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Plant Support Engineering: Life Cycle Management Planning Sourcebooks – Chillers

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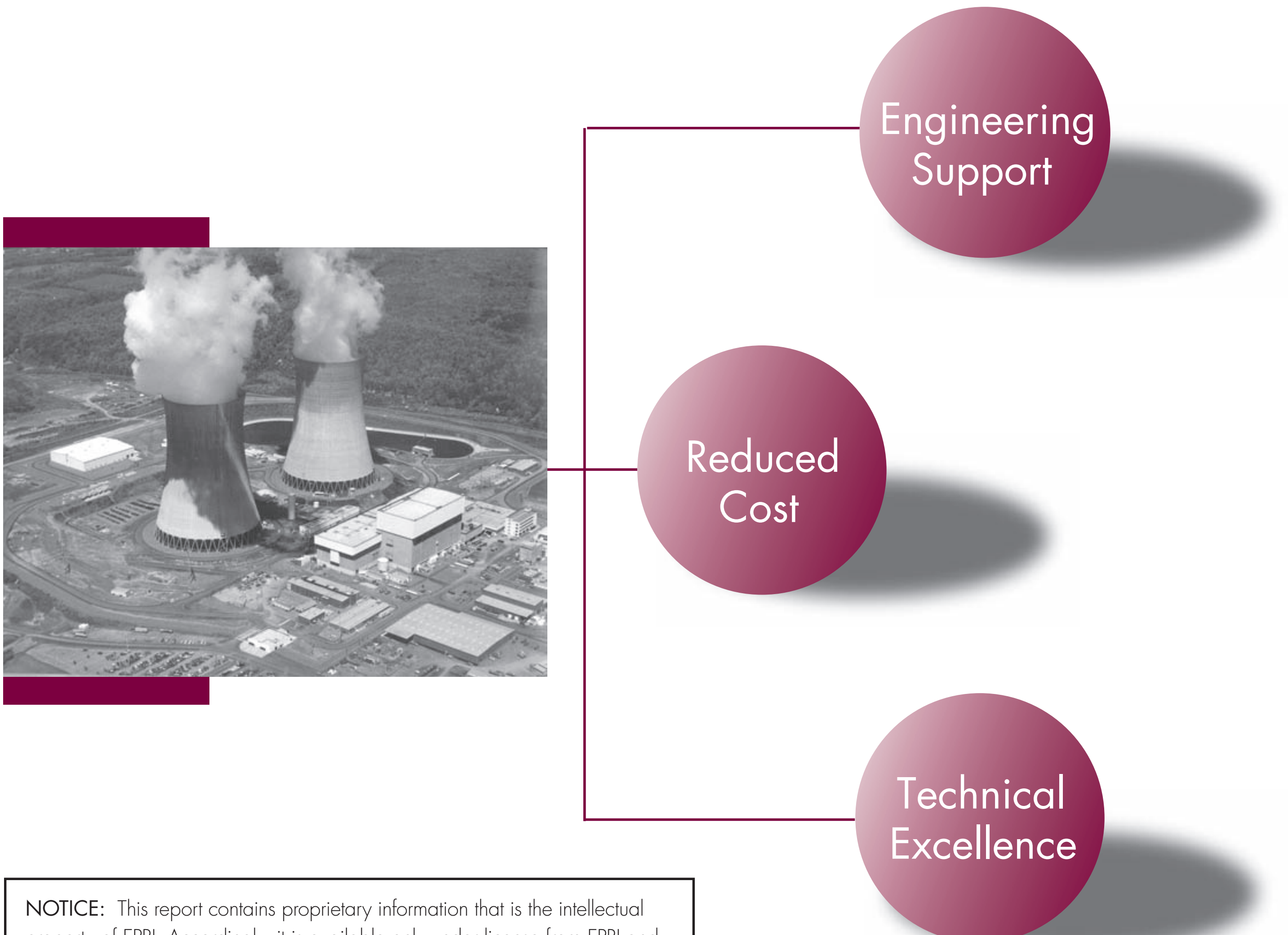

Plant Support Engineering: Life Cycle Management Planning Sourcebooks – Chillers

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Final Report, December 2007

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REPORT SUMMARY

The Electric Power Research Institute (EPRI) is producing a series of *Life Cycle Management Planning Sourcebooks*, each containing a compilation of industry experience information and data on aging degradation and historical performance for a specific type of system, structure, or component (SSC). In addition, this sourcebook provides information and guidance for implementing cost-effective life cycle management (LCM) planning for chillers.

Background

As explained in *Life Cycle Management Sourcebooks – Overview Report* (EPRI report 1003058), the industry cost for producing LCM plans for many important SSCs in operating plants can be reduced if LCM planners have an LCM sourcebook of generic industry performance data for each SSC they address. The general objective of EPRI's LCM sourcebook effort is to provide system engineers with generic information, data, and guidance they can use to generate a long-term equipment reliability plan for the plant-specific SSC. Also, this enables the plant's aging and obsolescence management plans to be optimized in terms of plant performance and financial risk. The equipment reliability plan or LCM plan for a plant SSC combines industry experience and plant-specific performance data to provide an optimum maintenance plan, schedule, and cost profile throughout the plant's remaining operating life.

Objective

- To provide plant engineers or their expert consultants with a compilation of generic information, data, and guidance typically needed to produce a plant-specific LCM plan for chillers

Approach

Experts in the maintenance and aging management of chillers followed the LCM process developed in *Demonstration of Life Cycle Management Planning for Systems, Structures, and Components: With Pilot Applications at Oconee and Prairie Island Nuclear Stations* (EPRI report 1000806). The scope of the physical system and the types of components included in the study were defined. The information and the data on historical industry performance of the selected types of the chillers within this scope were compiled, and the technical guidance for using this information was presented as a starting point for preparing plant-specific chiller LCM plans. This sourcebook was prepared following the format and content guidance of *Life Cycle Management Planning Sourcebooks – Overview Report* (EPRI report 1003058), Section 2.

Results

This sourcebook contains information on chiller components, such as compressors (including the drive mechanism), condensers, liquid refrigerant expansion or flow control devices, liquid coolers (evaporators), connecting piping, and monitoring and control devices. In addition, certain auxiliary components, such as lubricant cooler, lubricant separator, lubricant pump, lubricant return device, purge unit, refrigerant transfer unit, refrigerant vent, and additional control valves, are discussed. The information compiled includes performance monitoring issues, component aging mechanisms, and aging management maintenance activities. Based on the above, alternative LCM plan strategy guidance has been developed along with recommendations. The plan strategy guidance provides information for implementing cost-effective LCM planning for chillers. The sourcebook includes an extensive list of references, many of which are EPRI reports related to the maintenance and reliability of chillers.

EPRI Perspective

This report should enable the preparation of plant-specific plans for chillers with substantially less effort and cost than if planners had to start from scratch. The sourcebook captures both industry experience and the expertise of the sourcebook authors. Using this sourcebook, one needs only to add plant-specific data and information to complete an economic evaluation and LCM plan for the plant's chillers. EPRI plans to sponsor additional LCM sourcebooks for as many important SSC types that might be useful to operating plants (perhaps 30 to 40) and as are allowed by industry-wide resources. The process of using sourcebooks as an aid in preparing LCM plans improves as the industry gains experience. EPRI welcomes constructive feedback from users and plans to incorporate lessons learned in future revisions of LCM sourcebooks.

Keywords

Life cycle management
Nuclear asset management
Nuclear power
System reliability
Component reliability
Chillers

ACKNOWLEDGMENTS

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MANAGEMENT SUMMARY

This report, *Plant Support Engineering: Life Cycle Management Planning Sourcebooks – Chillers* (EPRI report 1015075), helps guide plant engineers or expert consultants in the preparation of a long-term reliability plan for the chillers at their plants. The generic information and the guidance presented in this sourcebook are expected to help plant engineers focus on areas where there might be significant opportunities for cost-effective improvements. Using this sourcebook will reduce the cost of preparing a plant-specific LCM plan by approximately 33% compared to starting an LCM plan from scratch.

The sourcebook identifies the component aging mechanisms together with the maintenance activities to manage them, as well as the issues of obsolescence and the available management options. It provides hypothetical LCM plan alternatives to serve as starting points for plant-specific applications. The guidance, consisting mainly of generic industry-wide information and references on chillers and their components, is provided on how to build alternative LCM plans that can be considered during long-term planning for critical components. Depending on the level of detail desired for the plant-specific LCM plan, the generic data in this sourcebook can allow the engineers to identify the areas where significant cost-effective improvements or a reduction in maintenance activity can be realized and where long-term planning for emerging obsolescence issues can be developed.

The components covered in this sourcebook are most commonly found in chillers and are listed as follows:

- Compressors
  - Reciprocating
  - Centrifugal
  - Orbiting scroll
  - Rotary screw
- Condenser
- Metering/expansion device
- Evaporator
- Connecting piping (including filters and strainers)
- Monitoring and control devices

There have been no generic issues regarding nuclear plant chillers over the past 10 years. A review and search of generic communications provides evidence that chillers have not experienced industry-wide problems that require regulatory consideration. A review of the operating experience shows that the industry continues to have maintenance problems resulting in multiple trains of chillers being inoperable at the same time, which is generally contrary to the plant's technical specifications.

Section 6 of the sourcebook provides details of the aging management review of chillers. Normal equipment wear has been noted for most of the components of chillers. Other age-related failure mechanisms identified with chillers are as follows:

- Tube fouling
- Tubesheet and head erosion
- Fatigue failures
- Set-point drift due to vibration
- Valve leakage due to vibration
- Gasket failure from heat and age
- Loose connections and pitted contacts from vibration
- Open and short circuits from high-temperature environments
- Worn and eroded impellers
- Valve binding due to age and vibration
- Bearing wear due to age and vibration
- Cavitation-induced corrosion
- Erosion and corrosion
- Aging

Counteracting activities have been developed to offset the aging effects stated above. These activities are generally common to most preventive maintenance (PM) programs. Some activities provide very simple yet repetitive actions to monitor the health of chiller components. However, some activities to offset the aging can be performed only by intrusive maintenance. These activities are discussed in Section 5 and are as follows:

- Operator round inspections
- External visual inspections
- Internal inspections
- System performance tests
- System functional tests
- Oil analysis

- Refrigerant analysis
- Calibrations
- Vibration analysis
- Overhaul
- Thermography
- Pressure monitoring
- Motor megger test
- Electrical insulation test

These mitigating activities must be considered when developing an LCM plan. The development of a generic alternative LCM plan is discussed in Section 7. The potential alternative LCM plan considers the following activities:

- Implement diagnostic maintenance, including vibration and oil analysis programs.
- Establish and revise PM and predictive maintenance (PdM) tasks and schedules.
- Establish a refurbishment program.
- Maintain the spare components in the same manner as the operating equipment.

2 INTRODUCTION

2.1 Purpose of LCM Sourcebooks

As indicated in the *Life Cycle Management Planning Sourcebooks – Overview Report* [1], an LCM sourcebook is a compilation of generic information, data, and guidance that an engineer typically needs to produce a plant-specific LCM plan for a system, structure, or component (SSC). This sourcebook enables plant engineers or outside experts to develop a plant-specific LCM plan for chillers with substantially less effort than if they had to start an LCM plan from scratch. The engineer needs only to add the plant-specific data and information to complete an economic evaluation and an LCM plan for chillers.

It must be recognized that not all generic information in a sourcebook is applicable to every plant. Some of the data can serve for comparison or benchmarking when preparing plant-specific LCM plans. Other data might show indicators or precursors to problems not yet experienced at a given plant. Therefore, caution and guidance are provided in the plant-specific guidance in Sections 5, 8, and 9 of the sourcebook for the use and application of generic information. These sections also contain useful tips and lessons learned from *Demonstration of Life Cycle Management Planning for Systems, Structures, and Components: With Pilot Applications at Oconee and Prairie Island Nuclear Stations* [2].

2.2 Relationship of Sourcebook to LCM Process

The process steps for an LCM plan are described in detail in *Life Cycle Management Planning Sourcebooks – Overview Report* [1]. The LCM planning flowcharts that are shown in Figures 2-1a, 2-1b, and 2-1c are essentially the same as Figures 1-1 through 1-3 of *Life Cycle Management Planning Sourcebooks – Overview Report* [1]. The chart is segmented into four elements of the LCM planning process: SSC categorization/selection, technical evaluation, economic evaluation, and implementation. The process step numbering has been maintained and is consistent with the LCM report. The color codes identify the topics in which generic data and plant-specific LCM planning guidance are provided by section reference and the topics that are not addressed in the sourcebook.

2.3 Basis for Selection of Chillers for LCM Sourcebook

An LCM sourcebook for chillers has been prepared because the component meets the following important objectives of the SSC selection process:

- Applicability to both boiler water reactors (BWRs) and pressurized water reactors (PWRs)
- Importance to power production
- Subject to significant degradation and obsolescence
- A history of chronic maintenance problems

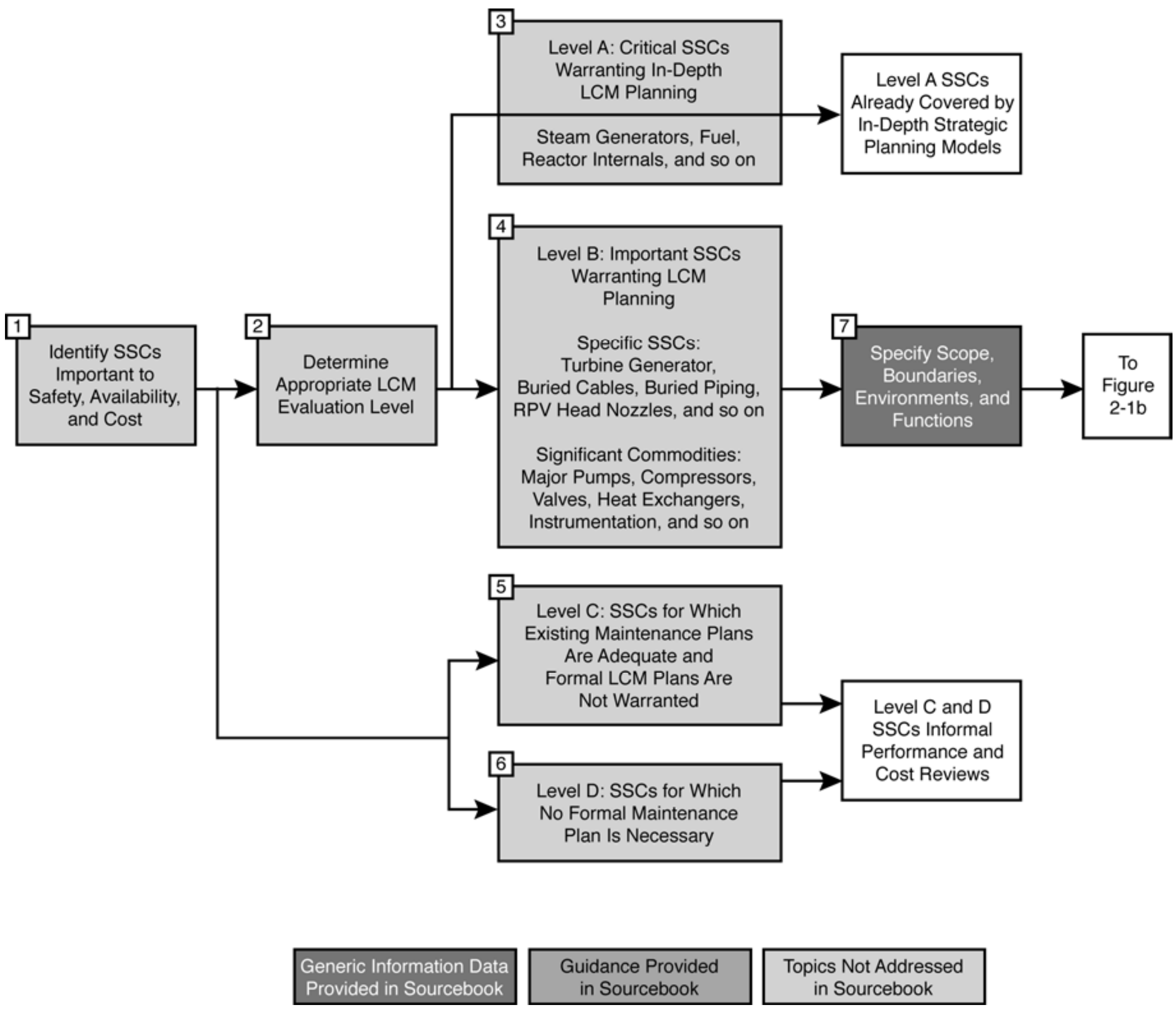

Figure 2-1a
LCM Planning Flowchart – SSC Categorization and Selection

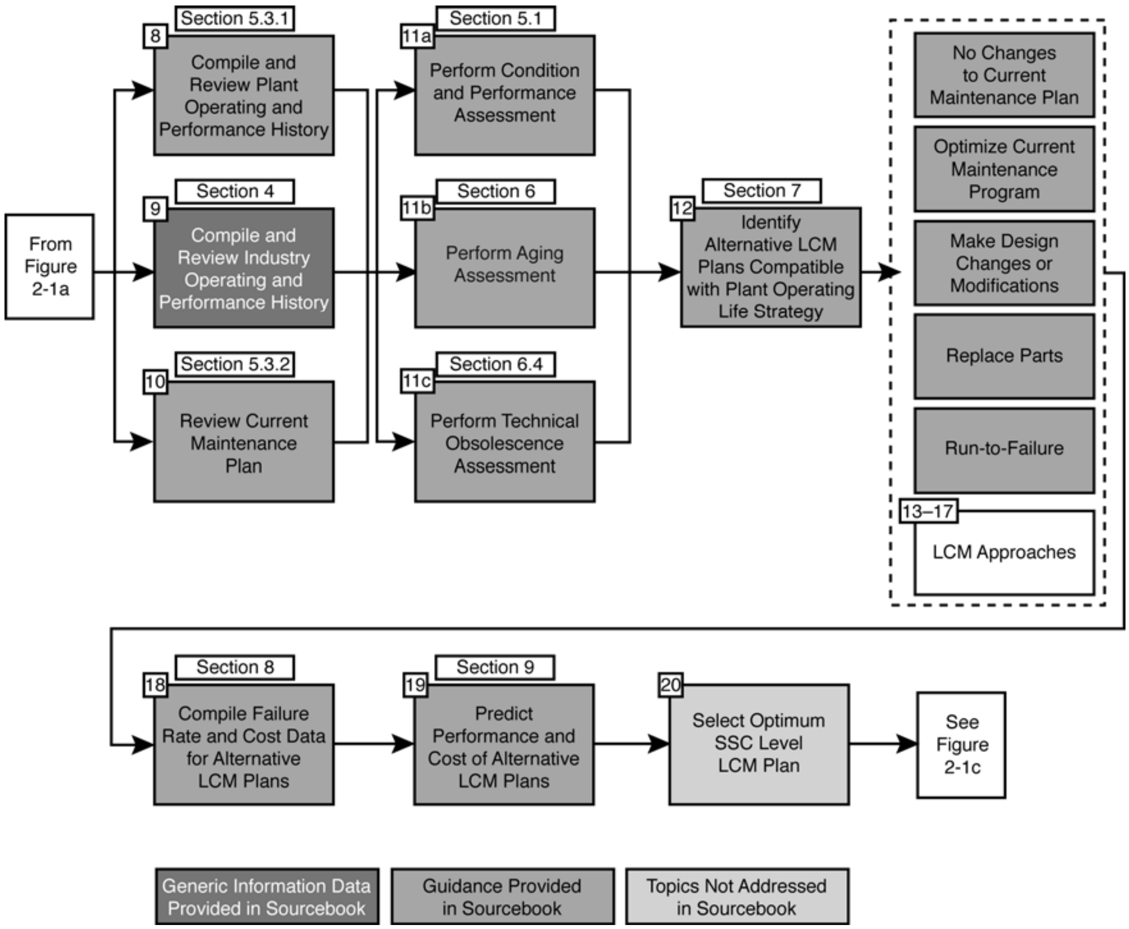

Figure 2-1b
LCM Planning Flowchart – Technical and Economic Evaluation

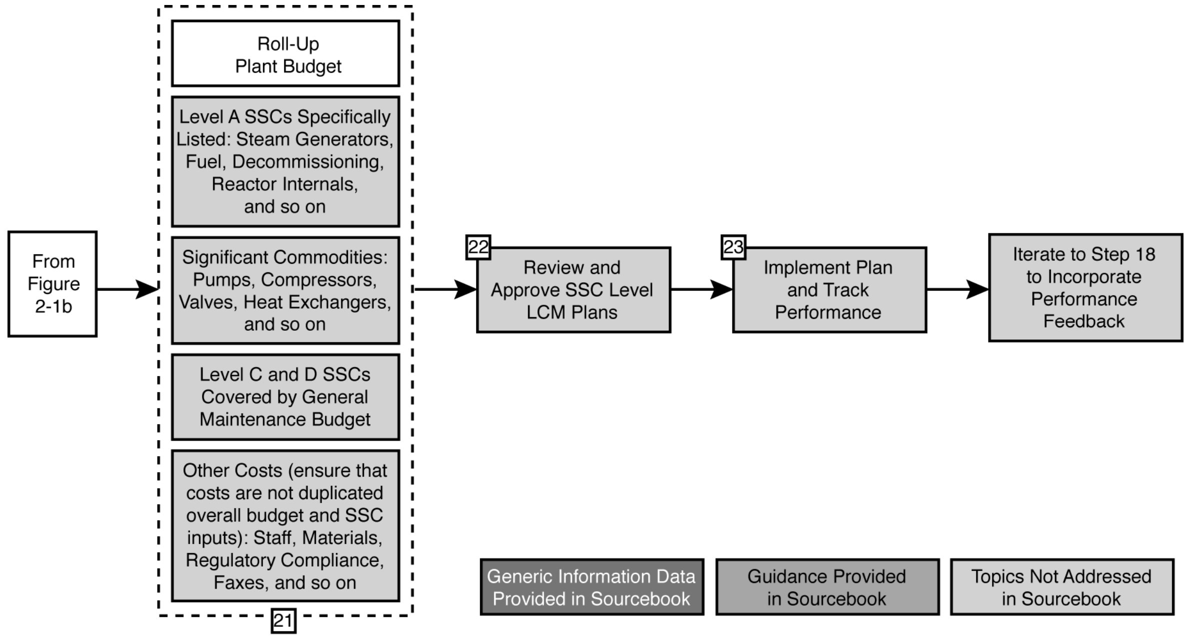

Figure 2-1c
LCM Planning Flowchart – Implementation

3 BACKGROUND INFORMATION ON CHILLERS

3.1 Safety and Operational Significance

Chillers provide chilled water to various safety-related and non-safety-related heating, ventilating, and air conditioning (HVAC) systems. A chiller is an assembly of refrigeration equipment designed to cool a liquid to meet the heat rejection requirements of a variety of components or areas by using heat exchangers. The safety-related HVAC systems can include control room HVAC, auxiliary building HVAC, and essential electrical equipment rooms HVAC. Non-safety-related HVAC systems may include turbine building HVAC, containment/drywell HVAC, and radwaste building HVAC. Chillers can be required for the normal power generation mode, the accident mode to mitigate the consequences of an accident, and the safe shutdown of the plant. When a chiller is required for mitigating the consequences of an accident and for the safe shutdown of the plant during and after an accident, it is classified as safety-related. Chillers required only for the normal mode of operation are classified as non-safety-related. Chillers are the most important component of HVAC systems. Chillers in safety-related HVAC systems must be maintained with a high degree of reliability.

