vacuum pump.

The inlet air is partially compressed in the first stage of the vacuum pump and is discharged with the seal water to the inlet of the second stage of the pump. The second stage compresses the air to atmospheric pressure and discharges all of the seal water and compressed air into the separator. Within the separator, the seal water drops from the air stream to the bottom. The discharge air passes through the separator outlet and through the air leakage test valve to the atmosphere.

An automatic float switch senses the level of water in the separator. If the level is too low, the float switch opens the makeup SOV, permitting makeup water to flow into the separator and then to the vacuum pump. When the water level in the separator is high enough to provide the proper reservoir of seal water for the vacuum pump, the float switch closes the makeup SOV. An overflow loop with a check valve to prevent flow back into the separator automatically controls the maximum water level in the separator. This prevents the loss of vacuum-pump capacity as a result of insufficient seal water reservoir and prevents condensed vapor from accumulating in the separator and entering the discharge vent piping.

4.3.3.2.2 CEU Control

Figure 4-20 provides CEU component identification and a schematic of its functional operation. When the CEU is shut down, an SOV in the control panel is de-energized. With the SOV de-energized, air pressure in the diaphragm of the system inlet valve (not shown) is vented through the SOV to the atmosphere, allowing the system inlet valve to remain closed

A differential vacuum switch is connected to the system piping upstream from the system inlet valve and to the vacuum pump inlet manifold. The differential vacuum switch is closed when the vacuum pump inlet pressure is within one inch of mercury of the system pressure. With the differential vacuum switch in the closed position, an SOV in the control panel can be energized to direct control air to the system inlet valve diaphragm.

At initial start-up when the system is at atmospheric pressure, the differential vacuum switch is in a closed position. (The system and vacuum pump inlet manifold are also at atmospheric pressure.) When the vacuum pump motor is energized, the SOV is energized, and control air flows to the system inlet valve diaphragm, opening the inlet valve.

If the system is at a pressure less than atmospheric pressure and the vacuum pump is shut down, the differential vacuum switch is in an open position. (The pressure in the pump inlet manifold is greater than the system pressure.) When the vacuum pump motor is energized, the system inlet valve remains closed while the pump is running until the pressure in the inlet manifold is within one inch of mercury of the system pressure. At this pump inlet pressure, the differential vacuum switch closes, energizing the SOV. Control air then flows to the system inlet valve diaphragm, opening the valve.

With the system valve open, air from the condenser system can flow through the inlet manifold to the first stage of the vacuum pump. During hogging mode operation, the discharge from the first stage pump flows through the first-stage discharge manifold and the second-stage inlet elbow to the second-stage inlet and discharge manifold. An inter-stage check valve, located inside the second-stage inlet and discharge manifold, is open at this time, permitting the air and water to be discharged into the separator. The water in this discharge is separated out, and the air flows through the air leakage test valve to the atmosphere.

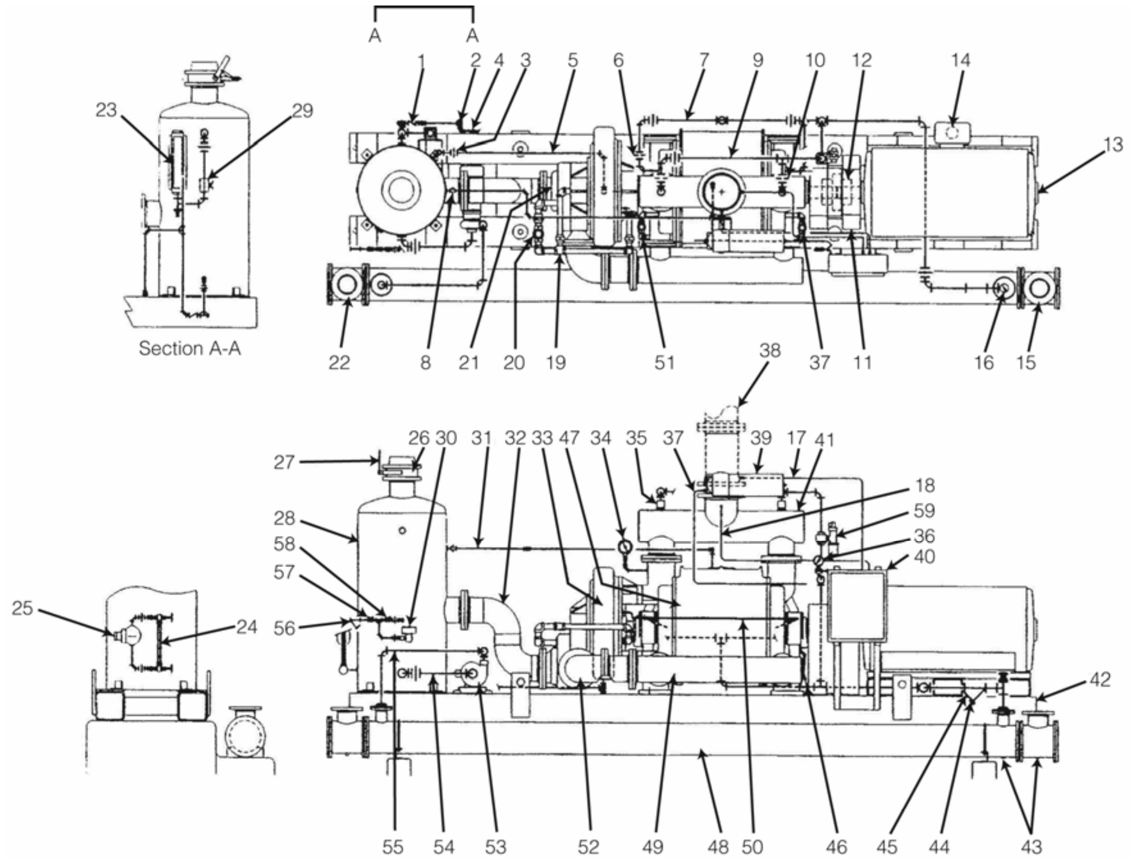
When the inlet vacuum increases to approximately 25 inches Hg vacuum, a vacuum switch actuates, which energizes an SOV to send water to spray nozzles for full seal flow. When the inlet vacuum decreases to approximately 23 inches Hg vacuum, a vacuum switch activates, which shuts off water flow to the spray nozzles.

Holding mode operation begins automatically when the second stage inlet capacity is equal to the volume of gas discharged from the first stage. (See the discussion in Section 4.3.3.1.) The discharge of the first stage flows through the inter-stage piping to the second-stage inlet. The second stage compresses the mixture to atmospheric pressure and discharges the air and water into the separator. The air flows through the air leakage test valve to the atmosphere.

The proper level of seal water is automatically maintained in the separator as previously described.

The seal water circulating (centrifugal) pump is used to ensure sufficient flow of seal water to the vacuum pump in order to maintain full pump capacity during hogging operation. During high-vacuum operation, the vacuum pump inlet vacuum is sufficient to maintain proper flow of seal water to the pump. Therefore, should the centrifugal pump fail when the vacuum pump unit is holding condenser back pressure, the vacuum pump automatically maintains proper flow of seal water and full holding capacity.

The centrifugal pump also provides a nominal pressure in the seal piping and heat exchanger. Should a failure in the heat exchanger occur, the seal pressure prevents the entry of relatively impure cooling water into the sealing water system.



1. Overflow Drain Check Valve
2. Overflow Loop and Stuffing Box Drain
3. Seal Unload Orifice Union
4. Stuffing Box Drain Line
5. Body to Separator Line
6. Cone Seal Orifice Union (One Each Side)
7. Cone Seal Piping
8. Lobe Vent Orifice Union
9. Spray Water Inlet Piping
10. Spray Water Orifice Union (One Each Side)
11. Coupling Guard
12. Coupling
13. Drive Motor
14. Drive Motor Conduit Connection
15. Cooling Water Inlet
16. Seal Water Dial Thermometer
17. Differential Vacuum (Pressure) Switch Control Line-System Pressure
18. Vacuum Switch Control Line - Vacuum Pump Inlet Pressure
19. Second Stage Shroud Vent Line
20. Second Stage Shroud Vent Check Valve
21. Second Stage Inlet and Discharge Manifold
22. Cooling Water Outlet
23. Rotameter
24. Gauge Glass
25. Low-Level Make-up Float Switch
26. Air Leakage Test Valve
27. Air Leakage Test Valve Handle
28. Separator
29. Rotameter Ball Valve
30. Low-Level Make-up Solenoid Valve
31. First Stage Love Vent to Separator Line
32. Second Stage Discharge Elbows
33. Vacuum Pump Second Stage
34. Inlet Vacuum Gauge
35. Spray Nozzle
36. Instrument Air Pressure Gauge
37. System Valve Control Line
38. System Air Inlet Line
39. System Inlet Valve
40. Control Panel
41. Inlet Manifold
42. Base
43. Heat Exchanger Drains
44. Seal Water Line Strainer Drain Plug
45. Seal Water Line Strainer
46. Stuffing Box Drain Line
47. Vacuum Pump First Stage
48. Heat Exchanger
49. First Stage Discharge Manifold
50. Latern Gland Supply Line
51. First Stage Shroud Vent Check Valve (One Each Side)
52. Second Stage Inlet Elbow
53. Centrifugal Pump
54. Centrifugal Pump Inlet Line
55. Centrifugal Pump Discharge Line
56. Seal Water Make-up Strainer
57. Seal Water Make-up Ball Valve
58. Initial Fill and Manual Bypass Ball Valve
59. Spray Water Pneumatic Control Valve

Figure 4-20
CEU Functional Operation
Source: Nash Gardner Denver

4.4 Hybrid CEU

Refer to Figure 4-21. In the hybrid CEU, an SJAE is used as the first stage of the unit. The SJAE discharges into an inter-condenser that is followed by a one or two stage liquid ring MVP. There are presently no known nuclear plants that have installed hybrid CEUs.

4.4.1 Principle of Operation

The first-stage SJAE boosts the inter-stage pressure to the vacuum pump. Thus, a smaller pump is required than if the entire compression was to be done by an MVP.

Condensate from the inter-condenser can be discharged directly into the liquid ring MVP. Thus, no barometric leg or special pumping device is needed for condensate discharge.

Cavitation can be a maintenance problem for standalone liquid ring MVP systems that must operate at pressures close to the vapor pressure of the pump service liquid. This problem is minimized when a hybrid system is used, as the MVP operates at a higher inter-stage pressure. Note that cavitation may still occur if air leakage is near zero.

The first-stage SJAE boosts the pressure, and the inter-condenser condenses the majority of the motive steam and water vapor load, greatly reducing the load to the MVP. Thus, a smaller MVP can be used. Hybrid units may be more energy efficient, can be optimized to account for low-cost steam or electric utilities, and can be optimized to achieve the best balance between steam and power usage.

Cooling is by condensate and/or closed cycle cooling water.

4.4.2 Part Load Operation

Improved Steam Condenser Gas Removal System authored by the American Society of Mechanical Engineers describes the disadvantage of liquid ring pump during operation at part load conditions. Liquid ring vacuum pumps are sized based on the assumption that the initial temperature difference (ITD) for a given condenser is a fixed number. ITD is the difference between the saturation temperature at the condenser pressure and the inlet cooling water temperature. As the ITD increases, vacuum pump capacity increases. Conversely, as the ITD decreases, vacuum pump capacity decreases. Once the ITD is calculated, the vacuum pump is chosen from the pump performance curve. A large ITD allows use of a small vacuum pump, while a small ITD requires a larger model.

Liquid ring vacuum pump selection is based on the condenser ITD, which is assumed constant. This assumption of a fixed ITD is acceptable when the condenser is operated under full steam load conditions. But what happens when this same condenser is operated under part load? The condenser ITD decreases rapidly under part load conditions. The reduced ITD causes a severe reduction in the vacuum pump capacity, especially when the condenser is operated at 50% load or below.

In the example given in the reference, the condenser was capable of operation at 1.97 inches (5.00 cm) Hg Absolute under full load conditions, and 1.33 inches (3.38 cm) Hg Absolute at 50% load. However, at this reduced load and reduced ITD, the vacuum pump capacity fell off to 75% of design, and it would operate at 1.75 inches (4.45 cm) Hg Absolute. Therefore, the vacuum pump would limit the condenser operating pressure, and the condenser would operate at the elevated pressure.

Hybrid systems are designed for the maximum anticipated cooling water temperature and are not dependent on the ITD. Capacity would be 100% for either condition given previously.

Many power plant operators are not aware that their CAR equipment may be limiting the condenser under part load conditions. Only reference to the condenser performance curve will reveal the fact that the operating pressure is above the pressure the condenser is capable of, robbing the plant of available energy.

Key O&M Cost Point

Plant CAR equipment may be limiting the condenser under part load conditions. Only reference to the condenser performance curve will reveal the fact that the operating pressure may be above the pressure the condenser is capable of, robbing the plant of available energy.

4.4.3 Retrofitting Hybrid Systems to Existing Plants

The operating advantages of the hybrid can be achieved by retrofitting existing SJAE or liquid ring vacuum pump systems. In existing SJAE systems, the second-stage SJAE and after-condenser can be replaced by a liquid ring pump. This results in the more efficient hybrid arrangement.

Existing liquid ring vacuum pumps can be combined with a new first-stage SJAE and inter-condenser to provide added capacity if the present system is not adequate. This inadequacy might be as a result of increased air leakage, decreased pump performance, or operation of the main condenser at off-design conditions. Also, with the advantages explained in Section 4.4.1, the retrofit will allow the system to achieve greater vacuum levels with an improved ability to maintain optimum condenser performance as well as reduce oxygen levels in the condensate.

System design should include all possible countermeasures to prevent leakage of live steam into the vacuum pump. The pump will be damaged if live steam enters the unit without cooling water supply to the inter-condenser and/or no seal water supply during vacuum pump shutdown.

Under no circumstances should steam flow be permitted to enter the pump during vacuum pump shutdown. Each of the following should be considered in the system design:

- A positive sealing valve should be used to isolate live steam from the pump during any time that cooling water to the system is shut off.
- If possible, the interlock system should be designed so that cooling water is continuously supplied to the inter-condenser/pump when steam is on.

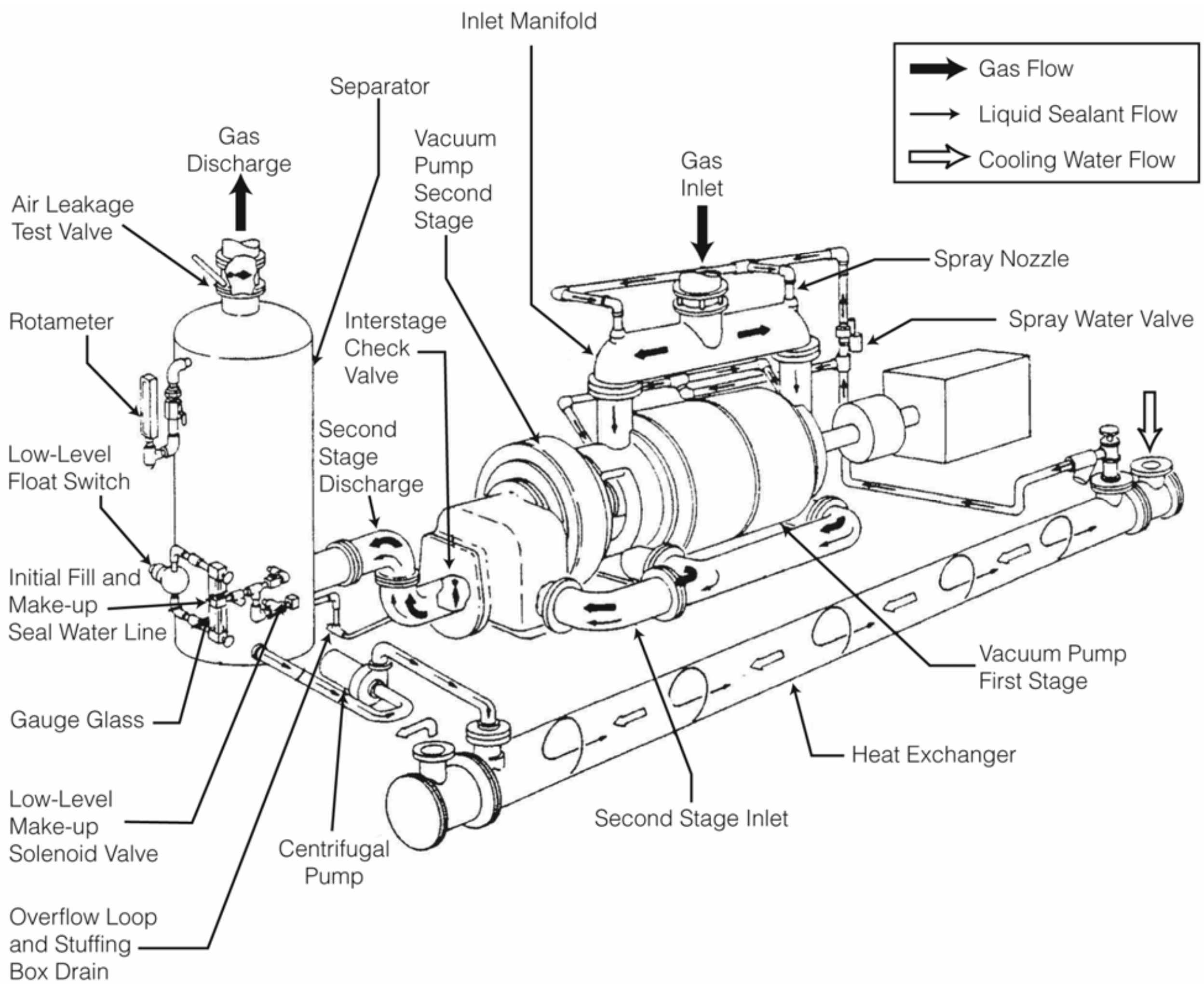


Figure 4-21
Hybrid Condenser Exhaust
Source: Heat Exchange Institute

5

FAILURE DATA AND FAILURE MODES

Failure modes and their causes are discussed in this section. The data presented here were obtained from searches of industry databases and other sources for CAR system equipment failures. The NRC Event Notification System and Inspection Report databases and the INPO OE database were searched. The INPO OE database includes NRC Licensee Event Reports. The individual results of the searches are tabulated in Appendix A.

The failure data presented here were supplemented with information obtained in a survey on CAR equipment sent to select nuclear plants and with information obtained in follow-up interviews from those surveys. Some technical advisory group members also provided additional failure information as part of their review of the draft document.

Thirty-eight percent of the CAR system failures occurred on SJAE-related systems, while 62% occurred on MVP-related systems. For failures occurring on the MVPs themselves and not to supporting equipment, helical rotor MVPs accounted for 55% of the failures, while liquid ring MVPs accounted for 45%.

