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Plant Support Engineering: Chiller Replacement Guideline for Nuclear Power Plants

2016 TECHNICAL REPORT

Plant Support Engineering: Chiller Replacement Guideline for Nuclear Power Plants

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ABSTRACT

This report provides information that is intended to support or supplement chiller upgrade or replacement projects. Chiller overhauls, refrigerant changes, potential digital control systems for chiller, and complete chiller assembly replacements are planned at many stations. There have been a number of highly successful chiller upgrade and replacement projects in the industry, but also several that have encountered multiple difficulties both during the project and after installation. Life cycle management and long range planning for major capital projects involving chillers face a complex combination of issues involving continuing changes in refrigerant regulations, an accelerating pace of obsolescence for hardware and controls, and regulatory uncertainties related to digital technology changes.

The report contains a collection of project experience based lessons learned related to chiller projects and provides up-to-date reference materials and guidance documents applicable to chiller upgrade or replacement projects. The report is not intended as a technical guide on chiller hardware or controls selection. The information provided on design, installation or operational issues is primarily based on lessons-learned experiences from previous chiller projects to address items that were missed or not adequately considered which subsequently contributed to project cost, schedule, and or reliability impacts.

The report addresses project aspects of a chiller replacement project for both safety related and non-safety applications at nuclear power plants, although there is added emphasis to safety related chillers due to the added complexity and issues involved.

Keywords
Design modification
Chiller
Refrigerant
Compressor
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EXECUTIVE SUMMARY

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PRIMARY AUDIENCE: Utility engineers and team members involved with chiller upgrade or replacement projects.

SECONDARY AUDIENCE: Utility system, design, and component engineers responsible for supporting chiller long range planning, upgrades, and replacement projects.

KEY RESEARCH QUESTION

Various documents developed by EPRI and other organizations discuss aspects of project management, component replacement, chiller maintenance and life cycle management, obsolescence, and digital control technology, but these references do not directly or cohesively address chiller upgrade or replacement project issues and considerations. The purpose of this report is to capture the latest industry and regulatory considerations and experience reports related to chiller replacements, with an emphasis on chiller digital control applications. This report is intended to provide supplemental information and direct the reader to relevant current references to improve the quality of chiller upgrade or replacement projects at nuclear power stations.

RESEARCH OVERVIEW

EPRI research and industry guidance related to chillers, refrigerants, commercial grade dedication, digital control technology, chiller maintenance, and project management was compiled. Experience and lessons learned related to chiller upgrade and replacement projects was collected from utilities, engineering firms, and vendors specializing in commercial grade dedication for nuclear chillers. The report is organized according to a typical project management sequence, with early chapters addressing the project scoping and technical considerations, followed by sections addressing specification development, bidding and vendor selection, fabrication and testing, and installation. An industry Technical Advisory Group (TAG) reviewed the report.

KEY FINDINGS

- Section 2.2.3.1 includes details on options to reduce/mitigate project risk for safety related chiller replacement projects involving dual-unit shared chillers such as control room chillers. Extended out-of-service (OOS) periods to support one-time project schedules have occurred, and the status of allowed recovery periods for two trains OOS is also noted with applicable references.
- Sections 2.2.5 and 5.1.2 discuss oversizing related issues for safety related chillers. The need to address operational capability and reliability over the full range of load and service conditions is emphasized. The possibility of reducing the magnitude of oversizing via more accurate heat load analysis is also discussed in Section 5.1.2.
- Section 2.2.1 and Section 4 describe the important influence of control system technology on the overall project, with an emphasis on digital technology. The potential benefits as well as problems with digital control systems are noted. A large number of reference resources are noted for additional guidance and basis.

- Sections 4.1 and 4.2 provide comments on the use of a back-up process to address potential uncertainties with digital control design, testing, reliability and regulatory considerations.
- Section 4.2.1 notes obsolescence should be considered when designing a digital control system and software obsolescence should also be considered. Sections 4.1.1, 4.2.1, and 13.2 discuss the need to address electronics obsolescence issues for control parts and software with the original equipment purchase. This may include purchases of significant quantities of replacement parts to cost-effectively support service life.
- Section 14 provides examples of industry experiences

WHY THIS MATTERS

Chillers in nuclear plants include both those relied upon for nuclear safety functions as well as to support equipment vital for power generation. Life cycle management and long range planning for major capital projects involving chillers face a complex combination of issues involving continuing changes in refrigerant regulations, an accelerating pace of obsolescence for hardware and controls, and regulatory uncertainties related digital technology changes. This report contains a collection of project experience based lessons learned from chiller projects as well as providing up-to-date reference materials and guidance documents applicable to chiller upgrade or replacement projects.

HOW TO APPLY RESULTS

Team members involved in chiller replacement or upgrade projects can use the information in this report for guidance, considerations, and supplemental information throughout various phases of a replacement or upgrade project. Engineers involved in project scoping and specification development should focus on Sections 2, 4, 5, 6, and 14, to ensure technical issues encountered with other projects are addressed and to obtain current references and resources for detailed topics such as digital controls. Engineers specifically involved with chiller control upgrades are directed to Section 4. This report can be used in support of operating experience reviews normally performed for major projects, with emphasis in Section 14.

Users of this report involved with digital controls may also want to consult EPRI reports 3002002989 (*Digital Instrumentation and Control Design Guide*), 3002005326 (*Methods for Assuring Safety and Dependability when Applying Digital Instrumentation and Control Systems*), and EPRI computer based training courses 3002005237 (*Digital Design Guide 2015*, CBT) and 3002000531 (*Digital Instrumentation and Control Computer-Based Training Modules 2013*), as well as other resources noted in Section 2.1 for additional information.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- One opportunity for engagement is through the Nuclear HVAC Users Group (NHUG) organization which has an annual conference which provides a forum for discussion, development, and communication of information on operation, maintenance, analysis, replacement, and regulatory issues involving chillers in nuclear power plants.
- The EPRI Heat Exchanger Performance Users Group (HXPUG) holds periodic meetings to present research to improve the reliability, availability, and operational capability of heat exchangers. The User Group also provides a forum for discussion, development, and communication of information on operation, maintenance, analysis, and performance testing of heat exchangers.
- Other EPRI component replacement reports may be of interest to the project team, such as reports 3002000542, *Guidance for Replacing Shell-and-Tube Heat Exchangers at Nuclear Power Plants*, 1013470, *Plant Support Engineering: Guidance for Replacing Heat Exchangers at Nuclear Power Plants with Plate Heat Exchangers*, 3002000809, *Guide for the Specification of Replacement and Spare AC Squirrel-Cage Induction Motors Having Voltage Ratings Up to 600 V*, and 1020625, *Plant Support Engineering: Guidance for the Replacement of Large Electric Motors at Nuclear Power Plants*.
- EPRI reports 1007361, *Chiller Performance Monitoring and Troubleshooting Guide* and 1015075, *Life Cycle Management Planning Sourcebooks – Chillers* can be used by engineers and project team members for additional information on basic chiller design and operation.

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ACRONYMS AND ABBREVIATIONS

ALARA	As Low As Reasonably Achievable
A/C	Air conditioning
ANSI	American Nuclear Standards Institute
ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
ASME	American Society of Mechanical Engineers
B&PVC	Boiler and Pressure Vessel Code (ASME)
BWR	Boiling Water Reactor
CBT	Computer Based Training
CCF	Common Cause Failure
CFC	Chlorofluorocarbon
CFR	Code of Federal Regulations
CGD	Commercial Grade Dedication
CR	Control room
CREATCS	Control room emergency air temperature control system
DI&C	Digital instrumentation and controls
DP	Differential pressure
ECT	Eddy Current Testing
EMI	Electromagnetic Interference
EPA	Environmental Protection Agency

EPRI	Electric Power Research Institute
EQ	Environmental Qualification
°F	Degrees Fahrenheit
FAT	Factory acceptance test
FME	Foreign Material Exclusion
FMEA	Failure Mode Effects Analysis
HCFC	Hydrochlorofluorocarbon refrigerant
HELB/MELB	High energy line break/Moderate energy line break
HFC	Hydrofluorocarbon refrigerant
HFO	Hydrofluoroolefin refrigerant
HVAC	Heating, ventilating, and air conditioning
IEEE	Institute of Electrical and Electronics Engineers, Inc.
INPO	Institute of Nuclear Power Operation
I&C	Instrumentation and Controls
LAR	License Amendment Request
LER	Licensee Event Report
LCO	Limiting condition for operations
NDE	Nondestructive examination
NEI	Nuclear Energy Institute
NHUG	Nuclear HVAC Users Group
NRC	Nuclear Regulatory Commission
NUPIC	Nuclear Procurement Issues Committee
O&M	Operations and maintenance

OEM	Original equipment manufacturer
OOS	Out-of-Service
OSHA	Occupational Safety and Health Administration (U.S.)
PLC	Programmable Logic Controller
PM	Preventive maintenance
PMT	Post-maintenance test
PWR	Pressurized Water Reactor
QA	Quality Assurance
QC	Quality Control
RAI	Requests for Additional Information
RFI	Radio Frequency Interference
SSC	System structure or component
SR	Safety-related
TS	Technical specification
UFSAR	Updated Final Safety Analysis Report
UHS	Ultimate Heat Sink
V&V	Verification and Validation

DEFINITION(S)

Chilled water system - A closed-loop system that circulates water cooled by a chiller to provide cooling to various components or areas via heat exchangers.

Chiller - An assembly of refrigeration equipment designed to cool a liquid to meet the heat rejection requirements to a variety of components or areas via heat exchangers.

Critical Digital Asset (CDA) - A digital device or system that plays a role in the operation or maintenance of a critical system and that can impact the proper functioning of that critical system. A CDA may be a component or a subsystem of a critical system, the CDA may itself be a critical system, or the CDA may have a direct or indirect connection to a critical system.

Digital IC System/Device - An I&C system whose functions are dependent on, or completely performed by, using microprocessors, programmed electronic equipment or computers. (Adapted from IEC 61513)

Efficiency – The ratio of the actual amount of heat transferred to the total amount of heat transfer possible.

Low-, medium- and high pressure chillers - These are determined by the type of refrigerant used in the system.

Preventive Maintenance (PM) – actions to detect, preclude, or mitigate degradation of a component and to improve its reliability and/or extend its useful life.