3.2 Refrigeration Cycle

To understand and monitor the chiller's performance, the refrigerant system and cycle must first be understood. Figure 3-1 depicts a simple refrigerant system, composed of a compressor, a condenser, a metering device/expansion valve, and a liquid cooler (evaporator). Figure 3-2 is a pressure-enthalpy diagram for the same refrigerant system.

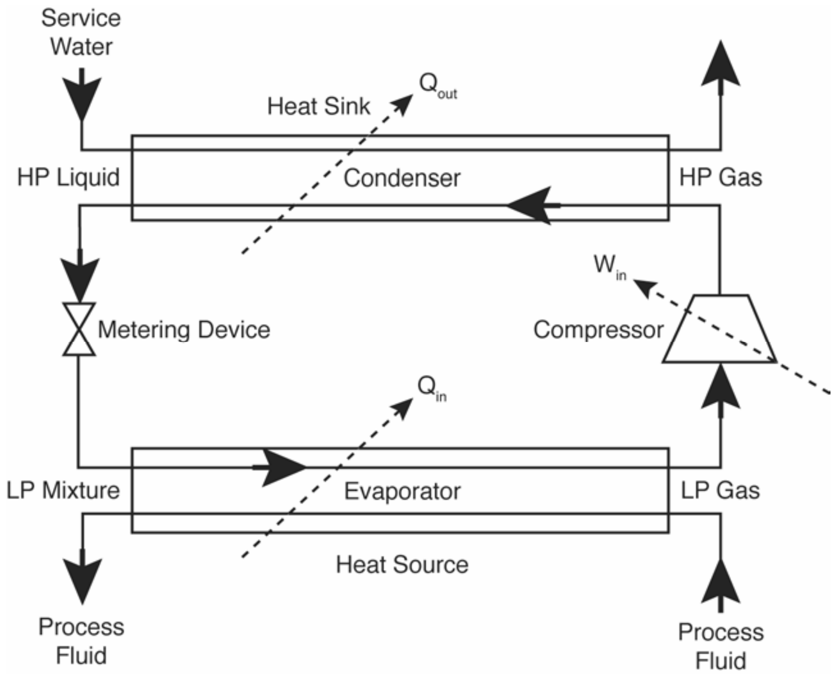

Figure 3-1
Basic Refrigerant Cycle

The typical refrigerant systems use three loops to perform their function: an evaporator loop, a refrigerant loop, and a condenser loop. The evaporator loop transfers heat from the medium to be cooled to the refrigerant. The refrigerant loop transfers heat from the evaporator to the condenser. The condenser loop rejects the heat from the refrigerant loop to the heat sink medium.

Figure 3-2 is a pressure-enthalpy diagram for the refrigerant system shown in Figure 3-1. Enthalpy (h) is a measure of the energy of a fluid and is usually given in units of British thermal units (Btu) or kilojoules (kJ). To the left of the curve in Figure 3-2, the refrigerant fluid is in a liquid state. To the right of the curve, the refrigerant fluid is in a superheated, gaseous state. Inside the curve, the refrigerant fluid is a liquid-gaseous mixture with 100% saturated liquid at the left edge and 100% saturated vapor at the right edge. Refer to Figures 3-1 and 3-2 during the following discussion:

- From points A to B, the refrigerant changes from a low-pressure (LP) hot gas to a high-pressure (HP) hot gas by passing through the compressor. Both the pressure and the temperature are increased during this step.
- From points B to C, the heat is rejected to the heat sink at a constant pressure as the refrigerant passes through the condenser and changes from an HP gas to an HP liquid. After the point where the gas is fully condensed to a liquid, the pressure still remains constant while the temperature is lowered as point C is approached.
- From points C to D, the refrigerant changes from an HP liquid to an LP mixture by passing through the metering device/expansion valve. Both the temperature and the pressure are lowered during this step, but no heat is added or rejected.

- From points D to A, the refrigerant changes from an LP mixture to an LP hot gas by passing through the evaporator and absorbs the heat from the medium being cooled. The pressure is held constant during this step. The temperature is held constant until the 100% vapor boundary is reached on the curve after which the temperature increases to point A as the refrigerant is superheated.

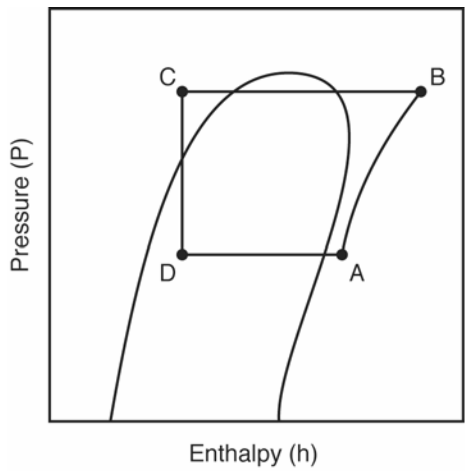

Figure 3-2
Refrigeration Cycle Pressure – Enthalpy Diagram

3.3 Chiller Description

A chiller consists of a compressor, a condenser, a liquid refrigerant expansion or flow control device, a liquid cooler (evaporator), and capacity controls. The chiller can also include a receiver, an economizer, an expansion turbine, and a subcooler. In addition, other chillers might include a lubricant cooler, a lubricant separator, a lubricant pump, a lubricant return device, a purge unit, a refrigerant transfer unit, a refrigerant vent, and additional control valves.

When selecting a chiller for a particular application, a number of critical parameters should be considered. For example, for a given cooling load, the chilled water flow rate can vary only within a limited range. When the flow rate is lowered, the velocity and the heat transfer coefficient are lowered. Therefore, the evaporator temperature must be reduced to maintain the required output. By increasing the flow rate, the pressure drop increases as the square of the velocity. When the flow rate is constant, the return water temperature is directly proportional to the load.

There is a significant impact of differential temperature on the chilled water flow rate in the system. The design of the system should provide the lowest chilled water flow rate consistent with the required dehumidification at the cooling coils. The result is lower pumped energy, lower compressor power, and a smaller piping distribution system. In addition, all pump energy imparted to the water results in a chilled water temperature increase, which requires greater cooling capacity. Care should be exercised to ensure an optimally designed chiller, chilled water, and chilled water distribution system specified for the particular application. Oversizing the chiller might cause operating problems, such as a less efficient operation, an excessive use of the hot gas bypass (HGBP) system, or an inadequate oil return, thereby requiring a field-installed, oil-bleed return system. The design of the chilled water system might consider the use of multiple chillers to provide a more efficient operation with a better match of load range and capacity. The use of multiple chillers provides more efficient refrigerant head pressure control (condenser water flow) and redundancy to allow proper maintenance.

The following subsections discuss the individual components and their respective functions and importance.

3.3.1 Compressor

The compressor circulates the refrigerant through the system and takes the LP gaseous refrigerant from the evaporator and compresses it before delivering it to the condenser. Compressors are chosen based on the cooling requirements and are often the most expensive and mechanically complex component of the chiller. The important factors to be considered in selecting compressors are their operating parameters, reliability, power consumption, and cost. Two useful measures of the compressor's performance are coefficient of the performance and the power per refrigeration output.

The compressors are manufactured in different types of housing configurations as well as in various sizes. The compressor types that are typically used in chillers are as follows:

- Reciprocating
- Centrifugal
- Orbiting scroll
- Rotary screw

The most common compressor is the reciprocating compressor. It has a piston that is driven by a pin and a connecting rod. The reciprocating compressor provides a relatively constant volume flow rate of refrigerant over a wide range of pressure ratios. Typically, single-stage reciprocating compressors are used in chiller applications.

A centrifugal compressor (see Figure 3-3) has one or more rotating impellers that spin the refrigerant vapor in a specially designed housing. The refrigerant vapor is forced against the housing walls using centrifugal force, and the velocity energy gained is converted to pressure.

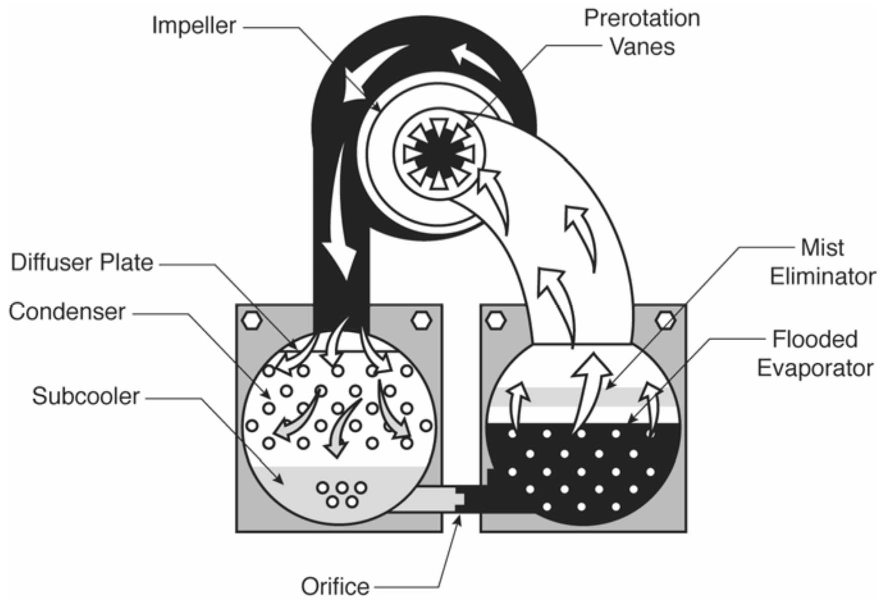

Figure 3-3
Centrifugal Compressor
Courtesy of York

An orbiting scroll compressor has two identical spirals in which one side is the involute of the other. One spiral is fixed and the other, an orbiting spiral, is rotated through 180 degrees relative to the first so that they touch at a number of points and separate the rotating chambers. As the spiral orbits, the chambers move toward the center and become smaller, thus compressing the refrigerant gas taken in at the outside.

The rotary screw compressor uses two mating lobes (see Figure 3-4). When the rotor threads (male and female) approach the suction port, the threads unmesh and create a void, and the gas is drawn through the suction port. As the two rotors continue to turn, the space between the male and female threads increases and more gas is drawn into the space between the threads. Further rotation starts decreasing the interlobe space. The confinement of the gas forces it into a smaller space and causes compression and an increase in gas pressure. These are usually used for continuous operation in the commercial and industrial applications. Their application can be from 3 hp to over 500 hp (375 kW) and from low pressure to very high pressure (>1200 psi [8.3 MPa]).

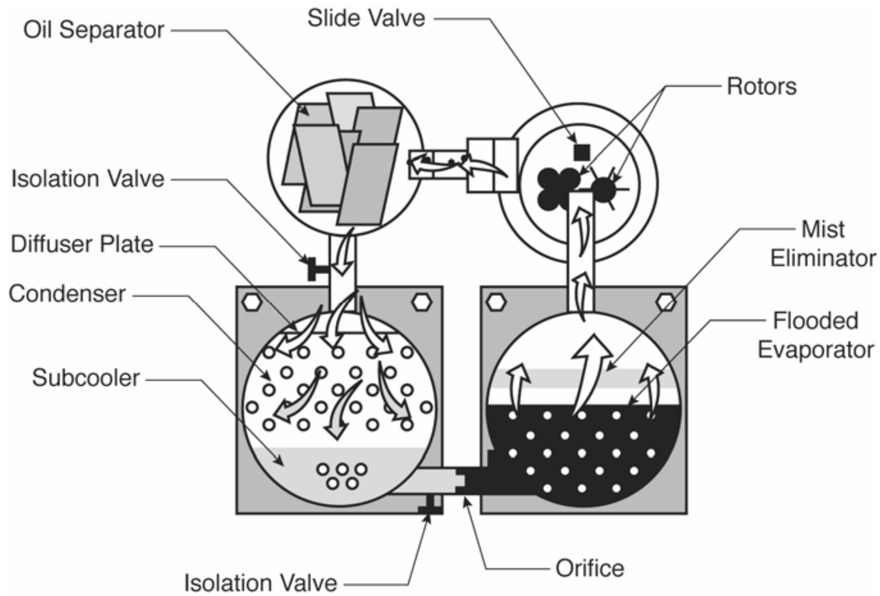

Figure 3-4
Screw Compressor
Courtesy of York

3.3.1.1 Compressor Drive

The compressor drive configurations include hermetic, semi-hermetic, and open-drive. In hermetic compressors, the motor and the compressors are contained in a sealed housing. A semi-hermetic compressor contains the compressor and the motor in a bolted housing and is available for servicing. In an open-drive compressor, the drive is external to the compressor and drives the compressor through a shaft extending through the seals of the crankcase. An open-drive compressor is more accessible for PM or repair activities. Therefore, consideration should be given to using the open-drive compressors whenever possible. The hermetic compressors have a higher probability for failure and higher costs for repair.

The compressor drives in the nuclear plants use electric motors because of the relative simpler maintenance versus the maintenance of the steam or gas turbine drives. The drive motor is linked directly to the compressor shaft by a coupling, a gear, or a belt drive. The motor is typically mounted on the compressor skid so that the motor shaft is used as the compressor shaft.

3.3.1.2 Compressor Lubrication Systems

The two primary methods of ensuring compressor lubrication are the splash system and the pressurized system. In a splash system, “flingers” are attached to the rotating crankshaft. As the crankshaft turns, oil is picked up by these flingers and thrown onto the bearing surfaces, the pistons, and the shafts. The preferred and dominant method is the pressurized system. In this system, an oil pump is often attached to the end of the crankshaft and maintains the oil flow through channels that keep a steady flow of oil on all surfaces that require lubrication.

In a reciprocating compressor, the refrigerant pressurization is created by a piston sliding within a cylinder. A seal must exist between the side of the piston and the wall of the cylinder. This seal is created by oil in the refrigerant as it travels through the compressor. Without this seal, the cylinder would not be able to provide adequate compression, which results in a loss of efficiency. A pressurized system allows the oil to continuously maintain a coating on the cylinder walls and piston.

A portion of the oil travels as a mist with the refrigerant through the system. Because some of the oil travels with the refrigerant, sufficient refrigerant gas velocity must be maintained in the system to prevent oil from collecting in other parts of the system and to maintain oil flow back to the compressor. This factor is taken into account by design engineers and manufacturers so that the subsequent provisions are made during the pipe sizing and configuration layout.

In the refrigeration circuit, the oil and the refrigerant are in all parts of the system. The oil does not chemically mix with the refrigerant but does travel with it. The oil is less dense than the refrigerant and floats on the liquid refrigerant. If the liquid refrigerant enters the compressor, the refrigerant washes out the oil; the oil then enters the compression chamber. Positive displacement, reciprocating, rotary, and screw compressors cannot compress the liquids. The phenomenon of the liquid refrigerant entering a compressor is called *flood back*. The phenomenon of the liquid oil (or refrigerant, for that matter) entering the compression chamber is called *slugging*. In both cases, irreparable damage can be done to a compressor. In the case of an oil washout, the bearing surfaces can be severely damaged. In the case of slugging, the connecting rods, pistons, and valves can be broken. With either event, the compressor internals can be destroyed very quickly, and the damage would occur before there was an opportunity to shut down the unit.

Oil that is in the system but outside of the compressor serves no lubricating purpose. Therefore, in larger systems, the refrigerant and oil mixture is not allowed to progress far from the compressor. To limit the oil flow to the remainder of the system, an oil separator is installed.

When enough oil enters the separator, the buoyancy of the oil raises the float, and the valve to the crankcase opens. Because the discharge refrigerant pressure is greater than the crankcase pressure, the greater pressure forces the oil back to the compressor crankcase. When the oil level drops, the float closes the valve. Separators are often insulated and heated to keep them warm, which ensures that the excess refrigerant is not mixed with the oil. Manufacturers typically provide guidelines on which type of oil to use.

3.3.2 Condensers

The condenser rejects heat to the heat sink. It receives the high-temperature HP gas from the compressor and cools it to provide a saturated or subcooled HP liquid to the metering/expansion device. The force that drives the refrigerant through the condenser is the differential pressure created by the compressor.

Condensers can be either water-cooled or air-cooled. In the larger systems used in nuclear plants, water cooling is the most common system. The water-cooled condensers are usually constructed in one of the following configurations:

- Double pipe (pipe-in-pipe)
- Double tube (tube-in-tube)
- Shell and coil
- Shell and tube

For water-cooled condensers, heat is transferred from the condenser to the water and carried by the water to an acceptable heat sink, such as a cooling tower, lake, river, or sea.

Air-cooled condensers are usually constructed of a number of tubes covered with fins. Air is directed over these tubes by either an external fan or natural circulation. The purpose of the fins is to increase the heat transfer area of the condenser and to ultimately increase heat transfer. Heat is then rejected to the surrounding environment. As heat is rejected, the refrigerant vapor changes from a gas to a liquid. At the outlet of the condenser, the refrigerant is a saturated or subcooled liquid. Some designs include an additional surface area to permit for subcooling. This prevents the refrigerant vapor from being introduced to the metering/expansion devices.

Condenser tubes are usually made of copper-nickel because of the potential corrosive nature of the condenser water. For the replacement condensers, titanium or 6% molybdenum stainless steel tubes should be considered to ensure a long life, depending on the quality of the raw water chemistry.

3.3.3 Refrigerant Flow Metering/Expansion Devices

The flow metering/expansion device provides the pressure drop necessary to expand the liquid refrigerant to a lower pressure, which in turn lowers the refrigerant temperature and provides cooling. Flow metering/expansion devices can be capillary tubes, orifices, automatic expansion valves (AEVs), thermostatic expansion valves (TXVs), or high-side or low-side float valves. The flow metering/expansion device separates the HP side from the LP side of a system and controls the flow of refrigerant into the evaporator.

3.3.3.1 Automatic Expansion Valves

An AEV is a pressure-operated flow metering/expansion device controlled by the pressure in the evaporator. As the evaporator pressure decreases, the pressure in the valve body is reduced, permitting the spring pressure from the adjusting screw assembly to open the valve. When the valve opens, the liquid refrigerant flows into the evaporator and vaporizes to maintain the evaporator at a constant pressure.

3.3.3.2 Thermostatic Expansion Valve

The most prominent type of flow metering/expansion device for a direct expansion evaporator is the TXV. This valve acts as a constant superheat valve and is also known as a *thermal expansion valve* (TEV). The purposes of a TXV are to control the flow of the refrigerant to the evaporator, keep the evaporator fully active, and close when the compressor stops. *Fully active* means that the liquid refrigerant evaporates or boils throughout the entire evaporator. In this situation, no portion of the evaporator contains superheated gas. In practice, some of the evaporator must be devoted to superheating the vapor in order to prevent the liquid from returning to the compressor. Figure 3-5 shows the operation of a TXV or TEV.