Helical rotor MVPs are a subset of the rotary screw group of MVPs, along with the subset of spiral rotor MVPs. There were no failures reported in the searched databases for spiral rotor MVPs. This is not to say there have been no failures, but that the application of the screening criteria for including the failures in the databases always eliminates them. The reason for this is that spiral rotor MVPs, when used, are installed in the hogging mode for BWRs. In this mode, the MVPs are typically operated to evacuate the condenser and turbine volume in parallel with reactor startup. The pumps are low-pressure pumps and are not typically intended to be able to establish sufficient vacuum by themselves to place the turbine online. At some point in the startup, the SJAEs are placed online, and the MVP is secured to continue the condenser evacuation. Therefore, MVP malfunctions that would require placing the SJAEs online earlier than desired would be corrected but would not typically be reported unless startup was significantly delayed.

5.1 SJAE System Failure Modes and Mechanisms

SJAE systems are fundamentally reliable because the SJAEs themselves have no moving parts. If the steam supply is dry, the cooling water is clean, and the materials of construction are matched properly to the corrosive nature of the process fluids, SJAE systems can, and do, last indefinitely. If the SJAEs are operated within their design parameters for steam pressure, condensate temperature, and SJAE backpressure, failures seldom occur, although failures of the supporting equipment do sometimes occur. The most common problem areas for SJAE systems based on the review of failure history are SJAE loss of vacuum and malfunctions of the SJAE steam supply and suction valves. The most common causes of SJAE loss of vacuum are operating the SJAE with a condensate temperature or SJAE backpressure outside of the design limits. The relative failures of the SJAE-related systems are further broken down in Table 5-1.

Table 5-1
Failures in SJAE-Related Systems

SJAE System Component	Percent of Failures
SJAE	44%
Suction valves	25%
Steam supply valves	31%

The failure modes of the SJAE-related system components are given in Table 5-2.

Table 5-2
Failure Modes in SJAE-Related Systems

SJAE System Component	Failure Modes
SJAE	Loss of vacuum
Suction valves	Failed to close
Steam supply valves	Failed to close Failed to open Stuck closed Failed to control pressure

5.1.1 SJAE Loss of Vacuum

Because SJAE failures seldom occur, there is limited failure history for this failure mode with which to provide associated failure mechanisms. However, additional failure mechanisms are provided in the Heat Exchange Institute's Tech Sheet # 102, "HEI Steam Jet Vacuum Systems Troubleshooting Guide." The failure mechanisms identified from the failure history are:

- Increased condensate temperature above system design as a result of changes in plant operation
- Increased SJAE backpressure above system design as a result of malfunctions or operational changes in the off-gas system (BWR only), downstream of the CAR system
- Flooded inter-condenser as a result of system design weaknesses that inhibited proper inter-condenser hotwell draining
- Lost inter-condenser loop seal as a result of failed SOV

Additional failure mechanisms from HEI Tech Sheet # 102 are:

- Plugged steam nozzles as a result of foreign material in steam supply
- Wear of internal working surfaces of nozzles and diffuser as a result of wet steam
- Too much friction in ejectors as a result of fouling of internal working surfaces

5.1.2 SJAE Suction or Steam Supply Valve Failure to Close or Stuck Closed

Most failure mechanisms for this failure mode are related to failures of SOVs to operate. SOV failures occurred throughout the failure history for other failure modes on other equipment as well, and are discussed in more detail later. The failure mechanisms identified from the failure history are:

- Interference with SOV operation by SOV mounting bracket as a result of less than adequate installation. Because new SOVs were physically different, new mounting brackets were fabricated out of angle iron. The angle iron interfered with the magnetic flux generated by the SOV coil, resulting in multiple failures of the valves to operate.
- Air leakage at bonnet-to-body flange that prevented SOV operation.
- Hardening of o-rings that prevented SOV operation as a result of the lack of PM.

5.1.3 SJAE Steam Supply Valve Failure to Open or to Control Pressure

The failure mechanisms identified from the failure history are:

- Disengagement of packing nut that caused a loss of valve packing as a result of less than adequate previous maintenance
- Blocked pressure controller sensing lines as a result of corrosion product buildup
- Inaccurate pressure indicator, used for manually setting supply pressure, as a result of instrument drift
- Failed auxiliary steam supply pressure controller as a result of untimely corrective maintenance

5.2 MVP System Failure Modes and Mechanisms

Liquid ring (single-stage and two-stage), helical rotor (two-stage), and spiral rotor (single-stage) MVPs are in use in nuclear power plants for CAR purposes. Spiral rotor MVPs are in limited use at some BWRs for hogging mode operation. MVPs used for holding mode operation consist of two-stage liquid ring MVPs, single-stage liquid ring MVPs coupled to an air jet air ejector, or helical rotor MVPs. The relative failures of the MVP-related systems are further broken down in Table 5-3.

Table 5-3
Failures in MVP-Related Systems

MVP System Component	Percent of Failures
Helical rotor MVP	43%
Liquid ring MVP	38%
Suction valves	19%

Based on the review of failure history, the most common problem areas identified for MVP systems are MVP trips, MVP failures to start, MVP degraded performances, and MVP suction valve failures. The failure modes of the MVP-related system components are given in Table 5-4.

Table 5-4
Failure Modes in MVP-Related Systems

MVP System Component	Failure Modes
Helical rotor MVP	Tripped Failed to start Degraded performance
Liquid ring MVP	Tripped Failed to start Degraded performance
Suction valves	Failed to close Failed to open

5.2.1 MVP Trips

The failure mechanisms identified from the failure history are:

- Elevated discharge temperature (helical rotor) as a result of design limitations or fouled seal water cooler
- Failed seal water pump (liquid ring) as a result of a faulted motor or seized impeller
- Tripped motor thermal overloads (helical rotor) as a result of a failed inter-stage relief valve, caused by a lack of PM
- Tripped oil pressure switch as a result of improper calibration during previous maintenance
- Tripped seal water flow switch as a result of improper adjustment during previous maintenance

5.2.2 MVP Failures to Start

The failure mechanisms identified from the failure history are:

- Tripped vacuum (pressure) switch (liquid ring) as a result of instrument drift
- Tripped motor thermal overloads for unknown reasons

5.2.3 MVP Degraded Performance

The failure mechanisms identified from the failure history are:

- Increased suction pressure (cyclically) (helical rotor) as a result of excessive motivating air being introduced into the pump suction to reduce the discharge temperature.
- Lifted inter-stage relief valve (helical rotor) as a result of motivating air being injected at too low an ambient temperature.
- Overheated outboard motor bearing as a result of insufficient quantity of grease applied to the bearing by a motor repair shop.
- Inability to hold condenser vacuum at 1.8 inches (4.57 cm) Hg absolute (liquid ring) as a result of the spray valve not opening. The spray valve was improperly installed during recent modification and was not detected during testing because the vendor’s note that the spray valve would be closed during low vacuum operation was misinterpreted by test engineer to mean low absolute vacuum.
- Flooded separator tank as a result of a stuck makeup water valve.

5.2.4 MVP Suction Valve Failure to Open or Close

The failure mechanisms identified from the failure history are:

- Isolated valve controller sensing lines as a result of root valves not being opened after maintenance.
- Failed SOV as a result of internal valve leakage.
- Failed differential pressure switch (liquid ring) as a result of initial incorrect calibration of a new switch, with the differential pressure applied in the reverse direction. Unclear vendor drawings were misinterpreted to establish calibration requirements.
- Failed differential pressure switch as a result of instrument drift.
- Failed SOV as a result of the repair kit diaphragm being installed in reverse orientation.

5.2.5 SOV Failures

Twenty-four percent of the CAR equipment failures were related to SOV failures. In EPRI publication NP-7414, *Solenoid Valve (SOV) Maintenance and Application Guide*, a failure modes and effects analysis was performed on a data source consisting of thousands of SOV failures across all nuclear plants and all systems. Five failure modes were identified. These are:

Failure to shift to the fully energized position

Failure to shift to the fully de-energized position

Excessive internal leakage

Excessive external leakage

Position indication failure

The major failure mechanisms associated with these failure modes are:

- Inadequate coil magnetic force
- Excessive residual magnetism
- Internal binding
- Seat wear or damage
- Valve body damage as a result of porosity, corrosion, or erosion
- Closure leakage

5.2.6 Other Considerations

Inappropriate human performance was involved in 45% of the failures. Some of the inappropriate performance was related to a less than adequate understanding of how the CAR equipment functions. Examples include the effects of iron brackets on SOV performance, proper cooling water spray valve operation, and the effects of induced motivating air on helical rotor vacuum pump performance. Training programs for system engineers and maintenance personnel should be reviewed and strengthened as appropriate to address these weaknesses.

Key Human Performance Point

Training programs for system engineers and maintenance personnel should be reviewed and strengthened as appropriate to address weaknesses in the understanding of how the CAR equipment functions.

Condition monitoring or PM activities were not being performed on 13% of the equipment prior to its failure. Examples include SOVs, the seal water cooler, the seal water pump, and the inter-stage relief valve. Condition monitoring and PM practices on CAR equipment should be reviewed as discussed in Sections 7 and 8.

6
TROUBLESHOOTING

Troubleshooting and industry experience help identify probable causes and provide suitable corrective actions. The following sections and tables provide potential problems, possible causes, and possible solutions. Troubleshooting guidance in some instances is provided for specific types of equipment, such as SJAEs, liquid ring vacuum pumps, and rotary screw vacuum pumps. In other instances, it is provided for areas common to more than one type of equipment, such as bearing problems, lubrication system problems, and noise level problems. For guidance on troubleshooting coupling problems, refer to EPRI 1007910, *Flexible Shaft Couplings Maintenance Guide*, and for guidance on troubleshooting speed reducer problems, refer to EPRI 1009831, *Gearbox and Gear Drive Maintenance Guide*.

6.1 SJAE Troubleshooting (Based on Heat Exchange Institute Tech Sheet # 102)

As vacuum systems age, problems may arise. A gradual loss of vacuum usually suggests an internal problem, such as erosion or corrosion, which should be addressed at the next routine inspection. A sudden loss of vacuum, on the other hand, suggests external factors, such as a change in quality of steam supply or quantity or temperature of water supply to the condensers. Because most unexpected issues arise from easier-to-investigate external causes, most troubleshooting begins on the outside. Issues arising from external and internal causes are included in the troubleshooting matrix of Table 6-2. Internal SJAE issues are more difficult to troubleshoot.

6.1.1 SJAE Troubleshooting Difficulties

The primary difficulties in troubleshooting an SJAE system result from the following factors:

- Not understanding how ejector systems work
- Not being able to easily observe the operation (fluids flowing inside)
- Becoming confused by the interaction of components
- Working in a high radiation field (for BWRs)

6.1.2 SJAE Troubleshooting Techniques

Three methods to use in overcoming troubleshooting difficulties and simplifying the troubleshooting process are:

1. Study the appropriate parts of the HEI Standard for Steam Jet Vacuum Systems and any available manufacturer's literature on how systems work and how ejectors behave.
2. Use the appropriate pressure and temperature gauges to determine fluid conditions and flow meters to determine their rates.
3. Isolate and check the system and its components by performing the following troubleshooting procedure.

6.1.3 SJAE Troubleshooting Procedure

The following procedure provides one method to isolate system components and check them for proper operation. Refer to Appendix C for SJAE terminology used in the procedure.

1. Check the operational history of the overall system (vacuum user and vacuum producer). Check for feed rate changes, trends, or abnormalities in the suction pressure being produced, operation of valves, gages, and meters.
2. Isolate the vacuum producer (steam jet vacuum system) from the vacuum user by closing off the suction valve or installing a blind flange on the jet system suction connection. (Ensure that no liquid is trapped in the isolated section.) If the load suction pressure (for a system designed to be stable at no load) is approximately as listed in Table 6-1, the steam jet system is most likely working.

Table 6-1
Multi-Stage SJAE No-Load Suction Pressure

Number of Operating Stages	No-Load Suction Pressure
1	35–50 mm Hg Abs
2	5 mm Hg Abs
3	1 mm Hg Abs
4	50–100 microns Hg Abs
5	5–10 microns Hg Abs

If the typical no load suction pressure is not obtained, keep the system isolated, install a blank on the last stage (z) ejector, and turn on its steam only. (Leave the water on to all condensers.) Check the z stage no-load suction pressure per Table 6-1 (one stage operating). If it works, put the blank on the next stage up (y), and turn steam on to the z stage first (to check for inter-stage leaks) and then to y and z stages. Check two-stage no-load suction pressure per Table 6-1. Continue until unsatisfactory results occur.

As you discover unsatisfactory operation, realize that an SJAE requires that only the following four basic mechanical conditions be satisfied:

1. No plugs (stoppage or fouling) in the nozzle or diffuser exist.
2. No leaks from the atmosphere or steam at the steam nozzle connection (inside the suctions head) exist.
3. The internal working surfaces of the nozzle and diffuser are reasonably smooth.
4. The correct parts are in place.

Similarly (inter-) and (after-) condensers (shell and tube type) require these four mechanical conditions be satisfied:

1. Reasonable clean tube surfaces exist (inside and out).
2. No blockage to fluid flow exists.
3. No leaks from the atmosphere (including condensate drains) or from the water side to the condensing side exist.
4. No flooding (of the condensing side) exists.

Call the manufacturer with the information you've obtained from (all or part of) this procedure. They will be able to lead you to the problem cause most effectively. Ninety-nine percent of all troubleshooting issues can be handled over the phone.

6.1.4 SJAE Troubleshooting Matrix

SJAE systems are fundamentally reliable vacuum producers, as they have no moving parts. If the steam supply is dry, the cooling water is clean, and the materials of construction are matched properly to the corrosive nature of the process fluids, SJAE systems can, and do, last indefinitely. However, the reality of some operating environments creates potential problems (both short term as well as long term). These are listed in Table 6-2, from the most common to the least common.

Table 6-2
SJAE Troubleshooting Matrix (Based on Heat Exchange Institute Tech Sheet #102)

Problem	Possible Causes	Possible Solutions
Plugged (completely or partially) steam nozzles.	Foreign material in the steam supply (particularly from pipe fabrication at installation).	Disassemble, inspect, and clean the nozzles.
Wear of internal working surfaces of nozzles and diffuser.	Wet steam.	Install a separator and trap at ejector system. Insulate lines. Trap low spots. Set line sizes for 150 ft/sec (45.7 m/sec). Superheat steam -50°F (27.8°C) max.
Insufficient energy supply.	Steam pressure lower than the design minimum pressure.	Raise steam pressure (at the ejector) above the design minimum (or ask manufacturer to redesign).
Suction flow overload and increased suction pressure.	Excessive air leaks and unexpected process loads.	Find and correct leaks and overloads.
Insufficient condensing and cooling or high condensing pressure.	Cooling water temperature higher than the design maximum. Cooling water flow lower than the design value	Correct supply temperature. Increase water flow.
Too much friction in ejectors and/or too little heat transfer rate in condensers and/or blockage of the condensate drain.	Fouling of internal working surfaces (process fluids or cooling water).	Clean parts.
Too much compression required given the design energy provided.	System discharge pressure higher then the design maximum.	Decrease discharge pressure drop or redesign (z) stage.
Too much pressure drop between vacuum user and vacuum producer.	Suction pipe conditions: • Smaller size than connection • Partially closed block valves • Fouling • Liquid traps • Undersized in-line equipment	Correct suction pipe condition.

Table 6-2 (continued)
SJAE Troubleshooting Matrix (Based on Heat Exchange Institute Tech Sheet #102)

Problem	Possible Causes	Possible Solutions
Flooding of condensers.	Insufficient condensate removal provisions.	Clean tail pipe and check for air leaks. Ensure operation of installed mechanical equipment.
Too much or too little steam flow.	Excessive steam pressure and/or temperature.	Limit overpressure to approximately 125%. Limit superheat to approximately 50°F (10°C).

6.2 Liquid Ring Vacuum Pump Troubleshooting

Table 6-3 provides a list of liquid ring vacuum pump potential problems, along with possible causes and possible solutions. Unless specifically identified as only applying to a two-stage pump, the problems apply equally to both single- and two-stage pumps.

Table 6-3
Liquid Ring Vacuum Pump Troubleshooting Matrix

Problem	Possible Causes	Possible Solutions
Condenser back pressure high or increasing.	High cooling water temperature. Low cooling water flow rate.	Resolve off-normal operating conditions.
In-leakage greater than 15 scfm (0.42 scmm) at 1 inch (2.54 cm) of Hg absolute.	High air in-leakage.	Investigate and repair leaks.
Inlet pressure and horsepower increased.	Back pressure in excess of five inches of water in the discharge separator.	Correct the separator back pressure issue.
Substantially higher vacuum at inlet horn of the vacuum pump than at the condenser.	Restriction in suction line.	Correct restriction in the suction line.
Speed not according to nameplate.	Motor or power supply voltage problem.	Correct motor or power supply voltage problem.
Temperature difference of seal water into and out of the heat exchanger greater than 15°F (8.33°C).	Blockage in strainer, orifice unions, or inlet spray nozzles.	Inspect strainer, orifice unions, and inlet spray nozzles for blockage.

Table 6-3 (continued)
Liquid Ring Vacuum Pump Troubleshooting Matrix

Problem	Possible Causes	Possible Solutions
Temperature difference between the cooling water into the heat exchanger and the seal water into the pump greater than 2°F (1.11°C).	Blockage in heat exchanger tubes.	Inspect and clean heat exchanger tubes.
Separator seal water level below minimum level.	Makeup SOV. Level float switch.	Check operation of low-level makeup SOV and level float switch. Inspect the check valve for proper operation and the strainer and orifice union for blockage.
Hogging capacity of the two-stage vacuum pump is satisfactory, but the vacuum pump does not evacuate the system to the proper operating pressure.	Excessive system leakage. Inter-stage check valve.	Investigate system leakage. Inspect inter-stage check valve inside the second stage discharge.
Two-stage vacuum pump shows no capacity either as indicated by checking leakage with the rotameter or by observing that turning the unit on has no effect on the system.	Low or no instrument air pressure. Control panel SOV. Differential vacuum switch.	Check all valves between the pressure gauge at the control panel and the instrument air source to be sure they are open. Check the solenoid coil to see if it is energized. Check the exhaust port for leakage of instrument air inside the SOV from the supply connection to the exhaust opening. Check the differential vacuum switch located inside the control panel to see if it is closed.

6.3 Rotary Screw Vacuum Pump Troubleshooting

Troubleshooting the rotary screw vacuum pump can be divided into two areas based on whether the problem is a performance problem or a mechanical problem.

6.3.1 Troubleshooting Rotary Screw Vacuum Pump Performance Problems

If the pump is not maintaining desired vacuum, check the following items before dismantling:

- Check for a restriction in the pump suction line. A substantially higher vacuum at the pump inlet than at the condenser will indicate a restriction.
- Check for excessive backpressure in the pump discharge line. Pressure measured at the vacuum pump discharge should be less than 2 psig.
- Check all valves for proper operation, and ensure that they are installed properly.
- Check all air and water lines to the pump to ensure that no valves are closed and no other restrictions exist.
- Check the seal water pressure at the seal water manifold. It should be 6 to 15 psig.
- Check the rotation of the vacuum pump by referring to the rotation arrow.
- If the unit has been disassembled, there is a possibility that some of the parts have been omitted or improperly installed.
- Make certain that the seal water cooler is clean and provided with sufficient water at a temperature at least 7.5°F (4.17°C) below the vacuum pump inlet temperature.
- Make certain that the inter-stage check valve seats properly.