Refrigerant - A refrigerant is any substance that can readily absorb heat, usually resulting in a change of state, which can readily dissipate heat again, usually resulting in a second change in state.

Refrigerant system - A system of components specifically designed to circulate a refrigerant throughout a system to transfer heat from the heat source to the heat sink.

Ton of refrigeration - A measure of heat flow equal to 12,000 Btu/hr (3.5 kW) derived from absorbing 288,000 Btu (3.04E+8 J) in the process of melting 1 ton (0.91 Metric Tons) of ice in a 24-hour period.

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INTRODUCTION

1.1 Background

This report provides information that is intended to support or supplement chiller upgrade or replacement projects. Chiller overhauls, refrigerant changes, control upgrades to digital chiller controls, and complete chiller assembly replacements are planned at many stations. There have been a number of highly successful chiller upgrade and replacement projects in the industry, but also several that have encountered multiple difficulties both during the project and after installation. Life cycle management and long range planning for major capital projects involving chillers face a complex combination of issues involving continuing changes in refrigerant regulations, an accelerating pace of obsolescence for hardware and controls, and regulatory uncertainties related to digital technology changes.

The report contains a collection of project experience based lessons learned related to chiller projects and provides up-to-date reference materials and guidance documents applicable to chiller upgrade or replacement projects. The report is not intended as a technical guide on chiller hardware or controls selection. The information provided on design, installation or operational issues is primarily based on lessons-learned experiences from previous chiller projects to address items that were missed or not adequately considered which subsequently contributed to project cost, schedule, and or reliability impacts. The report is not intended to provide a thorough presentation of digital control design and implementation issues versus pointing to current references for additional detailed treatment of that topic.

1.2 Scope

This guide can be used by nuclear utility project teams involved with chiller upgrade and replacement projects at nuclear power plants. The structure of this report follows the basic process sequence when replacing a major plant component such as a chiller. Section 2 addresses project scope development while Section 3 deals with project management and the project team. Sections 4 and 5 discuss considerations for the two principal chiller replacement actions of chiller digital controls upgrades and hardware replacement. Section 6 addresses how those design inputs for performance requirements are translated into the bid specification. Section 7 provides guidance on performing the bid evaluation, selecting an appropriate supplier, and resolving procurement issues.

Fabrication and shipping and handling issues are discussed in Sections 8 and 9, respectively. Section 10 provides receipt inspection guidance, followed by storage and staging guidance in Section 11. Sections 12 and 13 provide guidance on installing the replacement chiller and recommended PM activities, respectively. Finally, Section 14 discusses industry experience.

The report provides a guide of project related considerations which address both safety related and non-safety applications at nuclear power plants, although there is added emphasis to safety related chillers due to the added complexity and issues involved. The report scope does not include fans, cooling coils, and other related or interfacing equipment beyond those typically found on a skid-mounted refrigerant chiller assembly.

Figure 1-1 and Figure 1-2 illustrate installations of chillers of the types discussed in this report.

Figure 1-1
Set of Replacement Chillers at a Nuclear Station

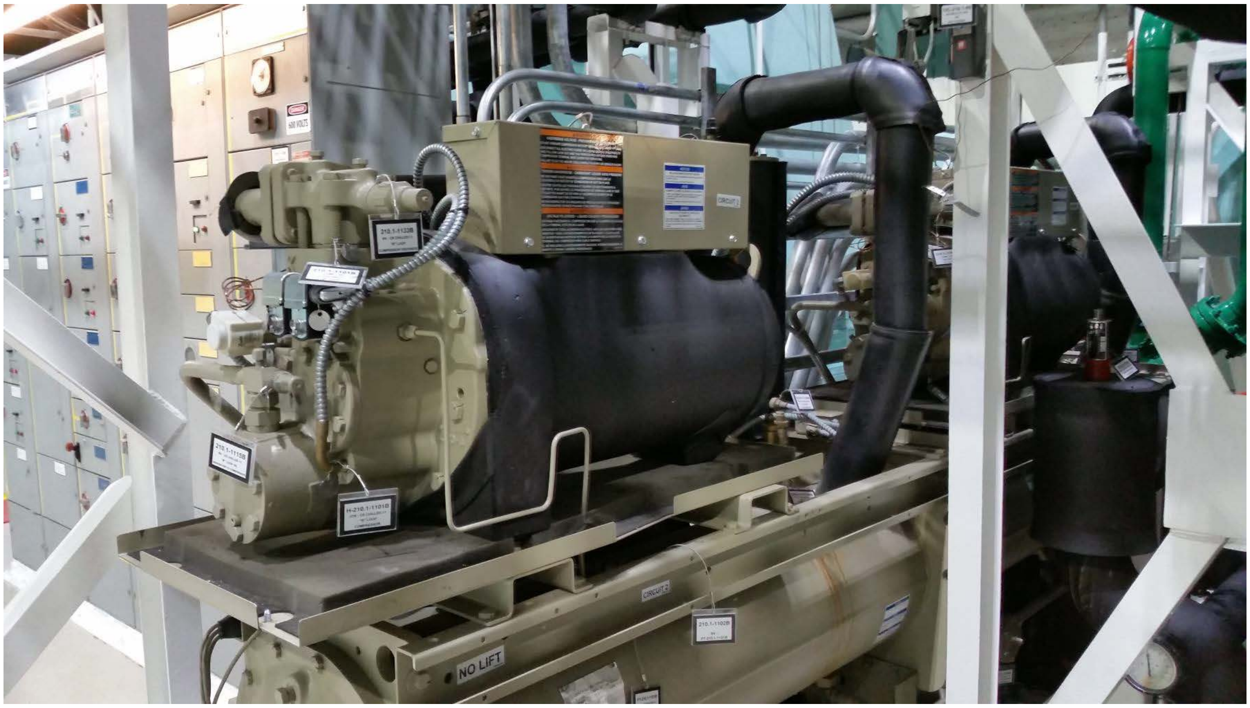

Figure 1-2
Chiller Assembly Replaced at a Nuclear Plant

This report assumes that utility personnel have already performed sufficient analysis to determine that replacement/upgrade is the most cost-beneficial option for long-term reliability. Accordingly, the report does not address repair, overhaul or troubleshooting of existing chillers. Information related to chiller operation and maintenance is available in the following EPRI documents:

- *Chiller Performance Monitoring and Troubleshooting Guideline*, EPRI 1007361 [8]
- *Electric Chiller Handbook*, EPRI TR-105951-R1 [12]
- *Life Cycle Management Planning Sourcebooks – Chillers*, EPRI 1016076 [11]

As a basis for the guidance provided in this report there are references to certain Quality Assurance (QA) implementing standards. Although the standards related to ANSI N45.2 [31] are often referenced, the user of this report should recognize that other QA implementation guidance might be equally applicable. In the U.S., American Nuclear Standards Institute (ANSI) standards apply to safety-related components; however, the project team might consider these standards for certain non-safety chiller replacements. The intent of this report is to present in generic terms the guidance that is most commonly applied for U.S. nuclear power plant licensees. International members will reference laws, codes and standards which are applicable in their country.

2

PROJECT SCOPE DEVELOPMENT

2.1 General Chiller Project Options

Chiller reliability issues, obsolescence, and life cycle management/long-range planning are the typical drivers for chiller replacement or major upgrades. The selected action tends to following one of the following:

- Refurbish/Upgrade Existing Hardware
- Upgrade/Replace Controls (may be in conjunction with hardware refurbishment/upgrade)
- Replace Entire Chiller

There are a wide variety of reasons a particular option may be selected as the best fit for a specific application. Examples of these variables may include logistics/access issues, the need for greater chiller capacity, the desire to reduce excess/unneeded capacity, reducing diesel generator electric load via more efficient units, desire to change refrigerant to reduce consumption rate of stock-piled inventory of obsolete refrigerant for other chillers, desire to improve reliability with low/partial load operation, loss of vendor support and parts for obsolete controls/software, constraints on capital budget, overall reliability of key components with failures dominated by controls, instruments, and ancillary components, as well as many other related considerations.

It may be necessary for the scoping project to evaluate all three options (i.e., refurbishment, controls upgrade, complete replacement) to determine which option or combination of options provides the optimum balance of project risks, schedules, and cost-benefit relative to the station's needs.

2.1.1 Refurbish Existing Hardware

One option is to refurbish the existing hardware. This option maintains the overall compressor/chiller assembly, but pursues a much more extensive scope of repairs, upgrade, and refurbishment than normal periodic preventive maintenance. The scope of the refurbishment is often targeted at addressing causes of past failures or operational problems. A comprehensive changeout of obsolete instruments may be performed. Replacement and rerouting of copper tubing and conduit may be included to address previously observed vibration issues, to improve accessibility, and/or reduce potential for damage from inadvertent contact. Major maintenance such as motor overhaul/rewind, compressor rebuild, condenser retube, or similar actions may be included considering their condition and/or schedule proximity for such actions.

The chiller refurbishment project could include refrigerant conversion, provided the chiller design, existing refrigerant, and performance impacts are acceptable. Such a change may support the station/utility long-range refrigerant management plan by decreasing use of obsolete refrigerant stockpiles, adding inventory (via recovery/recycle) from the upgraded chiller to stockpiles, and converting more easily changed chillers to refrigerant types that remain available for purchase.

The objective of this option is to improve reliability and address a backlog of identified issues via an overhaul the existing chiller, with component replacements and minor designs changes, and may include refrigerant management decisions, as noted above. Reasons for selection of this option often include:

- General satisfactory condition of the compressor
- Proven history of fundamental design to function properly over the full range of loading (including minimum load stability at high and low temperature extremes)
- Reliability issues have been limited and/or can be addressed via overhaul scope
- Significant adverse impacts /issues with chillers replacement
  - Physical limitations for installation of replacement chiller (including rigging path)
  - Reduced confidence in replacement chiller option due to past experience at the station or within the utility
  - Cost/budget considerations
  - Severe schedule constraints related to safety related chiller allowed out-of-service time (e.g., $\leq$72 hours)

Additional considerations related to the chiller rebuild/overhaul option include:

- Familiarity with design, operation, and maintenance of the existing chiller
  - Minimize procedure and training impacts for the maintenance and operations organizations
- Maintain consistency with other chiller types, controls, etc. at the station
- Refrigerant inventory management
  - Addressing/correcting causes of past leaks
  - Conversion from an obsolete refrigerant to an available replacement
- Cost may be Operations and Maintenance (O&M) versus capital
- Obsolescence concerns related to parts availability may be higher with continued use of older model chillers
- Life extension action to support longer-term deferral of or alternative to replacement

The overhaul/refurbishment planning for existing chiller assemblies should consider the examples and information in the Institute of Nuclear Power Operation (INPO) document IERL4-14-30, Analysis of Vibration-Induced Piping and Tubing Leaks [88]. Improvement to tubing, instrument, and similar equipment routing, location, and/or supports may be warranted to achieve optimum long-term reliability. Example issues from this document are noted in Section 5.4 of the report.