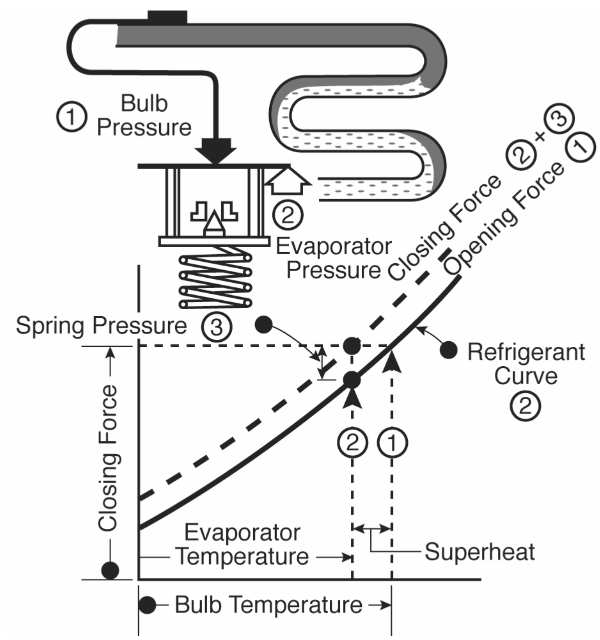

Figure 3-5
Thermostatic Expansion Valve
Courtesy of Sporlan

Three pressures affect the opening and closing of this refrigerant control device:

- Bulb pressure
- Evaporator pressure
- Spring pressure

Knowledge of these three pressures is essential to understanding the operation of a TXV. The basic pressure relationship is that the bulb pressure must be equal to the sum of the evaporator pressure and the spring pressure in order for the valve to be in an open position. The evaporator pressure is an essential factor in the operation of a TXV.

The evaporator pressure is applied under the diaphragm in the direction of valve closure, and it is always equal to the pressure that corresponds to the refrigerant saturation temperature. The spring pressure is also applied to the underside of the diaphragm to further implement the closing of the valve.

The bulb pressure is applied through a capillary tube to the top of the valve diaphragm. This pressure opposes the sum of the evaporator pressure and the spring pressure and acts to open the TXV. When a system is in operation, the bulb charge is part liquid refrigerant and part saturated vapor. The bulb temperature is equal to the suction gas temperature that is higher than the refrigerant saturation temperature, the increase being produced by superheat. Because of the higher bulb temperature, the pressure applied to the top of the diaphragm is higher than the opposing evaporator pressure. However, there must be sufficient pressure difference (increased superheat) to overcome the additional effect of the spring pressure to open the valve.

3.3.3.3 Float Valves

High-Side Float Valves

A high-side float valve controls the mass flow of the refrigerant liquid entering the evaporator and, as such, controls the rate at which the refrigerant gas is pumped from the evaporator by the compressor. The liquid refrigerant flows from the condenser into the high-side float valve body where it raises the float and moves the valve pin in an opening direction. This allows the liquid to pass through the valve port, expand, and flow into the evaporator. Most of the system refrigerant charge is contained in the evaporator at all times. The high-side float system is a flooded system. The float maintains a constant refrigerant level on the HP side of the system.

Low-Side Float Valves

The low-side float valve performs the same function as the high-side float valve, but it is connected to the LP side of the system. This flow metering/expansion device is used on the flooded evaporators to control the level of refrigerant in the evaporator. As the refrigerant level falls, the low-side float also falls and opens the valve or provides an electrical switch output to a solenoid to control the level. This admits the liquid refrigerant to the evaporator to replace the evaporated liquid to maintain the refrigerant level in the evaporator.

3.3.3.4 Capillary Tubes

This flow metering/expansion device is the most prevalent in small commercial applications. It can usually be employed in systems up to 10 tons (35 kW). As the liquid refrigerant nears the end of the capillary tube, the liquid starts to change to a vapor state. A capillary tube passes the liquid much more readily than the vapor due to the increased friction with the vapor. The HP and LP sides equalize when the compressor is off, thus permitting an easier start for the compressor.

3.3.4 Evaporators

The evaporator absorbs the heat from the medium being cooled and results in a change in the state of the refrigerant liquid. At this point, the refrigerant's LP permits the refrigerant to boil or evaporate at a lower temperature as it absorbs the heat. There are many design configurations for the evaporators. The design of the evaporator is typically based on the medium being cooled, the anticipated loads, the environmental conditions, and the type of refrigerant as well as other factors. The force that drives the refrigerant through the evaporator is the differential pressure created by the compressor.

Chilled water evaporators are generally constructed as either a flooded evaporator or a direct expansion evaporator. In a flooded evaporator, the shell contains a tube bundle through which the water to be chilled is pumped. In the direct expansion evaporator, the liquid refrigerant boils and evaporates inside the tubes while the water is circulated over the tube bundle.

In evaporators (coolers), the tubes are typically made of copper because of its better heat transfer characteristics as compared to the heat transfer characteristics of copper-nickel or other alloys. The chilled water system is a closed system with very little fouling. Therefore, the added cost of using other types of corrosion-resistant material is not justified.

3.3.5 Monitoring and Control Devices

As the load on the evaporator decreases, the suction pressure and the temperature to the compressor also decrease. If the loading continues to reduce without some method of controlling the capacity, the compressor would ultimately trip off due to the low suction temperature and the resulting LP cut-out. These devices include cylinder unloaders, HGBP valves, inlet guide vanes/slide valves, control switches, and solenoid control valves.

3.3.5.1 Cylinder Unloaders

Capacity control for the refrigerant system can be accomplished by a cylinder unloader. The cylinder unloader can function by preventing the suction valve from closing or by directing the pressurized refrigerant gas to be discharged back to the suction side of the compressor. This is performed by equipment generally designed by the manufacturer for the specific compressor.

3.3.5.2 Hot Gas Bypass

The HGBP provides for capacity modulation and has many variations. The HGBP provides a false load to the compressor by bypassing HP refrigerant gas from the compressor discharge to the system's LP side to maintain its operation under low load conditions. Proper bypass control is accomplished by a modulating-type pressure regulator, which opens when there is a decrease in the valve outlet pressure as would be created by a low load on the evaporator.

For all HGBP applications, the problem of head pressure control must be considered. The piping of the hot gas into the system's low side should be done in such a manner as to provide a homogeneous mixing of the gases. Pipe sizes usually dictate the best method to use. Most major equipment manufacturers have specific instructions concerning these bypass applications. The application manual provided by the compressor's or the unit's manufacturer should be consulted prior to making any configuration changes.

A solenoid valve in the liquid-line to liquid-injection valve is recommended to prevent the flow of liquid into the suction line during periods when the HGBP valve is not operating, such as during the high load periods.

Just as a solenoid is recommended for the liquid injection valve, a solenoid valve should be installed in the HGBP line ahead of the bypass regulator. This permits automatic pump down and unwanted high-side to low-side leakage. It also prevents a bypass during unwanted periods. The solenoid can be wired three different ways: into the system control circuit parallel with the liquid line solenoid, into the cylinder unloader circuit, or to a pressure switch. If the bypass valve is piped to a suction line, the bypass line solenoid must be wired in series with a discharge line thermostat set to terminate bypass if the discharge temperature exceeds 300°F (149°C).

The operation of the HGBP system, including the head pressure control valve, should be sequenced with the compressor inlet vane system to complete the capacity control system.

3.3.5.3 Inlet Guide Vanes and Slide Valves

The inlet guide vanes and the slide valves modulate the flow of refrigerant gas into the compressor suction. The slide valves are typical for a rotary screw compressor, and the inlet guide vanes are typical for a centrifugal compressor.

3.3.5.4 Control Switches

Control switches operate one or more sets of electrical contacts to control system components and respond to physical changes, such as pressure, temperature, liquid level, flow velocity, and proximity. Pressure and temperature responsive controls have one or more power elements that can use bellows, diaphragms, snap disks, or bourdon tubes to operate the mechanism. Level responsive controls can use floats, mercury balance tubes, or electronic probes to operate one or more sets of electrical contacts.

Refrigerant system controls can be categorized into three basic groups: operating, primary, and limit. Operating controls, such as thermostats, turn the systems on and off. Primary controls, such as the HP cut-out switch, protect a refrigeration system from unsafe operation.

Pressure control switches – The refrigerant pressure is applied directly to the element, which moves against a spring that can be adjusted to control any operation at the desired pressure. The types of pressure control switches are:

- HP cut-out (shuts off the compressor when excessive pressure occurs)
- High-side LP (shuts off the compressor under low ambient or LP conditions)
- High-side fan cycling (cycles the condenser fan on and off to provide the proper condenser pressure)
- Low-side LP (disengages the compressor when a low charge or a system blockage occurs)
- Low-side cycling (cycles the compressor on and off to provide the proper evaporator pressure)

Pressure transducers – These devices are most frequently used as a substitute for one or more pressure switches. The pressure transducer is typically an analog device that produces a continuous low-voltage output current proportional to the pressure applied.

Temperature control switches – An indirect temperature control switch is a pressure control switch in which the pressure-sensing element is replaced by a temperature-sensing element. The operation of the control switch results from these changes in pressure or volume. A direct temperature control switch generally contains bimetallic disks that activate electrical contacts when the temperature increases or decreases. As the temperature of the metallic disk or blade in the switch increases or decreases, the attached electrical contacts engage or disengage.

Fluid flow sensing switches – Both air flow and liquid flow sensing switches are available. The spring-loaded vanes of the air flow switch are installed in a regulated, high-velocity air stream. The pressure of the air causes the vane to deflect and make an electrical contact. The liquid flow switches work in a similar manner; the liquid flow sensing switches are normally used to indicate sufficient water flow or refrigerant flow through the evaporator or condenser.

Differential control switches – These switches sense a given difference in the pressure or the temperature between two pipes, lines, or spaces. The instrument differential is the difference in the pressure (or temperature) between the low- and high-pressure (or temperature) elements for which the instrument is adjusted. The operating differential is the difference in the pressure or temperature required to open or close the switch contacts.

Float switches – A float switch has a float that operates one or more sets of electrical contacts as the level of a liquid changes.

3.3.5.5 Control Valves

Control valves are used to start, stop, direct, and modulate process flow to satisfy system requirements in accordance with system load. The types of control valves include the following:

Evaporator pressure regulator – The evaporator pressure regulator (EPR) is located downstream of the evaporator. The purpose of the EPR is to maintain the pressure in the evaporator above an acceptable operating value. The EPR opens only when the evaporator pressure rises above the valve's pressure setting. An EPR can also be viewed as an evaporator temperature controller, as its purpose is to prevent the evaporator from becoming too cold and possibly freezing the coils or process lines.

Suction pressure regulators – The suction pressure regulator (holdback valve or crankcase pressure regulator) limits the compressor suction pressure (regulator outlet pressure) to a maximum value.

Condenser pressure regulators – Various condenser pressure regulating valves are used to maintain sufficient condensing pressure to allow air-cooled condensers to operate properly during the winter.

Solenoid valves – A solenoid valve is closed by gravity, pressure, or spring action and is opened by a plunger actuated by the magnetic action of an electrically energized coil, or vice versa.

Condensing water regulators – The condensing water regulator modulates the quantity of the water passing through a water-cooled refrigerant condenser in response to the condensing pressure. The condensing water regulator consists of a valve and an actuator that are linked together. A three-way regulator is similar to the two-way valve except that it has an additional port that opens to bypass the water around the condenser.

Check valves – Refrigerant check valves are normally used in refrigerant lines in which pressure reversals can cause undesirable reverse flows. A check valve allows flow in one direction only. The closing occurs either when a reversal of pressure takes place or when the pressure drop across the check valve is less than the minimum opening pressure drop in the normal flow direction.

3.4 Codes and Regulations

The American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) Standard 15, Safety Code for Refrigeration [3] governs the design, construction, installation, operation, and inspection of all refrigerating systems. This code classifies the system's type and refrigeration classification. The pressure limiting or relief devices must be provided on all systems containing more than 20 lb (9 kg) of refrigerant and operating above the atmospheric pressure. The discharge of the relief devices must be routed to the outdoors.

In addition, all nuclear safety-related chillers should comply with the American National Standards Institute (ANSI)/American Society of Mechanical Engineering (ASME) AG-1 code [4] and ASME Section III [5] with regard to the design, fabrication, construction, and testing requirements, including performance testing recommendations.

Non-safety-related chillers should meet the requirements of Section VIII of the ASME Boiler and Pressure Vessel Code [6].

3.4.1 Chlorofluorocarbon Regulations

Legislation has been passed by the U.S. government that eliminates the production of certain types of chlorofluorocarbons (CFC), that is R11, R12, and to a lesser extent, R-22, because of their effect on the atmosphere. Therefore, chiller designs using R11and R12 refrigerants should not be considered for future projects. If an R-11 machine is converted to R-123A, it must be recognized that this refrigerant is in the same classification of hydrochlorofluorocarbon (HCFC) as an R-22. For those chillers that already contain these refrigerants, strategic plans should be considered for either the containment of existing refrigerant, conversion of the refrigerant equipment, or replacement of the refrigerant.

A short-term strategy is to maintain a minimum inventory of refrigerant that will replace a charge in both trains of equipment in the event of a catastrophic leak. The concern is the future availability of refrigerants that are no longer manufactured, specifically R-11 and R-12. The manufacture of virgin R-22 is currently declining due to the phase-out schedule promulgated in the current regulations. Beyond the phase-out date of 2015, only reclaimed R-22 and R-123A can be purchased.

3.5 Scope and Equipment Covered by the Sourcebook

The scope of the LCM sourcebook includes major chiller components typically used in nuclear power plants. The common major components covered include centrifugal compressor, screw compressor, and direct expanding chillers. Both safety and non-safety chillers are included.

The components to be covered for each system type include:

- Compressor (including motor)
- Condenser
- Metering/expansion device
- Evaporator
- Connecting piping
- Monitoring and control devices

The heat sink and heat source system (for example, service water and room coolers) are not part of the scope of this sourcebook.

4
INDUSTRY OPERATING EXPERIENCE AND PERFORMANCE HISTORY

This section addresses step 9 in the LCM planning flowchart in Figure 2-1b. The information compiled in this section is to be used for a comparison or benchmarking to plant-specific conditions and operating experience. The qualitative data are intended as a checklist of potential conditions affecting plant-specific performance, while the quantitative failure data may provide insight into the potential for plant-specific enhancements and help identify where improvements can best be made.

For example, if the plant-specific component failure rates are much less than what the generic data indicate, one might conclude that the existing maintenance plan is effective and further improvements will be difficult to achieve. On the other hand, equipment performance may be attributed to an excessive maintenance program that might indicate that an overall reduction of the maintenance activities is desirable. Similarly, if the plant-specific component failure rates are substantially higher than the generic failure rates presented here, or if the contribution of chillers to lost power production significantly exceeds the generic (PWR- or BWR-specific) values, equipment replacement or major changes to maintenance practices may be required. If the reliability of the chiller system falls below a certain level, an increase in maintenance efforts will be required to satisfy Maintenance Rule performance criteria. Ultimately, replacement/ modification may be considered if reliable plant operation cannot be sustained.

It should be noted that this section addresses failure and failure data rather than repair practices and data. In general, repair times will be available from plant records and will depend on plant-specific maintenance practices. The mean time to repair (MTTR) has a direct impact on chiller system availability.

4.1 Nuclear Industry Experience

A review of the available industry operating experience and events has been performed to extract the pertinent information and to present the data such that the plant engineer can assess the plant-specific performance of the chiller in comparison to the industry.

4.1.1 Qualitative Data

Qualitative failure data indicate that several different failure modes exist for chillers. A review of the licensee event report (LER) data from the past seven years shows a relatively large number of failures as a result of personnel errors. Of the 25 LERs reported during this time period, 40% were caused by personnel errors. This would indicate that closer management attention is appropriate. This is so important because when an LER is issued, it means that the plant has entered or should have entered a load reduction as a result of having an insufficient number of chiller trains available. Although in only two instances an actual load drop was required, in each instance, the plant was nearing the end of the limiting condition for operation (LCO) grace period and would soon be required to take a load reduction had the repair not been completed.

When reviewing the functional failure data, there are four dominant component types that result in more than 85% of the failures (257 out of 301). These data were captured from the INPO EPIX database over the last 10 years. The following subsections describe the four dominant failure categories.

4.1.1.1 Instrumentation

Chiller instrumentation has caused 29% of the functional failures recorded over the last 10 years. The following are the major issues creating these failures:

- Pressure switch failures due to being out of calibration or failing to activate
- Temperature switch failures due to being out of calibration or failing to activate
- Thermostat and temperature controller failures
- Integrated circuit card failures

4.1.1.2 Compressors

Chiller compressors caused 26% of the functional failures recorded over the last 10 years. The following are the major types of failures:

- Spurious chiller compressor malfunctions
- Failure to start on demand
- Seal leakage
- Worn bearings and loss of lubrication
- Linkage, misalignment and/or binding, and vane adjustment problems

4.1.1.3 Electrical Equipment

Chiller electrical equipment caused 18% of the functional failures recorded over the last 10 years. The following are the major types of failures:

- Circuit breaker failures; over loads and shorts
- Open circuits due to loose wiring in panels, relays, circuit cards, and so on
- Relay failures due to faulted coils
- Miscellaneous electrical equipment failures, for example, fuses, heaters, starters, and power supplies

4.1.1.4 Valves

Chiller valves caused 12% of the functional failures recorded over the last 10 years. The following are the major types of failures:

- Temperature and flow control valve failures
- Motor operator valve failures due to binding
- Gasket and seat leakage
- Misalignment on butterfly valves and float valves

4.1.2 Multiple System Failures: LERs

Table 4-1 shows the cause categories for the 25 LERs identified in Figure 4-1. The cause listed in the table is the driving force that resulted in an LER. In many cases, the redundant train was inoperable due to scheduled maintenance and resulted in entering the technical specification shutdown requirement. There appears to be no significant trend regarding a specific cause, a reactor type, or a chiller system equipment type.

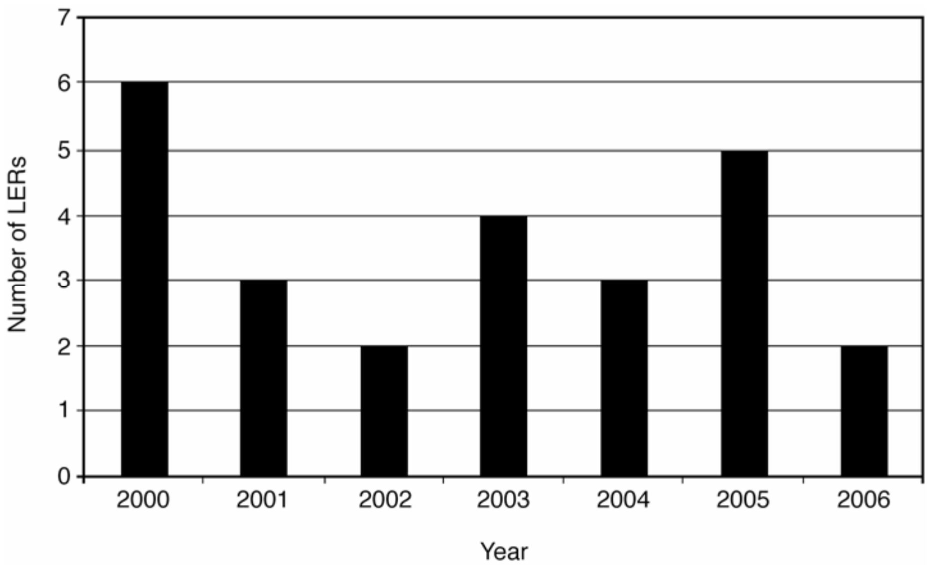

Figure 4-1
Chiller LERs

Table 4-1
Chiller LERs by Cause

Failure Cause	Category	Reactor Type	LER No.	Event Date	Load Drop
Failed motor temperature module	Equipment failure – electrical	PWR	2001-002	05-03-2001	No
Loose wires on relay	Equipment failure – electrical	PWR	2002-001	02-24-2002	No
Chiller motor O/L relays miscalibrated	Inadequate maintenance instructions	PWR	2003-001	06-11-2003	No
Incorrect maintenance installation	Inadequate instructions	PWR	2006-002	06-01-2006	No
Required manual actions not proceduralized	Administrative controls	PWR	2005-004	07-12-2005	No
Inadequate fill and vent	Operating error	BWR	2005-005	06-28-2005	No
Incorrect maintenance – reassembly	Inadequate instructions	BWR	2004-005	05-17-2004	No
Chiller oil system float arm failure	Equipment failure – mechanical	BWR	2004-002	09-19-2004	No
Chiller guide vane, pivot arm failure	Equipment failure – mechanical	BWR	2005-004	05-09-2005	No
Both chillers air-bound	Improper maintenance	PWR	2000-012	07-24-2000	No
Compressor seal failure	Poor manufacturing tolerances	BWR	2004-001	07-21-2004	No
Refrigerant tubing leaks	Inadequate maintenance instructions	PWR	2000-002	03-09-2000	Yes
Both chillers air-bound	Procedure inadequacy	PWR	2000-002	12-19-2000	Yes
Chiller temperature control valve, loss of power	Equipment failure – electrical	BWR	2003-006	12-21-2003	No
Invalid heat load assumption	Personnel error – design bases inadequacy	PWR	2000-004	09-25-2000	No
Nonessential heat load not isolated	Personnel error – valving error	PWR	2004-004	07-21-2004	No
Room cooler bearing failure	Equipment Failure – mechanical	PWR	2002-004	05-07-2002	No

Table 4-1 (continued)
Chiller LERs by Cause

Failure Cause	Category	Reactor Type	LER No.	Event Date	Load Drop
Chiller air-bound	Personnel error	PWR	2005-002	02-28-2005	No
Chiller fail to start – instrument failure	Equipment failure – instrumentation	PWR	2006-002	03-31-2006	No
Chiller oil level control system failure	Foreign material intrusion	PWR	2000-006	08-21-2000	No
Cavitation induced erosion piping failure	Equipment failure – mechanical	PWR	2005-004	07-11-2005	No
Cooling pump bearing failure – loss of cooling	Equipment failure – mechanical debris	PWR	2001-001	09-24-2001	No
Design bases deficiency	Station electrical load list not updated since mid-1980s	PWR	2001-02	09-14-2001	No
Chiller trip	Equipment failure – electrical loose wire	BWR	2003-004	06-11-2003	No
Design bases deficiency	Procedure inadequacy	PWR	2000-010	09-25-2000	No

4.1.3 Equipment Functional Failures

Data from the Institute of Nuclear Power Operations (INPO) Equipment Performance and Information Exchange System (EPIX) database are shown in Table 4-2. The EPIX database contains root cause information for failures and occurrences involving components that perform functions in support of systems within the scope of the Maintenance Rule. Therefore, the data are representative of chillers that are safety-related and non-safety-related. The Maintenance Rule systems are based on those SSCs that can affect power operation; chillers are included in this category.