6.3.2 Troubleshooting Rotary Screw Vacuum Pump Mechanical Problems

6.3.2.1 Rotary Screw Vacuum Pump Vibration

Vibration is always a sign of trouble and is often the only indication of trouble. It is always advisable to shut down the vacuum pump as quickly as possible if excess vibration is experienced, and not to restart the vacuum pump until the cause of the vibration has been determined and corrected. The most common causes of vibration are:

- Coupling misalignment.
- Rubbing or contact between rotating and stationary parts caused by loss of timing. If contact is indicated, check the timing.

6.3.2.2 Rotor Thermal Growth

Two-stage helical rotor vacuum pumps have tight internal clearances and, in some cases, were designed for lower inlet temperatures then actually experienced in the field. This sometimes caused rotors to thermally grow into the partition plate between the two stages and into the casing. Plants that have experienced this excessive thermal growth have developed several solutions.

- One plant trimmed the rotors to allow for increased thermal growth. This de-rated the pump capacity 3–5%, but it did change the designed pump discharge temperature from 190°F (87.8°C) to 201°F (93.9°C).
- Another solution implemented at several plants is to open vent valves to the turbine building on the pump suction line to introduce "motivating air" into the pump, thus reducing the inlet and outlet temperatures. Up to three vent valves are opened as condenser and ambient temperatures increase above a predetermined value. Caution must be exercised to monitor temperatures closely when large changes in day-to-night temperatures occur. With full motivating air still applied, the decreased nighttime temperatures can result in exceeding the pump capacity, and condenser vacuum may be reduced.

Key Technical Point

When vent valves on rotary screw pump suction lines are opened to introduce "motivating air" into the pump, caution must be exercised to monitor temperatures closely when large changes in day-to-night temperatures occur. With full motivating air still applied, the decreased nighttime temperatures can result in exceeding the pump capacity, and condenser vacuum may be reduced.

6.3.2.3 Rotary Screw Vacuum Pump Inspections

If a rotary screw vacuum pump is shut down as a result of unsatisfactory operation, the following inspection should be made:

- Check the operating conditions prior to shutdown to determine if the pump was operating within both normal temperature range and normal pressure range.
- Eliminate the possibility that the pump driver may be the source of the trouble.
- Secure all details that indicate abnormal operation. If the pump is operating and can continue to operate for a short period, attempt to determine the exact source of the trouble. Check for noise, heat, vibration, a leakage condition, and so on.
- If the pump has been shut down, review the operating characteristics before and at the time of shut down.

- If the trouble has not been determined, remove the inlet and discharge piping. Check the interior of the pump for foreign material or any indication of rotor contact.
- Check rotation. The rotation should be free, with no tight spots or excessive drag, and there should be no metallic sounds during the rotation.
- Check the internal clearances, the gear backlash, and the bearing adjustment.

6.4 Non-Equipment-Specific Troubleshooting Guidance

Tables 6-4 through 6-6 provide guidance for the generic problem areas of bearing problems, lubrication system problems, and noise level problems.

Table 6-4
Bearing Troubleshooting Matrix

Problem	Possible Cause	Possible Solution
High bearing temperature	Inadequate cooling	Verify water flow and temperature (self contained bearing cooling).
		Verify oil flow and temperature (circulating lube oil system). Verify pumps are operating and filters are not blocked.
	Erroneous data	Verify that thermocouple/RTD is operating correctly. A portable thermometer is often used to check bearing operating temperature against a fixed sensor.
	Lube oil contaminated	Verify that the correct amount of clean lube oil exists.
	Oil ring damage	Verify that the oil ring is operating correctly.
	Bearing alignment	Check bearing alignment.
	Bearing damage	Open and inspect bearing: • Check for excessive clearance or insufficient clearances. • Check for wiped bearing surfaces.
	External heat source	Verify that no externally applied heat source is present, including high ambient temperature.

Table 6-5
Lubrication System Troubleshooting Matrix

Problem	Possible Cause	Possible Solution
No lube oil flow	Low oil level	Add oil.
	Pumps not operating	Repair pumps.
	Dirty filter	Clean or replace the filter.
	Incorrect system lineup	Review the valve lineup.
	Heat exchanger plugged	Inspect the heat exchanger.
Low oil pressure	Dirty filter	Clean or replace the filter.
	Pump capacity	Examine pumps.
	Incorrect valve lineup	Verify proper valve positions.
	Oil viscosity	Check oil temperature and type.
	Pressure switches	Verify set points and operation.
	Relief valve	Verify set points and position.
	Flow orifice	Verify size.
Noise/vibration	Pump operation	Check pump alignment for damage.
	Relief valve	Verify position of relief valve.
	Oil viscosity	Check temperature and oil type.
Oil contamination	Cooling water leaks	Examine and test heat exchangers.
	Filter	Verify the integrity of filters.
	Storage tank	Verify that the oil source is clean.
High oil temperature	Heat exchanger fouled	Inspect heat exchangers.
	Cooling water	Check the temperature and flow rate of cooling water.
	High bearing temperature	Inspect bearing and bearing clearance to identify heat generation.

Table 6-6
Noise Level Troubleshooting Matrix

Problem	Possible Cause	Possible Solution
Noise	Insufficient bearing clearance	Adjust or replace bearing.
	Damaged bearing surface	Replace bearing or liner.
	Inadequate lubrication	Add oil or check lube oil system.
	Worn or damage coupling	Replace coupling.
	Coupling alignment	Realign coupling.
	Motor noise	Reference motor guide.
	Loose motor bolts	Tighten bolts.
	Defective bearings	Replace bearings.
	Rotor or timing gear	Check rotor clearances and gear backlash.

7
CONDITION MONITORING

EPRI 1000621, *Equipment Condition Monitoring Templates—Addendum to Preventive Maintenance Basis (TR-106857 Volumes 1–38)*, defines *condition monitoring* as any task that allows collection of data (periodically or continuously) on the operating condition of equipment, the purpose of which is to discover whether the condition of the equipment has changed and by how much. The scope of the condition monitoring task must be such that the equipment cannot be disassembled, opened, or changed in any way that materially compromises operation, or it would induce the risk of equipment failure or degradation as a result of maintenance-related errors, such as personnel errors, installation errors, or parts defects.

This broad definition includes tasks such as operator rounds, external visual inspections, general visual-off-line and online, and nondestructive examination (NDE) inspection. Broadening the definition to include these activities as condition monitoring allows a more comprehensive analysis of all data on equipment condition. External visual inspections do not include activities that require use of portals or removal of inspection covers, plates, or guards.

Predictive maintenance, which includes oil analysis, vibration analysis, and thermography, is viewed as a subset of condition monitoring activities. Refer to EPRI 1000621 for discussions of applicable condition monitoring templates. Condition monitoring uses advanced technologies to determine equipment condition and, potentially, predict failure. It includes, but is not limited to, technologies such as the following:

- Vibration measurement and analysis
- Oil analysis
- NDE
- Infrared thermography
- Motor current analysis

One goal of condition monitoring is to identify changes in the condition of the pump, motor, or auxiliary that could indicate some potential failure. Physical characteristics are measured, recorded, and analyzed so that trends can be identified.

Key Technical Point

One goal of condition monitoring is to identify changes in the condition of the pump, motor, or auxiliary that could indicate some potential failure.

7.1 Operator Rounds and External Visual Inspections

Operator rounds take place once per shift, while external visual inspections occur at longer intervals, typically once per month.

7.1.1 Operator Rounds

Operator rounds are predictive maintenance tasks that take place once per shift and involve observing and in some cases recording items such as:

- Bearing oil levels and temperatures
- Condition of condensate traps
- Discolored water that could indicate leaking cooler tubes
- Oil pressure
- Cooler pressures and temperatures
- Pressure drops across filters
- Fluid leaks

7.1.2 External Visual Inspection

External visual inspections include inspections for:

- Air, oil, and water leaks.
- Clogged or excessively dirty inlet air filters and motor intake screens.
- Indications of high operating temperatures, such as discolored paint.
- Unusual noises and odors.
- Visual indications of vibration.
- Unusual color of the condensate water in the traps.
- Normal oil levels and pressures.
- Loose, missing, or damaged parts, wiring, or tubing.
- Normal differential pressure and temperatures across filters and coolers. Record values for trending.
- Proper light indications on control panels.

7.2 Vibration Monitoring

Vibration monitoring consists of acquiring and analyzing specific machine operating parameters.

7.2.1 Parameters

The following parameters can be used to form a database for CAR equipment:

- Amplitude
- Frequency
- Phase angle
- Vibration form
- Vibration mode shape

7.2.1.1 Amplitude

Amplitude can be expressed in terms of displacement, velocity, or acceleration. Amplitude provides an indication of severity by measuring how smoothly or roughly the equipment is operating. Equipment that is operating within the manufacturer's recommended limits will have a stable amplitude reading. A change in this reading indicates a change in the condition of the machine. This change signals a need for further investigation.

7.2.1.2 Frequency

The frequency of vibration is expressed in either cycles-per-second, cycles-per-minute, or as multiples of the rpm. Examples of these multiples include the following:

- 1 x rpm: Vibration frequency is the same as the machine's rpm.
- 1/2 x rpm: Vibration frequency is one-half the machine's rpm.
- 0.43 x rpm: Vibration frequency is 43% of the machine's rpm.

Vibrations occurring at frequencies that are direct multiples (for example, lx, 2x, 4x) of the machine's rpm are termed *synchronous* or *harmonic*. Vibrations occurring at frequencies that are an integer fraction (for example, l/2x, 1/3) of the machine's rpm are termed *sub-synchronous*. *Non-synchronous* vibrations occur at frequencies other than direct multiples of the machine's speed.

Machine problems most often occur at low vibration frequencies, typically less than four times (4x) the running speed. Frequency should not be used as a measure of the problem's severity unless roller and ball bearings are involved. In certain cases, specific frequencies can be linked to specific problems such as unbalance and misalignment. However, this does not mean that there is a direct correlation between problems and vibration frequencies.

7.2.1.3 Phase Angle

The phase angle provides a reference measure of movement of a specific point on the shaft or rotor. This point can be a high spot located on a shaft or a concentration of uneven weight that may have collected on the pump rotor. The measurement is taken relative to either another moving point or to a fixed point, such as a transducer. The phase measurement or angle is expressed in degrees. Accurate phase-angle measurement plays an important role in balancing vacuum pump rotors and in analyzing the mode shape of the vibration.

7.2.1.4 Vibration Form

Vibration form is the actual vibration displayed as a wave pattern. The wave pattern generated represents shaft motion. Short-lived, transient types of vibrations are best analyzed through observing their wave form characteristics (shape, amplitude, and pattern) on an oscilloscope. This provides the ability to “see” what the equipment is doing at a particular instant of time.

Vibration form can be displayed as a time-based presentation or as an orbital presentation. Time-based presentation uses inputs from a displacement transducer displayed on an oscilloscope in the time-based mode. An orbital presentation uses the input from two probes spaced 90° apart from each other in the X-Y mode of an oscilloscope. This latter method allows operating engineers to observe the centerline motion of the shaft. As an example, if the probes were mounted on a bearing housing, the display would show the movement of the shaft centerline relative to the bearing.

7.2.1.5 Vibration Mode Shape

Vibration mode shape is obtained by recording vibration amplitude and phase values at many points on the structure of the entire machine, including pump bearings, driver, and foundation. The vibration mode of a piece of equipment provides a means of confirming resonance conditions, locating nodal points (points of minimum amplitude), and identifying points of structural weakness. By conducting casing measurements along a drive train, problems such as pipe resonance, structural resonance, or loose/cracked foundations can be determined.

7.2.2 Vibration Analysis

Vibration analysis can be accomplished through a variety of available techniques. The following techniques offer methods to obtain and display vibration data:

- Amplitude versus frequency
- Real-time spectrum analysis
- Time wave form

7.2.2.1 Amplitude-Versus-Frequency Analysis

The vibration amplitude-versus-frequency analysis method is considered to be the most useful. Over 85% of mechanical problems occurring on rotating equipment can be identified using this method. This technique has applications for both continuous monitoring/machinery protection and for diagnostic equipment checks.

Key Technical Point

The vibration amplitude-versus-frequency analysis method is considered to be the most useful. Over 85% of mechanical problems occurring on rotating equipment can be identified using this method.

The primary equipment needed to conduct this test includes a vibration-pickup (probe) and vibration analyzer. Use of an X-Y recorder provides the added feature of automatically producing a plot of frequency-versus-vibration amplitude. An additional option available on some vibration analyzers is an automatic frequency tuner. This feature eliminates the need for operators to manually tune through the frequency spectrum. Using an automatic frequency tuner provides extended troubleshooting capability. It reduces the element of human error by eliminating the chance of missing significant vibration frequencies, and it reduces the actual analysis time by eliminating time spent on fine-tuning to each significant frequency.

The following are additional recommendations to follow when using the amplitude-versus-frequency technique:

- Take vibration readings along the horizontal, vertical, and axial directions at each bearing.
- Select an amplitude range setting on the vibration analyzer sufficient for the maximum vibration signature in order to obtain data that are plotted on the same range.
- Select a single amplitude range setting sufficient for the entire analysis.
- Obtain an overall “filter out” reading (in each of the three positions) at each bearing.

7.2.2.2 Real-Time Spectrum Analysis

This method is most effective when the vibration is not steady-state or the vibration is transient. Use of a real-time spectrum analyzer allows O&M personnel to capture and analyze vibration signatures. Two features available with real-time analyzers are **Hold** and **Peak Hold**. The **Hold** control is operator-initiated when the transient frequency reaches its maximum amplitude. This action stores the transient signal into the analyzer’s memory for future analysis. The **Hold** feature provides a means to manually capture the transient signal. This method will work if the following conditions are met:

- The operator is fully aware of when the transient signal will occur.
- The transient signal occurs slowly enough for the operator to depress the **Hold** button.

The **Peak Hold** feature provides a method to capture and store a transient signal in situations that do not meet the previous two conditions. If this feature is used, the operator must set the trigger level, which specifies the percentage of the signal's amplitude used to begin the process. For example, if the operator chooses 50%, detection circuits will look for an amplitude level exceeding this value from incoming signals. Once this 50% criterion is met, the circuit will trigger and automatically capture an incoming transient signal.

7.2.2.3 Time Waveform Analysis

Time waveform analysis uses an oscilloscope to provide a time display of vibration amplitude. The oscilloscope can be set up to receive an input vibration signal either directly from the transducer or from a real-time spectrum analyzer. Either method allows operators to analyze vibration quickly and easily. Data obtained are not filtered, thereby providing a true measure of the maximum amplitude present. Using an oscilloscope can also provide an excellent means for observing and evaluating transient vibration signals that may be present because of pump pulsations or control problems.

Essential to any online monitoring system is the choice of sensors (transducers) to be used. For vibration measurement, there are three types of transducers available. These transducers are referred to as proximity (non-contact), velocity, and accelerometer probes.

7.2.3 Proximity Probes

A *proximity probe* is a transducer used for vibration and position measurement. Physical contact with the object such as a shaft being measured for vibration or position is not required. Proximity probes are used to measure the relative movement between the shaft and the bearing or bearing housing. Principal components include the probe, pickup, connecting cable, and driver. Inside the probe is a coil that receives high-frequency current from the driver. As this current passes through the coil, a magnetic field is established. Conductive material, such as a steel shaft, brought in proximity to the coil as a result of vibration or axial motion will "cut" the lines of the magnetic flux, thereby setting up eddy currents on the conductive material's surface. Stronger eddy currents are established as the shaft gets closer to the probe and weakens the magnetic field around it.

The strength of the magnetic field is directly related to the level of equipment vibration. In practice, the field strength is monitored by detection circuitry located in the driver. Output from the driver is either in the form of a dc signal or a combination of a dc and ac signal. When no vibration is present, a dc voltage directly proportional to the distance (gap) between the shaft and probe is transmitted from the driver. As vibration levels develop, a dc signal proportional to the average gap and an ac signal proportional to vibration amplitude are generated.

Applications

There are three applications for systems using proximity probes:

1. Radial vibration
2. Axial position, phase reference
3. Rotating speed reference

Advantages

A proximity probe offers the following advantages:

- It measures the motion of the shaft (primary source of machine vibrations) in terms of displacement.
- It makes no contact with the shaft.
- It has no moving parts and is small.
- It has an excellent frequency response.
- It is easily calibrated.
- It provides accurate low-frequency amplitude and phase angle information.

Disadvantages

A proximity probe has the following disadvantages:

- It requires an external power source.
- It is sensitive to certain shaft materials.
- It is sensitive to shaft mechanical and electrical run out.
- It may not detect looseness in support components.

7.2.4 Velocity Probes

Operation of a velocity probe is based on the movement of a conductor (in this case, the coil) through a magnetic field. The amount of voltage that is induced in the coil will be proportional to the relative velocity between it and the magnetic field. Unlike a displacement probe, a velocity probe requires no external power source to operate.

A velocity pickup consists of six principal parts: pickup case, wire coil, damper, mass, springs, and permanent magnet.

The pickup case provides a structure to house the remaining components. The wire coil is wrapped around the mass that, in turn, is suspended between the permanent magnet by the springs and damper. The permanent magnet is attached to the pickup case and provides a magnetic field around the suspended coil.

In certain applications, velocity probes and their cables can be susceptible to magnetic interference. This magnetic interference may be caused by the alternating magnetic field that is generated around large ac motors. Without proper shielding, these fields can induce a voltage in the pickup or cable. Consequently, an erroneous vibration signal may be generated.

If this condition is suspected, the magnetic field's intensity and presence can be determined. To perform this test, personnel will need a vibration analyzer connected to a portable velocity probe. The probe should be held steady by its cable near the permanently installed velocity probe, and the suspended probe should not come in contact with the operating equipment. During vacuum pump operation, a reading on the analyzer indicates that a strong magnetic field is causing interference. To alleviate this problem, a magnetic shield should be installed around the fixed velocity probe.

Advantages

A velocity probe offers the following advantages:

- The probe is mounted on the external housing of the machine component and it gives a strong signal in mid-frequency ranges.
- No external power supply is required.
- The signal can be electronically integrated to provide a displacement signal.

Disadvantages

A velocity probe has the following disadvantages:

- The probe is relatively large and heavy.
- The probe is difficult to calibrate and requires a shaker table.
- The probe has mechanical moving parts that can be expected to wear out.
- The probe may pick up outside magnetic interference.
- The probe only measures dynamic motion.
- The probe has a narrow frequency response and amplitude and phase errors can be generated at low frequencies.
- Because the probe is manufactured as a unit, a fault in any of the components will require replacement of the entire unit.
- The probe is susceptible to cross-axis sensitivity at high vibration amplitudes.