2.1.2 Controls Upgrade

This second option is to upgrade the controls. Chiller hardware often remains sound and while mechanical parts availability issues may exist or develop, they are often more easily addressed than instrumentation obsolescence issues. This option may be combined with the chiller mechanical overhaul/refurbishment option discussed in Section 2.1.1.

Digital controls allow more accurate control of parameters such as temperature and load, as well as greater troubleshooting capability by displaying operating parameters and trends. If the digital controls are connected to the plant monitoring system, then the chillers can be monitored remotely in the control room, system engineers or maintenance departments' desks.

However, in addition to the above added capabilities associated with digital controls, EPRI report 1011710 [18] notes the following challenges;

> "Digital systems are usually far more complex than their analog counterparts, and it is usually impossible to verify adequate quality and performance solely through testing. Digital systems can exhibit subtle and unexpected behaviors and failure modes, which can result in more severe and difficult-to-predict consequences compared to the predecessor analog systems. The most difficult problems to address are caused not by aging and wear-out of hardware, but by design errors and undesirable behaviors resident in the systems from the beginning. An effective method to evaluate digital systems and find such potential problems should assess the process actually used by the vendor in developing the system and its software. It must also be able to look "inside the box" to understand the designed-in failure modes and behaviors. Such evaluations need digital expertise often not available to utility engineers, and they can be costly and open-ended."

Replacement analog controls remain a possibility as a custom designed control system. Mixed digital and analog systems are also available, ranging from analog controls with a digital system providing monitoring and data trending, to a digital control system with an analog backup system and manual override or transfer capability to the backup analog controls. Such designs have been included in some recent nuclear chiller installations, including non-safety related chillers.

Additional controls upgrade considerations are provided in Section 4 of this report.

Reasons for selection of the controls upgrade option could include:

- General satisfactory condition of the compressor and basic hardware
- Reliability improvements can be achieved with digital controls and replacement/update of existing instrumentation
  - Partial load control capability improvements with digital controls
- Eliminate manual action to restart unit following loss of offsite power or similar power disturbance
- Familiarity with design, operation and maintenance of existing chiller hardware
  - Reduce parts, training, and procedure impact
- Maintain consistency with other chiller types at the station
- Refrigerant management plan supports conversion of obsolete to available refrigerant with acceptable impact on the equipment performance or obsolete refrigerant stock-pile combined with reclamation and recycling actions are deemed sufficient to support long-term operation of the existing chiller hardware
- Additional monitoring, alarm and operational interface options
  - Improved refrigerant and oil level/inventory indication, alarm, and control
- Address obsolescence problems with existing digital control system or analog parts
- Significant adverse impacts /issues with chillers replacement
  - Physical limitations for installation of replacement chiller (including rigging path)
  - Reduced confidence in replacement chiller option due to past experience at the station or within the utility
  - Cost/budget considerations

Additional considerations related to the controls upgrade option may include:

- Digital controls issues to be addressed
  - Common Cause Failure analysis (if safety related)
  - Cyber security
  - Configuration control issues/obsolescence with hardware, firmware, and software
  - Extensive test plan needed for control logic, alarms, sequence, interlocks, and trip functions
  - Training, procedure, and maintenance work package impacts for new digital controls
- Obsolescence concerns related to parts availability may be higher with continued use of older model chillers
- Life extension action to support longer-term deferral of or alternative to replacement

2.1.3 Complete Replacement

The third option is complete replacement. This option is influenced by a variety of factors, which often include one or more of the following:

- Parts obsolescence/availability
- Reliability issues include mechanical and control considerations
- Improving various design/operating margins
- Design requirements are not compatible with equipment capability

Replacement may involve changes to the compressor type, load control mechanisms/options, minimum/maximum load requirements, cooling water flows and/or temperatures, chilled water control range, and similar design parameters. The replacement chiller type selection will consider these inputs in combination with the station's refrigerant management and chiller long-range plans. Reasons for selection of this option often include:

- Address obsolescence/availability issues with mechanical and electrical components, including software
- Address obsolescence/availability issues with refrigerant
- Improved controls may provide better reliability/operation
- Design changes to chiller type or controls may improve reliability at part load, low temperatures, etc.
- Additional monitoring, alarm, and operational interface options

Additional considerations related to the chiller replacement option may include:

- Access/rigging/interference issues associated with replacing an entire assembly, which may exist even if chiller is rigged in sections
- Loss of organizational familiarity with design, operation and maintenance of the previous chiller (impact to procedures, operator rounds, training, etc.)
- Highest overall cost
- Digital versus analog control issues
- Extensive testing needed for changes to compressor type, hardware, control logic, alarms, interlocks, trip functions, etc., as applicable

Figure 2-1
Control Room Chiller Assembly Prior to Replacement

2.2 Key Early Considerations for Project Scoping

The project scoping phase involves selection of the upgrade, refurbishment or replacement option, and if replacement is selected, the scoping report typically includes identification of the type chiller to be purchased. The key parameters influencing the option selected typically include those noted below, although other issues may also exist.

2.2.1 Controls – Digital vs Analog

The selection of analog control or digital control for the chiller, has a significant impact on the complexity of the design and testing, needed to support the project. This difference is particularly significant for safety related chillers given the regulatory uncertainty in this area.

Safety Related Digital Controls:

The response submitted by the Nuclear Energy Institute (NEI) on behalf of the nuclear industry in April 2016 to the Nuclear Regulatory Commission's (NRC's) draft action plan to modernize the digital instrumentation and controls (DI&C) regulatory infrastructure, stated the following [61]:

> "The current digital DI&C regulatory framework is overly complex and difficult to navigate. There are both too many total documents and too many types/categories of documents with which licensees must be familiar in order to consistently succeed in

> executing DI&C upgrades that will pass muster (1) when prior NRC review and approval is necessary, and (2) during post implementation NRC inspection activities. Significant ambiguity and inconsistency exist across the full spectrum of DI&C regulatory guidance documents that challenge licensees considering significant DI&C projects without undue regulatory and project risk. This has led industry to defer some digital upgrade projects that, if implemented, would have provided significant plant safety improvements."
>
> "In the absence of clear guidance with respect to digital modifications, many needed important to safety digital projects are on hold, or are being planned as less capable analog projects, due to the risk from unclear regulatory expectations. Many of these waiting changes are to safety related support systems and not large scale protection system upgrades, such as; safety related chillers…"

While safety related chiller replacements have been successfully implemented, including with digital controls, the above statements convey the uncertainty and potential for delays associated with this option. When dealing with a major capital project, this type of uncertainty/risk has undoubtedly influenced the control selection process and even approval to proceed with the project at all. Thus, the control evaluation is a key part of the project scoping phase.

Projects involving digital upgrades to safety-related chillers should assess the experience level of station personnel and project team members with previous digital projects. Project teams lacking personnel with recent experience and/or a high degree of familiarity with digital controls issues may benefit from benchmarking trips to stations that have successfully implemented digital controls upgrades in recent years. This will improve the project scoping accuracy and risk assessment in order to adequately assess the cost-benefits of digital versus analog controls.

Mixed digital and analog systems are also available, ranging from a digital control system with an analog backup system and manual override or transfer capability to the backup analog controls, to an analog control with a digital system providing only monitoring and data trending. Such designs have been included in some recent nuclear chiller installations, including non-safety related chillers.

Section 4 of the report includes additional discussion of controls related topics.

2.2.2 Safety Classification

The chiller safety classification impacts the complexity, duration and resources associated with the project. While this may seem a rather obvious statement, the added impact to all aspects of the project have been underestimated in several instances. Replacement of large non-safety related chillers at a nuclear generating station is a major capital project that is infrequently performed at most stations. Replacement of safety related chillers is even less frequently performed and have encountered delays and complications due to a variety of reasons. These issues include the evolving complexities associated with digital controls, commercial grade dedication, seismic qualification, much greater oversizing of equipment, and difficulties achieving reliable control over a wide range of cooling loads and conditions. These topics are addressed individually within this report.

2.2.3 Schedule

Detailed schedules are utilized by the replacement project to track the various actions of design, procurement, fabrication, testing, shipping, and sequence of installation. In most cases multiple outages, or if installed on-line, multiple cycles are involved.

A minimum time period of 2 years is estimated to be required for a safety related chiller from project scoping, specification development, bid package submittal/review, vendor selection, fabrication, testing, and receipt of the first replacement chiller unit. The time for sequenced installation of the replacement chillers, either on-line or in refueling outages, will be in addition to this period. Factors most likely to extend this time period involve the potential need for a change to the station's operating license, such as via a License Amendment Requests (LAR) in the United States, to address the out-of-service period needed to complete installation and testing of the replacement chillers, as well as other potential changes as discussed in Section 2.2.3.1.

2.2.3.1 Safety Related Chiller Project – Schedule Considerations

For non-safety related chillers, the project schedule considerations should be typical of those addressed by other major equipment projects. Replacing a safety related chiller, or implementing an analog to digital control upgrade on a safety related chiller may result in additional schedule risks and/or schedule impacts associated with actions necessary to mitigate those risk, such as due to the following:

- Allowed out-of-service time for chiller replacement
- Dual unit impact for shared chiller equipment (e.g., control room chillers)
- Consequences of loss of opposite train chiller during the replacement window
- Regulatory concerns with Common Cause Failure (CCF) of digital control software may escalate in spite of on-going industry actions, and impact the need for prior regulatory approval via a license change for the station (see Section 4.2.2 of this report)
- Potential for impact to the testing/qualification schedule to resolve problems related to non-standard or customized equipment and/or controls

Mitigating Actions:

- Stations have requested and been granted a change to their operating license (such as via a License Amendment Request (LAR) in the United States) for an extension of Out of Service (OOS) period and/or allowance for response time for both trains OOS. The time needed to develop and obtain approval for a change to the operating license may impact the overall project schedule
- Coordinate CCF evaluation with latest industry/regulator communications on this topic as well as with specification development, vendor communications, and design change development to address regulatory concerns.