The data were obtained by searching on "chilled water systems" and "functional failures." The tabulation shows the number of chilled water system equipment functional failures listed by year and the cause of the failure. Failures associated with equipment components outside the actual chiller are not included in this database. Figure 4-2 illustrates the number of failures by the cause. Therefore, it is evident that more than 75% of the failures are caused by the last six causes listed in Table 4-2. Evaluation of plant chiller failures through the use of these failure causes can be an effective tool for plant engineers when planning long-term resources for chillers.

By identifying the specific failures at a particular site and categorizing them in a similar manner as shown in Figure 4-2, it will be readily evident where plant resources should be applied to reduce chiller failures and thus reduce the risk of lost power generation. Additionally, since most equipment replacement funds are limited, this type of failure chart can be used to show the potential gain in the reduction of the failures by focusing on the top few causes, thereby getting the biggest payback for the investment.

Table 4-2
Chiller Failures by Cause: 1997–2006

Failure Cause	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	Total
Testing	0	0	0	0	1	0	0	0	0	0	1
Installation	0	1	0	0	0	0	0	0	0	2	3
External conditions	0	0	0	1	0	0	0	2	0	1	4
Erosion/corrosion	0	0	0	2	0	0	1	1	0	2	6
Change management	0	0	0	3	0	1	1	1	0	0	6
Human interface	1	2	0	0	1	1	2	0	1	0	8
Work practices	0	1	0	1	2	1	1	1	0	2	9
Operations	1	1	1	1	1	0	3	5	0	1	14
Procedures (inadequacies and errors)	1	3	0	1	2	3	0	4	2	1	17
Equipment manufacturing	1	3	5	3	2	1	2	3	1	1	22
Design errors	3	2	5	3	2	5	1	4	0	1	26
Undetermined	10	4	2	5	2	3	3	1	2	0	32
Maintenance errors	4	4	4	3	8	4	0	2	5	8	42
Aging	7	9	3	3	6	5	1	5	6	1	46
Electrical process	2	1	3	13	3	9	5	6	10	12	64
Mechanical process	7	3	5	8	15	11	8	2	6	14	79
Yearly total	37	34	28	47	45	44	28	37	33	46	379

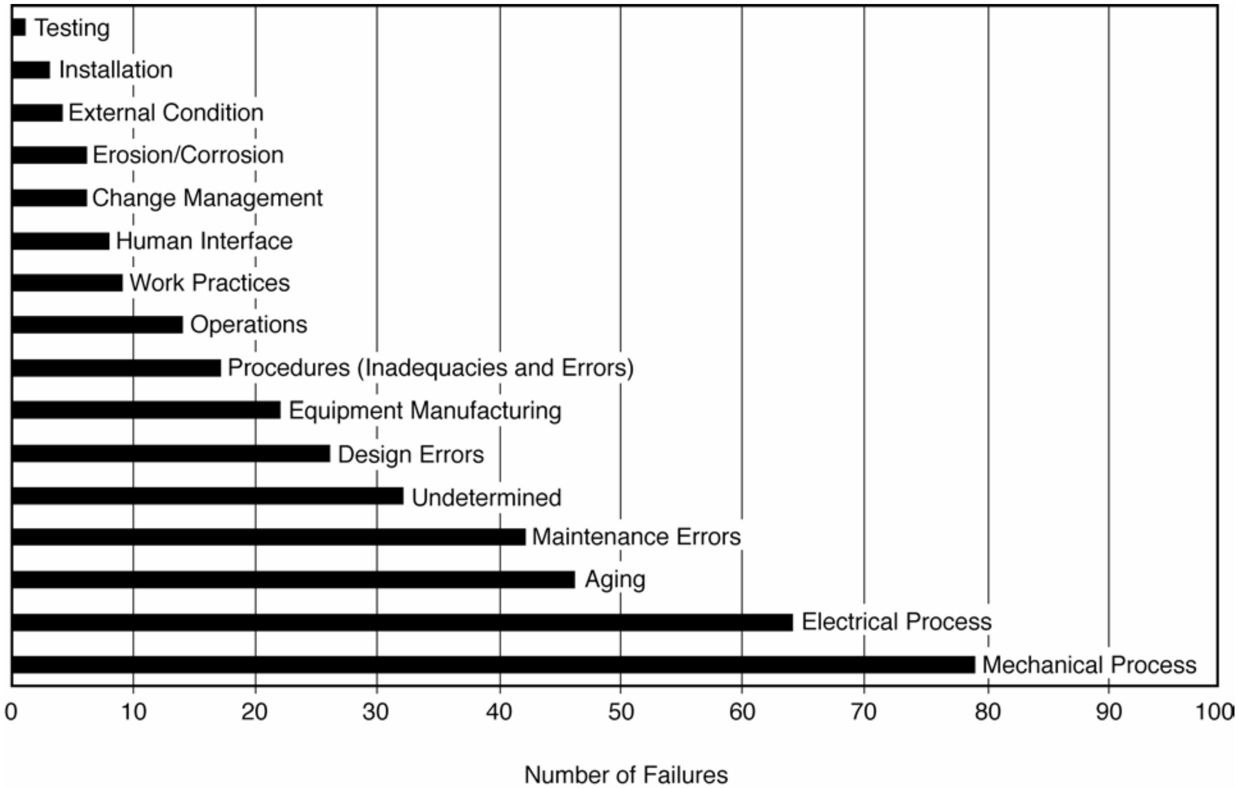

Figure 4-2
Total Failures by Cause: 1997–2006

4.1.4 Chiller Component Failures

By using the same EPIX data for chiller functional failures, the components of the overall system that are experiencing the most failures can be identified. The EPIX Maintenance Rule Functional Failure data from 1997–2006 are summarized by component in Table 4-3.

The instrumentation category includes all switches, indicators and elements, controllers, thermocouples, thermostats, and circuit cards. Each of the process variables within the chiller, such as temperature, pressure, flow and level of water, refrigerant, and oil systems, is included. The failure data do not make a distinction between a failed instrument and an out-of-calibration instrument, only the fact that the failure resulted in the chiller not being able to perform its design function.

The heat exchanger failures are limited to the evaporators, condensers, and coolers. The most predominant failure identified is due to the fouling of heat exchangers. Tube failure is the second most common failure mechanism.

The valve category includes valves and valve operators, plus float, HGBP, flow control, and temperature control valves. The typical modes of failure are external leaks, sticking operation, and binding.

The electrical equipment failure category includes all associated electrical equipment, such as breakers, motors, relays, panels, power supplies, fuses, heaters, resistors, starters, wiring, and terminal connections. Circuit board failures are included in this category.

The component failure data do not differentiate between safety-related and non-safety-related equipment. Non-safety-related equipment can affect power generation by causing area temperatures to reach the maximum level and, therefore, cause other equipment failures. This, in turn, can cause lost power generation or equipment failures and reduced service life of other components.

Table 4-4 shows the failure causes for each of the major components over the same 10-year period. From this table, it's easy to see which failure causes are creating the most problems for each type of major equipment. Monitoring and control devices include all control valves, all modulating equipment, and all instrument switches as well as cylinder unloaders, HGBP valves, guide vanes, and slide valves.

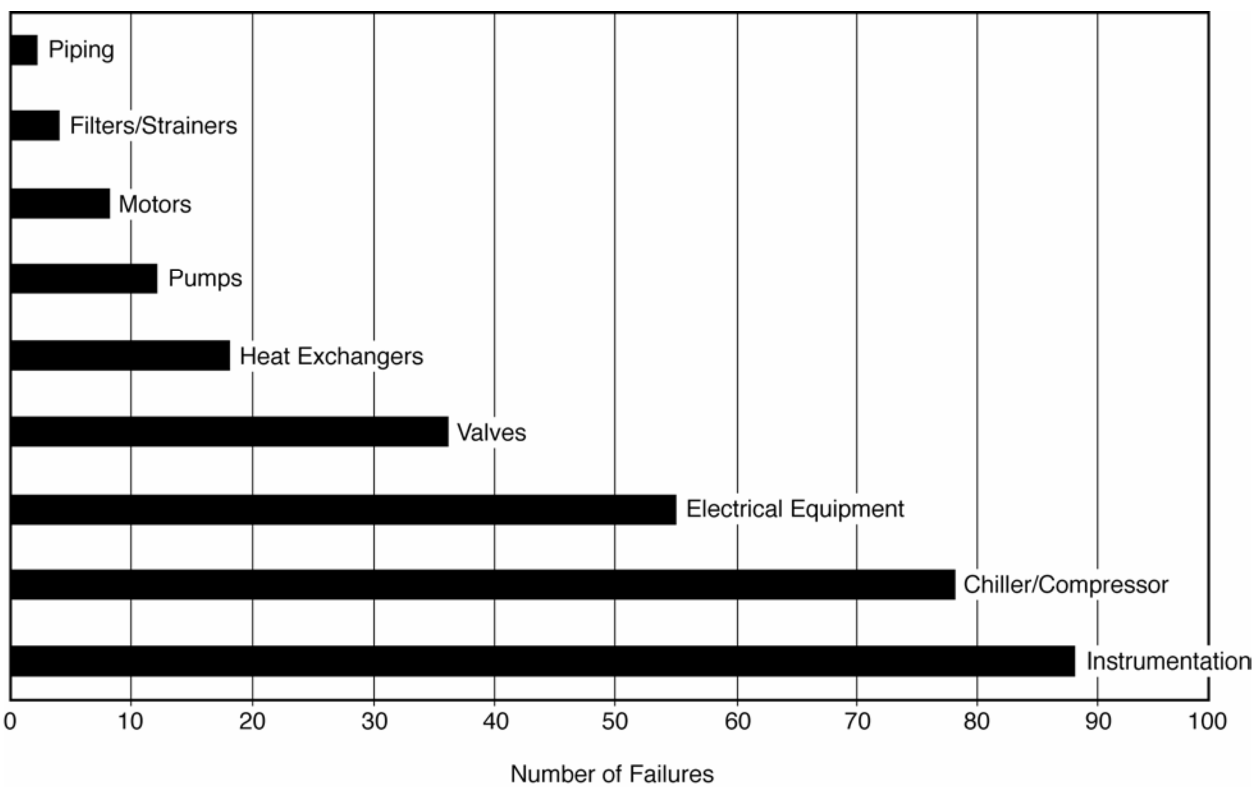

Figure 4-3
Maintenance Rule Functional Failures by Component

Table 4-3
Maintenance Rule Functional Failures by Component

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	Total
Piping	0	0	0	0	0	0	0	0	1	1	2
Filters/strainers	0	0	0	0	0	1	0	1	2	0	4
Motors	0	1	0	1	1	1	1	1	2	0	8
Pumps	1	1	1	0	0	0	2	1	3	3	12
Heat exchangers	0	2	3	4	2	1	3	3	0	0	18
Valves	5	1	7	6	2	4	2	6	0	3	36
Electrical equipment	4	8	2	6	4	5	2	8	7	9	55
Chiller/compressor	8	6	5	9	9	8	10	7	6	10	78
Instrumentation	8	8	7	13	16	10	6	4	8	8	88
Totals	26	27	25	39	34	30	26	31	29	34	301

Table 4-4
Failure Cause by Component

	Chiller/ Compressor	Condenser/ Evaporator	Metering/ Expansion Devices	Connecting Piping	Monitoring/ Control Devices	Valves	Totals
Electrical process	21	4	0	2	27	2	56
Mechanical process	25	5	2	2	14	6	54
Manufacturing	10	4	0	0	2	0	16
Aging	10	2	0	1	26	0	39
Maintenance	18	5	4	0	17	4	48
Procedures	7	1	1	0	3	0	12
Undetermined	20	2	0	0	6	1	29
Design	13	1	0	0	4	0	18
Operations	6	3	0	0	3	0	12
Other	3	1	0	0	11	0	15
Total	**133**	**28**	**7**	**5**	**113**	**13**	**299**

4.1.5 Relative Magnitude of Chilled Water Failure Frequency

The INPO EPIX database provides industry benchmarking for chiller failure data. The failure rate per year has been calculated using the failure data listed in Table 4-2. To make a comparison of the total failures per year to that of an individual plant's failures, the total count needs to be normalized into a failure rate. A failure rate per train per year is calculated and shown in Table 4-5. This table was generated by using the failures per year divided by the number of chilled water trains for all operating reactors during the year.

The number of chilled water trains is estimated by reactor type and vintage. Many older BWRs have fewer chillers and larger, newer PWRs can have as many as five or six chilled water trains per unit. Both safety-related and non-safety-related chillers are included in the total estimated number. The safety-related HVAC systems can include the control room HVAC, the auxiliary building HVAC, and the essential electrical equipment rooms HVAC. The non-safety-related HVAC systems can include the turbine building HVAC, the containment/drywell HVAC, and the radwaste building HVAC.

Table 4-5
Failure Rates Calculated from EPIX Data

Year	Number of Failures per Year from EPIX Data	Number of Chilled Water Trains Operating	Failure Rate (per train per year)
1997	37	434	0.085
1998	34	434	0.078
1999	28	434	0.065
2000	47	434	0.108
2001	45	434	0.104
2002	44	434	0.101
2003	28	434	0.065
2004	37	434	0.085
2005	33	434	0.076
2006	46	434	0.106
Average			0.087

4.1.6 Maintenance Rule

Maintenance Rule Section 50.65, *Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Plants*, states the following requirements:

> Each holder of a license to operate a nuclear power plant shall monitor the performance or condition of structures, systems, or components, against licensee-established goals, in a manner sufficient to provide reasonable assurance that such structures, systems, and components are capable of fulfilling their intended functions. Such goals shall be established commensurate with safety and, where practical, take into account industry-wide operating experience. When the performance or condition of a structure, system or component does not meet established goals, appropriate corrective action shall be taken.

Though chillers are both non-safety-related and safety-related, most of the non-safety-related chillers are also included in the scope of the Maintenance Rule (10CFR50.65). Therefore, the analysis of operating experience takes into account both classifications of chillers. Therefore, the reliability and availability criteria are applied and the data are gathered to monitor equipment performance against these criteria. Accordingly, plant-specific data gathered for Maintenance Rule purposes should also be useful for LCM planning purposes.

Additionally, plant-level performance addressing the number of plant trips, capacity loss, and the number of safety actuations can also apply. For most plants, safety-related and non-safety-related chillers are considered a risk significant and, therefore, would require system-specific availability or reliability performance monitoring under the Maintenance Rule.

The EPRI SysMon software program [7] contains recommendations for performance monitoring for 37 systems. The essential chilled water system is one of the systems addressed in SysMon as it is a safety-related system in the Maintenance Rule scope and a technical specification system. It is required to supply essential chilled water to various safety-related air handling units for personnel comfort in the control room envelope and provide cooling for safety-related equipment in the electrical auxiliary building, the mechanical auxiliary building, and fuel handling. SysMon identified the following goals for each essential chilled water system train:

- No more than five Maintenance Rule functional failures (MRFFs) per train in an 18-month period.
- No more than eight MRFFs per unit in 18 months.
- Fewer than 650 hours of unavailability per train in 18 months.
- No repeat MRFFs.
- Number of open corrective maintenance work orders is fewer than 25 per unit.
- The ratio of preventive to total (excludes modifications and support activities) maintenance work-hours spent on the system is greater than or equal to 75%.

4.1.7 EPRI PM Basis Templates

Chiller Performance Monitoring and Troubleshooting Guide (EPRI report 1007361) [8] provides a PM template and a strategy for PM to address degradation mechanisms of chillers and related components. It also provides the tasks identified in these templates, including the subtasks discussed in the PM task descriptions. Tables 4-5 through 4-11 provide a summary of the chiller PM template. The items listed below have been identified as the most common failure locations (mechanisms for chiller components):

- Centrifugal compressors
- Reciprocating compressors
- Rotary screw compressors
- Condenser/evaporator heat exchangers
- Expansion valves/control valves
- Connecting piping (including filters/strainers)
- Monitoring and control devices

Table 4-6
Centrifugal Compressor – PM Template

PM Task Component	Refrigerant Analysis	Oil Analysis	Vibration Analysis	Calibration	External Inspection	Internal Inspection	Performance Tests	Functional Tests	Operator Rounds	Overhaul
Oil system	1 year				3–6 months				As required	
Impeller						2 years				
Capacity control (guide vanes)					3–6 months	2 years				
Bearings		1 year	3–12 months							
Gearbox		1 year	3–12 months						As required	
Gaskets	1 year				3–6 months	2 years				
Fasteners and hardware					3–6 months	2 years			As required	
Coupling			3–12 months		3–6 months	2 years			As required	5 years

Note:
This template does not apply to the run-to-failure (RTF) components; non-critical here means not critical but important enough to require some PM tasks.

Table 4-7
Reciprocating Compressor – PM Template

PM Task Component	Refrigerant Analysis	Oil Analysis	Vibration Analysis	Calibration	External Inspection	Internal Inspection	Performance Tests	Functional Tests	Operator Rounds	Overhaul
Lubrication		1 year			3–6 months				As required	As required
Cylinders – valves						2 years				
Cylinders – piston rings					3–6 months	2 years			As required	
Cylinder body					3–6 months				As required	
Cylinders – gaskets	1 year					2 years				As required
Bearings		1 year			2 years					As required
Shaft		1 year								As required
Gaskets	1 year					2 years				As required
Fasteners and hardware			2 years		3–6 months					
Unloader valve										As required
Relief valve						2 years			As required	
Pulley sheaves			3–12 months		3–6 months					
Coupling			3–12 months		3–6 months	2 years				As required

Note:
This template does not apply to the run-to-failure (RTF) components; noncritical here means not critical but important enough to require some PM tasks.

Table 4-8
Rotary Screw and Orbiting Scroll Compressors – PM Template

PM Task Component	Refrigerant Analysis	Oil Analysis	Vibration Analysis	Calibration	External Inspection	Internal Inspection	Performance Tests	Functional Tests	Operator Rounds	Overhaul
Lubrication		1 year			3–6 months				As required	
Oil pressure					3–6 months				As required	As required
Rotors			3–12 months		3–6 months	2 years				As required
Capacity slide control valve									As required	
Bearings		1 year	3–12 months			2 years			As required	As required
Shaft seal					3–6 months				As required	
Gaskets	1 year				3–6 months					As required
Fasteners and hardware					3–6 months	2 years				
Coupling			3 months to 1 year		3–6 months	2 years				As required
Oil pump										As required
Oil separator					3–6 months				As required	

Note:
This template does not apply to the run-to-failure (RTF) components; non-critical here means not critical but important enough to require some PM tasks.

Table 4-9
Condenser/Evaporator – PM Template

PM Task Component	Refrigerant Analysis	Oil Analysis	Vibration Analysis	Calibration	External Inspection	Internal Inspection	Performance Tests	Functional Tests	Operator Rounds	Overhaul
Condenser	6 months				3–6 months	2 years	As required to 2 years		As required	
Evaporator				2 years	3–6 months	2 years	As required to 2 years		As required	
Refrigerant metering device	1 year	1 year				2 years	As required to 2 years			
Relief valve						2 years			As required	
Rupture disk										
Purge unit	1 year				3–6 months	2 years	As required to 2 years		As required	
Control valve					3–6 months	2 years			As required	

Note:
This template does not apply to the run-to-failure (RTF) components; noncritical here means not critical but important enough to require some PM tasks.

Table 4-10
Metering and Expansion Devices – PM Template

PM Task Component	Refrigerant Analysis	Oil Analysis	Vibration Analysis	Calibration	External Inspection	Internal Inspection	Performance Tests	Functional Tests	Operator Rounds	Overhaul
Refrigerant metering device	1 year	1 year				2 years	As required to 2 years			
Capacity slide control valve						2 years			As required	
Expansion valve	1 year	1 year			3–6 months	2 years	As required to 2 years	2 years	As required	
Float valve						2 years				As required

Note:
This template does not apply to the run-to-failure (RTF) components; noncritical here means not critical but important enough to require some PM tasks.