7.2.5 Accelerometer Probes

The internals of an accelerometer probe are made up of four components: mounting stud, frame, piezoelectric disks, and mass.

The mounting stud provides a means to attach the probe assembly to the equipment being monitored. The frame assembly houses the mass and the piezoelectric disks. The last two components form the heart of an accelerometer probe.

Piezoelectric material can generate an electric charge when it undergoes mechanical stress. This stress can be compressive or tensile. Disks of piezoelectric material are rigidly sandwiched between the frame and the mass. In the event of vibration, these disks undergo a series of compressive and tensile reactions. These, in turn, produce an electric signal proportional to the magnitude of the force imparted to the mass. Because the amount of mass is known, the signal generated represents the acceleration of the mass.

Accelerometers are small, lightweight, and rugged. A principal advantage of this type of probe is its ability to operate over a wide frequency range. This capability makes an accelerometer well suited for monitoring high-frequency vibrations that can develop in anti-friction bearings or gears.

Accelerometers are unaffected by magnetic fields that may originate from nearby electric machinery. They require no special shielding or other provisions.

Advantages

Accelerometer probes offer the following advantages:

- They are easy to install.
- They are useful for high frequency measurements above 2 kHz, highly reliable, relatively lightweight, and have no moving parts.
- They are available for high-temperature applications.

Disadvantages

Accelerometer probes have the following disadvantages:

- They can be influenced by vibration transmitted to the vacuum pump housing by the surrounding environment.
- Transducer fault will require replacement of the entire unit.
- They are difficult to calibrate and feature a poor signal/noise ratio.
- Double integration to displacement is susceptible to noise problems.
- They require and external power source and usually require filtering in the monitor.

7.2.6 Data Acquisition

Accurate data acquisition is the basis for a successful vibration-monitoring program. It is essential to adopt a systematic approach to obtaining and recording data for use in the analysis process.

For machines equipped with installed vibration sensors, obtaining data means monitoring and recording vibration levels displayed on the gauges or output devices provided. Monitoring programs using portable equipment either to supplement existing installed vibration sensors or to check equipment not outfitted with an installed monitoring system will require personnel to identify specific locations on which to place the probes. These locations should be identified both on the equipment or component and on the forms used to record the data. This procedure will help ensure that consistent and reliable information is obtained. Use of color-coded marks such as red dots provides operators with an easily seen reference point from which to take vibration readings. The avoidance of confusion should be a prime consideration, because introducing incorrect data into trending and equipment history files will produce erroneous results.

Machine Diagram

An important part of the data acquisition process is the machine diagram. A diagram of this type forms a link between the actual physical location on the equipment or component and the record used to log the results. To be effective, the diagram should show all the essential elements. For a vacuum pump, these elements should include the driver (motor), driven unit (pump), bearings, coupling, speed changer (if applicable), and installed vibration sensors. Additional information, such as motor rpm, type of bearings (sleeve or antifriction), pickup points, date, name of persons performing the check, and space to enter vibration amplitudes and frequencies, should also be incorporated onto the form.

Tri-Axial Readings

Recommended practice indicates that readings should be taken in the horizontal, vertical, and axial directions at each bearing housing. This three-axis approach can assist the maintenance organization in distinguishing between various mechanical problems, such as imbalance and misalignment. For example, both of these problems are manifested as an increase in vibration. The frequency of this vibration level is typically lx rpm for both misalignment and imbalance. A pump out-of-balance will have high vibration levels in the radial directions (horizontal and vertical); vibration levels observed in the axial direction would be significantly less. Misalignment, however, typically produces high vibration levels in all three directions.

Analyzing horizontal and vertical readings can also provide insight into the condition of the equipment. For vacuum pumps with a floating outboard bearing, the vibration levels in the horizontal direction will be higher than those in the vertical direction. This difference is considered normal for rigidly mounted pumps where the vertical stiffness is greater than the horizontal stiffness. A deviation from this condition may indicate loose equipment hold-down bolts, damaged grout layers and/or foundation, wiped bearings, or excessive bearing clearance.

7.3 Oil Analysis

Oil samples taken for purposes of oil analysis are also appropriate for out-of-service checks. A basic spectro-chemical analysis can provide maintenance personnel with the following information:

- Particle count
- Viscosity
- Total acid/base measure
- Condition of oil additives

This information can be used to determine whether it is necessary to open and inspect a bearing for wear and damage as well as provide a snapshot picture of the lube oil's quality. However, there are not any recognized industry standards for what is acceptable in lubricating oil. The oil analysis should, therefore, be used to identify changes and trends. Oil analysis tests are often offered free or for a nominal charge by the lubricant supplier as part of the overall service provided. If the physical design of the equipment prevents ready access to the bearings, the pre-startup checks should be accomplished during the out-of-service maintenance period before closing up the pump for operation.

Key O&M Cost Point

Oil analysis tests are often offered free or for a nominal charge by the lubricant supplier as part of the overall service provided.

7.4 Infrared Thermography

Infrared thermography is typically used to identify problems with electric motors and electrical terminations. Other than on motors and electrical terminations, thermography has not been typically used on CAR equipment. However, thermography can be effectively used wherever temperature differentials or temperature changes signify degraded conditions. One nuclear station routinely uses thermography to successfully identify sources of condenser air in-leakage that challenges the performance of the CAR system by monitoring temperature differentials and temperature changes on condenser attached piping, flanges, and so on. This station has also used it to identify leaks and blockages in CAR equipment process lines and drains containing hot fluids.

Key Technical Point

Thermography can be effectively used to identify sources of condenser air in-leakage that challenges the performance of the CAR system and to identify leaks and blockages in process lines and drains containing hot fluids.

7.5 Motor Current Analysis

Condition monitoring of the electric motors is addressed in EPRI NP-7502, *Electric Motor Predictive and Preventive Maintenance Guide*.

8
PREVENTIVE MAINTENANCE

This section identifies recommended maintenance tasks and their frequencies. As each application could be different, the experience at a given plant should be reviewed, and any recommended frequencies should be adjusted. MVPs require periodic inspection and maintenance to ensure their reliable operation. SJAEs typically do not. Internal SJAE problems usually result from erosion or corrosion and usually reveal themselves by a gradual loss of performance that affords the plant staff adequate time to schedule an overhaul. The discussion in this section relating to SJAEs applies also to the atmospheric jet air ejectors previously described as used in conjunction with a single-stage liquid ring vacuum pump in one type of packaged CEU.

In order to support the utilities in their need to assess both the effectiveness and underlying bases of their PM programs, EPRI developed and published between 1997 and 1999, TR-106857, Volumes 1–38, *Preventive Maintenance Basis Documents (PM Basis)*. These volumes are now considered historical, as PM basis are now included and updated in the EPRI PM Basis Database Component Data Tables.

8.1 Developing a PM Program

The evolution from a fix-when-fail philosophy to a PM philosophy begins with developing a list of maintenance checks for each vacuum pump and its supportive auxiliary systems. This list of checks is based on manufacturer's recommendations, operational experience, and EPRI component-level maintenance guides and PM templates. Knowing the capabilities of the maintenance department helps determine which maintenance checks in-house staff can accomplish and which must be contracted out. Use of recommendations from the manufacturer, along with industry and plant operational experience, can provide valuable insight in determining not only what checks should be done, but also how often they should be done. Conversely, for maintenance checks that show no signs of wear, inspection intervals should be increased. Section 8.4.3 presents a methodology that one plant used to optimize the PM activities on their CAR equipment.

Key O&M Cost Point

Use of recommendations from the manufacturer, along with industry and plant operational experience, can provide valuable insight in determining not only what checks should be done, but also how often they should be done.

Warning signs, such as excessive equipment failure after maintenance has been completed, could be indications of inadequately trained personnel and/or poor quality control standards. The philosophy of "if it works, don't fix it" should be considered in any maintenance program. Opening and inspecting components, such as bearings or actuators, can lead to additional problems and equipment down time. A balance must be attained by doing PM but avoiding opening and inspecting equipment if no problems (such as high temperature or pressure) are present. This balance is achieved by carefully determining an adequate time period (frequency) between checks. Note that this does not in any way suggest that basic sound operating engineering practices—such as ensuring adequate lubrication, clean lubrication, daily visual inspection of the equipment, and cleaning equipment—should be ignored.

Key O&M Cost Point

A balance must be attained by doing PM but avoiding opening and inspecting equipment if no problems (such as high temperature or pressure) are present.

Once this list of checks is finalized, the next step is to develop written formatted PM tasks. Each PM task should provide an itemized listing of what is required to accomplish the specific maintenance action. Actual procedures to conduct a specific maintenance action may also be incorporated on this PM task sheet. For example, a well-thought-out PM task should include information such as the trades involved in the check, related additional checks that could be accomplished simultaneously, special tools required to accomplish the job, man-hours required, technical manuals and drawings required, and data readings to be taken. A database incorporated into a PM task can provide a ready reference for personnel to use during equipment maintenance periods. In certain cases, a "pictorial map" could also be attached to a task sheet to provide standard locations to take measurements.

8.2 Basic Rules for Conducting Maintenance

To avoid unnecessary injury to personnel or damage to the equipment, sound basic maintenance rules should be practiced at all times:

- Keep the area around the disassembled equipment clean.
- Take inventory of the tools brought in and out of a job.
- Use the correct tool for the specified job.
- Do not take shortcuts when safety is involved.
- Follow proper tag-out and valve-out procedures.
- Keep the shop supervisor informed of the progress and any problems encountered.
- For PM actions, verify that the required parts are available before starting the job.

8.3 SJAE Maintenance Recommendations

The review of the maintenance history did not reveal any CAR system failures as a result of internal SJAE problems. Responses to an industry survey conducted in support of the preparation of this guide identified that plants that use SJAEs for CAR equipment typically do not perform PM activities on their SJAEs unless indications of problems exist. An EPRI PM Basis Database Data Table for SJAEs was developed as part of the preparation of this guide and is discussed in Section 8.3.1.

8.3.1 EPRI PM Basis Database—SJAE

The following PM activity listed in Table 8-1 is based on the newly developed EPRI PM Basis Database–Steam Jet Air Ejectors. (Refer to the EPRI PM Basis Database Data Table—Steam Jet Air Ejectors for additional condition monitoring activities.)

Table 8-1
SJAE PM Activities Based on EPRI PM Basis Database Data Table

Duration	Activity	Basis
10 years	Perform nozzle and condenser inspection.	Expected life is 20 years with continuous operation. Nozzle degradation as a result of erosion would be expected after 10 years with poor steam quality.

8.3.2 Ejector Internal Inspections

Erosion or corrosion that is obvious to the eye and touch will affect performance. There are several things to look for when performing internal inspections of an ejector:

- Wet steam will cause “wiredrawing” lines etched up and down the inside of the steam nozzle.
- Wet steam will also cause gouging at the point along the diameter where the steam contacts the venture.
- Steam leaking around the nozzle puts an additional load on that stage, resulting in poor vacuum. This will be noticeable as a discoloration where the nozzle seats on the steam chest or as erosion of the nozzle threads.
- Corrosion or buildup of material on the ejector internals will also affect the performance of that unit.
- Compare critical dimensions, such as nozzle orifice or venture bore diameter, against the manufacturer’s drawings to determine extent of wear.

Part numbers of the various ejector components should be checked to ensure that they are in the right unit. Many ejector parts, and sometimes complete stages, are physically interchangeable and care must be taken not to mix them up.

Key Human Performance Point

Care must be taken to ensure that the various ejector components are in the right unit. Many ejector parts, and sometimes complete stages, are physically interchangeable.

8.3.3 Ejector Spare Parts

As a minimum, keep at least the following components in stock:

- One steam nozzle for every single-nozzle ejector stage
- One diffuser for every stage

Because most nozzles are relatively inexpensive, they should be considered sacrificial. If wear is evident, they may be discarded and easily replaced. A complete (z) stage should be kept in stock.

8.4 Liquid Ring MVP Maintenance Recommendations

Two sources of PM recommendations were used for the development of this guide:

1. EPRI PM Basis Database Data Table—Liquid Ring Rotary Compressor and Pump: In the course of the preparation of this guide, this data table was revised to recommend a 10-year overhaul of the vacuum pump and to increase the frequency of the pressure switch calibration to once every six months.
2. Liquid Ring Vacuum Pump Equipment Vendor Manual.

8.4.1 EPRI PM Basis Database Data Table—Liquid Ring Rotary Compressor and Pump

EPRI categorizes a liquid-ring type CAR pump as a critical, high—duty cycle piece of equipment that is exposed to severe service conditions.

- It is categorized as *critical* because it is required for power production or other regulatory requirements.
- It is categorized as *high-duty cycle* because it is frequently cycled or partially loaded for the greater part of its operational time.
- It is exposed to *severe service conditions*, such as high or excessive humidity, excessive temperatures, or excessive environmental conditions.

Based on this categorization, the EPRI PM Basis Database Data Table—Liquid Ring Rotary Compressor and Pump recommendations include the following PM activities listed in Table 8-2. (Refer to the EPRI PM Basis Database Data Table—Liquid Ring Rotary Compressor and Pump for additional condition monitoring activities.)

Table 8-2
Liquid Ring PM Activities Based on EPRI PM Basis Database Data Table

Duration	Activity	Basis
10 years	Overhaul MVP.	Based on expected life of 10 years.
5 years	Replace mechanical seals.	Expected life is five years with continuous operation.
2 years	Replace SOVs.	Could be relaxed for those SOVs with low duty cycles. Refer to EPRI TR-106857-V7, "Solenoid Valves."
	Coupling inspection.	Based on coupling life of at least 10 years.
	Instrument calibration.	Collective significance of device failure mechanisms supports this interval.
1 year	Check valve, strainer, and trap inspection: • Inspect and clean check valves, looking for internal seat leakage, binding, and broken or weak springs. • Inspect and clean strainers and traps. • Inspect flow control orifice for evidence of wear.	Check valves are affected by debris, strainers can become clogged in as little as a few months, and traps can become clogged in as little as six months to a year.
As required	Boroscope inspections of pump internals (rotor, cone, lobe, internal casing, inlet and outlet flanges) for erosion or corrosion.	Done in conjunction with condition monitoring activities, such as vibration analysis or performance monitoring, which would indicate a problem.
	Moisture separator/seal water tank inspection for rust, corrosion, sediment, or clogging of float valve.	Interval based on water quality.

8.4.2 Liquid Ring Vacuum Pump Manufacturer's Recommendations

The liquid ring vacuum pump vendor recommends the PM activities as shown in Table 8-3. The schedule can be modified based on plant-specific operating conditions and maintenance history.

Table 8-3
Liquid Ring PM Activities Based on Vendor's Recommendations

Duration	Activity
12 months	Inspect and clean heat exchanger tubes.
	Inspect soft seating surface of system inlet valve.
	Check and lubricate vacuum pump bearings.
12 months	Check low-level float switch for proper operation.
	Clean and lubricate SOVs.

Table 8-3 (continued)
Liquid Ring PM Activities Based on Vendor's Recommendations

Duration	Activity
12 months	Replace packing in stuffing box in each head and bracket.
	Check inter-stage check valve to ensure free movement of linkage.
6 months	If coupling is of the lubricated type, re-lubricate it.
	After initial 6 months of service, check and lubricate vacuum pump bearings.
As required	Check packing in stuffing box to ensure that there is a constant drip. (Vendor has informed some plants that this constant packing leakoff is not necessary.)

If the unit is shut down for two to three weeks, the manufacturer recommends that pump be rotated by hand at least once every week to prevent rust buildup between cast iron parts. If the unit must be taken out of service for more than three weeks, the manufacturer provides a detailed lay-up procedure in the vendor manual to prevent seizing of the pump as a result of rust formation during storage.

Key O&M Cost Point

To prevent pump damage as a result of the built up rust between cast iron parts, follow the manufacturer's recommendations for short- and long-term lay up.

8.4.3 Case Study for Optimizing Liquid Ring Vacuum Pump PM Activities

One plant that uses liquid ring vacuum pumps as part of its CAR equipment had not previously determined PM activities and intervals for the equipment. This plant is part of a utility that owned a fleet of nuclear plants and was able to draw on the collective maintenance experience of personnel from throughout the fleet. The flowing steps were followed by the utility to establish PM activities and intervals:

1. A basic CAR equipment PM template containing activities and intervals was established using the historical EPRI TR-106857-V27, *Liquid Ring Rotary Compressor and Pump* as a guide.
2. This template was reviewed by a peer group comprised of members from all the plants in the fleet. A standard template was issued for the fleet.
3. Each plant reviewed the standard template against their operating and maintenance history and created site-specific requirements.

The outcome of this process for the plant in question includes the following:

- Although EPRI TR-106857-V27 categorizes liquid ring rotary pumps in CAR applications as *critical*, *high duty cycle*, and *severe service condition*, the process resulted in a categorization of *mild service condition*.
- The main pumps and their motors are rebuilt every 10 years. Boroscope inspections between these overhauls are not required.
- Soft-seated valves and valve operators are rebuilt every five years.
- Couplings are inspected and re-greased every 36 months.
- SOVs are rebuilt every 24 months.
- Vacuum pump heat exchanger tubes are cleaned every 12 months.
- Thermography is performed every 12 months.
- Vacuum switches are calibrated every six months.
- Oil analysis is performed every three months.
- Vibration analysis is performed every 45 days.

8.5 Rotary Screw MVP Maintenance Recommendations

Two sources of PM recommendations were used for the preparation of this guide:

1. EPRI PM Basis Database Data Table—Rotary Screw Air Compressor
2. Rotary Screw Vacuum Pump Equipment Vendor Manual

8.5.1 EPRI PM Basis Database Data Table—Rotary Screw Air Compressor

EPRI PM Basis Database Data Table—Rotary Screw Air Compressor was developed for rotary screw machines used in an air compressor application, not in a CAR application. However, it can be used as a guide for a vacuum pump application. For the same reasons the liquid ring type CAR pump was categorized as a *critical*, *high duty cycle*, *severe service condition* piece of equipment, the rotary screw CAR pump would be categorized also in the same way. Based on these categories, EPRI PM Basis Database Data Table—Rotary Screw Air Compressor recommendations include the PM activities in Table 8-4. (Refer to PM Basis Database Data Table—Rotary Screw Air Compressor for additional condition monitoring activities.)

Table 8-4
Rotary Screw PM Activities Based on PM Basis Database Data Table—Rotary Screw Air Compressor

Duration	Activity	Basis
6 months	Internal inspection: • Inspect motor bearing and coupling for indications of loss of grease or oil. • Ensure that motor air intake is not clogged or dirty.	Need to ensure that components that may be replaced during annual overhaul avoid failure during intervals between overhauls.
12 months	Overhaul: • Clean the float valve. • Inspect check valves. • Test relief valves. • Calibrate pressure and temperature sensors. • Pressure-test coolers. • Inspect and lubricate coupling. • Inspect condition of pump elements.	12-month period could be extended based on plant experience.