- Reduce level of deviation from previously tested/installed designs or increase allowed schedule periods for equipment testing and issue resolution
- In some cases, temporary back-up chillers or temporary connections to other chillers may need to be installed by the project to manage risk during the replacement window.

The need for additional actions to manage risk during chiller replacement varies according to the equipment and station design as well as the applicable regulatory/licensing requirements. Stations with a third installed full-capacity swing/spare chiller that can be aligned to either train, or with the capability to align Essential Service Water (i.e., ultimate heat sink function cooling water) directly to cooling coils to support operability when cooling water temperatures are low enough to provide the necessary cooling, will have long available replacement windows and low project risks associated with installation schedules. In contrast, much higher project risks result from a dual unit station with a common control room envelope supplied by one redundant set of chillers. The project must address the risk to the operating unit(s) associated with exceeding the allowed OOS time interval as well as the potential consequences of unexpected loss of the in-service chiller during the replacement interval.

Reducing the project schedule risks to an acceptable level may require a change to the allowed OOS time period for an individual chiller and/or for both chillers being inoperable. Changes to the stations regulatory/licensing requirements, such as via the License Amendment Request process in the U.S., may require an extended period to support development of the supporting documentation and bases for the submittal, as well as responses to requests for additional information (RAIs) from the regulator. Licensing changes modeled after similar submittals that have been previously approved for other stations provide the most schedule and resource efficient means to obtain approval.

Allowed Out-of-Service (OOS) Time:

The allowed out-of-service (OOS) time for safety related chillers may be stated directly in the station’s license documents, such as technical specifications in the U.S., or it may be based upon the allowed OOS time for the supported electrical or mechanical equipment being cooled. Adequate margin must be available between the allowed OOS time and the estimated time necessary to remove the existing equipment, install the replacement equipment and complete testing required to establish operability, if the chiller replacement is to be performed in a mode when the equipment is required to be operable. Otherwise, the replacement work will need to be performed when operability is not required, such as during an outage. Outage critical path impacts must then be carefully considered.

As noted previously, many dual-unit stations include a common or shared control room envelope with only one redundant set of safety related control room chillers. Simultaneous shutdown of both operating units is not typically planned, resulting in the allowed OOS time impacting one of the units, even if the replacement is scheduled during an outage for the other unit. In this case, the need for a change to the station’s operating license may be indicated by project risk management reviews if the estimated replacement duration exceeds the allowed OOS time or results in unacceptably low margin to the allowed OOS period. Requests for one-time extension of OOS intervals (e.g., 30 days to 60 days) have been approved in the U.S. related to chiller equipment modification activities [70,71,72,73]. Other license changes may also provide schedule risk mitigation, such as approval to rely on opposite unit equipment or other measures specific to the station.

Allowed OOS Time for Both Trains of Control Room Chillers:

Replacement of a chiller during an allowed OOS time period must consider the consequences of an unexpected loss of the operable chiller. For some stations, the condition may invoke immediate shutdown requirements for the operating units based on loss of both trains of safety related equipment (such as per Technical Specification 3.0.3, for U.S. licensed plants). This scenario results in significant project risk consequence. An option to reduce this project risk is via the applicable license change process (i.e., License Amendment Request for U.S. plants) to allow a recovery period for the second chiller, if not already addressed by the stations license documents. Industry efforts have been underway for several years to provide such relief for U.S. licensed units. The below summary is from the Technical Specifications Task Force (TSTF) transmittal of TSTF-553, Add Action for Two Inoperable Control Room Emergency Air Temperature Control Systems (CREATCS) Trains, [36] submitted October 31, 2015:

- TSTF 477 R3 for BWR 4 stations is approved, and implemented at 10 of 13 applicable stations, for remainder it requires submittal of a LAR. NUREG-1433, Section 3.7.5 provides 72 hours to restore one of the two inoperable control room cooling subsystems provided control room temperature is verified to be below a plant-specific limit every 4 hours [36].
- NUREG-1434, the improved standardized technical specifications (ISTS) for BWR 6 plants includes in Section 3.7.4 an allowance of 7 days to restore one of two inoperable control room cooling sub-systems provided control room area temperature is verified to be below a plant-specific limit every 4 hours. This allowance was included in the ISTS as part of TSTF-477, but has existed in the TS for all BWR6 plants since their conversion to the ISTS [36].
- NUREG-1432, the ISTS for Combustion Engineering (CE) plants, TS 3.7.11, provides 24 hours to restore one of two inoperable control room cooling trains provided mitigating actions are implemented. This was approved on May 30, 2013 as TSTF-426, Rev. 5 (adopted by 4 of 8 CE plants to date) [36].
- TSTF 553 for Westinghouse and B&W plants is in review [36]. The initial submittal was on October 31, 2015 (ML15304A002) [36], with additional questions/responses issued in February (ML16028A453) [37] and May (ML16215A129) [41] of 2016, respectively, followed by additional questions and proposed changes related to control room habitability impacts issued in August 2016 (ML16215A125) [58]. The document proposes a period of 24 hours to restore a Control Room Emergency Air Temperature Control System (CREATCS) train to operable status provided the control room area temperature is maintained below a plant-specific limit. The allowed time period would not be applicable if the condition was entered intentionally. A station could request a temporary change similar to TSTF 553 and/or the related TSTF-426 for CE plants, for a control room chiller replacement project, if approval of this change for continuous plant operation was still in review [36].

2.2.4 Access and Installation Logistics

The rigging path for a replacement chiller and interferences to be removed must be carefully evaluated in the scoping phase of a chiller replacement project. The need to temporarily remove interferences to facilitate installation of a replacement chiller may result in significant cost and schedule impacts depending upon the type, quantity, and function of the interference items to be addressed. Their removal may affect security, high energy line break/moderate energy line break (HELB/MELB) boundaries, fire protection, seismic qualification, safety related equipment operability, control room habitability, ventilation analysis, and other similar design bases. The rigging path review will also address Seismic II/I (two over one) issues, in accordance with applicable site procedures/processes, if the move is over or in the vicinity of safety related equipment.

Laser mapping is a widely used tool in most major equipment projects at nuclear power plants. Mapping of the existing chiller assembly, the room in which it is currently installed, and the entire rigging haul path are typically performed. These precision measurements provide multiple benefits such as:

- Size verification of connecting services (i.e., deviations from original drawings)
- Location verification of connections for chilled water, condenser cooling water, etc.
- Identification of the space envelope in the room
- Identification of interferences for various size replacement chiller assemblies

Laser mapping of the as-fabricated replacement chiller at the vendor's facility is an option to ensure critical dimensions are consistent with the rigging plan, approved drawings, and the connection point locations for piping and auxiliaries to minimize field fit-up delays.

To minimize the impacts of rigging replacement chillers, designs have included segmentation of the chiller skid into smaller modules that can disassembled and reassembled in the field. This adds complexity to the design and testing, since the equipment seismic qualification testing must address the final field assembled condition, but this cost may be much lower than that associated with interference removal to facilitate installation of a fully assembled chiller package unit. Figure 2-2 and Figure 2-3 show examples of a replacement chiller provided in separate sub-assemblies for rigging and handling that were reconnected at the final installation location. Figure 2-4 shows another chiller designed in modular segments to reduce interference issues during installation.

Other options to address rigging/access constraints could involve reducing the size of the chiller by a change in compressor type, reduction in load/capacity (as discussed in Section 5.1.2, or the use of multi-circuit/compressor chillers in place of a single large unit.

Additional general project discussion of installation items are included in Section 12.

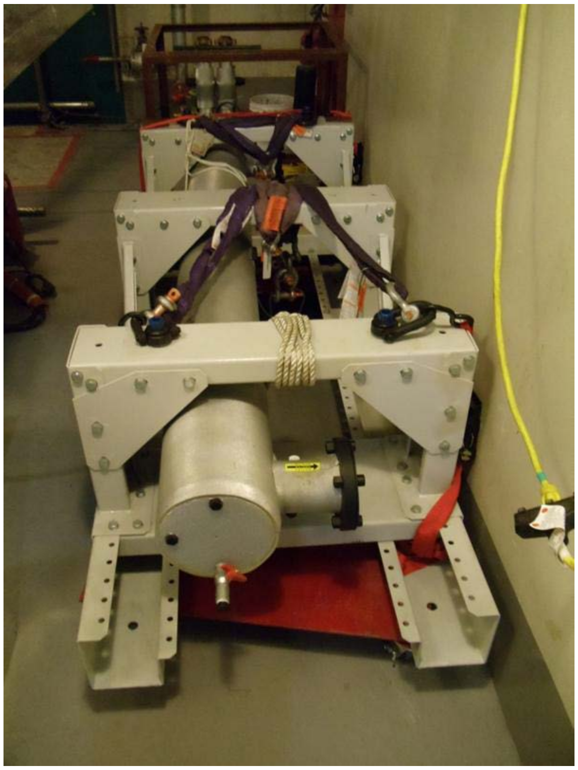

Figure 2-2
Lower Section of Replacement Chiller Separated and Prepared for Rigging and Transport

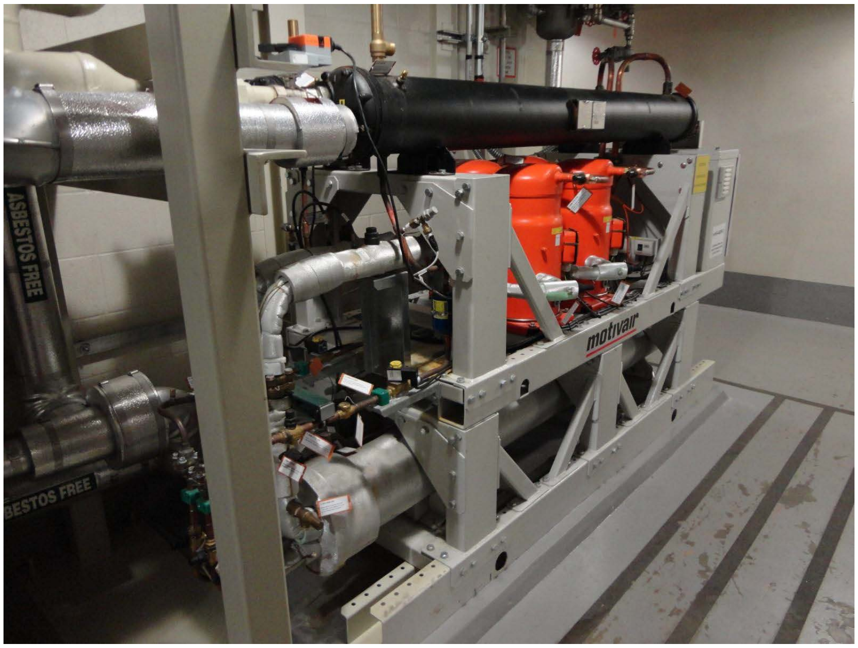

Figure 2-3
Fully Assembled Replacement Chiller Skid

Figure 2-4
A Large Replacement Chiller with Modular Segmented Design

2.2.5 Reliability Improvements

The objectives of the project are developed in the project scoping phase. When equipment reliability improvement and/or correcting operational problems are part of the project objectives, then identifying the underlying causes for reliability or operational problems with an existing chiller can be an important part of the project scoping activities to avoid simply replacing an old component with a new component that may have similar issues. Broad statements such as the component being obsolete or "worn out" are of little value for determining the causes for performance or reliability issues.