Table 4-11
Connecting Piping – PM Template

PM Task Component	Refrigerant Analysis	Oil Analysis	Vibration Analysis	Calibration	External Inspection	Internal Inspection	Performance Tests	Functional Tests	Operator Rounds	Overhaul
Tubing and fittings					3–6 months	As required			As required	
Small bore piping					3–6 months	As required			As required	
Flanges					3–6 months	As required			As required	
Filters/ strainers					3 months	As required			As required	

Note:
This template does not apply to the run-to-failure (RTF) components; noncritical here means not critical but important enough to require some PM tasks.

Table 4-12
Monitoring and Control Devices – PM Template

PM Task Component	Refrigerant Analysis	Oil Analysis	Vibration Analysis	Calibration	External Inspection	Internal Inspection	Performance Tests	Functional Tests	Operator Rounds	Overhaul
Unloader valve					3–6 months	2 years				As required
HGBP valve							5 years	2 years		As required
Guide/slide vanes					3–6 months	2 years	5 years	2 years		As required
Pressure switches				2 years				2 years		
Temperature switches				2 years				2 years		
Control valves					3–6 months	2 years		2 years		As required

Note:
This template does not apply to the run-to-failure (RTF) components; noncritical here means not critical but important enough to require some PM tasks.

4.1.8 Chiller Classification Comparison

The MRFF data take into account both safety-related and non-safety-related chillers. The criteria for an MRFF do not consider the classification that the equipment has been given. In addition, the PM recommendations do not consider the safety classification. The key consideration is preventing failures by the performance of maintenance at the appropriate frequency. Interviews were conducted with system engineers in charge of chilled water systems at nuclear power plants. Four questions were presented to ascertain if any differences existed between safety and non-safety chillers. Those questions were as follows:

1. Are there major differences in the components of a safety-related versus a non-safety-related chiller system?
2. Are there differences in the way the two systems are maintained, such as additional PM or PdM activities? Do the same technicians work on both systems, that is, site maintenance personnel versus contract HVAC personnel?
3. Are there any appreciable differences in the number of failures between the two systems?
4. What are the typical failures on the non-safety-related system equipment?

The outcome of the interviews was conclusive in that there were no specific differences in the equipment, maintenance activities, or failures in the two classifications of chillers. One site did acknowledge that the non-safety-related chillers had more failures because they were nearly 20 years older than the safety-related chillers. Failure types were common to both classifications of chillers.

4.2 NRC Generic Communications and Other Reports

4.2.1 NRC Communications

A review of the generic communications issued by the Nuclear Regulatory Commission (NRC) identified the following documents as being related to chillers and their effect on nuclear plants. Although these documents are quite old, the potential concerns expressed are appropriate to ensure a reliable chiller and should have been addressed at the time of issuance.

NRC Information Notice No. 94-82: Concerns Regarding Essential Chiller Reliability During Periods of Low Cooling Water Temperature. This information notice addresses a concern regarding chiller operation during periods of low cooling water temperatures. Overcooling the condenser refrigerant for essential chillers when the condenser's cooling water supply temperature is abnormally low can cause unstable chiller operation or actuate a self-protection feature that removes the chiller from service. Because cold weather can increase the rate of heat loss from both the source of the cooling water and the structures served by the chilled water loop, low cooling water temperatures and low chiller heat loads tend to occur concurrently during periods of cold weather. The potential for loss of a chiller at low cooling water temperatures due to over-cooling of the condenser refrigerant is increased at low heat loads.

NRC Information Notice 96-45: Potential Common-Mode Post-Accident Failure of Containment Coolers. This information notice addresses a potential for a common-mode failure causing all containment coolers to become unavailable. At many plants, containment coolers provide a significant safety function in reducing containment pressure and removing heat from the containment building. A postulated failure scenario could cause a common failure of all containment coolers, thereby potentially challenging the integrity of the containment building.

NRC Information Notice No. 89-76: Biofouling Agent: Zebra Mussel. This notice discusses the concern over biofouling of vital plant equipment. Zebra mussels have the potential to foul the critical cooling components. Periodic maintenance of intake areas and water treatment chemicals are needed to ensure that the intake structure is not fouled to allow adequate flow to vital plant cooling equipment.

NRC Information Notice No. 86-96: Heat Exchanger Fouling Can Cause Inadequate Operability of Service Water Systems. This notice, similar to the last, addresses fouling of service water-cooled equipment. Service water systems have the potential to become clogged with aquatic growth. Periodic maintenance of intake areas and water treatment chemicals are needed to ensure that the intake structure is not fouled to allow adequate flow to vital plant cooling equipment.

4.2.2 Other Industry Data

Other industry literature has been produced regarding chiller maintenance and operation. Of most notable interest is the topic of CFC refrigerant replacements. As dictated by law, the manufacturing of R-11 and R-12 stopped in the United States in 1995. Older plants with chillers installed prior to this date might likely have these coolants installed as the refrigerant. The following article discusses some of the options to consider.

"Operation and Maintenance Planning for the CFC Phaseout," Doc # 448, June 2000. This article, issued by The Hartford Steam Boiler Inspection and Insurance Company, provides strategic choices on how to deal with chillers containing the referenced refrigerants. Depending on whether the existing system is a high- or low-pressure system, different alternatives are available. Additionally, three options are discussed: contain the existing refrigerant to make it last for the life of the equipment, convert the refrigerant to an approved type, or replace the chiller equipment. Each option must be carefully studied based on the economics of the situation.

4.2.2.1 Containment of Existing CFC Refrigerant

The decision to continue to use the existing refrigerant by containment results in an increase in the maintenance and surveillance of the chiller. The older the equipment, the more PM activities are required to prevent and stop refrigerant leaks. New tubing, gasket and seal replacements, and new maintenance valves and fittings might be appropriate in lieu of continual repair. Depending on the age of the chiller, it would be reasonable to assume an increase of 25% in maintenance costs to monitor and repair the chiller depending on the present material condition of the chiller.

4.2.2.2 Refrigerant Conversion

Converting to an acceptable refrigerant replacement should include an economic analysis of the options. A direct replacement of the refrigerant reduces the efficiency of the chiller by as much as 6–16% [9]. Additionally, some chiller parts must be replaced if they are not compatible with the new refrigerant. Some items, such as gaskets, seals, O-rings, and occasionally, the hermetic drive motor if the windings are not compatible with the refrigerant, must be replaced. This reduction in efficiency and the added cost must be weighed against an optimized conversion. Most major vendors, such as Trane, Carrier, and York, offer higher efficiency retrofit kits to offset the reduction in efficiency and capacity. New impellers, higher rated or rewound drive motors, and drivetrain gear set replacements are a few of the upgrades offered.

A straight refrigerant conversion is estimated to cost about 25% of the installed cost of a new chiller, and an optimized conversion is estimated to cost about 50% [9].

Whether a plant is contemplating containment or conversion, the life expectancy of the chiller, the loss in efficiency, and the life of the plant must be considered before deciding on a course of action.

4.2.3 Non-Safety-Related/Non-Maintenance Rule Chillers

The failure history of non-safety-related/non-Maintenance Rule-related chillers is not available in the EPIX database. Discussions with some of the plant personnel indicate that the failure rate of chillers is no different from that of the safety-related/Maintenance Rule-related chillers and that the failure rates depend on their age. The discussions also indicate that the PM and PdM tasks performed on both categories of chillers are the same, but the safety-related/Maintenance Rule-related chillers are monitored more closely due to regulatory concern. Therefore, it is not surprising that the failure rates of both categories are about the same.

5 GUIDANCE FOR PLANT-SPECIFIC SSC CONDITION AND PERFORMANCE ASSESSMENT

This section addresses steps 8, 10, and 11A in the LCM planning flow chart (see Figure 2-1b) and provides guidance for the plant-specific LCM planning for chillers. A compilation and description of available and useful condition or performance monitoring programs are also included in this section (see Section 5.4).

- In step 8, the plant-specific operating and performance history is compiled as discussed in Section 5.1.
- Step 10 comprises a compilation and review of the plant-specific maintenance program for chillers, leading to the establishment of a complete inventory of current maintenance tasks and providing a basis of determining if enhancements or changes are desirable. These details are discussed in Section 5.2.
- The intent of step 11A is to characterize the present plant-specific physical condition and performance of chillers and the implementation of effective PM procedures, diagnostics, and component condition monitoring. The assessment of the maintenance tasks should pay close attention to whether and how the tasks address any deviations identified in this SSC performance assessment and the SSC condition review. The deviations might be positive in that the plant-specific SSC performance and conditions are superior to the industry average, in which case, unnecessary or overly frequent PM might be performed, or the deviations can be negative, indicating a need or opportunity for improvement. Details of the condition and performance assessments are discussed in Section 5.3.

5.1 Compiling SSC Operating and Performance History

The current condition and age of chillers have a major bearing on the LCM planning choices. In conjunction with performance reviews, a thorough assessment of the existing equipment is of paramount importance in making realistic decisions as to what maintenance options or strategies are feasible. Several elements are needed to complete the SSC condition review. These include reviewing:

- Records of the periodic visual inspections
- Diagnostic test and monitoring device data
- Test results that have been performed on the equipment
- Predictive technologies employed and their results

- Modifications
- Work orders
- Refurbishment data

5.1.1 SSC Condition Reviews

The review of plant chiller performance is important in determining LCM options and includes:

- Assembling the maintenance history for chillers, particularly the corrective maintenance actions from the last five years as a minimum. The maintenance history can also provide evidence of performance concerns or failures of critical components, such as compressors, condensers, coolers, expansion valves, and refrigerant load controllers.
- Trending the failure rates to identify any specific type of chiller components that can exhibit unusual performance challenges or high failure rates.
- Reviewing the inspection reports and condition monitoring reports to see if the current maintenance is effective in maintaining the equipment.
- Reviewing the Maintenance Rule performance parameters and trends, system health reports, Maintenance Rule periodic assessments, and the effectiveness of the corrective actions implemented.
- Reviewing the plant scrams and trip history to determine the events attributable to chillers and their components. For those events caused by chillers, an analysis can be done to calculate the historical cost of the failures. The results provide a basis for projecting future trends for LCM planning.
- Reviewing the design changes and technology upgrades that have been implemented for replacement and equipment upgrades.

5.1.2 Periodic Visual Chiller Inspections

A condition assessment entails a visual inspection of the external condition of chiller components to look for abnormalities, such as:

- Oil leaks
- Paint deterioration, discoloration, or peeling
- Evidence of corrosion or rust
- Staining from water or oil leaks
- Foundation crumbling or cracking, which indicates abnormal thermal expansion
- Loose and missing parts
- Deformation or vibration of tubing, coils, or conduit

- High sound level or humming
- High or low oil levels
- Loose grounding or terminal connections
- Other signs of abnormal conditions

5.1.2.1 Inspection Frequency

A periodic chiller inspection is an effective maintenance tool for locating situations and problems that are not indicated by sensors or other means. The problems are usually noted early so that a corrective action can be taken before a more serious condition occurs. Chillers with a history of problems should be inspected frequently. The suggested periodicity of inspections is provided in Tables 4-6 through 4-12.

5.1.2.2 Typical External Visual Inspections

The external visual inspection is focused on the detection of oil, air, water, or refrigerant leaks and the verification of operating parameters, including system capacity and control in the form of local area pressures and temperatures. Important parameters are condenser water-side pressure and flow rate, temperature control valve (TCV) position, and refrigerant temperature, all of which assist in detecting water-side fouling of condenser tubes. External leaks are most likely from failed shaft seals, gaskets, pneumatic control device tubing and fittings, and refrigerant-actuated control valves. An additional significant problem is the sticking of control valves.

The following is a list of typical inspection tasks applicable to most chillers. It should be noted that the items inspected depend on the type of equipment installed and the record of performance in service. Those plants that perform inspections more frequently do not necessarily need to check all the following items during each inspection:

- Verify the general condition and performance of the unit.
- Inspect for loose, missing, or damaged hardware, parts, and components.
- Verify that the superheat and subcooling temperatures are within specifications.
- Verify that the refrigerant control valve is functioning within its expected operating range.
- Ensure that the refrigerant level is correct and that there is no evidence of leakage.
- Ensure that the cooling water flow rate to the heat exchanger is correct and that the inlet and outlet temperatures and pressures are within specification.
- Verify that the pressure relief device is closed with no evidence of leakage.
- Verify that the purge unit is seated and not venting.
- If present, verify that the refrigerant-operated control valve is operating properly.

- Inspect all pneumatic devices for evidence of leaks and loose or damaged air supply tubing.
- Verify that all lubrication levels are correct and that there is no evidence of leakage.
- Inspect all compressor/motor couplings for wear and proper alignment.

On centrifugal compressors, check the following items:

- Verify that the oil pump is operating correctly and providing specified pressures.
- Inspect the oil lines for damage.
- If applicable, verify that the oil level is correct.
- Ensure that the capacity control valves are free and not bound.
- Verify that the shaft seal and all gaskets show no evidence of leakage.
- Verify the proper operation of the oil separator heater.

On reciprocating compressors, check the following items:

- Inspect the cylinders and heads for evidence of cracking.
- Verify that the shaft seal and all gaskets show no evidence of leakage.
- Verify that the unloader and relief valves are operating correctly.
- Inspect the belts and sheaves for evidence of wear and misalignment.
- Verify that the oil level is correct.
- Verify that the oil pressure is correct.
- Verify that the oil filter or screen is not clogged and is free of debris and that the oil lines are not damaged and show no evidence of leakage.

On rotary screw and orbiting scroll compressors, check the following items:

- Verify that the oil level in the oil separator is correct.
- Verify that the oil pressure is correct.
- Verify that the oil filter or screen is not clogged and is free of debris and that the oil lines are not damaged and show no evidence of leakage.
- Verify that the cooling water flow to the compressor is at the specified temperature and pressure.
- Verify that the shaft seal and all gaskets show no evidence of leakage.
- Verify that the oil separator heater is operating properly.

5.1.2.3 Typical Internal Visual Inspections

Heat Exchangers

The internal inspection is focused on fouling, improper water-side flow rate, leaking gaskets, and corrosion and erosion in general. The frequency of PM on heat exchangers is largely based on the water system quality and determined by operating experience.

The internal inspection should include the following activities:

- Complete all task items from the external visual inspection.
- Inspect for loose, damaged, or missing parts, fasteners, and components.
- Inspect the condenser heat exchanger for evidence of fouling, corrosion, and tubesheet degradation and the condition of the sacrificial anode; clean and recoat the tubesheet as necessary.
- If required, eddy current test (ET) the heat exchanger and look for tube wall thinning and tubesheet and baffle damage or wear.
- Replace the condenser heat exchanger seals and gaskets.

Compressors

This inspection provides an opportunity to address worn, eroded, or cracked impellers and binding pre-rotation vanes in centrifugal compressors and to inspect the inlet and outlet head valves and check valves on reciprocation compressors. Other important internal tasks on reciprocating compressors include the inspection of the piston rings and liners. Internal inspections of compressors should be based on run-time hours.

Internal inspection should include the following activities:

- Complete all task items from the external visual inspection.
- Inspect for loose, damaged, or missing parts, fasteners, and components.
- Inspect the metering orifice for cleanliness.
- Check the integrity of the pressure rupture disk and for the presence of moisture in the vent line.
- Check the pressure control tubing for integrity and damage. **Note:** The replacement of plastic pressure control tubing on chillers does not need to be performed during every inspection and might only require replacement approximately every three years.
- Change the oil filters and refrigerant dryers.

On centrifugal compressors, check the following items:

- Megger the compressor motor if it is the hermetically sealed type.
- Inspect the float valve for proper operation and check for evidence of wear, sticking, or a leaking float.
- Inspect the capacity control device for binding.
- Perform an electrical insulation test on the oil pump motor if it is internal to the refrigerant system.
- Inspect the gaskets and seals, including the seal of motor leads on hermetic units.
- Inspect the impeller for wear and damage. However, this does not need to be done every inspection interval.

5.1.3 Review of Diagnostic Tests – Performance Tests

5.1.3.1 Performance Tests

These tests address the integrated system performance, and therefore, are not directly separable from the performance testing for air handling equipment, ducting, and dampers. A major focus is the performance of controls and instrumentation. Drift, component failures, and maladjustments of these components form one of the dominant failure causes for chiller systems. Water-side fouling of condenser heat exchangers is a common failure cause and can be detected by performance testing.

Performance tests should include the following activities:

- Verify that the cooling capacity is within specification.
- Measure, track, and trend the ΔT, ΔP, and flow of the water-side of condensers and evaporator heat exchangers.
- Measure and verify that the refrigerant is within normal temperature and pressure ranges.
- Measure, track, and trend the compressor motor amperage as a function of chiller load.

5.1.3.2 Functional Tests

The functional test consists of a start and load sequence on large reciprocating and rotary screw compressors. It verifies that the capacity control devices respond correctly, the flow switch operates correctly, and the key parameters are in the normal operating range. It can be conducted as a post-maintenance test to verify the operability and the readiness to return to service and as an in-service test on standby equipment or on swapping over trains.

Performance tests should include the following activities:

- Verify that the capacity control devices respond as expected.
- Verify that the flow switch operates correctly.
- Verify that the key operational parameters are in the normal operating range.

5.2 Review of Current Maintenance Plans

5.2.1 Compiling Maintenance History

To develop a clear picture of past equipment performance from which projections can be generated, a thorough review of the maintenance history dating back 3–5 years (depending on the quality of the records) is needed. This maintenance history is captured by most plants in work orders (WOs), often managed by the plant computerized maintenance management system (CMMS). WOs are written to execute PM or corrective maintenance (CM) and to implement other activities, such as design changes, replacements, or upgrades.

The most important WOs are those implementing corrective actions as a result of equipment failures, performance enhancements, and design changes. They often contain information concerning the root cause of the failure to ensure that the corrective action is effective, whether repetitive failures were involved, the cost and work-hours spent on the corrective action, and the reason that the failure was not detected in its incipient stage. This information is used to identify additional PM or PdM activities, potential enhancements to the current maintenance program, and the need for replacement, redesign, or upgrades. The basic premise is that the performance can be improved only by preventing failures; therefore, it is critical to identify the historical failure causes and to determine the action that could have prevented the failure.

The WO review also provides detailed information as to the component failure rates presently experienced by chillers. These rates can be compared with the generic data presented in Section 4 to ascertain whether there is the potential for significant reductions in failure rates. These actual failure rates are also used in the economic modeling of LCM plans to calculate the cost of CM and the consequences of component failure (lost power production, regulatory cost, the costs of monitoring under the Maintenance Rule, EPIX reporting, and so on).

The WO review can also be used to trend the annual CM activities over past years to see if the equipment failures are increasing or decreasing and what additional corrective actions might be justified to effect a positive change.

Lastly and most importantly, a review should be conducted of plant transients, power reduction events, and scrams in which chiller equipment is involved. Again, depending on the quality of the records kept, a review of the past 5 years should be sufficient. This review should focus on the cause of the event, the principal systems or components involved, and whether the chiller was a direct or indirect contributor to the event.

5.2.2 Inventory of Current Maintenance Activities

Once the plant-specific maintenance history has been compiled, the current maintenance activities need to be identified. When using the word *maintenance* in LCM planning, the activities associated with the system include preventive, predictive, and corrective actions, whether required by regulations (testing, inspection, surveillance, walkdowns, monitoring, and sampling), applicable codes (ASME, NFPA, and state and local requirements), the insurance carrier, or plant procedures, programs, or policies. Collecting the associated activity parameters, such as the annual frequency of the task, the number of components involved, the labor hours required, the indirect labor associated with the activity, and the material costs, will provide the key input to developing a base case for LCM planning. This base case is not only important to create an inventory of the current activities and the total annual maintenance cost for the system, but it provides a benchmark for comparison to industry practice and a basis from which the need for additional activities, enhancements, or task reduction opportunities can be judged.

Intervals should be determined and adjusted by each utility based on individual plant experience, original equipment manufacturer (OEM) information notices, and insurance and regulatory requirements. Intervals provided in the EPRI PM templates are suggested starting points for this process, although in general, where these tasks are already being performed, the existing intervals could be used as the starting point provided that a basis for the intervals exists. Such a basis could be constructed from diagnostic data, past inspection data and failure history, and information in this document. A key point is that it is prudent to change time-directed intervals so that intervals are short enough to protect against unacceptable equipment deterioration but not so short as to waste maintenance resources or to introduce unnecessary sources of maintenance error.

When selecting time intervals for intrusive PM tasks, it is not necessarily conservative to select shorter rather than longer time intervals in a possible range. Shorter intervals expose the equipment to more opportunities for maintenance error and to the potential for nonoptimal setup. Furthermore, the reliability data for other complex plant component types suggest that components receiving a higher proportion of intrusive PM tasks might experience more failures than those that receive predominantly nonintrusive maintenance.

5.3 Conducting the Condition and Performance Assessment

The generic performance data and information presented in the preceding sections can be used for plant-specific LCM planning in many ways. In particular, for plants not having a large data basis of experience, the generic data provide a basis for a sound component-specific PM program. Furthermore, the data can be used for comparison trending or projecting performance or failure data into the future when attempting long-term LCM planning. If the plant is of recent vintage, the failure data provide an indication of the types of failures to be expected as the plant ages and shows potential precursors of problems to be anticipated. Lastly and most importantly, the benchmarking of plant-specific data against generic (or industry) performance data for chillers provides LCM planners with the information necessary to focus on areas where there are significant opportunities to achieve economic and technical improvements. The steps involved in plant-specific performance and condition assessment (including benchmarking) are summarized in the following paragraph.