8.5.2 Rotary Screw Vacuum Pump Manufacturer's Recommendations

The rotary screw condenser vacuum pump vendor recommends the PM activities as shown in Table 8-5. The vendor does not provide a recommended interval but states that the schedule should be based on specific operating conditions and maintenance history. Also, the vendor only provides recommendations for inspection of the vacuum pump and not for the supporting equipment, such as motors, check valves, and instrumentation.

Table 8-5
Rotary Screw PM Activities Based on Vendor's Recommendations

Duration	Activity
General inspection, with interval based on plant-specific operating conditions	Remove inlet and discharge piping and accessories, and check condition of rotors. If rotors show signs of contacting each other or the housing, then check rotor timing. Disconnect coupling and rotate pump by hand. Pump should rotate freely with no indication of drag and no metallic sound Check timing gear backlash to determine wear. Replace bearings and mechanical seals. Drain lube oil reservoir, clean reservoir, and refill with clean oil. Remove oil lines and end covers and inspect all oil spitters. Clean spitters if required.

8.6 Component Maintenance

The following subsections describe the maintenance tasks for the components and support equipment of SJAEs and MVPs.

8.6.1 Bearings

Ensuring that the lubricant is at the correct level, clean, and of good quality is essential to prolonging the operational life of a bearing. An inadequate amount of oil being supplied to a bearing will result in its operating at higher-than-normal temperatures. High temperature conditions can cause the oil to break down and the bearing to be damaged by excessive friction levels. Similarly, excessive amounts of oil or grease can cause the bearing to overheat as well. Levels recommended by the manufacturer should be adhered to.

Static lubricating oil systems offer a particular challenge to a maintenance department. If a low-level condition is discovered during operation, personnel should proceed with caution when adding oil to the affected bearing while the pump is in operation. Relatively colder oil that is added while the shaft is rotating can disrupt the oil film that has been formed. If this condition occurs, metal-to-metal contact can be expected with resulting damage to the bearing.

Key Technical Point

If oil in a self-contained sump is below normal level, adding relatively cold oil may disrupt the oil film. Shut the vacuum pump down before adding oil.

The quality of the oil being used is best determined by taking an oil sample. Visual inspections taken before pump startup can provide operators with assurance that the oil quality is satisfactory. Periodic oil samples taken while the pump is in operation are recommended for bearings lubricated by a circulating oil system. Taking an oil sample on a static system during pump operation is not recommended. Use of a drain valve installed in place of a drain plug can provide some measure of control if personnel consider it necessary to sample oil during vacuum pump operation. If a drain valve is used, it is good practice to install a cup or plug to seal the discharge line from dirt and to act as a safeguard to prevent draining of the system if the valve is accidentally opened. Two primary concerns are that the oil film may be disrupted as the oil is being replenished with colder oil and that the sump may run dry while the vacuum pump is in operation.

Do not mix oils in the lubrication system or bearing housing. Chemical additives in different oils can cause a breakdown in the viscosity, cooling, or bearing lubrication.

Key Technical Point

Do not mix oils in the lubrication system or bearing housing. Chemical additives in different oils can cause a breakdown in the viscosity, cooling, or bearing lubrication.

There are four general indicators of impending bearing failure: vibration, excessive noise, steady increase in bearing operating temperature over time, and/or a lube oil sample contaminated with babbitt or water.

8.6.1.1 Routine Maintenance Recommendations

Routine maintenance should include the following:

- Verifying that oil is at the proper level
- Visually inspecting the seals for leakage
- Checking the bearing temperature and ensuring that heaters (if installed) are placed in operation; adjusting the cooling water flow to maintain correct temperature

The recommended minimum temperature varies for each manufacturer. For bearings cooled by a circulating oil system, the following tasks should be performed:

- For bearings fitted with inspection covers, verify lube oil flow through the bearings, check for proper operation of oil rings, and visually observe oil circulation.
- Wipe the inspection cover thoroughly before opening to prevent any dirt/debris from entering the bearing system. Bleed any air pockets from the system by cracking open a vent valve.
- Inspect the bearing cooling systems:
  - Verify alignment and start system.
  - Inspect for leaks.
  - Verify flow has been established.
  - For a closed system, bleed any air pockets from the system by cracking open a system vent valve.
- Draw an oil sample and conduct a visual inspection for the following:
  - Water contamination
  - Particulate contamination (dirt, metallic)
    Note: When drawing an oil sample, ensure that the sample bottle is clean and dry; if not, it should be wiped with a lint-free rag.
- Ensure that the area around the sample petcock/sample plug is clean before opening.
- For systems having sample lines, adequately flush the line to remove any dirt or condensation that may have collected inside the line.

8.6.1.2 Bearing Overhaul

Worn components should be replaced as required. The replacement criteria are directly related to physical damage caused by cuts, heat, corrosion, or other factors.

The following provides a list of components most susceptible to wear:

- Gaskets
- Packing rings
- Seals (including any auxiliary seals)
- Seal springs
- Laminated shims
- Garter springs
- Wave springs

For sleeve bearings, an inspection should be made of the babbitt surface for surface scoring or wiping. (Axial scoring is unacceptable; circumferential scoring is not to exceed manufacturer's recommendations.) The following should be noted during the inspection:

- Fatigue cracking
- Corrosion
- "Black scab" or "wire wool" damage
- Pitting as a result of electrical discharge
- Overheating
- Uneven wear
- Fretting
- Inadequate lubrication

An inspection should be made of the shaft journal for ridges, grooves, and/or sharp edges. If they are present, they should be removed with an approved abrasive cloth. The shaft journal should have a finish range specified by the manufacturer.

Thrust collars should be inspected for axial runout and radial runout. On a thrust bearing, the face-to-face dimension is critical. A check should be made to ensure that the passes are perpendicular to the face.

Clearance checks should be made to verify the following:

- Total indicated runout clearance between the sleeve thrust face and the thrust collar
- Distance from shaft to the bearing housing seal groove/recess
- Clearance between outer diameter of seal and inner diameter of bearing housing
- Clearance between inner face of oil conveyor disc and orifice partition
- Clearance between scoop and guide assembly

Some bearings require a specific housing-to-bearing clearance, which must be set.

The following alignment checks should be done:

- Inspect shaft journal, sleeves, thrust collars, and interior of bearing housings for corrosion and dirt. Clean surfaces with an approved cleaning solvent, such as mineral spirits or kerosene.
- Inspect water cavities and oil cavities for dirt and corrosion; clean as required.
- Inspect oil rings and oil conveyor for damage or looseness.
- Inspect threads of various bolts, pipe nipples, and so on, for burrs or corrosion.

- Inspect sensor cavities for dirt and corrosion.
- Replenish oil to bearing sump.
- Enter accomplished maintenance actions on equipment PM records.

Maintenance will vary with the complexity of this system. Specific components requiring various degrees of maintenance include the following:

- Pumps and motors
- Gauges/pressure relief valves/pressure switches/temperature switches/motor controllers
- Piping/valves
- Heat exchanger
- Cooling fan
- Sump

8.6.2 Lubrication System

8.6.2.1 Routine Maintenance

Some routine maintenance tasks should be completed to verify that the lube oil is at the proper level in the sump and at the required temperature. To control the temperature through the heaters or cooling system (air/water), it should be verified that the cooling fans are running (if installed). The cooling water flow should be checked, and correct heater operation should be verified.

Discharge filters and pump suction strainers should be cleaned and inspected. In addition, all electrical connections (cables for pumps, sensors, and so on) should be checked for cracks or looseness, and all control panel access doors should be checked to verify that they are closed and properly secured.

Any unusual noise or vibration should be noted. The differential pressure across filter elements should be checked (shift, inspect, and clean as required).

8.6.2.2 Circulating Lube Oil System Overhaul

The calibration and inspection of all system instrumentation and sensors should include the following:

- Pressure switches
- Thermostats
- Relief valves
- Liquid-level switches

Pump operation and alarms at given system test pressures should be verified.

The inspection of a water-cooled heat exchanger should include the following:

- Open and inspect heat exchanger interior; remove sludge and scale deposits.
- If suspected, check for tube leakage (cracked tubes, damaged tube joints).

In the event of low-discharge pressure, the pump should be opened and the impeller surfaces and wear ring as well as the foot valve should be inspected.

When poor oil quality is suspected, the sump should be drained and cleaned. All door gaskets should be inspected and replaced as necessary. Before re-closing the sump, it is important to ensure that all rags have been removed.

In the maintenance of all electrical components, the following tasks should be performed:

- Conduct continuity checks on electric motors and heater coils.
- Inspect all cables for cracking or other damage.
- Open, inspect, and clean all control and relay boxes.
- Verify that all electric motors have been connected properly by checking component rotation.

All exterior surfaces should be inspected and cleaned. All corrosion should be removed. Priming and painting should be performed as required.

An inspection and cleaning of cooling fan blades and air-cooled heat exchanger surfaces should also be performed.

All filters and strainers should be inspected and cleaned. The location of filters is very important. Filters installed only at the suction side of the oil pump do well in protecting the pump. However, pump wear or damage can pass to the bearings if oil is not final-filtered before is enters the bearing. The optimum system has both suction filters and final filters. These final filters should be installed as close to the bearings as possible.

All system components and lines should be primed and vented.

8.6.3 Couplings

Couplings provide a means of connecting the prime mover (electric motor or steam turbine) to the designated load (the vacuum pump rotor). There are two types of couplings: flexible and rigid. Flexible couplings are used extensively in vacuum pump service.

Depending on the design and service requirements, flexible couplings can provide the following benefits:

- They can provide protection for slight misalignment caused by thermal expansion and contraction between the prime mover and its load.
- They can lessen vibrational torque to reduce noise and absorb any torsional oscillation that may be generated during a transient condition (startup, shutdown, and speed changes associated with a variable-speed motor).

There are four types of flexible couplings that could be used with vacuum pumps: grid, gear, elastomeric sleeve and elements, and disc. These couplings can be divided into two broad categories:

- Sealed lubricated (grid and gear types)
- Non-lubricated (rubber sleeve, rubber elements, and disc)

Gear and grid type couplings are designed with limited end float to prevent motor rotor axial movement that can cause damage to the motor.

Coupling maintenance is discussed in more detail in EPRI report 1007910, *Flexible Shaft Couplings Maintenance Guide*.

8.6.3.1 Routine Maintenance Recommendations

Some routine maintenance recommendations include the following:

- Verify that the coupling has correct type and amount of grease (grease lubricated couplings only).
- Ensure that the fasteners and grease fittings are properly tightened.
- Visually inspect the area around the coupling for:
  - Leaks
  - Rags or other obstructions
- Ensure the coupling guard is installed.

These checks are performed on vacuum pumps having couplings that are readily accessible for a pre-start inspection:

- Inspect for cracked discs (disc-type coupling).
- Visually inspect for unusual noise or vibration.
- Visually check for collection of rubber-like dust directly below coupling (elastomeric sleeve/element type only).

8.6.3.2 Coupling Overhaul

For a gear-type coupling, an overhaul would include the following tasks:

- Disassemble and inspect the coupling in accordance with manufacturer's guidelines.
- Thoroughly remove and clean old grease from the coupling and inspect the following areas for signs of wear or fatigue cracks:
  - Teeth
  - Grid
  - Fasteners
  - O-rings, gaskets, grease seals
- Obtain a sample of the grease for testing.
- Reassemble the unit.

Key Technical Point

Verify that components used to restrict motor shaft movement are installed.

- Replenish grease.
- Perform the following alignment checks:
  - Parallel alignment
  - Angular alignment
- Note that the gap spacer is in place and correctly installed (limited end float coupling designs).

For a disk-type coupling, an overhaul would include the following tasks:

- Conduct a visual inspection for cracks developing in the disc(s).
- Disassemble the coupling, checking the extent of the disc cracks and replacing any damaged disc.
  Note: The order or number of the shims in a disc pack coupling must not be changed.
- Replace the fasteners if the locking feature is in doubt.
  Note: The locking feature of these fasteners becomes compromised when they are removed and reinstalled a certain number of times. As an example, Rexnord recommends replacing the fasteners after they have been removed/reinstalled between 7 to 10 times.

Key Human Performance Point

The locking feature of disc-type coupling fasteners becomes compromised when they are removed and reinstalled a certain number of times.

- Perform the following alignment checks:
  - Parallel alignment
  - Angular alignment

8.6.3.3 Coupling Alignment

Misalignment can result in high vacuum pump vibrations. For vacuum pump installations that have high vibration sensitivity, the coupling can be aligned to a tighter tolerance, which reduces vibration. A tighter tolerance on coupling alignment can be achieved by using a computerized alignment device.

It is important to verify that the thrust load of the vacuum pump is not imposed on the motor thrust bearing. This requires knowledge of the magnetic center of the motor.

For more detailed information on alignment, refer to EPRI TR-112449, *Shaft Alignment Guide*.

Key Human Performance Point

It is important to verify that the thrust load of the vacuum pump is not imposed on the motor thrust bearing. This requires knowledge of the magnetic center of the motor.

8.6.4 Structural Support System

The structural support system (SSS) is a five-component system comprised of a concrete foundation, a grout layer, anchor bolts, pedestal, and soleplate/baseplate. Maintenance of these components is often nonexistent. The SSS is no different from any other supportive auxiliary system and, therefore, should be incorporated into a PM program.

8.6.4.1 Concrete Foundation

An annual visual inspection of foundation is recommended.

8.6.4.2 Repairing Concrete Foundations

Assuming that the soil base has been properly stabilized, the repair of concrete foundations encompasses two areas:

1. Surface cleaning
2. Crack repair

To obtain maximum effectiveness, each of these maintenance actions should include both prevention and detection. Prevention is a two-tier process. Early detection through regular inspections will provide a decisive step toward prevention of major problems and the major repairs that follow. Investigating and determining the cause of the casualty is the second part of a PM action. Maintenance personnel should avoid hasty repairs without first addressing the question, "What caused this problem?" This is especially true in the case of concrete foundation repair. If the foundation continues to crack, hidden problems, such as voids in a concrete foundation or an unstable soil base, should be considered for investigation.

The correction or repair of a concrete foundation involves the choice between a permanent fix (which may require the erection of a new foundation) and a semi-permanent fix used as a stop-gap measure to keep the vacuum pump online until a scheduled outage or until the needed logistics are brought together to affect more permanent repairs.

8.6.4.3 Surface Cleaning

Over time, oil may degrade the structural integrity of concrete by causing a physical breakdown in the matrix structure of the concrete. This breakdown process is not immediate and may take years to develop into a serious problem. However, it is one problem that can certainly be prevented and corrected.

Steam cleaning provides one possible solution for concrete surfaces that have been subjected to oil spillage over a period of years.

8.6.4.4 Crack Repair

Curing cracks do not have any appreciable depth or pattern; structural cracks, however, are large and deep. If structural cracks are not addressed, they may continue to develop in severity. As the foundation continues to degrade, operators and maintenance personnel can expect equipment misalignment, bearing problems, and an increase in vibration amplitude. Early detection is critical to limiting damage to both the foundation and the vacuum pump.

Because anchor bolts are stress risers, structural cracks will appear most often in the immediate vicinity of these bolts. Proper installation of these anchor bolts and correction of equipment vibration offer the best courses of action to take in avoiding this problem.

Before actual repairs can begin, the following several factors should be considered:

- Choice of the correct grout
- Severity of the damage
- Urgency to bring the vacuum pump back on line
- Access to the damaged area

The effectiveness of a grout is based on its ability to act as an adhesive and to bond the damaged area into a structurally sound joint. Determining which grout resin system to use is an important factor in the repair process. Variables such as pot life (curing time), non-shrink capability, ability to bond through oil films, viscosity, and wetability all factor into the effectiveness of the grout to penetrate the crack and bond the two cracked segments into a cohesive unit.

The extent of damage is the final determining factor in deciding whether a foundation can be repaired. Experienced personnel in the field of concrete foundation repair should be consulted to assist in the decision process. Once it has been determined that the foundation can be repaired, the need for the vacuum pump provides an important input into the decision to conduct temporary repairs or defer the maintenance action until a scheduled outage.

8.6.4.5 Anchor Bolts

An anchor bolt functions as a clamp to provide a secure means for holding the baseplate to concrete foundation. This clamping effect is accomplished through a spring-type action between the anchor bolts and the concrete foundation/grout layer system. As the bolt nuts are tightened, the bolt itself begins to stretch. This stretching phenomenon plays an important part in the successful application and performance of the anchor bolt. As each anchor bolt is tightened, the bolts become a system of springs that will collectively apply a clamping or compressive effect around the entire baseplate. The net effect achieved is a secure base for the vacuum pump to operate on.

8.6.4.5.1 Forces Affecting Anchor Bolts

During the operational life of the vacuum pump, anchor bolts will be subjected to three loading conditions:

- Initial preload: The load that develops when the anchor bolt is first tightened
- Residual preload: The load remaining after all anchor bolts have been properly tightened
- Working load: The load the anchor bolt is subjected to while the vacuum pump is in operation

If properly installed and tightened, the residual pre-load on the bolts should be less than any load caused by operation.

8.6.4.5.2 Proper Installation

Critical to achieving a good installation is the need to properly isolate the anchor bolt. There are two areas that require special attention to ensure anchor bolt isolation. Use of foam insulation in the area around the grout where the bolt penetrates can provide adequate isolation. Failure to accomplish this allows the grout to bond the bolt. Should this occur, the bolt would be limited to stretch in a short section. Two consequences of this condition are the following:

- Loose bolts after vacuum pump startup with subsequent cracking of the grout around the bolt
- Inability of the anchor bolt to flex in case the baseplate moves laterally

The area between the sleeve and the anchor bolt is the second area requiring isolation. It is suggested to fill the sleeve with a pliable material, such as silicone rubber. If the sleeve is filled with grout or other rigid material, extremely high stresses can develop in the foundation by preventing the anchor bolts from developing the spring action. As a direct consequence, cracking can occur in the foundation in the area around the affected anchor bolt(s).

There are three principal checks associated with these components. Maintenance is based on good housekeeping practices and consists of surface cleaning, corrosion prevention, and inspecting hold-down bolts for proper tightness.

An oil-soaked surface can easily mask small leaks and provides a slip hazard to personnel required to work in the affected area. It also provides a mechanism for oil to migrate down to the grout and concrete foundation, encourages an attitude that accepts leaks or standing oil as normal station procedure, and presents a potential fire hazard. Conversely, a clean surface provides a visual baseline for personnel to quickly detect leaks, prevents oil from reaching the grout and concrete, and allows inspections of bearing housings or hold-down bolts to be accomplished without danger to personnel.

Corrosion prevention begins with the initial installation. Surfaces that will be in contact with the grout layer should be coated with a primer that is compatible with the grout being used. Base metal, blisters, rusted surfaces, and oil- or grease-soaked surfaces are all unacceptable. Failure to take this precaution will prevent adequate bonding between the baseplate/soleplate and the layer of grout. This condition will lead to the grout cracking over time.

Inadequate corrosion prevention and unchecked corrosion can have serious consequences to machinery using cementatious grout with metallic filings. If corrosion develops at the metal-grout interface, it will continue and spread to the metallic filings. The pressure caused by the corrosive forces can be of such magnitude as to cause misalignment of the machinery and cracking of the concrete foundation.