Compiling the reliability history with the associated causes of past failures during the project scoping phase is a method to help identify changes to the equipment design to avoid similar future occurrences. Simply installing a new chiller may not address the underlying cause and may result in similar performance problems occurring with a new chiller. Discussing the performance and failure history of the existing chiller with the chiller vendors prior to selecting a specific design, provides the opportunity to receive input on changes to the design which may provide better reliability and control over the full range of design and operating conditions.

Reliability problems may be associated with the difference in the actual operating load relative to the chiller sizing, particularly for safety related chillers. Significant over sizing of safety-related chillers is a design necessity. The chiller must be capable of removing the bounding heat load under extremes of meteorological and accident conditions, with worst-case condenser cooling water conditions (i.e., fouling factor at design limit, maximum cooling water temperature, cooling water flow at design minimum, maximum allowed tube plugging). Often the bounding heat load includes significant conservatism with service heat loads during normal operation being only a fraction of the design load, and condenser cooling capability may exceed the limiting worst-case design conditions by a large margin. Challenges to chiller reliability under minimum operating conditions has long been recognized in the nuclear industry. In some cases, alterations or adjustments have been made to the original chiller design or operation to handle the wide range of service load and operating conditions. It is important for a chiller replacement project to understand such factors in order to select the optimum replacement design. Section 5.1 includes further discussion on this topic.

An example of operational and maintenance issues with a chiller and chilled water system is provided in Section 24 of EPRI report 1003059 [10]:

- Re-occurring mechanical maintenance problems were characterized as:
    - Low system heat load causes the operating chiller to cycle on and off
    - Chiller performance problems due to air-in leakage (approximately 2 per year),
    - Chiller motor cooler cartridge leakage (currently considered resolved by electronic leak detection and snooping)
    - Purge system leakage, typically requires a float switch replacement and flushing (approximately 1 occurrence per year per chiller).
- Corrosion products have been observed in the oil and are believed to emanate from the condenser and evaporator surfaces. A clean-up system was added to chiller C and significantly reduced the amount of corrosion products and eliminated the need to periodically replace the jet pumps and other close tolerance parts. It appears that the corrosion products are increasing in chiller B.
- Chiller A is the best running unit with respect to performance and reliability. The chiller duty is rotated on two-week intervals. The idle chillers are prone to oil migration problems and air in-leakage (refrigerant circuit is maintained at a vacuum).
- The available workspace around the chillers was characterized as tight. Often several crafts need to work in parallel and the tight space reduces efficiency.
- Vibration testing continues to show a vibration noise in chiller A. The noise is attributed to a gear set. The signature has not noticeably changed for several years and the oil analysis does not show any symptoms of gear wear. The vendor does not believe the noise is a concern.
- The chilled water pumps that were originally installed were replaced early in the plant operating history. The original pumps were designed for chemical service and were sensitive to the volume of particulate in the piping system during initial plant start-up. The replacement pumps are an industry type design and have not experienced any wear problems. However, system flushing and strainer operation has reduced the volume of particulate in the chilled water.

EPRI report 1015075 also included the listing of chiller related Licensee Event Reports (LERs), with the failure causes and categories noted [11]. A compilation of "Maintenance Rule" functional failures of chillers over a 10 year period was in the report, with the main causes of failures attributed to instrumentation (29%), compressors (26%), electrical equipment (18%), and valves (12%).

2.2.6 Refrigerant and Chiller Selection

The selection of a refrigerant type and chiller design are directly related and are effectively part of the outcome of the project scoping report versus an input. But when dealing with a replacement component, the selection is also influenced by types of chillers installed at the station, and an integrated approach to managing refrigerants and chillers at the site.

There are three general refrigerant groups, differentiated by the operating pressure of the system, with low, medium and high pressure system categories. Various refrigerants exist for each pressure group. Several of the chiller designs as well as equipment manufacturers are associated with a specific pressure group.

Refrigerants used in new chillers have been changing for decades associated with ozone depletion and greenhouse gas contribution concerns, and are expected to continue changing for an extended period. The progression of refrigerants from Chlorofluorocarbons (CFCs) to hydrochlorofluorocarbons (HCFCs), to hydrofluorocarbon (HFC) refrigerants, is being followed by a transition to hydrofluoroolefins (HFOs) [76]. Accordingly, a long-range refrigerant management plan is a useful tool to assist stations and utilities with their use of existing and replacement refrigerant types, sharing plans between plants, availability changes, and the selection of refrigerant types for replacement chillers.

The phase-out of refrigerants should be a consideration when selecting the refrigerant type for a replacement chiller. This may not constitute a dominant factor given the wide-spread experience with managing refrigerant availability for an extended service life after it is no longer manufactured via reclamation and similar processes. The leak tightness of replacement chillers should be a design consideration to manage future operating costs and administrative burden associated with leakage, as discussed in Section 5.1. Newly developed refrigerants should be cautiously considered to ensure adequate operational experience exists to evaluate its performance. Trade-offs between thermal efficiency, environmental and personnel safety, material compatibility, vendor/industry experience, and related parameters are likely to exist with the selection of the optimum refrigerant for a replacement chiller.

Section 5 provides additional discussion on chiller and refrigerant selection.

2.3 Benchmarking, Industry Experience and Industry Guidance

Benchmarking chiller replacement projects at other stations is a beneficial means to learn from both their positive and negative experiences. The use of benchmarking and industry experience reviews may be useful for all phases of the project including scoping, specification development, vendor selection/bid review, vendor oversight/testing, and installation/startup.

There have been several successful chiller replacement projects, as well as those that have encountered multiple difficulties, including after being placed in service. While refrigerant chillers are a relatively common HVAC component installed in commercial and industrial facilities world-wide, the project teams would be wise not to underestimate the potential complexity and range of issues involved with a chiller replacement. Utilization of benchmarking at other stations provides an opportunity to improve understanding of details that are important to the successful outcome of the project.

The project should include research into industry experience related to the component being replaced and the performance of manufacturers under consideration. In general, the project team should consider the following sources for industry experience (see Section 4.2 for digital control references):

- EPRI Guidance
- NHUG Presentations and Reports related to chiller replacement
- INPO operating experience
- Regulatory communications such as NRC bulletins and/or 10CFR21 notices
- Technical bulletins
- Other utility experience with similar component replacement
- NUPIC database

3

PROJECT MANAGEMENT AND PROCESS OVERVIEW

3.1 Generic Process

Figure 3-1 shows a generic process that a project team can follow when replacing a chiller at a nuclear power plant. The process is structured as a typical Gantt chart, with each activity shown in approximate chronological order and each duration roughly depicting overlaps in various activities throughout the entire process.

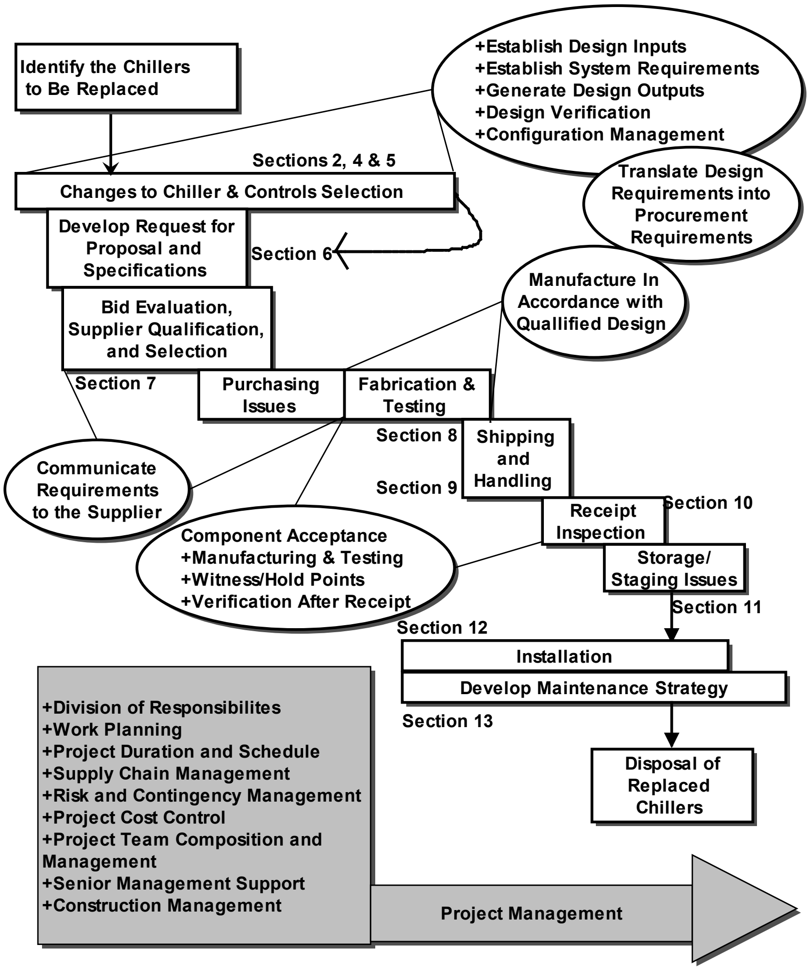

Figure 3-1
Process Flowchart for Chiller Replacement

3.2 Key Issues and Report Structure

Figure 3-1 illustrates that a replacement project should follow a logical sequence that provides the project team sufficient time to evaluate all aspects of the replacement, including interface points between the component and adjacent equipment/operating systems. The categorization of issues is based upon the typical delegation of activities among the key organizations involved (for example, design engineering, procurement engineering, purchasing, QA, and supply chain). Figure 3-1 also depicts the overall flow of information and the primary purpose of each element of the process. Each process element is cross-referenced to the corresponding section in this report that supplies more detailed implementation guidance.