Based on a review of the generic data on the system functional failures of chillers, most failures occur due to:

- Instrumentation
- Compressors/chillers
- Electrical equipment and connections
- Valves

Although the above list of components causing functional failures is not in order of frequency or significance, the information from these events can be used to compare the plant-specific performance data to generic (or industry) performance data for chillers. In Section 4, Table 4-2 through Table 4-5 show the number of chiller functional failures listed by cause and component. These events are based on INPO's gathering of information for the last 10 years. Benchmarking of plant-specific data against generic (or industry) performance data for chillers provides LCM planners with the information needed to focus on the areas where significant opportunities to achieve economic and technical improvements exist. The steps involved in benchmarking can be summarized as follows:

1. At the system level, benchmark the contribution of chiller LERs to the number of LERs experienced in the industry (see Table 4-1). This provides a preliminary assessment as to the current and past plant system health and indicates if the chillers at the site perform at, above, or below industry averages with respect to LER reportable events.
2. At the component level, compare the plant-specific chiller component failures with those discussed in Section 4.1 and Table 4-4 to diagnose and identify the potentially unacceptable component performance.
3. Compare the plant-specific chiller PM tasks against the industry recommendations (Tables 4-6 through 4-12) to identify the opportunities for the addition or deletion of PM or PdM activities and adjustments to the associated task intervals. If the performance of the chiller has been exceeding industry standards and failure rates are below average, changes to the chiller PM/PdM program should be implemented cautiously and with good reason. On the other hand, if the performance of the chiller measurably lags the industry average and the plant chiller PM/PdM program significantly deviates from industry recommendations, the deviations should be reviewed critically to identify the causes and any opportunities for enhancement.
4. Review the operating practices and procedures to ensure that chiller performance and operation are within the rated values specified in the design and nameplate data provided by the manufacturer.
5. Review the corrective WOs and the root cause evaluations of the chiller failures to determine if the failure causes are commensurate with industry experience.
6. Similarly, from the corrective WO review, tabulate the failure detection modes for the failed chiller to determine if the plant's PM and PdM programs are capable of detecting chiller degradation and incipient failures.

7. To ensure that the long-term maintenance plans include a thorough and critical review of the aging and obsolescence concerns, establish plant chiller failure rates, projected spare parts use, potential replacement models or refurbishment kits, the current spare parts inventory, exchange or reuse opportunities, and the reliable suppliers of parts, services, and replacements.

5.4 Condition Monitoring Technologies

A review of chiller inspection results and data from monitoring devices may require that further tests be performed. Analysis of the test results provides information regarding the internal condition of the chiller and the next steps for further sampling.

5.4.1 Refrigerant Analysis

Refrigerant analysis tests the refrigerant for the presence of moisture, acid, and oil. The task is important to detect conditions that could lead to oil return system failures on centrifugal compressors, whether from a plugged eductor, inadequate system differential pressure, or other component failure. The refrigerant analysis also addresses gasket failures, excessive or ineffective purging of noncondensable gases, and plugged refrigerant metering devices.

All of the failure causes for the oil return system contribute to making oil return problems a dominant failure mechanism for chiller units with centrifugal compressors, but only the plugged eductor and inadequate system differential pressure have random occurrences that can affect the interval for this task. Leaking gaskets and several other causes of failure in the oil return system are expected after periods significantly greater than 1 year. The refrigerant metering device and excessive or ineffective purging also have random occurrences and contribute to the chance of a failure on a time scale of 1 or 2 years.

Refrigerant analysis is recommended at an interval of 1 year to control failures from the above causes. The only practical backup to this task for the oil return system degradation is in the form of an observation during operator rounds.

5.4.2 Glycol Analysis

Glycol analysis is applicable only when a glycol fluid is used, and it addresses the change in fluid composition that results from fluid leaks. If a fluid leak goes unchecked, glycol fouling of the condenser heat exchanger will result. Glycol leakage that is sufficient to cause this particular failure mechanism in condenser heat exchangers has a random occurrence pattern on a scale of 1 to 2 years.

Glycol analysis at a six-month interval provides an assurance of system integrity and is expected to detect degradation before a system failure.

5.4.3 Oil Analysis

Oil analysis is performed on compressor oil regardless of the type of compressor, and it measures the degradation of the oil, the presence of particulates, and moisture and acid content. Oil analysis reveals incorrect or degraded oil as well as wear particles from worn bearings in all types of compressors. In the reciprocating compressors subject to impulsive mechanical stress, scored shafts and worn journals can also be detected.

Oil system-related degradation can occur in relatively short time (less than 2 years). Therefore, this failure mechanism requires detection relatively frequently. An interval of approximately 1 year provides an adequate degree of protection, although larger compressors used for service air and instrument air require oil sampling more frequently than this. During the oil analysis for chiller compressors, efforts must be made to protect the oil samples from contamination by atmospheric moisture. In addition to altering the moisture level content, exposure to the atmosphere results in the formation of additional acid. The analysis laboratory must be specifically experienced in chiller oil analysis and in providing the treatment and storage of chiller oil samples.

5.4.4 Vibration Analysis

The vibration analysis is focused on the detection of wear and misalignment in the bearings and couplings on all types of compressors, worn pulleys, belts, and sheaves, and of loose mounting bolts or a cracked frame on reciprocation compressors. Worn gears on centrifugal compressors and worn screw elements on rotary compressors can also be detected.

Quarterly data collection for trending should provide an adequate degree of protection for all compressors.

5.4.5 Instrument Calibration

Calibration addresses drift, misalignment, leaks, loose connections, and component failures of chiller controls, such as refrigerant freeze protection, high and low refrigerant pressure, oil level and pressure, and capacity controls. The instruments and controls include pressure switches, relays, electrical or electronic transmitters, TCVs, programmable logic controls, level and flow switches, RTDs, I-to-P transducers, solenoid valves, and pneumatic devices.

Many of the causes of drift in instrumentation and controls are random on a relatively short time scale of 1–2 years. There are many failure causes and a relatively high proportion of control devices in chillers. It is not surprising that control failures are a dominant degradation mechanism for chiller systems.

An interval of 2 years is believed to provide sufficient protection from instrument drift. For the majority of the instruments and controls, calibration is the only means available of performing PM. Failure to calibrate is usually equivalent to run-to-failure for this equipment except for capacity, oil, and refrigerant controls that are also subject to performance testing.

5.4.5.1 Operation Recommendations

The manufacturer's representative should be requested to adjust the HGBP system to ensure that its sole purpose is to prevent surging of the compressor. If the condenser water contains sulfides or other corrosive chemicals, the water should not be allowed to stand stagnant in the vessel for periods exceeding 2 weeks. A circulation system should be considered.

5.4.5.2 Maintenance Recommendations

PM including periodic eddy current testing of the heat exchanger tubes is recommended to ensure replacement before tube failure. Systems with raw water cooling should be tested on a frequent basis, whereas closed water treated systems could be done quite infrequently, such as every 10 years. Water leakage into the refrigerant side creates highly corrosive hydrochloric or hydrofluoric acids that can cause serious internal damage.

A tube puller of the type recommended by the heat exchanger manufacturer should be available at each plant to facilitate tube removal and replacement. Tube replacement should be supervised by a manufacturer's representative. Of the two most common methods, dimension rolling (while checking the measurement) is preferred over torque rolling.

A filter-dryer system should be considered to enable purging rust particles or moisture from the cooler. Basically, this system consists of a filter-dryer with all but one element removed and a hot gas eductor. The purging connection should be located near the bottom of the cooler and outside of the liquid feed trough. The flow is induced by a hot gas eductor and returned to the cooler above the liquid level.

6
GENERIC AGING AND OBSOLESCENCE ASSESSMENT

This section addresses steps 11B and 11C in the LCM planning flowchart (see Figure 2-1b). The intent is to help characterize the aging of passive SSCs, the wear of active components, and the obsolescence of SSCs. This characterization serves to address the need for and the timing of replacement of chiller equipment in the LCM planning process.

6.1 Aging Mechanism Review

An aging management review is an integral factor to LCM maintenance planning. *Chiller Performance Monitoring and Troubleshooting Guide* (EPRI report 1007361) [8] provides valuable information on chiller component aging. The information contained in this report can be used to identify the effects of aging on various components and the appropriate aging management programs. The following list of aging mechanisms for use in the development of aging management programs was derived from the report and is presented in Table 6-1.

Table 6-1
Common Maintenance Issues and Surveillance Techniques

Chiller Component	Aging Mechanism	Aging Effect	Maintenance and Surveillance Techniques
Centrifugal Compressor			
Impeller	Wear and erosion due to age	• Reduced cooling capacity • Low head pressure	• Internal inspection
Capacity control (prerotational vanes)	Binding due to age and vibration	• Improper operation • Spurious trips	• Internal inspection • External visual inspection
Bearings	Wear due to age and vibration	• Decreased oil pressure • Compressor trip	• Vibration monitoring • Operator rounds • Oil analysis
Shaft seal	Leakage from age-related wear	• Oil leakage • Reduced oil level • Abnormal refrigerant levels	• Operator rounds • External visual inspection
Gaskets	Leakage from thermal cycling and aging	• Refrigerant and oil leaks • Reduced availability	• External visual inspection • Refrigerant analysis
Coupling	Wear due to aging	• Compressor trip • Damaged shaft	• Vibration monitoring • Overhaul • Internal inspection • External visual inspection

Table 6-1 (continued)
Common Maintenance Issues and Surveillance Techniques

Chiller Component	Aging Mechanism	Aging Effect	Maintenance and Surveillance Techniques
Centrifugal Compressor – Lubrication System			
Lubricant	Oil leakage due to age	• Spurious trips • Component failures from lack of lubrication	• Operator rounds • External visual inspection
	Oil degradation from age	• Component failures from lack of lubrication	• Oil analysis
	High/low oil pressure due to aging pump	• Spurious trips • Damaged components	• Operator rounds • External visual inspection
Oil eductor	Failed due to age	• Low oil level • Reduced capacity • High head pressure	• Operator rounds • External visual inspection • Refrigerant analysis
Solenoid-operated valve (SOV)	Coil failure due to high temperature	• Reduced capacity • Improper operation	• Inspection
	Elastomer and gasket failure due to thermal aging	• System leaks • Reduced availability	• Inspection • Operator rounds
Centrifugal Compressor – Lubrication System			
Lubricant	Oil leakage due to age	• Spurious trips • Component failures from lack of lubrication	• Operator rounds • External visual inspection
	Oil degradation from age	• Component failures from lack of lubrication	• Oil analysis
	High/low oil pressure due to aging pump	• Spurious trips • Damaged components	• Operator rounds • External visual inspection

Table 6-1 (continued)
Common Maintenance Issues and Surveillance Techniques

Chiller Component	Aging Mechanism	Aging Effect	Maintenance and Surveillance Techniques
Oil eductor	Failed due to age	• Low oil level • Reduced capacity • High head pressure	• Operator rounds • External visual inspection • Refrigerant analysis
SOV	Coil failure due to high temperature	• Reduced capacity • Improper operation	• Inspection
	Elastomer and gasket failure due to thermal aging	• System leaks • Reduced availability	• Inspection • Operator rounds
Centrifugal Compressor			
Impeller	Wear and erosion due to age	• Reduced cooling capacity • Low head pressure	• Internal inspection
Capacity control (prerotational vanes)	Binding due to age and vibration	• Improper operation • Spurious trips	• Internal inspection • External visual inspection
Bearings	Wear due to age and vibration	• Decreased oil pressure • Compressor trip	• Vibration monitoring • Operator rounds • Oil analysis
Shaft seal	Leakage from age-related wear	• Oil leakage • Reduced oil level • Abnormal refrigerant levels	• Operator rounds • External visual inspection
Gaskets	Leakage from thermal cycling age	• Refrigerant and oil leaks • Reduced availability	• External visual inspection • Refrigerant analysis
Coupling	Wear due to aging	• Compressor trip • Damaged shaft	• Vibration monitoring • Overhaul • Internal inspection • External visual inspection

Table 6-1 (continued)
Common Maintenance Issues and Surveillance Techniques

Chiller Component	Aging Mechanism	Aging Effect	Maintenance and Surveillance Techniques
Reciprocating Compressor			
Lube oil pump failure	Low oil due to aging of pump	• Compressor trip or failure	• Overhaul • External visual inspection
Cylinders	Valve wear due to run time and fatigue	• Reduced cooling capacity • Compressor trips	• Internal inspection
	Piston ring wear due to run time	• Reduced capacity	• Internal inspection
Shaft	Journal wear due to run time	• Compressor trip	• Overhaul • Oil analysis
Bearings	Wear due to age and vibration	• Decreased oil pressure • Compressor trip	• Vibration monitoring • Operator rounds • Oil analysis
Shaft seal	Leakage from age-related wear	• Oil leakage • Reduced oil level • Abnormal refrigerant levels	• Operator rounds • External visual inspection
Gaskets	Leakage from thermal cycling age	• Refrigerant and oil leaks • Reduced availability	• External visual inspection • Refrigerant analysis
Coupling	Wear due to aging	• Compressor trip • Damaged shaft	• Vibration monitoring • Overhaul • Internal inspection • External visual inspection

Table 6-1 (continued)
Common Maintenance Issues and Surveillance Techniques

Chiller Component	Aging Mechanism	Aging Effect	Maintenance and Surveillance Techniques
Reciprocating Compressor (continued)			
Unloader valves	Spring failure from fatigue	• Reduced capacity • Compressor trip	• Overhaul
	Regulator failure due to run time	• Reduced capacity • Compressor trip	• Overhaul
	Seat wear from fatigue	• Reduced capacity • Compressor trip	• Overhaul
Relief valve	Spring failure due to fatigue	• Reduced cooling capacity	• Operator rounds • Internal inspection
	Set point drift from vibration	• Reduced cooling capacity	• Operator rounds • Internal inspection
Pulleys and belts	Wear due to normal aging	• Compressor trip	• Vibration monitoring • External visual inspection
Rotary Screw Compressor			
Lube oil pump failure	Low oil due to aging of pump	• Compressor trip or failure	• Overhaul • External visual inspection
Rotors	Wear/damage to screw elements due to vibration	• Reduced cooling capacity • Compressor trips	• Vibration analysis • Operator rounds • Overhaul
	Clogged water cooling ports from silt accumulation	• Reduced cooling capacity • Compressor trips	• Internal inspection • External visual inspection
Capacity slide control valve	Control failure due to vibration	• Reduced capacity • Compressor trip	• Operator rounds

Table 6-1 (continued)
Common Maintenance Issues and Surveillance Techniques

Chiller Component	Aging Mechanism	Aging Effect	Maintenance and Surveillance Techniques
Rotary Screw Compressor (continued)			
Bearings	Wear due to age and vibration	• Decreased oil pressure • Compressor trip	• Vibration monitoring • Operator rounds • Oil analysis
Shaft seal	Leakage from age-related wear	• Oil leakage • Reduced oil level • Abnormal refrigerant levels	• Operator rounds • External visual inspection
Gaskets	Leakage from cyclic thermal aging	• Refrigerant and oil leaks • Reduced availability	• External visual inspection • Refrigerant analysis
Coupling	Wear due to aging	• Compressor trip • Damaged shaft	• Vibration monitoring • Overhaul • Internal inspection • External visual inspection
Oil pump	Wear due to age and vibration	• Low oil pressure • Compressor trips	• Overhaul
Separator oil heater	Open circuit due to age	• Low oil pressure • Low oil temperature	• Operator rounds • External visual inspection

Table 6-1 (continued)
Common Maintenance Issues and Surveillance Techniques

Chiller Component	Aging Mechanism	Aging Effect	Maintenance and Surveillance Techniques
Chiller Instrumentation and Control			
Oil pressure and level instruments	Drift or failure due to age and vibration	• Improper operation • Spurious trips • Failures to start	• System performance tests • Calibration
Refrigerant pressure instruments	Drift or failure due to age and vibration	• Improper operation • Spurious trips • Failures to start	• System performance tests • Calibration
Pressure switches	Leakage from worn parts	• Improper operation • Spurious trips • Failures to start	• System performance tests • Calibration
	Burnt contacts from pitting	• Improper operation • Spurious trips • Failures to start	• System performance tests • Calibration
	Failed sensors due to vibration or cyclic failure	• Improper operation • Spurious trips • Failures to start	• System performance tests • Calibration
	Loose connections from vibration	• Improper operation • Spurious trips • Failures to start	• System performance tests • Calibration
Relays	Pitted or loose contacts from vibration and/or run time	• Improper operation • Spurious trips • Failures to start	• System performance tests • Inspection

Table 6-1 (continued)
Common Maintenance Issues and Surveillance Techniques

Chiller Component	Aging Mechanism	Aging Effect	Maintenance and Surveillance Techniques
Chiller Instrumentation and Control (continued)			
Electronic devices	Drift due to vibration	• Spurious trips • Failures to start • Reduced capacity	• Calibration • Inspection
	Open/short circuit from temperature or dirt	• Spurious trips • Failures to start	• Calibration • Inspection
Solenoid valves	Coil failure from high-temperature environment	• Reduced capacity • Improper operation	• Inspection
	Elastomer and gasket failure from thermal aging	• System leaks • Reduced availability	• Inspection
Other Chiller Components			
Condenser	Water-side fouling	• Reduced heat transfer capability • Differential pressure increase	• Operator rounds • System performance tests • Internal inspection • External visual inspection
	Tubesheet and head erosion	• Reduced heat transfer capability • Loss of refrigerant	• Internal inspection
	Glycol fouling	• Chiller trips • Elevated refrigerant pressure	• Glycol analysis

Table 6-1 (continued)
Common Maintenance Issues and Surveillance Techniques

Chiller Component	Aging Mechanism	Aging Effect	Maintenance and Surveillance Techniques
Other Chiller Components (continued)			
Evaporator	Water-side fouling	• Reduced heat transfer capability	• Operator rounds • System performance tests • Internal inspection • External visual inspection
Refrigerant metering device	Plugged due to corrosion and wear	• High head pressure • Low suction pressure • Reduced cooling capacity	• System performance tests • Internal inspection
	Failed float valve	• High head pressure • Low suction pressure • Reduced cooling capacity	• System performance tests • Internal inspection
Pressure relief valve	Spring failure due to fatigue	• Reduced cooling capacity	• Operator rounds • Internal inspection
	Set point drift due to vibration	• Reduced cooling capacity	• Operator rounds • Internal inspection
Purge unit	Excessive purge from leaking SOVs	• High head pressure • Reduced capacity • Loss of refrigerant charge	• Operator rounds • Internal inspection • Refrigerant analysis
	Ineffective purge from fouled condenser	• High head pressure • Reduced capacity	• Operator rounds • Internal inspection • Refrigerant analysis

Table 6-1 (continued)
Common Maintenance Issues and Surveillance Techniques

Chiller Component	Aging Mechanism	Aging Effect	Maintenance and Surveillance Techniques
Other Chiller Components (continued)			
Refrigerant operated control valve	Leaking due to age and vibration	• Head pressure out of range	• Operator rounds • External visual inspection
	Water-side leak due to failed gasket	• Reduced capacity	• Operator rounds • External visual inspection
	Failed spring due to fatigue	• Head pressure out of range	• Operator rounds • External visual inspection
Thermostatic expansion valve	Plugged due to corrosion and wear	• High head pressure • Low suction pressure • Reduced cooling capacity	• System performance tests • Internal inspection
	Failed spring due to fatigue	• Head pressure out of range	• Operator rounds • External visual inspection
Tubing and fittings	Leaking due to age and vibration	• Reduced capacity and pressure	• Operator rounds • External visual inspection
Filters/strainers	Plugged due to corrosion and wear	• High head pressure • Low suction pressure • Reduced cooling capacity	• Operator rounds • External visual inspection
Flanges	Leaking due to age and vibration	• Reduced capacity and pressure	• Operator rounds • External visual inspection

6.2 Other Sources of Generic Failure Data

Failure data for components used in chillers are presented in Table 3-1 in *Chiller Performance Monitoring and Troubleshooting Guide* (EPRI report 1007361) [8] and are reproduced in Table 6-2. The data indicate the specific chiller components, degradation mechanisms, failure timing, and the PM program required to prevent such an event.