8.6.5 Electric Motors

Problems with motors can be identified early and corrected through a maintenance program that is structured around motor cleanliness, lubrication, and routine inspections. These three elements will form the necessary foundation for an effective electric motor maintenance program that will lead to dependable and economical operation.

8.6.5.1 Dirt

Dirt is a common element to any generating station. Controlling this problem is a 24-hour-a-day job. Electric motor ventilating spaces will be restricted over time if dirt is allowed to build up. This problem will have a direct impact on the ability of the motor to cool itself. Consequences of this problem (if it is allowed to go unchecked) include the following:

- Breakdown of motor insulation
- Increase in auxiliary power consumption
- Potential for abrasion and wear of motor internal components

An effective cleaning program requires regularly cleaning the exterior of the electric motor, regularly cleaning the motor’s filter assemblies, and cleaning the motor internals. Components such as access panels and covers also play an important role in keeping dirt outside. Verifying that gasket material and dust seals are in good condition, together with properly installing the access panels, will pay valuable maintenance dividends in the battle to keep dirt out. Use of a pre-filter assembly has the added advantage of allowing personnel to clean the filters without requiring the motor to be shut down. Cleaning should be performed during every scheduled boiler shutdown.

Use of clean, dry, compressed air is effective in removing dry, loose dust and particles. Air pressure at 30 psig (207 kPa) can be effective in blowing out a motor. Considerations when using compressed air include the following:

- Blow out any accumulation of water in the air line and hose before using it.
- Consult the manufacturer on recommended air pressure. Pressure exceeding the recommended value can cause abrasive particles to be driven into the insulation and puncture it.
- Use recommended safety equipment when blowing out the motor. Safety goggles, respirators, and hearing protection are highly recommended.
- Install a suction blower or similar device at the opposite end to remove dirt-laden air.

Additional options for removing dirt include the use of clean lint-free rags and vacuum cleaners. Lint will adhere to the insulation, resulting in an increase in dirt collection. Lint is also particularly damaging on high-voltage insulation, because it causes corona discharge to concentrate in one area.

8.6.5.2 Moisture

In all of the previous cases, simple anti-moisture precautions such as the following can be taken to avoid motor damage:

- Protect motors opened for maintenance against moisture by using space heaters, coverings, and, when feasible, reinstalling access panels.
- Identify and remove sources of moisture in and around the motor:
  - Verify that all piping is properly insulated.
  - Correct all leaks.
  - Install protective coverings over motors when required, ensuring that these coverings do not restrict air movement.

8.6.5.3 Friction

To avoid damage caused by friction, the motor manufacturer's lubricating instructions should be followed, and the proper type of lubricant in the proper quantities and intervals suggested should be used. Verifying the proper quantity of lubricant is vital. Excess amounts of lubricant can be just as damaging as insufficient lubricant. Too much grease can promote friction and heat and can leak onto stationary windings and rotating elements. This, in turn, can cause overheating and deterioration of insulation, resulting in eventual grounds and shorts.

8.6.5.4 Vibration

Excessive vibration can damage electrical connections, loosen fasteners, promote frictional wear, and cause portions of the metallic structure to develop cracks. Checks to avoid vibration damage include the following:

- Verify correct alignment between the motor and vacuum pump.
- Inspect the foundation for cracks.
- Open and inspect bearings when heavy wear or damage is suspected.
- Verify that machinery hold-down bolts are installed and properly torqued.
- Inspect the motor bearings at regular intervals during operation. Personnel should check for signs of rapid heating and unusual noise.

8.6.5.5 Rotor Shaft End Play

The rotor shaft assembly of induction motors will have a certain amount of end play designed into it. *End play* refers to the axial distance through which the motor's shaft is free to move when it is uncoupled from the load. This freedom of movement occurs because of tolerances that inevitably occur in the design and manufacturing process. These tolerances include machining variations, bearing design requirements to prevent binding, and allowances for any thermal growth of the rotor shaft assembly during motor operation.

Induction motors designed with sleeve bearings have a larger end play than those that use roller bearings. Typical values given for large motors with sleeve bearings are 1/4- to 1/2- inch. Motors outfitted with roller bearings may have an end play range from 1/32- to 1/8- inch. If a bearing locking arrangement is used, this range will be even smaller. Because induction motors with sleeve bearings do not have any locking arrangement, the rotor shaft assembly is free to float. This does not become a problem while the motor is in operation and is not subjected to any external forces. Under these conditions, the rotor shaft assembly will align itself to the magnetic center of the applied field.

Endwise restraint that limits the movement of the rotor shaft is achieved through one of the thrust bearings. The forces of these bearings are designed to withstand the momentary thrust that may develop during the starting or stopping of the motor. Damage from continuous thrust occurs when external forces are applied that prevent the rotor shaft from seeking its magnetic center. External forces can result from coupling misalignment or locking. When a coupling is misaligned, asymmetrical forces between the hubs develop. This imbalance may cause the load and motor coupling halves to move apart. This separation is limited by the thrust bearings on the load and motor. Continuous thrust resulting in damage to the motor bearing thrust faces is likely to occur. Limited end float couplings will prevent motor damage to the motor journal bearings by excessive axial movement of the motor rotor.

External forces may also develop from a coupling locking. If a coupling is worn or poorly lubricated, torque transmission through the coupling gear teeth sets up high friction, which resists endwise movement (in-and-out or side-to-side movement of the coupling gear teeth or grids). This condition could prevent the motor shaft from seeking its magnetic center and could subject the thrust faces of the motor bearings to continuous thrust.

8.6.6 Solenoid Operated Valves

In addition to parts replacement during corrective maintenance, periodic replacement of age-sensitive parts and rebuilding of selective SOVs are often performed to maintain long-term SOV performance. The two major SOV component classes that may benefit from periodic replacement are the SOV coil and the elastomeric components (for example, seats, diaphragms, and seals).

Minimum periodic SOV or part replacement intervals may be required by special technical or licensing commitments. Environmental qualification, per 10CFR50.49, is the best example of a program requiring such replacements. The periodic rebuilding of BWR scram SOVs is another example of an established SOV refurbishment frequency. When SOVs are not controlled by these programs, periodic replacement intervals can be determined using manufacturer recommendations, rules of thumb, and operating experience. Because general recommendations are, by their very nature, imprecise, the best method of establishing refurbishment/replacement intervals is operating experience with the same or similar applications.

Key Technical Point

One of the most important factors for selecting periodic replacement frequencies is operating experience.

The importance of operating experience is related to the lack of proven SOV condition monitoring or diagnostic techniques. Without condition monitoring methods, SOV periodic maintenance is generally based on calendar time. Unfortunately, because application conditions vary widely, the uncertainty about the actual SOV condition can be significant. Under these circumstances, the best method of determining the level and extent of in-service deterioration is prior operating and maintenance experience in similar applications.

8.6.6.1 Coils

When SOV coils are properly protected from humidity damage and are not continuously energized, they can have an indefinite life. When subjected to continuous energizing, particularly at high ambient temperatures, their life is reduced considerably. As a rough rule of thumb, coil insulating systems can be expected to remain functional at their insulation class rated temperature for times ranging from four to 10 years. Conservatively, their thermal life should double for every 15°F to 20°F (8.3°C to 11.1°C) decrease in temperature. Coils should not be used continuously above their rated temperature because of rapid deterioration and failure.

If SOVs or materials are controlled by the EQ program, then the EQ qualified life for the material in that application can be considered a very conservative estimate of the coil's life in similar applications not controlled by the EQ program. In a recent test, air-pilot SOV coils were successfully tested for time intervals six times longer than the previous established service interval based on the SOV’s environmental qualification test.

8.6.6.2 Elastomers

The service time limits for elastomers are more difficult to establish because they vary with the material, the part design, and its function. In general, manufacturer recommendations should be followed when establishing initial intervals. The effects of contaminants and debris are application specific and cannot be predicted. Assuming an otherwise ideal application, temperature does have a significant effect on elastomer life.

If similar SOVs are controlled by the EQ program, then the EQ qualified life for the material in that application can be considered a very conservative estimate of the elastomer's life. For elastomers wetted by the process fluid and in SOVs that are normally open with fluid flow, the elastomer temperature should be similar to the process temperature. When air-pilot SOVs are energized for prolonged periods, the seat and seal temperatures can increase roughly 45°F–90°F (25°C to 50°C) above ambient temperatures.

When operated near their upper service temperature limits, elastomers should be usable for a few years. Long-term performance (for example, 5–10 years and longer) is achieved when the elastomers are operated at temperatures well below these service limits.

When SOVs are periodically removed from service for repair or replacement, the elastomers should be examined and their condition documented. Generally, an elastomer will continue to be serviceable if it remains flexible and shows little evidence of swelling, cracking, compression set, or shrinkage. Because elastomers are supplied in a wide range of hardness values, comparisons should be made with new parts to gauge the amount of deterioration that has occurred. This information can then be used to modify part replacement and valve refurbishment intervals.

Key Technical Point

Examine the condition of elastomers when valves are disassembled. Compare the condition to that of new components. Adjust service intervals to keep the elastomers in a flexible condition.

8.6.6.3 Periodic Valve Cycling

With the possible exception of high pressure, high temperature applications, manufacturers collectively agree that periodically cycling SOVs is one of the best SOV PM techniques. One air-pilot SOV manufacturer’s instruction manual for commercial SOVs recommends monthly cycling.

The potential for SOV sticking varies widely among valve styles. For example, SOVs with elastomer sliding seals appear more susceptible to sticking than direct-acting SOVs with globe-type seats. Application factors, such as process medium, contamination, debris, temperature, and coil voltage, can all affect a valve’s susceptibility to sticking. In many commercial/industria1 applications (for example, pneumatic control SOVs on metal stamping machines) sticking often occurs when the SOVs are idle for only a few days. In power plant applications, it appears that SOVs on air systems are more prone to sticking than in other plant applications.

As a result of the variety of factors affecting SOVs, there cannot be one recommended cycling frequency. The most relevant factor for selecting a cycle frequency is operating experience. Other important factors include operating temperatures, valve design, and the level and types of process contamination. As a general rule of thumb, air system SOVs should be cycled quarterly. Longer intervals are readily justified when operating experience indicates no prior operating or sticking problems. If SOV sticking is observed and the root cause cannot be readily determined, the test interval should be shortened.

Key Technical Point

One of the best SOV PM techniques is periodic valve cycling. No one cycle frequency can be recommended. The most important factor for selecting a cycle frequency is operating experience.

Refer to EPRI NP-7414, *Solenoid Valve Maintenance and Application Guide,* for a complete discussion on SOV maintenance practices.

9 REFERENCES

"Component Data Tables." EPRI Preventive Maintenance Database. EPRI, Palo Alto, CA.

Condenser Application and Maintenance Guide. EPRI, Palo Alto, CA: 2001. 1003088.

Electric Motor Predictive and Preventive Maintenance Guide. EPRI, Palo Alto, CA: 1992. NP-7502.

Equipment Condition Monitoring Templates—Addendum to Preventive Maintenance Basis (TR-106857 Volumes 1–38). EPRI, Palo Alto, CA: 2000. 1000621.

Flexible Shaft Couplings Maintenance Guide. EPRI, Palo Alto, CA: 2003. 1007910.

Gearbox and Gear Drive Maintenance Guide. EPRI, Palo Alto, CA: 2004. 1009831.

"Installation and Operation Nash Vacuum Pumps CL Series." *Nash Bulletin 406-I*, 1966.

"Installation, Operation, and Maintenance of Nash Condenser Exhaust Unit Size AT-3004E." *Nash Bulletin 829-B.*

"Instructions for Axi-Vac Type "H" AXI Packaged Two-Stage Vacuum Pump." Dresser-Rand Form 11169A, 1967.

"Instructions for Type "L" AXI Compressor Series 787L165." Ingersoll-Rand Form 110121966.

Performance Standard for Liquid Ring Vacuum Pumps. Heat Exchange Institute, 2005.

Preventive Maintenance Basis, Volume 15: Rotary Screw Air Compressors. EPRI, Palo Alto, CA: 1997. TR-106857-V15.

Preventive Maintenance Basis, Volume 27: Liquid-Ring Rotary Compressor and Pump. EPRI, Palo Alto, CA: 1997. TR-106857-V27.

Shaft Alignment Guide. EPRI, Palo Alto, CA: 1999. TR-112449.

Solenoid Valve Maintenance and Application Guide. EPRI, Palo Alto, CA: 1992. NP-7414.

Standards for Steam Jet Vacuum Systems. Heat Exchange Institute, 2000.

Tech Sheet #102. Steam Jet Vacuum Systems Troubleshooting Guide. Heat Exchange Institute, 2004.

Thermal Performance Engineering Handbook, Volume II: Advanced Concepts in Thermal Performance. EPRI, Palo Alto, CA: 1998. TR-107422-V2.

W. J. Kubik and E. Spencer. *Improved Steam Condenser Gas Removal System.* The American Society of Mechanical Engineers.

A
FAILURE HISTORY OF INDUSTRY CAR EQUIPMENT

Table A-1 contains the results of searches of industry databases for CAR equipment failures. CAR system failures caused by failures of power supply equipment were not included in the search. As a result, while motor failures are included in the tabulation, failures of circuit breakers that supply the motors are not. In several cases, the same failure was reported in multiple databases. In these cases, the same failure number was assigned to each line item.

The NRC Event Notification System (ENS) and Inspection Report (IR) databases and the INPO OE database were searched. The INPO OE database includes NRC Licensee Event Reports (LER). Search criteria included the following:

- CAR system
- Condenser vacuum
- SJAE
- Vacuum pump

Additionally, the INPO EPIX database was searched for:

- CAR system
- All manufacturers for component types of accumulators, tanks, receivers, blowers, compressors, vacuum pumps
- Specific manufacturers: Ingersoll Rand, Nash, and Foster Wheeler

Table A-1
CAR Equipment Failure History

Failure Number Source and Report Number	Plant	Event Date	Power Change	Event Description	Cause	Corrective Action	Failed Equipment
Failure 1 LER 2000-005-00	PWR #1	4/17/2000	Manual scram as a result of low condenser vacuum.	Steam pressure was lost to auxiliary steam header, resulting in a loss of condenser vacuum.	Failure of air diaphragm packing in auxiliary steam supply PCV as a result of disengagement of packing nut. Packing nut became disengaged as a result of inadequate previous maintenance.	The valve was repaired, tested, and returned to service.	SJAE steam supply valve.
Failure 1 IR 05000334 / 2000-004	PWR #1	4/17/2000	Manual scram as a result of low condenser vacuum.	There was inadequate steam supply to SJAEs as a result of steam supply PCV failing to close.	Actuator packing nut disengaged as a result of inadequate previous maintenance, resulting in PCV going closed.	The valve was repaired, tested, and returned to service.	SJAE steam supply valve.
Failure 2 EPIX 119	PWR #2	2/24/1998	Output decreased by 15 Mwe, vacuum decreased by 1.1" Hg.	Pump suction valve went fully open when pump was started.	Pump suction valve controller sensing line isolation valves were not opened following previous maintenance.	Valves were opened.	MVP liquid ring-suction valve.
Failure 3 System Health Report–Condensate	PWR #3	10/1/2003	No change.	Unit SJAEs stall on occasion as a result of improper inner-condenser draining.	Inner-condensers did not drain properly because the condenser drip receiver was under a vacuum.		SJAE inter-condenser.
Failure 4 EPIX 284	BWR #1	12/29/2001	No generation lost.	Pump suction valve failed to open when MVP was being started for plant startup.	Solenoid pilot valve was blowing air and failed to transfer.	SOV was replaced.	SOV-MVP liquid ring-suction valve.

Table A-1 (continued)
CAR Equipment Failure History

Failure Number Source and Report Number	Plant	Event Date	Power Change	Event Description	Cause	Corrective Action	Failed Equipment
Failure 5 EPIX 553	BWR #1	4/17/2005	No generation lost.	SJAE isolation valve SOV failed to operate after replacement. New brackets had been fabricated to mount the solenoids during the previous modification installation.	New brackets were made from angle iron. One was slightly longer than the other three and came close enough to the coil to absorb or redirect enough magnetic energy so that the SOV would not actuate.	Bracket was shortened, and all brackets will be replaced in the future with ones made of aluminum.	SOV-SJAE suction valve.
Failure 6 EPIX 551	BWR #1	2/26/2006	No generation lost.	SJAE isolation valve failed to close after a scram. All four SJAE inlet valve pilot solenoids were replaced under a modification with a different type during RE22.	The SOV coils were not aligned properly when they were initially installed.	The SOV coil did actuate the valve when it was adjusted upward on the sub-base.	SOV-SJAE suction valve.
Failure 7 EPIX 562	BWR #1	5/22/2006	No generation lost.	SJAE inlet valve failed to close when demanded by control room as part of scram recovery. This is a repeat of events in 4/2005 and 2/2006.	SOV failed to cycle.		SOV-SJAE suction valve.

Table A-1 (continued)
CAR Equipment Failure History

Failure Number Source and Report Number	Plant	Event Date	Power Change	Event Description	Cause	Corrective Action	Failed Equipment
Failure 8 EPIX 426	PWR #4	10/30/2001	No generation lost.	New two-stage vacuum pump cannot maintain condenser vacuum at 1.8" Hg absolute.	Spray valve was not opening because it was improperly installed during recent modification.	Spray valve malfunction was not detected during mod test because test engineer incorrectly interpreted vendor note that spray valve would be closed during low vacuum operation to mean low absolute vacuum. Problem was not corrected on 10/30/2001 because another problem masked it.	MVP-liquid ring-seal water spray valve.
Failure 9 EPIX 427	PWR #4	11/29/2001	No generation lost.	New two-stage vacuum pump cannot maintain condenser vacuum at 1.8" Hg absolute.	Spray valve was not opening because it was improperly installed during recent modification.	The spray valve configuration was corrected. The mod package for the other MVP was corrected.	MVP-liquid ring-seal water spray valve.
Failure 10 EPIX 478	PWR #4	12/12/2002	No generation lost.	Suction valve did not open when pump started.	Inlet header-to-pump suction differential PS did not actuate because it had been set in reverse direction when recently replaced. The vender drawing used to determine setting was not clear.	PS was recalibrated to proper dp in proper direction. Other PS setpoints will be reviewed.	MVP-liquid ring-PS-inlet header-to-pump suction differential PS.