The design of the replacement chiller is an iterative process most effectively performed through close collaboration with the equipment designer/manufacturer. Also, the design should concurrently consider maintainability of the equipment and installation issues.

3.3 Project Management Team

3.3.1 General Guidance

The success of chiller replacement project in contingent on the ability to effectively manage the entire project; ensuring it remains on schedule, within budget, and confirming that the replacement chiller is suitable for the intended application. Although the main focus of this report is the replacement chiller assembly, the project manager must have an appreciation for the entire scope of work associated with replacing the existing chiller. This may involve modifications to interfacing system components. Figure 3-1 illustrates that project management activities span the entire duration of the project and include issues that are neither directly related to the replacement chiller nor technical in nature. These issues might include:

- Division of Responsibilities: Assigning roles and responsibilities among the various internal and external organizations associated with the design, procurement, manufacture, testing, installation, maintenance, and operation of the replacement chiller.
- Work Planning: Coordinating the work activities associated with the replacement chiller and interfacing system components.
- Project Duration and Schedule. Establishing a project scope, duration, and milestones so that all activities are appropriately planned and scheduled. The project manager should consider the following issues when establishing the project schedule for a chiller replacement:
  - Pre-design activities: walkdowns, inspections of the existing chiller, conceptual design studies, and review of chiller designs and performance capabilities
  - Pre- and post-award activities: design engineering activities, specification development, and bid evaluation
  - Formation of a High Impact Team (HIT TEAM) including representatives from all impacted/ affected organizations
  - Manufacturing lead time (including testing)

  - Shipping time
  - Receiving and staging times
  - Construction management
  - Removal schedule (including decontamination prior to removal, as applicable)
  - Installation schedule
  - Post-installation testing and startup activities
  - Turnover activities
  - Closeout activities

  After each of these major elements have been planned, the overall project schedule and milestones are integrated into the site's schedule in accordance with utility/site procedures.

- Supply chain management involves interface with organizations in the supply chain to verify each has the necessary capabilities and can implement those controls for the components being replaced or modified.
- Risk and contingency management involves developing plans for unexpected issues and ways to estimate the risks associated with implementing various corrective actions.
- Project cost control ensures the project remains within the budget.
- Project team composition and management ensures appropriate individuals are available to support the project, possibly including members of the supply chain.
- Senior management maintains awareness of the project scope, budget, and progress in order to provide the necessary support throughout the duration of the replacement work activities.
- Configuration management ensures design change processes are implemented and the as-built configuration of the replacement component is properly conveyed to design documents.
- Training ensures operations and maintenance personnel are adequately trained for the safe and reliable performance of the replacement chiller.

Important considerations and expectations for the project include satisfying design requirements, reliable post-installation chiller and system performance. Successful projects recognize the importance of maintaining close interface with both internal and external organizations.

3.3.2 Project Management Team and Interface Controls

3.3.2.1 Project Management Interface Controls

ANSI N45.2.11 [31] provides guidance for control of external and internal interfaces encountered during component design. It suggests the project manager should do the following:

1. Identify the interface
2. Establish responsibilities

3. Establish appropriate lines of communication
4. Establish procedures (if not existing) to control the flow of design information

3.3.2.2 Project Management Teams

Because the design process occurs sequentially and in an iterative manner, some expertise is needed to ensure awareness of parameters affecting the chiller during the design phase. Multiple areas of expertise may be needed at each project stage.

The project team members should include the required expertise and be a multidisciplinary group that guides the component replacement from beginning to end. Table 3-1 lists typical organizations in a project team and their estimated extent of involvement.

Table 3-1
Typical Project Team for Chiller Replacements

Organization in Project Team	Anticipated Level of Involvement
Engineering (design and systems)	High
Procurement engineering	Medium
Maintenance	Medium
Installer	High
Project manager	High
QA/QC	Medium (if safety-related)
Work control/planner/scheduler	High
Licensing	Low (Medium if LARs involved)
Operation	Low
Senior management	Medium
Component supplier	High
Plant security	Low
Training	Low
Supply chain	Low (during actual purchasing)
Health physics	Low/Med (pending location)
Chemistry	Low
Authorized Nuclear In-Service Inspector (if safety related)	Low

3.3.3 General Project Considerations

Successful project managers recognize the importance of various aspects of the replacement as the design of the component progresses. This is often referred to as *concurrent design* because the design evolves throughout the project. EPRI report *Guidelines for Reverse Engineering at Nuclear Power Plants* [3] describes concurrent design in the following way:

> A systematic approach to the integrated, concurrent design of products and their related processes, including manufacturing and support. Causes developers to consider from the outset all elements of the product life cycle.

In general, design engineering occurs in a sequential manner. Most design must occur before the replacement chiller is manufactured; testing and inspection commence after manufacturing has started. Next, the replacement chiller is shipped, stored, installed, operated, and maintained.

ANSI N45.2.11 recommends, and a review of industry experience suggests, that the project manager consider the parameters bulleted below during the design of replacement equipment. The project team should use plant procedures to ensure appropriate design aspects are considered during the component replacement. Accordingly, the following list is not intended to be inclusive:

- Personnel requirements:
  - Qualification and number of personnel for installation, maintenance, and testing
  - Radiation exposures for work areas (considering ALARA and other human factors)
- Transportation requirements and limitations (i.e., local, state, and federal regulations)
- Fire protection requirements
- Handling, storage, and shipping requirements
- Industrial safety requirements:
  - Controls for dangerous or hazardous materials
  - Grounding of electrical systems
  - Other general concerns as prescribed by applicable Occupational Safety and Health Administration (OSHA) regulations (U.S.)
  - General industrial safety precautions
- Special cleanliness requirements

4

CHILLER CONTROLS

The selection of the control type to be used is a key decision point, whether the project scope involves controls upgrades for an existing chiller or complete chiller replacement. For projects involving safety related chillers, the use of digital controls may require more engineering resources than all other aspects of the project design and installation and requires a thorough understanding of current industry and regulatory guidance to ensure the technical, operational, regulatory, schedule, and economic factors are properly considered.

Digital chiller controls are the industry standard for chillers and practically all other electronic control systems. Design considerations for digital versus analog chiller controls include:

- Improved chiller control, particularly with low cooling loads, and expanded control range/capability have been achieved with existing chillers following conversion from analog to digital controls
- Improved reliability and extended service life intervals between required maintenance have been observed with digital controls
- Digital controls have allowed the elimination of manual operator actions such as providing automatic versus manual restart following power disturbances
- The use of packaged controllers versus a custom design combined with the selection of a vendor experienced with the specific software and controls has supported shorter overall project schedules
- Software Verification and Validation (V&V) is major activity for safety related chiller controls
- Analog – Digital control combinations are available through some vendors allowing manual override of digital control and operation with a backup analog control
- Some stations have experienced unexpected problems despite efforts to thoroughly test new equipment [73,74,82]
- Changes to hardware and software models/versions as well as obsolescence occur rapidly and life cycle management planning should be incorporated into the project with the initial purchase
- Actively changing regulatory guidance for digital control systems warrants thorough understanding and monitoring by the project team to manage project risk

This section addresses chiller project considerations and actions to address related to the use of analog and/or digital controls. This report directs the user to various other resources for additional and more detailed information on these topics.

4.1 Analog Controls

Analog controls remain a viable option for chillers. Analog control may be supplied as the sole means of chiller control, or it may be supplemented with a digital based monitoring and data trending feature, or analog control may serve as a back-up to a digital control system. The use of an analog control system may require customization, since the chiller manufacturers may not offer this as an available option. The vendors supporting nuclear commercial grade dedication (CGD) of chillers offer a variety of customization options related to analog and analog/digital hybrid control systems.

While obsolete in other applications, nuclear chiller replacement projects continue to install analog controls, primarily for safety related chillers. A recent example involved replacement of smaller chillers (30 tons each) with scroll compressors, with each chiller having four scrolls, allowing 25%, 50%, 75%, and 100% load variations. The selected design allowed a wide range of potential heat loads, which addressed oversizing related to conservative heat load analysis and the need to bound conditions for air and water temperatures, fouling factors, etc. The cost differential for digital versus analog was 2:1 per the CGD vendor. This cost difference did not include the added cost to the site associated with engineering and other costs for a digital upgrade. The cost of digital versus analog controls may differ between applications based on the complexity of the chiller control scheme, the number of instruments, type of chiller, etc.

Other utilities long-range plans for safety related chillers also involve continued use of analog controls, with a change to digital controls limited to non-safety related chillers.

Mixed digital and analog systems are available from the CGD vendors that include the installation of analog controls with a digital system providing monitoring and data trending only, as well as an option for manual override of a digital control systems to allow operation via a backup analog control design. Such designs have been included in some recent nuclear chiller installations, including a non-safety related chiller. Careful testing of the chiller with both the normal digital and backup analog controls over its full range of operational control (i.e., load and temperature minimums) would be necessary to determine if different limits, actions, or other operating instructions were applicable when operating with analog versus digital control.

Figure 4-1 provides an example of a custom analog control system replacement.