Table 6-2
Degradation Mechanisms

Failure Location	Degradation Mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery/ Prevention Opportunity	PM Strategy
Compressor – Centrifugal						
Lubrication failure	Low oil level	Personnel error Leakage	Random	Random	Inspection	Operator rounds External visual inspection Lubrication program
	Incorrect oil	Personnel error	Random	Random	Oil sampling	Oil analysis
	Oil degradation	Age	Continuous	Expect to be failure-free for up to 5 years	Oil sampling	Oil analysis
	High or low oil pressure	Aging of pump	Continuous	Failure-free for many years	Inspection	External visual inspection Operator rounds
		Clogged/ crushed lines	Random	Random	Inspection (low oil use) DP across the filter	External visual inspection Operator rounds
		Weak relief spring	Continuous	Failure-free for many years	Inspection (oil pressure)	External visual inspection Operator rounds
Oil return system: • Eductor • Sump level switch • SOV	Plugged	Foreign material	Random	Random (consequent upon burn out or tube rupture)	Low oil level Capacity reduction High head pressure	Operator rounds Refrigerant analysis External visual inspection
	Failed	Age	Continuous	Expect to be failure-free for ~5 years	Low oil level Capacity reduction High head pressure	Operator rounds Refrigerant analysis External visual inspection

Table 6-2 (continued)
Degradation Mechanisms

Failure Location	Degradation Mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery/ Prevention Opportunity	PM Strategy
Oil return system: • Eductor • Sump level switch • SOV (continued)	Stuck	Contamination	Random	Random, on a scale of at least 3 years	Low oil level Capacity reduction High head pressure	Operator rounds Refrigerant analysis External visual inspection
	Coil failure	High temperature (normally energized are most susceptible)	Continuous	Many years of trouble-free operation	Low oil level Capacity reduction High head pressure	Operator rounds Refrigerant analysis External visual inspection
	Elastomer and gasket failure	Aging (cycles) Heat	Continuous	Many years of trouble-free operation	Low oil level Capacity reduction High head pressure	Operator rounds Refrigerant analysis External visual inspection
System failure	Inadequate system differential pressure	Low load	Continuous or seasonal (depends on application)	Random	Low oil level Capacity reduction Low head pressure	Operator rounds Refrigerant analysis External visual inspection
Impeller	Wear Erosion Cracks	Age Two-phase process fluid	Continuous Random	Expect to be failure-free for ~ 20 years Random, but can be rapid	Low head pressure Capacity reduction	Internal inspection External visual inspection Refrigerant analysis

Table 6-2 (continued)
Degradation Mechanisms

Failure Location	Degradation Mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery/ Prevention Opportunity	PM Strategy
Capacity control (prerotation vanes)	Binding	Control failure Bound broken linkage Vibration Age	Random Continuous	Random Expect to be failure-free for 5–10 years	Low head pressure Capacity reduction	Internal inspection
Bearings	Wear	Vibration Age Two-phase process fluid (shock loading) Lubrication Failure	Continuous Random	Random on a scale of 20 years	Vibration Audible noise Decreased oil pressure Oil sampling	External visual inspection Internal inspection
Gearbox	Wear	Misalignment Lubrication failure Age Two-phase process fluid (shock loading)	Random Continuous Random	Random on a scale of 20 years	Vibration Audible noise Oil sampling	Vibration Operator rounds Oil analysis
Shaft seal	Leakage: • Wear • Cracking	Age Heat Misalignment	Continuous Random	Random, on a scale of ~5 years	Inspection Refrigerant level	Operator rounds External visual inspection

Table 6-2 (continued)
Degradation Mechanisms

Failure Location	Degradation Mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery/ Prevention Opportunity	PM Strategy
Gaskets	Leakage	Improper torquing Assembly error Aging (thermal cycling)	Random Continuous	Random, can be immediate Expect to be failure-free for more than 5 years	Inspection Refrigerant leak	Internal inspection External visual inspection Refrigerant analysis
Fasteners/ hardware	Loose/ missing	Vibration Improper torquing	Random	Random	Inspection	External visual inspection Internal inspection
Coupling	Wear	Misalignment Lubrication Aging	Random Continuous	Random, from weeks to months Expect to be failure-free for more than 5 years	Vibration Inspection	Vibration analysis Overhaul Internal inspection or External visual inspection depending on type
Compressor – Reciprocating						
Lubrication failure	Low oil level	Personnel error Leakage	Random	Random	Inspection Oil level	Operator rounds External visual inspection
	Incorrect oil	Personnel error	Random	Random	Oil sampling	Oil analysis
	Low oil flow	Aging of pump Clogged/ crushed lines Clogged suction screens	Continuous Random	Expect to be failure-free for many years Random	Inspection	Overhaul External visual inspection

Table 6-2 (continued)
Degradation Mechanisms

Failure Location	Degradation Mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery/ Prevention Opportunity	PM Strategy
Cylinders	Wear of inlet and outlet valves and check valves	Run time Fatigue	Continuous	Expect to be trouble free for 1 year run time	Inspection on a sampling basis ~6 months	Internal inspection
		Inlet air quality Contamination Lack of lubrication Incorrect materials/ assembly	Random	Random, but more than 1 year	Inspection on a sampling basis ~6 months	Internal inspection
	Wear of piston rings/liner	Run time Lack of lubrication, where appropriate Incorrect material/ specification Contamination	Continuous Random	Expect to be trouble-free for more than 1 year for lubricated and less than 1 year for non-lubricated Random – essentially immediate	Inspection	Internal inspection

Table 6-2 (continued)
Degradation Mechanisms

Failure Location	Degradation Mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery/ Prevention Opportunity	PM Strategy
Cylinders (continued)	Cracked cylinder body or head	Poor cooling Wrong fasteners Manufacturing defects Improper head torquing	Random	Random	Inspection for cracks and leaks	External visual inspection Operator rounds (increase in drain trap blow down)
	Gasket failure	Improper torquing Assembly error	Random	Random	Inspection	Internal inspection Refrigerant analysis Overhaul
Bearings	Wear	Misalignment of coupling or pulley Lubrication failure Run time Manufacturing defect	Random Random Continuous Random	Random Expect to be failure-free for 5–10 years Random	Oil analysis Audible Noise Inspection	Internal inspection Oil analysis Operator rounds Overhaul
Shaft seal	Wear Cracking	Run time Heat/friction	Continuous	Expect to be failure-free for 5–10 years	Inspection	Operator rounds External visual inspection Overhaul

Table 6-2 (continued)
Degradation Mechanisms

Failure Location	Degradation Mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery/ Prevention Opportunity	PM Strategy
Shaft	Scoring	Lubrication failure	Random	Random	Oil analysis Inspection	Oil analysis Overhaul
	Journal wear	Run time Lubrication failure	Continuous Random	Expect to be failure-free for more than 20 years Random	Oil analysis Inspection	Oil analysis Overhaul
	Cracking	Alignment Bearing failure	Random	Random usually after overhaul	Inspection	Overhaul
Gaskets	Leakage	Improper torquing Assembly error Aging (thermal cycling)	Random Continuous	Random, can be immediate Expect to be failure-free for more than 1 year	Refrigerant leak Inspection Reduced capacity	Internal inspection Overhaul Refrigerant analysis
Fasteners/ hardware	Loose/ missing	Vibration Improper torquing	Random	Random	Inspection (no loss of capacity)	External visual inspection Internal inspection

Table 6-2 (continued)
Degradation Mechanisms

Failure Location	Degradation Mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery/ Prevention Opportunity	PM Strategy
Unloader valve	Spring valve	Fatigue	Continuous	Failure-free up to 5 years	Inspection Reduced capacity	Overhaul
	Diaphragm failure of the regulator	Wear (run time)	Continuous	Expect to be failure-fee for more than 1 year	Inspection Reduced capacity	Overhaul
	Seat wear or cracking	Fatigue Contamination	Continuous	Expect to be failure-free for more than 5 years	Inspection Reduced Capacity	Overhaul
	Inadequate disc or ring clearance	Personnel error	Random	Random, could be immediate	Inspection Reduced capacity	Overhaul
Relief valve	Spring failure	Fatigue	Continuous	Expect to be failure-free for more than 5 years	Reduced Capacity Inspection	Internal inspection Operator rounds
	Seat wear	Debris Installation error	Random	Random, but rare	Reduced capacity Inspection	Internal inspection Operator rounds
	Fails to reseat	Debris Installation error	Random	Random	Reduced capacity Inspection	Internal inspection Operator rounds
	Set point drift	Vibration	Continuous	Random	Reduced capacity Inspection	Internal inspection Operator rounds

Table 6-2 (continued)
Degradation Mechanisms

Failure Location	Degradation Mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery/ Prevention Opportunity	PM Strategy
Pulleys and belts	Wear of sheaves and belts	Misalignment Improper belt tension Contamination Aging (normal wear)	Random Continuous	Random, could be rapid Expect to be failure-free for 7–10 years (belts), 15–20 years for sheaves	Vibration Inspection	Vibration analysis External visual inspection
Coupling	Wear	Misalignment Lubrication Aging	Random Continuous	Random, from weeks to months Expect to be failure-free for more than 5 years	Vibration Inspection	Vibration analysis Overhaul Internal inspection or External visual inspection depending on type
Frame and mounting	Cracked	Vibration Soft Foot	Continuous	Random, on a scale of a few years	Vibration Inspection	Vibration analysis External visual inspection
	Loose mounting bolts	Vibration	Continuous	Random, on a scale of 1 year	Vibration Inspection	Vibration analysis External visual inspection

Table 6-2 (continued)
Degradation Mechanisms

Failure Location	Degradation Mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery/ Prevention Opportunity	PM Strategy
Compressor – Rotary Screw						
Lubrication	Low oil level (in separator)	Personnel error Leakage	Random	Random	Inspection	Operator rounds External visual inspection Lubrication program
	Incorrect oil	Personnel error	Random	Random	Oil sampling	Oil analysis
	Low/high oil pressure	Aging of pump	Continuous	Failure-free for many years	Inspection Compressor trip on low oil level	External visual inspection
		Clogged/ crushed lines	Random	Random	Inspection (low oil use) DP across the filter	External visual inspection Operator rounds
		Weak relief spring	Continuous	Failure-free for many years	Inspection trend oil pressure	Operator rounds
		Clogged suction screens	Random	Random	Inspection, low oil use	Operator rounds External visual inspection Overhaul

Table 6-2 (continued)
Degradation Mechanisms

Failure Location	Degradation Mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery/ Prevention Opportunity	PM Strategy
Rotors	Wear or damage to screw elements	Moisture in inlet air Vibration	Continuous or random	Random, on the scale of many years; shorter if subject to rotor float	Vibration Audible noise	Overhaul Operator rounds Vibration analysis
	Clogged water cooling ports	Water chemistry Silt accumulation Low cooling water flow	Continuous or random	Expect to be failure-free for 1–3 years	Inspection Water flow and temperature trending	Internal inspection External visual inspection
	Gasket failure	Improper torquing Assembly error	Random	Random	Inspection	Internal inspection Overhaul
Capacity slide	Control failure	Vibration	Continuous	Expect to be trouble free for at least 1 year	Trend inlet temperature as % of load and as % of motor current	Operator rounds
Bearings	Wear	Misalignment of coupling Lubrication failure Run time Manufacturing defect	Random Random Continuous Random	Random Random Nominal bearing life Random	Oil analysis Audible noise Shock pulse measurement Inspection Vibration	Internal inspection Oil analysis Operator rounds Overhaul Vibration analysis

Table 6-2 (continued)
Degradation Mechanisms

Failure Location	Degradation Mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery/ Prevention Opportunity	PM Strategy
Shaft seal	Wear Cracked	Run time Heat/friction	Continuous	Expect to be failure-free for 2 years	Inspection (rate of filling of oil collection bottle)	Operator rounds External visual inspection
Gaskets	Leaks	Improper torquing Assembly error Aging (thermal cycling)	Random Continuous	Random, can be immediate Expect to be failure-free for more than 5 years	Refrigerant leak Inspection	Internal inspection Overhaul Refrigerant analysis External visual inspection
Fasteners/ hardware	Loose/ missing	Vibration Improper torquing	Random	Random	Inspection	External visual inspection Internal inspection
Coupling	Wear	Misalignment Lubrication Aging	Random Continuous	Random, from weeks to months Expect to be failure-free for more than 5 years	Vibration Inspection	Vibration analysis Overhaul Internal inspection or External visual inspection depending on type
Oil pump (where applicable)	Wear	Age Vibration Low oil level	Continuous	Expect to be failure-free for ~10 years, depending on vibration level Random	Compressor trip Fails to build oil pressure	Overhaul

Table 6-2 (continued)
Degradation Mechanisms

Failure Location	Degradation Mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery/ Prevention Opportunity	PM Strategy
Separator oil heater	Open circuit	Age Control failure	Continuous Random	Expect to be failure-free for ~6 years Random	Low oil temperature Low oil pressure	Operator rounds External visual inspection
Chiller Equipment						
Condenser	Water-side fouling	Water quality Debris Biofouling	Continuous Random	Random	Chemistry control DT reduction DP increase Temperature control valve position Elevated refrigerant temperature Inspection	Operator rounds System performance test Internal inspection External visual inspection
	Tubesheet and head corrosion	Water quality Flow velocity	Continuous	Expect to be failure-free for 15 years	Loss of refrigerant Inspection	Internal inspection

Table 6-2 (continued)
Degradation Mechanisms

Failure Location	Degradation Mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery/ Prevention Opportunity	PM Strategy
Condenser (continued)	Improper water-side flow rate	Control valve mis-set Degraded control valve Plugged suction strainer	Random	Random	DT reduction DP increase Temperature control valve position Inspection Elevated refrigerant temperature	Operator rounds System performance test Internal inspection External visual inspection
	Glycol fouling	Fluid leak	Random	Random, on a scale of 1–2 years	Elevated refrigerant pressure Chiller trips	Glycol analysis
Evaporator	Water-side Fouling	Poor water chemistry	Random	Random	Water chemistry	No task; water chemistry PM tasks are not specific to chillers
	Water-side freezing	Control failure	Random	Random, but very rapid	Chiller trips	Calibration
Refrigerant metering device	Plugged	Dryer mechanism failure Corrosion Wear products Foreign material from maintenance actions	Random Continuous Random	Random	High head pressure Low suction pressure Reduced cooling capacity	Internal inspection Refrigerant analysis Compressor oil analysis System performance test

Table 6-2 (continued)
Degradation Mechanisms

Failure Location	Degradation Mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery/ Prevention Opportunity	PM Strategy
Refrigerant metering device (continued)	Failed float valve	Float ball failure Missing lever pins Stuck	Continuous Random	Expect failure-free for 5 to 10 years Random	High head pressure Low suction pressure Reduced cooling capacity Inspection	Internal inspection System performance test
Pressure relief valve	Spring valve	Fatigue	Continuous	Failure-free up to 5 years	Reduced capacity Inspection	Internal inspection Operator rounds
	Seat wear	Debris Installation error	Random	Random, but rare	Reduced capacity Inspection	Internal inspection Operator rounds
	Fails to reseat	Debris Installation error	Random	Random	Reduced capacity Inspection	Internal inspection Operator rounds
	Setpoint drift	Vibration	Continuous	Random	Reduced capacity Inspection	Internal inspection Operator rounds

Table 6-2 (continued)
Degradation Mechanisms

Failure Location	Degradation Mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery/ Prevention Opportunity	PM Strategy
Pressure relief device	Rupture disk misoperation	Improper Installation Personnel error Design of discharge piping causing vibration to break disk	Random	Random over a very long time scale	Chiller trip Loss of refrigerant Inspection	No task
Purge unit	Excessive purge Ineffective purge, allows noncondens-ibles to remain in the condenser	Control malfunction Leaking SOVs: • Seals • Coils Fouled heater Fouled condenser Failed refrigerant system, loss of charge Environment	Random Continuous Random Continuous	Random Expect less than 2 years of failure-free operation; very environment dependent Random	High chiller condenser head pressure Reduced capacity Refrigerant analysis Loss of refrigerant charge Inspection Operational checks	Internal inspection Operator rounds External visual inspection Refrigerant analysis System functional test

Table 6-2 (continued)
Degradation Mechanisms

Failure Location	Degradation Mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery/ Prevention Opportunity	PM Strategy
Refrigerant operated control valve	Stuck	Water quality	Continuous	Expect to be failure-free for 5–10 years	Head pressure out of range Inspection	Operator rounds External visual inspection
	Leak: • Bellows • Capillary	Vibration Age/cycling	Continuous	Expect to be failure-free for 10 years	Head pressure out of range Inspection	Operator rounds External visual inspection
	Water-side leak	Failed gasket	Random	Random	Inspection	Operator rounds
	Failed spring	Fatigue Foreign object	Continuous Random	Expect to be failure-free for 10 years Random	Head pressure out of range Inspection	Operator rounds External visual inspection Internal inspection
Chiller Instrumentation and Control						
Capacity Oil pressure Oil level Refrigerant High and low pressure Freeze protection	Drift	Age Heat Vibration	Continuous	Random, on a scale of 1 year	Improper operation Calibration Capacity testing	System performance test Calibration
	Misalignment	Personnel error	Random	Random	Improper operation Calibration Capacity testing	System performance test Calibration

Table 6-2 (continued)
Degradation Mechanisms

Failure Location	Degradation Mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery/ Prevention Opportunity	PM Strategy
Capacity Oil pressure Oil level Refrigerant High and low pressure Freeze protection (continued)	Component failure	Age Heat Vibration	Continuous Random	Random	Improper operation Calibration Capacity testing	System performance test Calibration
	Plastic tubing failure	Age (refrigerant attack) Vibration	Continuous	Expect to be failure-free for 3 years	Inspection Improper operation	Internal inspection
	Transducer failure or drift	Age Heat Vibration	Continuous	Random, on a scale of 1 year	Improper operation Calibration Capacity testing	System performance test Calibration
	Elastomers	Age Heat	Continuous	Expect to be failure-free for 5–10 years; affected by service conditions	Improper operation Calibration Capacity testing	System performance test Calibration
	General tubing failure	Vibration	Continuous		Inspection Improper operation	Internal inspection

Table 6-2 (continued)
Degradation Mechanisms

Failure Location	Degradation Mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery/ Prevention Opportunity	PM Strategy
Chiller and Compressor Instrumentation and Control						
Pressure switches	Leak-by	Worn orifice parts	Continuous	Expect to be failure-free for several years	Inspection Calibration check	Calibration
	Stuck Plugged orifices	Contamination Environmental conditions Moisture from gasket failure (sticking only)	Random	Random, on a scale of several years	Inspection Calibration check	Calibration
	Burnt contacts	Contact alignment Failure of arc suppression Pitting/ contamination	Random	Random, on a scale of several years	Inspection Calibration check	Calibration

Table 6-2 (continued)
Degradation Mechanisms

Failure Location	Degradation Mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery/ Prevention Opportunity	PM Strategy
Pressure switches (continued)	Failed sensors: • Diaphragms • Capsules • Bourdon tubes	Run time/cycling from: • Vibration • Contamination Vibration Vibration Clogging from contaminated air	Continuous Random Continuous Continuous Random	Random, on a scale of several years	Inspection Calibration check	Calibration
	Loose connections	Vibration Personnel error	Continuous Random	Random	Inspection Calibration check	Calibration
	Miscalibration	Personnel error	Random	Random	Inspection Calibration check	Calibration
Relays	Pitted or worn contacts Stuck or loose contacts	Run time Contamination Vibration	Continuous Random Continuous	Continuous, expect to be failure-free for several years Random, on a scale of several years	Inspection Calibration check	Calibration

**Table 6-2 (continued)
Degradation Mechanisms**

Failure Location	Degradation Mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery/ Prevention Opportunity	PM Strategy
Electronic/ electrical devices: • Transmitters • Temperature control valves • Programmable logic controllers • Level/flow switches • RTDs • I/P transducers	Drift Open circuit Short circuit Loose connections Miscalibration	Contamination Vibration Personnel error Environment: • Dirt • Temperature Installation method and location	Random	Random, on a scale of years	Inspection where accessible Calibration check	Calibration
Solenoid valves	Stuck	Contamination	Random	Random, on a scale of at least 3 years	Inspection Calibration check	Calibration
	Coil failure	High temperature (normally energized are most susceptible)	Continuous	Many years of trouble-free operation	Inspection Calibration check	Calibration
	Elastomer and gasket failure	Aging (cycles) Heat	Continuous	Many years of trouble-free operation	Inspection Calibration check	Calibration

Table 6-2 (continued)
Degradation Mechanisms

Failure Location	Degradation Mechanism	Degradation Influence	Degradation Progression	Failure Timing	Discovery/ Prevention Opportunity	PM Strategy
Pneumatic devices	Leak-by	Gasket failure Worn parts				
	Stuck Plugged orifices	Contamination Environmental conditions Moisture from gasket failure (sticking only)	Random	Random, on a scale of several years	Inspection Calibration check	Calibration
	Failed sensors: • Diaphragms • Capsules • Bourdon tubes	Run time/cycling from: • Vibration • Contamination Vibration Vibration Clogging from contaminated air	Continuous Random Continuous Continuous Random	Random, on a scale of several years	Inspection Calibration check	Calibration
	Loose tubing and fittings	Vibration Personnel error	Continuous Random	Random	Inspection Calibration check	External visual inspection Calibration
	Miscalibration	Personnel error	Random	Random	Inspection Calibration check	Calibration

6.3 Expected Lifetimes of Major Components

In addition to long-term aging of passive components, active components of chillers are susceptible to wear or degradation. This degradation must be addressed by routine PM, including overhaul and component replacement. The typical failure timing for active chiller components is presented in Table 6-2 along with information on degradation influence and cause. It should also be noted that the PM or CM entailed in replacing worn-out components can be addressed through the maintenance programs identified in Section 5.4, considering the failure rates discussed in Section 4.1.5.

6.4 Repair

If a device is no longer supported by the manufacturer, one of the options available is to repair the device. The failed parts within the device may be replaced with parts manufactured to other rigorous industry standards, such as MIL standards. For example, if a capacitor on a circuit board fails, it may be replaced with a capacitor of the same specifications manufactured to the MIL specification.