Table A-1 (continued)
CAR Equipment Failure History

Failure Number Source and Report Number	Plant	Event Date	Power Change	Event Description	Cause	Corrective Action	Failed Equipment
Failure 11 EPIX 523	PWR #4	12/8/2003	No generation lost.	Suction valve did not open when pump started.	Inlet header-to-pump suction differential PS did not actuate because it was out of calibration.	PS was recalibrated.	MVP-liquid ring-PS-inlet header-to-pump suction differential PS.
Failure 12 IR 05000333 / 2000-003	BWR #2	4/1/2000	Automatic scram as a result of low condenser vacuum.	Recombiner bypass valve went closed while taking recombiner OOS, isolating the main condenser,	BPV SOV failed as a result of seat material embrittlement, resulting in bypass valve going closed.	SOV had not been overhauled in 26 years. SOV was overhauled.	SOV-recombiner bypass valve.
Failure 13 EPIX 266	PWR #5	7/2/2000	No generation lost.	MVP (Train B) failed to start.	Vacuum (pressure) switch failed to actuate as a result of setpoint drift, preventing CB from closing.	Switch was recalibrated.	MVP-liquid ring-PS-inlet vacuum switch.
Failure 14 EPIX 267	PWR #5	7/11/2000	No generation lost.	MVP (Train A) failed to start.	Vacuum (pressure) switch failed to actuate as a result of setpoint drift, preventing CB from closing.	Switch was recalibrated.	MVP liquid ring-PS-inlet vacuum switch.
Failure 15 EPIX 9	BWR #3	9/16/1997	183984 MWHr generation lost.	"A" SJAE steam PCV stuck closed until operator tapped on valve with pocketknife.	O-rings in positioner were hard. The positioner had been in service since 6/16/1981.	Positioner was overhauled.	SJAE steam supply valve.

Table A-1 (continued)
CAR Equipment Failure History

Failure Number Source and Report Number	Plant	Event Date	Power Change	Event Description	Cause	Corrective Action	Failed Equipment
Failure 16 OE12086	PWR #6	12/20/2000	Power cycled 30–50 MWe as a result of cycling of condenser vacuum.	Backpressure transients on 12/20/2000, 12/21/2000, and 1/22/2001, which were caused by increases in MVP suction pressure and caused electrical output transients.	Air being injected into the MVP suction to lower the discharge temperature overloaded the pump and caused the suction pressure to increase.		MVP-helical rotor.
Failure 17 EPIX 104	PWR #6	10/23/1995	No generation lost.	This EPIX was to document a historical review of the CAR system WRs for Maintenance Rule applicability. One failure applied to this review. Helical rotor pump tripped on high temperature.	Inter-stage relief valve failed, resulting in internal pump damage.	The rotors, timing gears, and inter-stage relief valve were replaced.	MVP-helical rotor.
Failure 18 EPIX 610	PWR #6	8/15/1999	88 MWHr lost generation.	I-R pump tripped when started.	Pressure switch was incorrectly calibrated during previous maintenance.	Switch was recalibrated.	MVP-helical rotor-PS-oil.

Table A-1 (continued)
CAR Equipment Failure History

Failure Number Source and Report Number	Plant	Event Date	Power Change	Event Description	Cause	Corrective Action	Failed Equipment
Failure 19 EPIX 847	PWR #6	5/20/2002	20 MW lost for about 50 minutes.	Megawatts were lost as a result of a reduction in helical rotor vacuum pump efficiency.	The pump inter-stage relief valve lifted as a result of cold ambient temperature with motivating air still aligned.	Procedural compliance was enforced to remove motivating air when discharge temperature in 145ºF.	MVP-helical rotor.
Failure 20 IR 50-352/02-05	BWR #5	7/23/2002	Manual scram as a result of low condenser vacuum.	CAR system failed to function when condensate temperature in SJAE condenser exceeded 147ºF.	Plant staff changed procedure from 135ºF to 150ºF in support of main turbine replacement.	Procedures were revised to reflect operating limitations.	SJAE.
Failure 20 LER 2-02-001	BWR #5	7/23/2002	Manual scram as a result of low condenser vacuum.	Outside air temperature increased to 95ºF caused increase in condensate temperature. Elevated temperature caused insufficient cooling in SJAE inter-condenser, stalling first stage SJAE.	Impact of elevated temperature was not addressed during turbine retrofit.	Procedures were revised to reflect operating limitations.	SJAE.
Failure 20 EPIX 290	BWR #5	7/23/2002	125,038 MWHr of generation lost as a result of manual scram because of degraded condenser vacuum.	All four first-stage SJAEs stalled as a result of high condensate temperature.	Vender information indicated SJAE would fail at a SJAE condenser temperature of 147ºF. Station procedures allowed continued operation up to 150ºF.	Administrative controls were applied.	SJAE.

Table A-1 (continued)
CAR Equipment Failure History

Failure Number Source and Report Number	Plant	Event Date	Power Change	Event Description	Cause	Corrective Action	Failed Equipment
Failure 21 EPIX 288	BWR #6	7/10/2005	No generation lost.	MPV tripped.	MPV seal water pump thermals initially tripped. After resetting the thermals, seal water pump ran for two hours before magnetics tripped.	MVP seal water pump motor was replaced.	MVP-liquid ring-seal water pump-motor.
Failure 22 EPIX 293	BWR #6	9/11/2005	No generation lost.	MVP failed to start.	Motor tripped thermal overloads.	Thermal overloads were reset.	MVP-liquid ring.
Failure 23 EPIX 178	BWR #7	10/2/2001	No generation lost.	MVP did not have adequate seal water to maintain operation and pump tripped.	Seal water pump impeller seized.	Pump was repaired and placed in the PM program.	MVP-liquid ring-seal water pump-motor.
Failure 24 EPIX 301	BWR #7	10/14/2005	No generation lost.	While attempting to start MVP, it tripped on low seal water flow.	Low seal water flow switch was not adjusted properly.	Seal water switch was adjusted.	MVP-liquid ring-seal water flow switch.
Failure 25 OE2900	BWR #8	9/16/1988	Shutdown from 100% to 0% power as a result of loss of condenser vacuum.	Condenser vacuum began decreasing, along with decreasing off-gas flow. A second SJAE was started with no improvement in vacuum.	Local temperature measurements on SJAE second-stage nozzles indicated degraded SJAE performance as a result of either flooded inner-condenser or loss of inner-condenser loop seal.		SJAE inter-condenser.

Table A-1 (continued)
CAR Equipment Failure History

Failure Number Source and Report Number	Plant	Event Date	Power Change	Event Description	Cause	Corrective Action	Failed Equipment
Failure 26 LER 5000265-2007-00	BWR #9	2/28/2007	Manual scram as a result of low condenser vacuum, caused by reduction in SJAE efficiency.	Reduction in SJAE efficiency was caused by SJAE supply pressure at 120 psig, instead of 127 psig.	Corrosion products accumulated in PCV sensing line, causing valve to open, causing RV to lift, and resulting in loss steam pressure.		SJAE steam supply valve.
Failure 27 IR 50-458/00-13	BWR #10	8/21/2000	Manual scram as a result of low condenser vacuum.	Too much off-gas purge air created backpressure on SJAEs, and they stalled.	Operator fully opened service air valve used to add purge air instead of throttling it, resulting in too much purge air.	The solenoid drain valves for the off-gas cooler condensers were replaced.	SOV-off-gas.
Failure 27 OE12187	BWR #10	8/21/2000	Manual scram as a result of low condenser vacuum.	Too much off-gas purge air created backpressure on SJAEs, and they stalled.	Operator fully opened service air valve used to add purge air instead of throttling it, resulting in too much purge air. Operations and Engineering personnel did not communicate to task performer to only throttle valve.	The solenoid drain valves for the off-gas cooler condensers were replaced.	SOV-off-gas.
Failure 28 EPIX 216	BWR #10	9/23/2003	No generation lost; unit in hot S/D.	SJAE Off-gas suction valve would not close. Valve failed to open on loss of air.	SOV had body-to-bonnet joint air leak.	Solenoid was replaced and loop setpoint was re-established at 16 psig air.	SOV-SJAE suction valve.

Table A-1 (continued)
CAR Equipment Failure History

Failure Number Source and Report Number	Plant	Event Date	Power Change	Event Description	Cause	Corrective Action	Failed Equipment
Failure 29 LER 84-008-00	PWR #7	3/10/1984	Automatic scram on low condenser vacuum.	Main condenser vacuum started decreasing as a result of air removal piping restriction when circulating water pump was stopped.	Clogged piping drain lines caused water to back up into the air-removal piping.	The drain lines were cleaned.	SJAE-piping drain lines.
Failure 30 IR 05000335/2003006 IR 05000389/20004008	PWR #8	4/1/2003	Manual scram as a result of low condenser vacuum.	Low condenser vacuum was caused by through-wall hole in SJAE inter-condenser loop seal piping return to condenser. Operators attempted to place hogging SJAE into service to help degrading backpressure, and backpressure rapidly went from 3.0" to 5.6".	Out-of-calibration PI resulted in establishing inadequate steam pressure (115 psig instead of 200 psig) to hogging SJAE. SJAE acted as a vacuum breaker.	The loop seal piping was replaced. The pressure gage was replaced. The hogging SJAEs were inspected.	SJAE inter-condenser piping. Pressure Indicator.

Table A-1 (continued)
CAR Equipment Failure History

Failure Number Source and Report Number	Plant	Event Date	Power Change	Event Description	Cause	Corrective Action	Failed Equipment
Failure 31 OE6382	PWR #9	11/4/1993	Power decreased to prevent turbine trip on low condenser vacuum.	Two of the three MVPs are normally in operation. Pump A was taken OOS, while B and C were running. Vacuum immediately began to drop. Pump A tripped when a restart was attempted.	Vacuum was lost because Pump A suction valve did not close when pump was stopped. Pump rotated in reverse, causing low vacuum. Attempt to start Pump A while spinning backwards damaged pump. Valve did not close because SOV failed. SOV failed because repair kit was installed wrong during previous maintenance.	The vendor manual was changed to identify need for proper orientation of SOV components. A training session was held to provide instructions on proper assembly of valve, emphasizing subtle differences between proper and improper assembly.	SOV-MVP helical rotor-suction valve.
Failure 32 EPIX 226	PWR #9	6/2/2000	No generation lost.	Pump tripped on high discharge temperature during hot ambient conditions.	Modification to eliminate noise and vibration during normal operation isolated inlet seal vent line that feeds second stage of compressor. As a result, discharge air temperature increased.	A temporary change was initiated to allow operation of the isolation valve so operations could maintain balance between pump noise and vibration and discharge air temperature.	MVP-helical rotor.
Failure 33 EPIX 243	PWR #9	1/3/2001	No generation lost.	Pump failed to start after maintenance on cooler.	Problem could not be identified. Breaker worked in test position and MVP started normally.	A work request was written to replace "X" relay and direct trip actuator, which are original to the breaker.	MVP-helical rotor.

Table A-1 (continued)
CAR Equipment Failure History

Failure Number Source and Report Number	Plant	Event Date	Power Change	Event Description	Cause	Corrective Action	Failed Equipment
Failure 34 EPIX 278	PWR #9	6/20/2001	No generation lost.	Pump tripped as designed when discharge temperature exceeded 200ºF. Standby MVP started as designed.	Vacuum discharge high temperature was caused by seal water high temperature. Seal water high temperature was caused by a fouled seal water cooler. The fouled seal water cooler was caused by an inadequate maintenance activity that did not include cleaning the cooler.	The cooler was cleaned.	MVP-helical rotor-seal water cooler.
Failure 35 EPIX 292	PWR #9	11/19/2001	No generation lost.	Pump tripped on high motor current during plant startup at point where the inter-stage relief valve should have actuated to place the second stage into service.	The inter-stage relief valve was found damaged and did not allow the MVP to transition from hogging to holding modes.	The relief valve was replaced and the MVP ran without any problems.	MVP-helical rotor inter-stage relief valve.
Failure 36 EPIX 438	PWR #9	7/28/2003	No generation lost.	AXI-VAC-15 pump tripped on high discharge temperature.	No abnormal equipment conditions were found. High discharge temperature is a common occurrence in the summer when ambient temperatures are high.	Steps were previously added to the operating procedure to add supplemental cooling through the use of fans when discharge air temperature reaches 195ºF.	MVP-helical rotor.

Table A-1 (continued)
CAR Equipment Failure History

Failure Number Source and Report Number	Plant	Event Date	Power Change	Event Description	Cause	Corrective Action	Failed Equipment
Failure 37 EPIX 437	PWR #9	6/6/2004	No generation lost.	Pump removed from service as a result of smoke coming from the outboard motor bearing.	The motor bearing failed as a result of insufficient quantity of grease applied to bearing by motor repair shop.	The motor was repaired.	MVP-helical rotor- motor.
Failure 38 EPIX 485	PWR #9	11/21/2005	No generation lost.	Pump tripped on overload. The MVP was in hogging mode at the time.	The MVP was later started and ran normally without any unusual parameters exhibited by the MVP.		MVP-helical rotor.
Failure 39 EPIX 130 Event 1	PWR #10	10/2/1999	No generation lost, but vacuum below minimum to operate steam dump valves.	Event 1: Started SJAE # 1 on auxiliary steam. Loop seal was lost, resulting in air leakage.	Event 1: SOV failed, resulting in blown loop seal.	Event 1: SOV was replaced; loop seal was refilled.	SJAE LCV SOV.
Failure 40 EPIX 130 Event 2	PWR #10	10/2/1999	No generation lost, but vacuum below minimum to operate steam dump valves.	Event 2: Started SJAE #2 on auxiliary steam, but SJAE did not work.	Event 2: Auxiliary steam to SJAE # 2 PCV had outstanding maintenance issue, but no caution tag was placed on control board.	Event 2: SJAE #2 was switched to main steam.	SJAE steam supply PCV.
Failure 41 System Engineer review of draft guide	PWR #11	1995	No generation lost.	MVP tripped soon after periodic vibration test was performed. Vibration readings were within normal range.	Tapered bearings failed catastrophically after 25 years in service.	Bearings were replaced and a nine-year MVP overhaul frequency was established.	MVP bearings.

Table A-1 (continued)
CAR Equipment Failure History

Failure Number Source and Report Number	Plant	Event Date	Power Change	Event Description	Cause	Corrective Action	Failed Equipment
Failure 42 System Engineer review of draft guide	PWR #11	12/31/2006	No generation lost.	MVP tripped as a result of flow blockage when jet air ejector lost flow	Jet air ejector nozzle froze as a result of nozzle heating element burning out.	Heating element was repaired.	MVP flow path.

B
KEY POINTS

Key O&M Cost Point

Emphasizes information that will result in reduced purchase, operating, or maintenance costs.

Section	Page	Key O&M Cost Point
4	4-35	Plant CAR equipment may be limiting the condenser under part load conditions. Only reference to the condenser performance curve will reveal the fact that the operating pressure may be above the pressure the condenser is capable of, robbing the plant of available energy.
7	7-11	Oil analysis tests are often offered free or for a nominal charge by the lubricant supplier as part of the overall service provided.
8	8-1	Use of recommendations from the manufacturer, along with industry and plant operational experience, can provide valuable insight in determining not only what checks should be done, but also how often they should be done.
8	8-2	A balance must be attained by doing PM but avoiding opening and inspecting equipment if no problems (such as high temperature or pressure) are present.
8	8-6	To prevent pump damage as a result of the buildup of rust between cast iron parts, follow the manufacturer's recommendations for short- and long-term lay up.

Key Technical Point

Targets information that will lead to improved equipment reliability.

Section	Page	Key Technical Point
3	3-2	It is the steam condensation process and the specific volume change from steam to liquid that produces the condenser vacuum. The lower the backpressure, the more work that is done by the steam in the turbine.
4	4-9	Ensure that the drain flow check valve is in the right geometric orientation and the drain piping is sloped down and away from the machine to keep the water seal from over flowing and filling up the compressor such that the water intrudes into the oil.
4	4-16	Maintaining the seal water to always be cooler than the condenser at its operating pressure provides the most efficient air removal at any condenser vacuum level. The vacuum pump will automatically track the condenser, thereby providing maximum air removal under any condenser load during the whole year.
4	4-20	Even if a liquid ring vacuum pump is oversized, it cannot obtain lower vacuum levels than those permitted by the vapor pressure of the seal water. To prevent cavitation, the operating vacuum of the liquid ring MVP must be limited to approximately 0.25 inch (0.64 cm) Hg above the vapor pressure of the seal liquid.
4	4-21	Cooling water to the liquid ring MVP heat exchanger should be condenser circulating water whenever possible. Because of the vapor pressure existing within the MVP, the pump will tend to track the main condenser whenever both are fed the same temperature of coolant.
6	6-8	When vent valves on rotary screw pump suction lines are opened to introduce “motivating air” into the pump, caution must be exercised to monitor temperatures closely when large changes in day to night temperatures occur. With full motivating air still applied, the decreased nighttime temperatures can result in exceeding the pump capacity, and condenser vacuum will be reduced.
7	7-1	One goal of condition monitoring is to identify changes in the condition of the pump, motor, or auxiliary that could indicate some potential failure.
7	7-5	The vibration amplitude-versus-frequency analysis method is considered to be the most useful. Over 85% of mechanical problems occurring on rotating equipment can be identified using this method.

7	7-11	Thermography can be effectively used to identify sources of condenser air in-leakage that challenges the performance of the CAR system and to identify leaks and blockages in process lines and drains containing hot fluids.
8	8-9	If oil in a self-contained sump is below normal level, adding relatively cold oil may disrupt the oil film. Shut the vacuum pump down before adding oil.
8	8-10	Do not mix oils in the lubrication system or bearing housing. Chemical additives in different oils can cause a breakdown in the viscosity, cooling, or bearing lubrication.
8	8-16	Verify that components used to restrict motor shaft movement are installed.
8	8-24	One of the most important factors for selecting periodic replacement frequencies is operating experience.
8	8-25	Examine the condition of elastomers when valves are disassembled. Compare the condition to that of new components. Adjust service intervals to keep the elastomers in a flexible condition.
8	8-26	One of the best SOV PM techniques is periodic valve cycling. No one cycle frequency can be recommended. The most important factor for selecting a cycle frequency is operating experience

Key Human Performance Point

Denotes information that requires personnel action or consideration in order to prevent injury or damage or ease completion of the task.

Section	Page	Key Human Performance Point
5	5-6	Training programs for system engineers and maintenance personnel should be reviewed and strengthened as appropriate to address weaknesses in the understanding of how the CAR equipment functions.
8	8-4	Care must be taken to ensure that the various ejector components are in the right unit. Many ejector parts, and sometimes complete stages, are physically interchangeable.
8	8-17	The locking feature of disc-type coupling fasteners becomes compromised when they are removed and reinstalled a certain number of times.
8	8-17	It is important to verify that the thrust load of the vacuum pump is not imposed on the motor thrust bearing. This requires knowledge of the magnetic center of the motor.

C
SJAE TERMINOLOGY

The first stage of a multi-stage SJAE system is the stage into which the vapor or gas being compressed first enters, the second stage is that which it enters second, and so on. Figure C-1 shows the standard method of referring to each stage's components based on their position in the system. The last stage always has the letter Z assigned to it. The remaining stages are assigned letters in reverse order from Z. For example, in a two-stage system, the first stage would be labeled Y, while in a four stage, the first stage would be W. An inter-condenser is assigned the two letters of the stages it is between. An after-condenser is assigned the combination ZA. A pre-condenser is assigned the letter P followed by the letter for the stage following it.