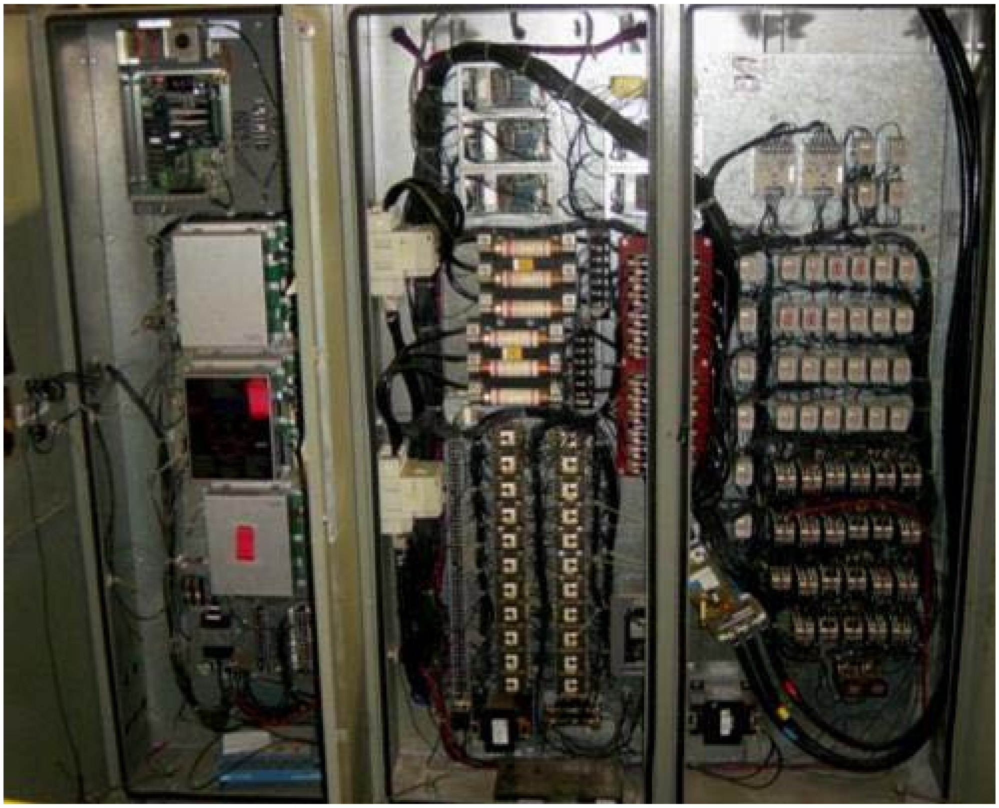

Figure 4-1
Example of Custom Analog System Replacement

4.1.1 Obsolescence and Life Cycle Management Planning – Analog Controls

Obsolescence of control devices must be considered regardless of the decision to use analog or digital controls. The use of analog controls for a chiller replacement remains a viable option and continues to be selected/installed, it also normally involves a customized design due to digital controls being the standard technology used by chiller manufacturers for many years.

The procurement of an extensive inventory of spare parts up through multiple entire control systems to support expected maintenance needs over the projected operational life of the chiller is an option to address obsolescence and reduce overall life cycle costs. The method of managing control hardware obsolescence should be addressed by the original project plan and implemented in conjunction with initial equipment purchase. This strategy is applicable to both safety related and non-safety related chillers that are important to unit operation.

4.2 Digital Controls

Digital controls are the current technological standard for instrumentation and equipment controls. It is a field that is rapidly evolving, in an almost continual state of change from equipment manufacturers/suppliers. It presents significant opportunity for improvement to chiller operation and control as well as opportunity for project delays, added costs and chiller malfunction due to inadequate design, analysis, and/or testing.

A great deal of information exists regarding the use of digital instrumentation and controls in the nuclear industry. Guidance on digital control projects can be found in EPRI, INPO, NEI, IEEE, NRC, and utility documents. Much, but not all, of the guidance relates to the safety related application of digital technology. The below documents, with selected excerpts and summaries, are some of those most relevant to a safety related chiller digital control upgrade project.

EPRI Guidance:

- *Digital Instrumentation and Control Design Guide*; 3002002989 [85]
- *Methods for Assuring Safety and Dependability when Applying Digital Instrumentation and Control Systems*; 3002005326 [17]
  - 3002005326 has pointers to several other guidance documents
- *Cyber Security Technical Assessment Methodology, Vulnerability Identification and Mitigation*; 3002008023 [100]
- EPRI Computer Based Training
  - *Digital Instrumentation and Control Computer-Based Training Modules 2013*; 3002000531 [83]
  - *Digital Design Guide 2015*; 3002005327 [84]

***Digital Instrumentation and Control Design Guide*, EPRI report 3002002989 [85]:**

This report provides guidance for implementing design control in plant modifications involving digital instrumentation and control (I&C) equipment and systems. It is intended to complement existing policies and procedures used to control engineering changes. A “generic” plant modification process was used to describe the interrelations between the activities needed to address digital issues in eight key topic areas, showing suggested activity assignments, sequencing, and interactions that could be expected among various stakeholders. For each of the digital topic areas—analysis, requirements, procurement, human factors engineering, data communications, cyber security, plant integration design, testing, configuration management, and licensing—the report offers descriptions and recommendations, including pointers to other, more detailed sources of information and guidance.

Methods for Assuring Safety and Dependability when Applying Digital Instrumentation and Control Systems; EPRI report 3002005326 [17]:

This report provides practical guidance that will help utility engineers, equipment suppliers, and system integrators address a full range of potential digital failure and common-cause failure (CCF) contexts. Potential vulnerabilities can be managed using a combination of preventive and mitigation measures. The report includes steps for identifying and assessing susceptibilities in terms of their likelihood, failure effects, and the measures in place to protect against them. The report also includes guidance on using susceptibility and coping analyses to screen and prioritize potential vulnerabilities. The guidance draws from industry standards and practices, lessons learned, and related EPRI products published over the last several years. It addresses both safety and non-safety applications.

EPRI Computer Based Training:

EPRI has developed computer based training (CBT) modules covering the key fundamentals of digital upgrades, which could be useful for project engineers and key project team members. The modules address life cycle of a digital project, digital component and communication architectures, vendor/construction oversight, human factors engineering, configuration management, and cyber security. The CBT “Digital Design Guide” [84] serves as an introduction and roadmap to the more detailed report 3002002989. The “Digital Instrumentation and Control” CBTs are available through the utility training networks or as EPRI product 3002000531 [83].

INPO

INPO has developed extensive guidance and operating experience based information reports. The project team is directed to the following INPO documents and resources for review and consideration:

- INPO 10-008, Ensuring Engineering Quality in Digital System Projects, Rev. 1 (March 2015) [86]
- INPO Topical Report TR8-64: Microprocessor-Based Digital Hardware Related Events [87]
- INPO 12-014, Software Quality Assurance, Rev. 1 [89]
- INPO Digital Assist Visits

NEI presentations at a 2016 Digital Workshop included the following points: [90]

- Responsibilities - not always clear for licensees, vendors, NRC
- Regulatory guidance - not clear and/or lack of common understanding with industry
- Implementation issues remain - 50.59, architecture design (i.e., CCF), design consistency
- Result: Regulatory and implementation issues lead to perception of high risk and creates barriers to implementation
- Licensee’s must ensure vendor and product quality. No short cuts.

- Implementation of INPO digital guidance for excellence.
- Better understanding of the 50.59 process that results in promoting digital design quality and ensures LARs are properly processed.
- Improved training and mandatory peer reviews, technical and 50.59

Utility Guidance

Each utility is likely to have a site and/or corporate procedure addressing digital system development, procurement, and implementation. Excerpts from an example utility include:

- Off the shelf components …should be less expensive over the life of the system.
- Off the shelf components may have unneeded features or provide additional complexity than custom components
- Custom components may not be available in the near future, thus requiring reengineering or complete replacement of the system due to the unavailability of replacement parts.
- Digital components are revised frequently…sometimes as much as every 6 months.
- Obtain a listing of projects…with a user contact list, the vendor has performed…that were similar in scope. Contact the users and discuss the pros and cons of the vendors.
    - Make sure that the project lists have not been filtered (eliminated problem projects) from the list. Most products should have had some type of problems. A perfect product should raise warning flags and require a closer look at the product's performance.
- Probe the vendor on their product's operating history, problem reporting process along with their corrective action process.
- Evaluate the vendor's support experience such as field support, startup tuning support, replacement component delivery times, and product end of life (manufacturing stops).
- For identified problems, determine what caused the bad performance. Also, determine the same for good performance. Why did the device perform so well? In addition, review both new and old product's performance. Has the vendor consistently provided a quality product? Have revisions introduced problems?
- A system that is less complex…is simpler to understand, qualify, and maintain.
- The need for Electromagnetic Interference (EMI)/Radiofrequency Interference (RFI) testing and/or software development reviews should be identified prior to the bidding process

Regulatory Guidance and Requirements (U.S. example) (for safety related digital applications):

- Regulatory Guide 1.152, Criteria for Use of Computers in Safety Systems of Nuclear Power Plants [48]
  - Endorses IEEE 7-4.3.2 and IEEE 603 [35]
- Reg. Guide 1.173, Software Life-Cycle Processes for Digital Computer Software Used in Safety Systems [54]
  - Includes Reg. Guides 1.168, 1.169, 1.170, 1.171 and 1.172 [49-53]
  - Follows (with some exceptions) IEEE 1074-2006 [34]
- Reg. Guide 1.180, Guidelines for Evaluating EMI/RFI in Safety Related I&C Systems [55]
- Reg. Guide 5.71, Cyber Security [56]
- NUREG-0800, Standard Review Plan [64a-h]
  - Section 7.0, Instrumentation and Controls – Overview of Review Process; Revision 7, August 2016
  - Appendix 7.0-A, Review Process for Digital I&C Systems; Rev. 6, Aug. 2016
  - Section 7.1, Instrumentation and Controls – Introduction; Rev. 6, Aug. 2016
  - Section 7.1-T, Table 7-1 Regulatory Requirements, Acceptance Criteria, and Guidelines for I&C Systems Important to Safety; Revision 6, Aug. 2016
  - Appendix 7.1-A, Acceptance Criteria and Guidelines for Instrumentation and Controls Systems Important to Safety; Revision 6, August 2016
  - Appendix 7.1-B, Guidance for Evaluation of Conformance to IEEE 279; Rev. 6, August 2016
  - Appendix 7.1-C, Guidance for Evaluation of Conformance to IEEE 603; Rev. 6, August 2016
  - Appendix 7.1-D, Guidance for Evaluation of the Application of IEEE Std 7-4.3.2; Rev. 1, August 2016
  - Branch Technical Position 7-14, Guidance on Software Reviews for Digital Computer-Based Instrumentation and Control Systems, Revision 6, August 2016 [45]
  - Branch Technical Position 7-18, Guidance on the Use of Programmable Logic Controllers in Digital Computer-Based Instrumentation and Control Systems, Revision 6, August 2016 [46]
  - Branch Technical Position 7-19, Guidance for Evaluation of Diversity and Defense-In-Depth in Digital Computer-Based Instrumentation and Control Systems Review Responsibilities; Revision 7, August 2016 [47]