A particular obsolescence issue mentioned earlier in this sourcebook is the issue with refrigerants R-11 and R-12 no longer being manufactured in the U.S. However, only the manufacturing of these refrigerants has been halted, not the use of existing material. Alternative refrigerants have already been tested and are readily available if conversion is chosen as a solution to this issue. Because continued use is allowed, this provides ample time to assess the economics of continued use, conversion, or equipment replacement. All of these factors must be weighed with the expected life of the existing chiller equipment and the life expectancy of the plant.

6.5 Technical Obsolescence

Guidance is provided using the evaluation method provided in Table 2-2 of the *Life Cycle Management Planning Sourcebooks – Overview Report* [1].

Many systems in a nuclear power plant, in particular, those with electronic instrumentation, are susceptible to technical obsolescence. Components might have to be replaced because of the unavailability of spare parts. In these cases, the likelihood and timing of the need to perform a replacement of the system or components is determined by the failure or degradation rate of the part and the availability of spares from other sources. The feasibility and cost of reverse engineering the obsolete components should also be considered.

To ascertain whether a given system is susceptible to technical obsolescence, the evaluation method provided in the *Life Cycle Management Planning Sourcebooks – Overview Report* [1] and shown as Table 6-3 can be applied as a first step. Using the criteria from this table emphasizes the seriousness of technical obsolescence for the following reasons:

- The application of chillers to cool water systems and area spaces is not unique to the nuclear industry, and therefore, chillers are expected to be available today and in the future.
- Multiple vendors produce a myriad of chiller sizes. These manufacturers, such as York and Carrier, have been producing chillers for decades.
- The failure rate of chillers appears sufficiently low to be able to plan the purchase and installation of new units without jeopardizing plant output.
- Some chillers cannot be unavailable for the amount of time it takes to perform the replacement. Therefore, a replacement requires an outage and detailed planning and scheduling.
- Some older chillers contain control components consisting of electronic circuit boards that have become obsolete. This aspect of obsolescence should be addressed in developing LCM alternatives.

Table 6-3 identifies an example of the application of obsolescence evaluation criteria for a large chiller unit.

Table 6-3
Application of Obsolescence Evaluation Criteria for a Chiller

	Technical Obsolescence Evaluation Criteria	Score	Yes
1.	Is the SSC still being manufactured, and will it be available for at least the next five years?	5.0	5.0
2.	Is there more than one supplier for the SSC for the foreseeable future?	3.0	3.0
3.	Can the plant or outside suppliers manufacture the SSC in a reasonable time (within a refueling outage)?	3.0	3.0
4.	Are there other sources or contingencies (from other plants, shared inventory, stockpiled parts, refurbishments, secondary suppliers, imitation parts, commercial dedications, and so on) available in case of an emergency?	3.0	
5.	Is the SSC frequency of failure/year times the number of the SSCs in the plant times the remaining operating life (in years) equal to or lower than the number of stocked SSCs in the warehouse?	3.0	
6.	Can the spare part inventory be maintained for at least the next five years?	3.0	
7.	Is the SSC immune to significant aging degradation?	1.0	1.0

Table 6-3 (continued)
Application of Obsolescence Evaluation Criteria for a Chiller

	Technical Obsolescence Evaluation Criteria	Score	Yes
8.	Can new designs, technology, or concepts be readily integrated with the existing configuration (hardware-software, digital-analog, solid-state, miniaturized electronics, smart components, and so on)?	3.0	3.0
9.	Is technical upgrading desirable, commensurate with safety, and cost effective?	3.0	
	Total Obsolescence Score:		15.0

Ranking Guidance for Table 6-3:

- If the total score is less than 6, the SSC obsolescence is serious. Potential options to deal with obsolescence and contingency planning should be identified. Guidance on the modeling, timing, and costs of these contingencies and the associated risks should be provided.
- If the total score is 6–10, the SSC might have added long-term concerns for obsolescence. Contingency planning and options should be considered.
- If the total score is greater than 10, the SSC is not likely to be affected by obsolescence.

7 GENERIC ALTERNATIVE LCM PLANS

This section addresses steps 12–17 in the LCM planning flowchart (see Figure 2-1b) to provide guidance for developing alternative plans. *Demonstration of Life Cycle Management Planning for Systems, Structures, and Components: With Pilot Applications at Oconee and Prairie Island Nuclear Stations* [2] summarizes alternative LCM plans as follows:

> Following the assessment of aging and reliability, potential alternative LCM plans should be identified. The objective here should be to explore whether there are potentially better ways of addressing the aging management of the SSC. These inputs can come from plant staff but input should also be solicited from outside experts and industry benchmarking projects.

The following guidance for these steps includes the identification of possible plant operating life strategies and the development of alternative LCM plans that are compatible with or integral to the strategies identified. A hypothetical illustration of alternative LCM plans for chillers with the attendant discussions of the logic for building the alternatives and the derivation of assumptions is also provided.

7.1 Plant Operating Strategies and Types of LCM Planning Alternatives

The determination of LCM planning alternatives will be driven mainly by the plant operating strategies that, implicitly or explicitly, are being followed or evaluated and the current reliability performance of chillers and the associated component parts. Accordingly, the LCM planning alternatives that are evaluated are very plant-specific. The typical plant operating strategies and standard approaches to LCM planning alternatives are discussed below.

7.1.1 Plant Strategy 1: Operate the Plant for the Currently Licensed Period of 40 Years

This strategy requires minimizing risk during the remaining operating period until the plant's license expires and identifying the limiting SSCs that could result in premature power reduction or replacements forcing an economic decision regarding early decommissioning. LCM plan alternatives that might be developed under this strategy include:

- **LCM Plan Alternative 1A**. This is a base case to determine the cost of the activities performed under the current maintenance plan, assuming that the activities will continue as-is until the end of the licensed plant life. This case also assumes the continuation of the existing maintenance program without any major capital investments unless absolutely necessary.

- **LCM Plan Alternative 1B**. This is an alternative plan in which the current maintenance plan is optimized and an aggressive PM program is implemented to reduce equipment failures, lost power production, and regulatory risk.
- **LCM Plan Alternative 1C**. This is an alternative plan in which the current maintenance plan is optimized and older chillers are refurbished or replaced with more reliable equipment. Variations to this alternative include schemes such as:
  – Replace the chiller skids with state-of-the-art equipment.
  – Replace the individual components based on their maintenance history.
  – Add redundant chiller trains to enhance their reliability.
  – Refurbish major components such as compressors, condensers, and evaporators.

7.1.2 Plant Strategy 2: Operate the Plant for 60 Years Under a License Renewal Program

This strategy recognizes the potential for license renewal and extended operation of the plant. Major investments are required to achieve an extended operation. These investments can be justified only by additional revenue generated in the additional 20-year operating term. LCM planning alternatives that might be considered under this strategy include:

- **LCM Plan Alternative 2A**. This plan is a rigorous preparation for license renewal with an aggressive aging management program, system performance enhancements, and timely component replacements or upgrades. This LCM plan recommends a timely replacement of like-for-like components, such as compressors, motors, evaporators, condensers, flow control components, and level and temperature indicators.
- **LCM Plan Alternative 2B**. This plan prepares for an eventual license renewal with aggressive PM and PdM programs but delays the plans for major capital improvements until the actual extended license is implemented (that is, in year 35 of the plant life).

7.2 Development of Detailed Alternative LCM Plans

For each alternative LCM plan proposed, detailed maintenance activities and schedules need to be identified and developed. Each plan involves some mix of the LCM approaches in steps 13 to 17 in Figure 2-1b. This section provides guidance on developing alternative LCM plans. The following may be considered when developing the alternative LCM plans:

- Adjust the frequency of time-directed maintenance activities to enhance the reliability of major chiller components or reduce maintenance costs.
- Consider the diagnostics (PdM) to convert from time-directed to condition-directed maintenance.
- Perform preventive and non-invasive maintenance activities on-line, if feasible.

- Add routine PM and PdM activities that might enhance the reliability of chillers. A number of these activities are listed in Section 4.1.7.
- Tasks that are specifically devoted to chiller aging. While many of the routine maintenance tasks performed on or proposed for chillers might broadly be regarded as being intended to address aging, a number of tasks are identified in Table 6-1 that specifically address the aging of passive components. The addition or deletion of these tasks should be considered in alternative LCM plans.
- Tasks that address, facilitate, or enable operating changes to minimize or equalize component wear. By staging redundant component run times, efficiency can be optimized. The installation of run-time meters and start counters can help ensure that compressors run equally, thus avoiding excessive wear on any one component. Start counters also facilitate the scheduling of time-directed maintenance for active standby equipment.

7.3 Hypothetical Illustration of Assembling LCM Planning Alternatives

This section illustrates the process of creating LCM planning alternatives. A hypothetical case is discussed with assumptions identified.

During the life of a chiller, all of the components undergo wear and aging due to operating conditions. If the unit is operated and maintained within the manufacturer's recommendations, the chiller should operate for the entire design life. However, many of the components, such as the compressors, condensers, evaporators, pumps, and expansion devices, can be replaced once the worn condition is detected. These are reversible life components that help to extend the life of the chiller when replaced in a timely manner.

All chiller equipment will experience degradation due to aging, and the older the chiller, the more special attention that is required. The replacement of most chillers is not easy because the amount of time allowed for inoperability is dictated by the plant's technical specifications. This means that it may be necessary to use valuable time and resources during a refueling outage to replace the chiller. Therefore, an in-service failure of a chiller causing plant downtime is not a hypothetical situation but a very real threat.

Based on this situation, alternatives should be considered to ensure continuous plant operation. When preparing alternative LCM plans, the following may be considered:

- Review the original design with an objective of "fit-for-service" status.
- Analyze the system disturbance and the impact on the chiller.
- Consider closer monitoring of the chiller loading and operation.

The following items may be considered as LCM planning progresses:

- A spare chiller may be a prudent investment for plants that have a short technical specification limiting condition of operation.
- Table 7-2 provides a sample cost analysis for the major components of the chiller and the process of creating LCM planning alternatives. The inspection, maintenance, and repair frequencies as well as the cost associated with these tasks are approximate numbers. The effort here is to provide a hypothetical illustration that can be followed as an example when actual costs are known to allow selection of the best alternative.
- Labor hours used in the hypothetical illustration are different for daily and monthly inspections. Monthly inspections involve more detailed tasks.
- Labor charges may be higher for outside contractors compared to in-house personnel. Outside contractors might not be as well informed as in-house personnel regarding plant-specific equipment.

Table 7-1
Hypothetical Example for a Hermetic Centrifugal Liquid Compressor

Item #	Activity Description	No. of Components	Labor Hours	Labor Cost ($)	Material Cost ($)	Frequency/ Year	Alternative A Existing Maintenance Program	Alternative B Partial Upgrade and Aggressive PM Program	Alternative C Refurbishment and Aggressive PM Program	Alternative D New Chiller and Aggressive PM Program
1.1	Inspection									
1.1.1	Daily	1	1	80		365	29,200	29,200	29,200	29,200
1.1.2	Monthly	1	2	80		12	1,920	1,920	1,920	1,920
1.2	Calibration (18 months)									
1.2.1	Protective relays	2	16	80		0.5	1,280			
1.2.2	Pressure relief	2	24	80		0.5	1,920			
1.2.3	Indicators (temperature and level)	6	48	80		0.5	11,520			
1.2.4	Switches (temperature and level)	4	32	80		0.5	5,120			
1.2.5	Protective relays	2	16	80		0.75		1,920	1,920	1,920
1.2.6	Pressure relief	2	24	80		0.75		2,880	2,880	2,880
1.2.7	Indicators (temperature and level)	6	48	80		0.75		17,280	17,280	17,280
1.2.8	Switches (temperature and level)	4	32	80		0.75		7,680	7,680	7,680
1.3	PdM									

Table 7-1 (continued)
Hypothetical Example for a Hermetic Centrifugal Liquid Compressor

Item #	Activity Description	No. of Components	Labor Hours	Labor Cost ($)	Material Cost ($)	Frequency/ Year	Alternative A Existing Maintenance Program	Alternative B Partial Upgrade and Aggressive PM Program	Alternative C Refurbishment and Aggressive PM Program	Alternative D New Chiller and Aggressive PM Program
1.3.1	Oil analysis	1	8	80	200	1	840			
1.3.2	Oil analysis	1	8	80	200	2		1680	1680	1680
1.3.3	Glycol analysis	1	8	80	100	1	740			
1.3.4	Glycol analysis	1	8	80	100	2		1480	1480	1480
1.3.5	Vibration analysis	1	8	80		1	1280			
1.3.6	Vibration analysis	1	8	80		4		2560	2560	2560
1.4	Maintenance									
1.4.1	Compressor	1	24	80	400	1	2320			
1.4.2	Compressor	1	24	80	400	2		4640	4640	4640
1.4.3	Condenser	1	18	80	300	1	1740			
1.4.4	Condenser	1	18	80	300	2		3480	3480	3480
1.4.5	Evaporator	1	16	80	500	1	1780			
1.4.6	Evaporator	1	16	80	500	2		3560	3560	3560
1.5	Repairs									
1.5.1	Compressor	1	72	80	2000	1	7760			
1.5.2	Compressor	1	72	80	2000	0.50		3880		
1.5.3	Compressor	1	72	80	2000	0.25			1940	1940
1.5.4	Condenser	1	54	80	1000	0.25	1330			
1.5.5	Condenser	1	54	80	1000	0.10		532		

Table 7-1 (continued)
Hypothetical Example for a Hermetic Centrifugal Liquid Compressor

Item #	Activity Description	No. of Components	Labor Hours	Labor Cost ($)	Material Cost ($)	Frequency/ Year	Alternative A Existing Maintenance Program	Alternative B Partial Upgrade and Aggressive PM Program	Alternative C Refurbishment and Aggressive PM Program	Alternative D New Chiller and Aggressive PM Program
1.5.6	Condenser	1	54	80	1000	0.05			266	266
1.5.7	Evaporator	1	48	80	1000	0.25	1210			
1.5.8	Evaporator	1	48	80	1000	0.10		484		
1.5.9	Evaporator	1	48	80	1000	0.05			242	242
1.6										
1.6.1	Compressor replacement	1	160	80	20,000	One time		32,800		
1.6.2	Condenser replacement	1	160	80	25,000	One time		37,800		
1.6.3	Evaporator replacement	1	160	80	25,000	One time		37,800		
1.7										
1.7.1	Upgrade some chiller components	1	120	80	7,000	One time		16,600		
1.7.2	Refurbish compressor	1	100	80	4,500	One time			12,500	
1.7.3	Refurbish condenser	1	100	80	3,500	One time			11,500	
1.7.4	Refurbish evaporator	1	100	80	3,500	One time			11,500	
1.7.5	Install new chiller	1	500	80	130,000	One time				170,000

Table 7-1 (continued)
Hypothetical Example for a Hermetic Centrifugal Liquid Compressor

Item #	Activity Description	No. of Components	Labor Hours	Labor Cost ($)	Material Cost ($)	Frequency/ Year	Alternative A Existing Maintenance Program	Alternative B Partial Upgrade and Aggressive PM Program	Alternative C Refurbishment and Aggressive PM Program	Alternative D New Chiller and Aggressive PM Program
1.8	Lost generation									
1.8.1	Lost power generation ($250,000 per day) (Note 1)					0.2	400,000			
1.8.2	Lost power generation ($250,000 per day)					0.1		200,000		
1.8.3	Lost power generation ($250,000 per day)					0.05			100,000	
1.8.4	Lost power generation ($250,000 per day)					0.03				60,000
	Total recurring cost						69,960	83,176	80,726	80,726
	Lost generation cost						400,000	200,000	100,000	60,000
	Total one time cost						0.0	125,000	35,500	170,000
	Total						469,960	408,176	216,226	310,726

Note:

1. A failure of both trains of the chillers requires a plant shutdown in approximately 12–24 hours. Assuming that the chillers can be restored to operability quickly, a loss of 2 days of generation is used in the calculation. Also, assuming that a day's worth of nuclear (single-unit) generation replacement is approximately $1,000,000/day and this type of incident occurs once every 5 years, the estimated lost power generation is $1,000,000/day x 2 days x 0.2 = $400,000.

8
GUIDANCE FOR ESTIMATING FUTURE FAILURE RATES

This section addresses a part of step 18 of Figure 2-1b. Failure rates are a main driver of the LCM planning process.

General guidance for estimating SSC future failure rates can be found in Section 2.6 of *Life Cycle Management Planning Sourcebooks – Overview Report* [1]. The following are some useful ideas for estimating the failure rates in the chillers' LCM planning studies:

- Table 6-2 provides the estimated failure timing. These data can be used to estimate the expected remaining life of chiller components. If in-kind replacements are made, the existing failure rates can be applied for the future.
- Plants that have a chiller performance trending program can extract the component failure data and compute failure rates for the major components. The data can be plotted to determine the effects of aging and whether the current PM programs are effective.
- Approximately 17% of EPIX-reported failures are due to human or maintenance errors. When evaluating and determining plant-specific failure rates, human and maintenance errors need to be included in the basis.
- Corrective WOs provide a means of reconstructing the chiller failures and computing the failure rates. The WO review should encompass, at a minimum, the last five years of data to generate meaningful results.
- Failure rate reductions can be achieved by replacing accessories such as compressors, pumps, motors, and valves that exhibit frequent breakdowns or failures. If the LCM plan considers such accessory replacements, future failure rate projections must consider the effect of replacement as discussed in *Life Cycle Management Planning Sourcebooks – Overview Report* [1].
- When chiller accessories, such as motors or pumps, are replaced with similar models from different vendors, the failure rates might be different. A reasonable projection is to use the existing failure rate until a new failure rate can be determined (based on failure rate trending) unless the vendor has reliable data to support a different rate.
- Chillers provide cooling to critical plant equipment. Chiller failures might not trigger an immediate trip or power reduction, but they might require an entry into an LCO. Various time limits are established from a few hours to 30 days based on the time estimated to repair the failed chiller or its accessories. A failure to repair or replace the failed equipment and return to an operational status within the time limit requires steps for a plant shutdown.

- Routine maintenance task tickets and corrective WOs provide failure cause information of chiller components and accessories. This information can be used to establish the base case. Probabilistic risk assessment (PRA) based failure rates can be used in projecting future failure rates for the chiller and its components and accessories.
- When the plant-specific PRA is used as a basis for the plant-specific system failure rates, a verification of the basis for the PRA input should be considered.
- If plant-specific chiller failure rates are not readily available from plant databases, the plant-specific PRA may be a source of reliability values for use in LCM planning. Establishing a comprehensive chiller and accessory performance trending program is an important step in LCM planning.
- The chiller failure rates from Table 4-5 can be used in the absence of a performance trending program. If no plant-specific failure data exist or are of questionable accuracy, it would be reasonable to assume an average industry failure rate (over the last 10 years) of about 0.087 per year as a starting point in the LCM analysis. The absence of chiller failures could be verified by reviewing the LER for the plant. An LER is generally required by the plant's technical specifications when redundant chillers are found to be inoperable.
- Table 6-2 provides the failure timing of the major components of chillers. This information can be used to project the possible remaining life of a component or to plan for chiller replacement.

In summary, the failure rate predictions for plant-specific chiller components are made using the above specific guidance and the generic guidance presented in Section 2.6 of *Life Cycle Management Planning Sourcebooks – Overview Report* [1]. PRA and Maintenance Rule records can be an important source of information. The LCM planning process should be fairly complete with carefully defined specific activities for each of the LCM alternative plans. Therefore, the influence of new or additional PM activities and the implementation of replacements and redesigns can be appropriately considered in estimating future failure rates for input to LCM economic evaluations.

9
PLANT-SPECIFIC GUIDANCE FOR ECONOMIC MODELING

This section addresses the cost prediction portion of step 19 in the LCM planning flowchart (see Figure 2-1b).

In this chiller LCM sourcebook, the generic cost data are presented below from the INPO data and should be corrected for individual plants, given the variations in the equipment types and sizes and plant-specific accounting practices.

Table 4-3 shows a total of 379 chiller failures in U.S. plants over a period of 10 years (1997–2006). With approximately 434 chiller trains operating, this calculates to approximately 0.85 failures per year per system train. This means that a plant with five chiller trains can expect approximately four failures a year on the average. It is then possible to obtain the maintenance repair costs for previous maintenance work and calculate the total projected costs of unplanned maintenance per unit.

This value can be of use when considering implementation or corrective actions capable of reducing the failure probability.

When developing alternatives, it is best to formulate plans that are relatively simple and do not include massive changes at one time. A step-wise approach provides simplicity and retains an overview of the plan. For instance, a first step from the base case would be the conversion to a more effective PM program for chillers, including oil, glycol, and vibration analyses and failure trending. The additional costs and savings can then be determined for the remaining life of the plant, and the impact on chiller failure reduction can be illustrated.

Although the initial cost for an aggressive PM program is high, the reduction in the failure rate of the chilled water components offsets the cost as the equipment and plant outages are reduced. Section 3.8 of *Life Cycle Management Planning Sourcebooks – Overview Report* [1] contains a generic discussion and a listing of typical financial data to be collected and specified as input to the economic evaluations of alternative LCM plans.

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