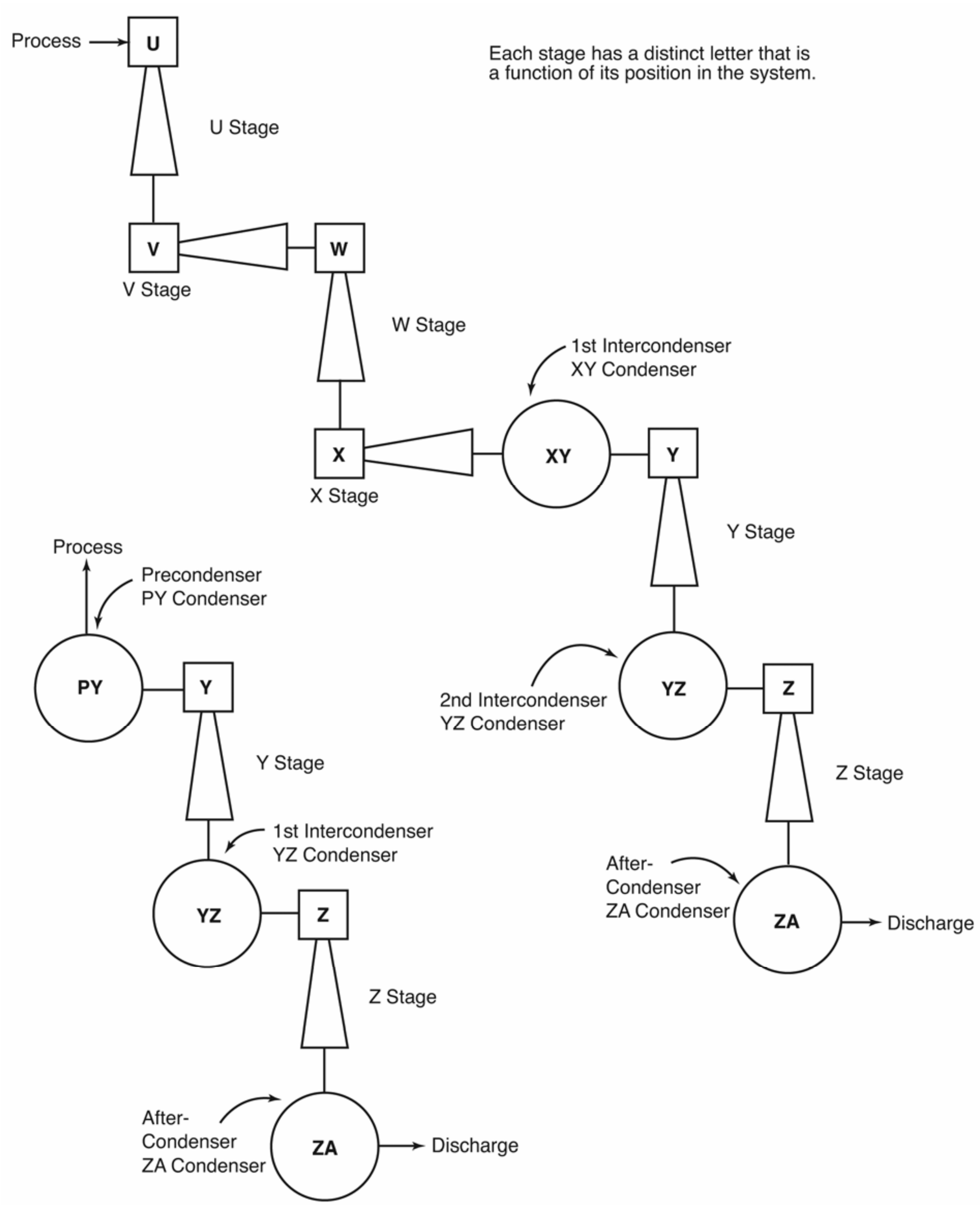
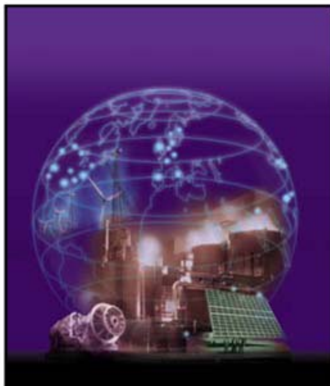


Figure C-1
Designations for Ejector Assemblies
Source: HEI Standards for Steam Jet Vacuum Systems

D

TRAINING SLIDES



EPRI NMAC

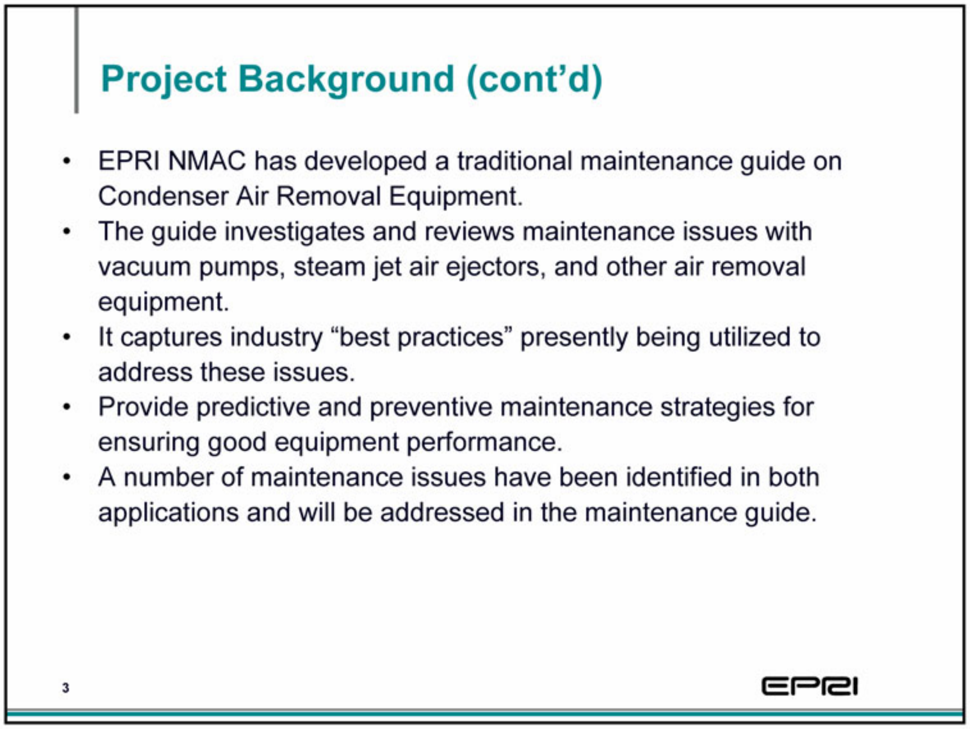
Condenser Air Removal Equipment Maintenance Guide Training Slides

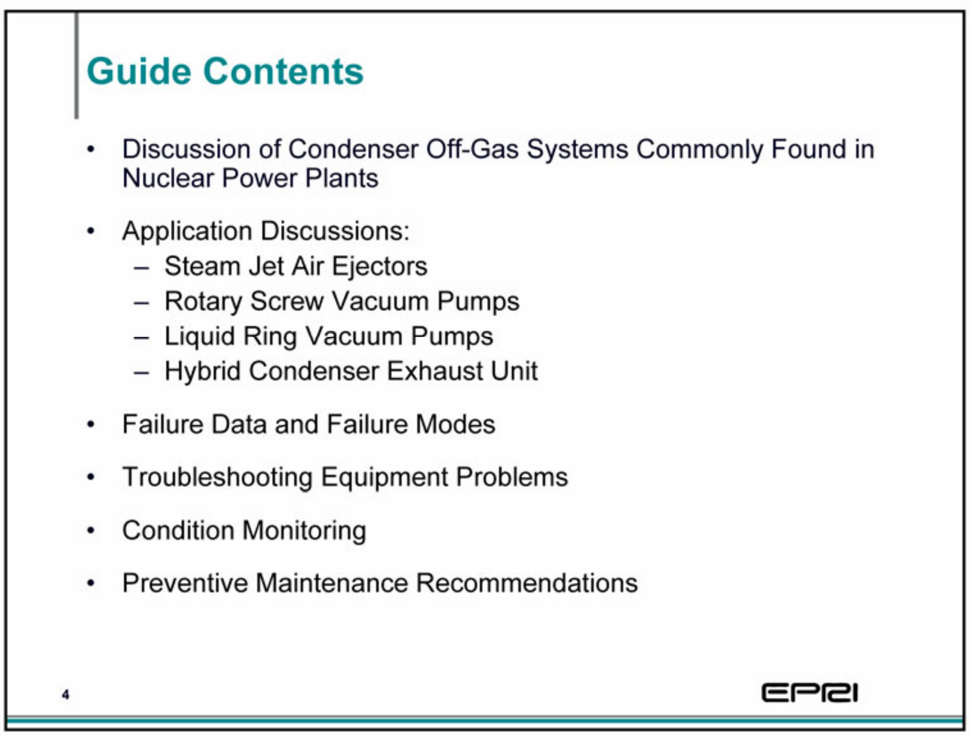
EPRI 1015058

Project Background

- Most NMAC member plants utilize either steam jet air ejectors or vacuum pumps to remove air and noncondensible gases from the condenser.
- This equipment is vital for good plant performance
  - because if noncondensible gases are allowed to build up in the condenser, vacuum will decrease and the saturation temperature of the condensate will increase reducing overall plant efficiency.
  - because these undesirable gases can also blanket the tubes of the condenser which effectively reduces the heat transfer capability of the condenser.
- For most plants, air removal equipment also serves to establish an initial condenser vacuum during plant startup.

2


Project Background (cont'd)
• EPRI NMAC has developed a traditional maintenance guide on Condenser Air Removal Equipment.
• The guide investigates and reviews maintenance issues with vacuum pumps, steam jet air ejectors, and other air removal equipment.
• It captures industry "best practices" presently being utilized to address these issues.
• Provide predictive and preventive maintenance strategies for ensuring good equipment performance.
• A number of maintenance issues have been identified in both applications and will be addressed in the maintenance guide.
3
EPRI


Guide Contents
• Discussion of Condenser Off-Gas Systems Commonly Found in Nuclear Power Plants
• Application Discussions:
– Steam Jet Air Ejectors
– Rotary Screw Vacuum Pumps
– Liquid Ring Vacuum Pumps
– Hybrid Condenser Exhaust Unit
• Failure Data and Failure Modes
• Troubleshooting Equipment Problems
• Condition Monitoring
• Preventive Maintenance Recommendations
4
EPRI

Guide Contents (cont'd)

- Appendices
  - Condenser Air Removal Equipment Failure History
  - Key Points Summary
  - Steam Jet Air Ejector Terminology
  - Guide Training Material

5 EPRI

Steam Jet Air Ejectors

- Fairly simple device
- Can be single installation or multiple combinations
- Use steam to create vacuum

Rotary Screw Mechanical Vacuum Pump

- Typically a single stage pump
- Usually used in the initial 'hogging' mode
- More common in BWRs versus PWRs

6 EPRI

Liquid Ring Mechanical Vacuum Pump

- Rotary positive displacement pump, single and dual stage
- Most often used as sole air removal component
- Single stage occasionally used in hogging mode
- Use liquid to create seal inside rotary pump

Hybrid Condenser Exhaust Unit

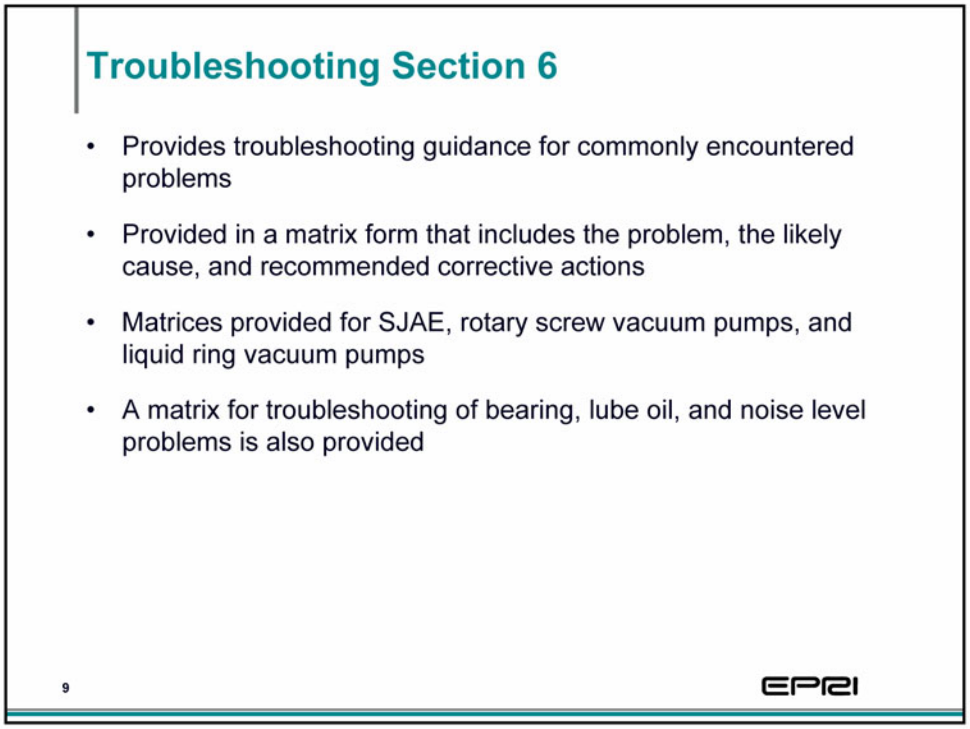
- Not used in nuclear plants
- An SJAE is used that exhausts into a liquid ring vacuum pump
- More common in fossil units

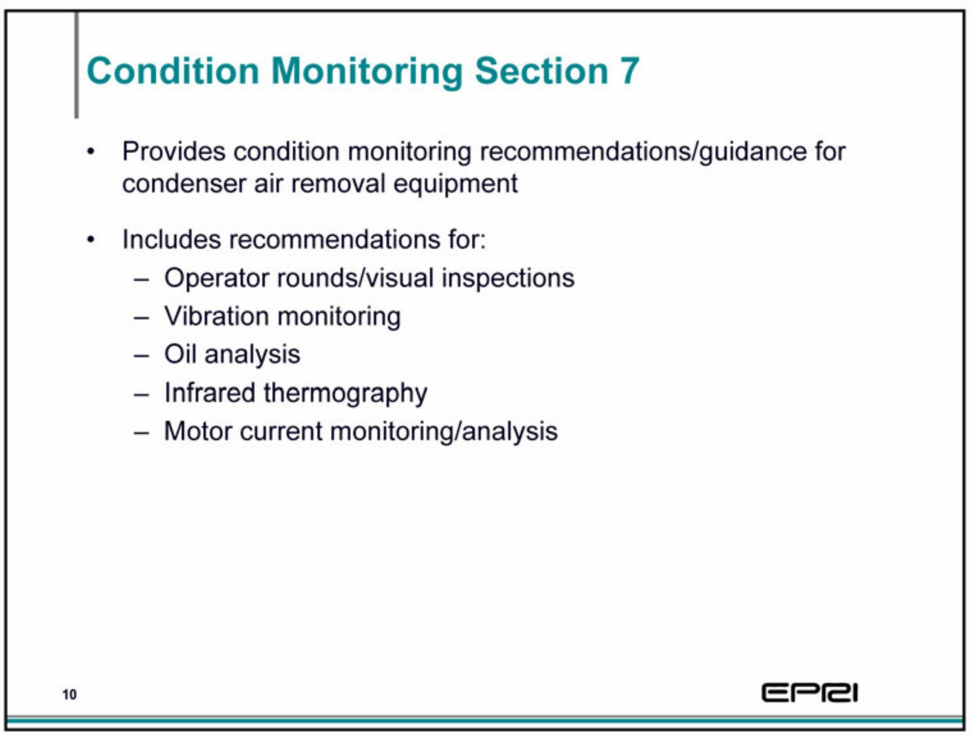
7 EPRI

Common Failure Mechanisms

- Steam Jet Air Ejectors
  - Most common failures occur in the valves
  - Other causes, although rare, involve operating conditions outside of design: high condensate temperatures, high back pressures, water intrusion
- Mechanical Vacuum Pumps
  - Most failures relate to pump trips, failure to starts, degraded performance, and suction valves
  - Inadequate human performance is cited as a factor in about half of the problems
    - Lack of understanding on equipment and operation
    - Lack of training

8 EPRI


Troubleshooting Section 6
• Provides troubleshooting guidance for commonly encountered problems
• Provided in a matrix form that includes the problem, the likely cause, and recommended corrective actions
• Matrices provided for SJAE, rotary screw vacuum pumps, and liquid ring vacuum pumps
• A matrix for troubleshooting of bearing, lube oil, and noise level problems is also provided
9


Condition Monitoring Section 7
• Provides condition monitoring recommendations/guidance for condenser air removal equipment
• Includes recommendations for:
– Operator rounds/visual inspections
– Vibration monitoring
– Oil analysis
– Infrared thermography
– Motor current monitoring/analysis
10

Preventive Maintenance Section 8

- Provides recommendations for establishing PM program for SJAE and mechanical vacuum pumps
- Includes tasks and frequencies that are based on common failures of condenser air removal equipment
  - Routine maintenance activities
  - Overhauls
  - Inspections
  - Subcomponent tasks/replacement

11 EPRI

Key Point Summary

- Identifies key information contained in the guide and its location.
- The primary intent of a Key Point is to emphasize information that will allow individuals to take action for the benefit of their plant.
- The Key Points are organized according to three categories: Operation and Maintenance (O&M) Cost, Technical, and Human Performance.
- Each category has an identifying icon to draw attention to it when quickly reviewing the guide.

12 EPRI

E

TRANSLATED TABLE OF CONTENTS

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Sargent & Lundy, LLC

報告概要

宗旨

- 描述典型的CAR設備
- 為CAR設備的預防性維護(PM)，修理和替換以及故障檢修建議提供指導

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宗旨

- 描述典型的CAR设备
- 为CAR设备的预防性维护(PM)，修理和替换以及故障检修建议提供指导

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RESUME DU RAPPORT

Objectifs

- Décrire les équipements typiques CAR
- Fournir un guide sur la maintenance préventive (PM), la réparation et le remplacement et des recommandations sur le dépannage des équipements CAR

TABLE DES MATIERES

LISTE DES FIGURES

LISTE DES TABLEAUX

復水器空気除去機器保全ガイド

報告書の要約

目的

- 典型的な復水器空気除去機器を説明すること
- 復水器空気除去設備の予防保全（PM）、修理および交換、およびトラブルシューティングの推奨事項についてのガイドを提供すること

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RESUMEN DEL INFORME

Objetivos

- Describir los equipos de extracción de aire del condensador típicos (siglas en inglés: *CAR*)
- Ofrecer directrices para el mantenimiento preventivo (MP), reparación y sustitución, así como recomendaciones para la identificación y resolución de problemas en los equipos CAR

CONTENIDO

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LISTA DE TABLAS

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