- Interim Staff Guidance (ISG), Digital Instrumentation and Controls
  - DI&C-ISG-01, Cyber Security; Rev. 0, Dec. 31, 2007 [65]
  - DI&C-ISG-02, Diversity and Defense-in-Depth Issues; Rev. 2 (NOTE: ISG-02 has been superseded by BTP 7-19, Rev. 6) [66]
  - DI&C-ISG-06, Licensing Process; Rev. 1, Jan. 19, 2011 [67]
- 10CFR50.55a (h)(2) Protection systems [91]
  - For nuclear plants with construction permits issued after January 1, 1971, but before May 13, 1999, protection systems must meet the requirements in either IEEE Std. 279 or in IEEE Std. 603–1991, and the correction sheet dated January 30, 1995.
  - For nuclear power plants with construction permits issued before January 1, 1971, protection systems must be consistent with their licensing basis or IEEE Std. 603-1991 requirements, and the correction sheet dated January 30, 1995.
- Information Notice, IN 2014-11; *Recent Issues Related to the Qualification and Commercial Grade Dedication of Safety-Related Components* [40]
- Regulatory Issue Summary (RIS) 2016-05, Embedded Digital Devices in Safety-Related Systems; April 29, 2016 [62]
- Regulatory Issue Summary (RIS) 2002-22, *Use of EPRI/NEI Joint Task Force Report, Guideline on Licensing Digital Upgrades*. Nov. 2002 [39]

Regulatory guides provide recommended methods to comply with the laws, but are not requirements. The Standard Review Plan contains criteria used by the NRC to inspect new design.

4.2.1 Obsolescence – Life Cycle Management Plan for Hardware and Software

Several utilities have reported experience with controls hardware and software not only changing models/revision, but becoming fully obsolete and no longer available before completion of the project.

The pace of technology upgrades for digital equipment, both hardware and software, has accelerated to the point it can effectively be considered continuous. The equipment manufacturers are not typically well positioned to support the configuration control needs of the nuclear power industry, particularly in light of the dynamic environment that exists for electronic equipment and controls. In commercial industry applications, these changes are often invisible to the end-user. Service technicians routinely perform part and component replacements and install software updates. In most cases, a suitable replacement part (as determined by the vendor/manufacturer) remains available to support the equipment, but the acceptability of the latest parts change per the commercial grade vendor's review method is not consistent with the level of review and range of considerations applied for nuclear safety related applications.

This disconnect is certainly not exclusive to chillers, but it has been found to be a major issue with chiller replacement projects. Most projects have reported that electronic parts, software versions, and the entire control system have been changed by the manufacturer between when the products were selected for purchase and when the project was completed. This has resulted in cannibalizing parts from new uninstalled units to keep installed units in operation without the need for resource intensive engineering evaluation and testing of replacement parts or software versions.

The chiller manufacturers do not maintain a nuclear quality assurance program, but may be partnered or aligned with companies that provide commercial grade dedication (CGD) of products for safety related applications. Close coordination with the selected nuclear CGD vendor is needed in the specification development phase and procurement phase to address items related to the controls hardware, firmware, and software for life cycle management.

The procurement of an extensive inventory of spare parts up through entire control panels to support expected maintenance needs over the projected operational life of the component is an option to address obsolescence and reduce overall life cycle costs. The method of managing control hardware and software obsolescence should be addressed by the project plan and implemented in conjunction with initial equipment purchase. This strategy is applicable to both safety related and non-safety related chillers that are important to unit operation.

The life cycle of software is limited. Vendor assurances to support selected software products may be for a limited time (for example, five years), after which vendor product support may end. Warranties and even vendor assured support periods may expire prior to final installation of all phases of the project in a multi-unit station. Therefore, software life cycle management should be addressed by the project. Purchase of a control system simulator (or similar), to allow proposed hardware and software changes to be tested prior to installation, is a means of coping with limited vendor support.

The life cycle management review by the project team may support purchases of critical spare parts, particularly for components that have a short manufacturing life span (for example, chips, circuit boards and capacitors). Operating experience reveals that the functional service life of a digital control system may be dictated by the continued availability of spare parts. The cost of equipment and software upgrades to the latest vendor supported model and revision, when the engineering, procurement, and configuration management update cost are all considered may far outweigh the cost of having purchased and stocked large quantities of spares, particularly when reduced cost opportunities existed in conjunction with the original equipment purchase.

INPO Topical Report TR8-64: Microprocessor-Based Digital Hardware Related Events, includes experience based guidance applicable to chiller projects involving digital controls [87].

EPRI report 3002007023, *Digital Equivalency Evaluation: Screening Checklist and Considerations* [63], provides assistance in managing obsolescence of digital components. The report includes information to assist with determining if an equivalency evaluation can be used to accept proposed replacements for digital equipment or parts, or if a design change might be needed.

4.2.2 Common Cause Failure and 50.59 Evaluation

It is important for the project team to be aware of regulatory concerns regarding changes from analog to digital controls introducing the potential for a Common Cause Failure (CCF). The Nuclear Energy Institute (NEI) has been working on behalf of nuclear utilities with the U.S. NRC on issues related to digital controls upgrades. Communication is on-going in this area with frequent workshops for information exchange and question/response sessions [60,79]. The issues and guidance regarding CCF and defense-in-depth are actively evolving. Therefore, it will be beneficial for chiller projects that involve digital controls to not only be familiar with previously issued guidance, such as EPRI report 1019183 [22], but also remain up-to-date on this regulatory dialog and the potential for changes to related industry guidance and/or regulatory requirements.

The NRC has been tasked with improving the regulatory requirements associated with digital technology. Industry response the initial draft of the plan [61], have noted the following key issues:

- Resolution of CCF concerns
- "The NRC and industry….common understanding on improved guidance for 10CFR50.59 reviews of DIC&C upgrades"

The industry response document goes on to state:

> "…the U.S. nuclear industry has been slow to adopt digital I&C systems despite need to replace obsolete analog and early digital components with modern technology" "One of the primary barriers is the NRC policy…on mitigating software common-cause failure (CCF) in I&C designs. This has led nuclear plants to adopt inferior technical designs in an attempt to respond to NRC concerns with…CCF."
>
> "The NRC staff has stated…the policy on digital system CCF is in the Staff Requirements Memorandum (SRM) to SECY-93-087…..states in part that the "…applicant shall analyze each postulated common-mode failure for each event that is evaluated in the…safety analysis report," and that the "…applicant shall demonstrate adequate diversity within the design"."
>
> "The staff's interpretation of the policy is expressed in …BTP 7-19, which has evolved into the position that there are only two design attributes that may be credited to eliminate the need for further consideration of CCF: diversity within the digital I&C system, or "testability" based on device simplicity (Section 1.9 of BTP 7-19)." "Both the current policy and the staff interpretation do not provide clear means to credit other digital design attributes that are effective in reducing the likelihood of CCF, or allow for an engineering judgment that CCF is sufficiently unlikely that a deterministic analysis of coping is not required."

> "Because the NRC policy…effectively mandates that the licensee must show that the plant can tolerate a (software) CCF, it is challenging for most utilities to evaluate these modifications as acceptable under the 10CFR50.59 rule. Arguments for establishing low CCF likelihood have not been accepted by the NRC, so CCF typically is treated as a new malfunction. This conclusion would force many modifications to be submitted as a license amendment request (LAR) under 10 CFR 50.90." "The net effect of the NRC focus on (software) CCF discourages digital modifications"
>
> "EPRI and others' research shows that extensive testing should not be relied upon as a sole CCF preventive measure. Testing will not reveal a requirements error or omission, which is a common source of design errors leading to potential CCF. Note that testing is still a very valuable activity simply to reveal design and implementation errors, but its value in reducing software design errors that could lead to CCF is at best debatable."
>
> "Secondary issues…include the scope of the CCF policy, versus the range of Structures, Systems and Components (SSCs) that fall under the scope of 10 CFR 50.59. Changes made under 10 CFR 50.59 are reviewed based on adverse impact to design functions of SSCs described in the FSAR without consideration for the CCF policy which imposes different requirements and assumptions on the credibility or likelihood of CCF for those items in scope. The 10 CFR 50.59 regulation and guidance do not differentiate between safety and non-safety and certainly not between protection and safety."
>
> "Unless a clear regulatory path to implement more digital modifications under 10 CFR 50.59 and without prior NRC approval is identified, the industry and NRC will remain reactive, implementing digital modifications only when necessary to maintain safety, rather than proactively utilizing digital technology to continuously improve safety."

As noted in Section 14 of this document, the complexity of control system inputs combined with inadequate review of all imbedded settings and inputs for supporting firmware and hardware have resulted in previous reliability problems with chiller replacement projects involving digital upgrades.

A utility involved in a control room chiller replacement project to be installed in 2017 noted a great deal of engineering effort was required to document the basis for not having to apply defense in depth approach to digital controls.

4.2.2.1 NEI 96-07 Appendix D (Draft)

NEI 96-07 provides guidance for 10CFR50.59 Evaluations. Appendix D to NEI 96-07 [59] is a recently developed draft titled "*Supplemental Guidance for Application of 10CFR50.59 to Digital Modifications*", that was submitted to the NRC for review and approval April 4, 2016. Guidance on this topic has been provided in NEI 01-01/EPRI TR-102348 (updated by EPRI 1002833 [20]), "*Guideline on Licensing of Digital Upgrades*", which was endorsed (with some qualifications) by the NRC via RIS 2002-22 [39].

The background discussion in NEI 96-07 Appendix D states the application of guidance in NEI 01-01 "has not been consistent or thorough across the industry, leading to NRC concern regarding…the effectiveness of NEI 01-01 and the need for clarity to ensure an appropriate level of rigor is being applied". The background information also notes that NEI 01-01/EPRI TR-102348 contained guidance for designing digital modifications as well as the application of 10 CFR 50.59 to the modification, and the NRC has proposed addressing design guidance separately from 10 CFR50.59 guidance. EPRI report 3002005326 [17], *Methods for Assuring Safety and Dependability when Applying Digital Instrumentation and Control Systems*, has been issued as an updated guide for the design of digital control systems. Appendix D to NEI 96-07, when finalized/approved, is intended to provide updated guidance for the application of 10 CFR50.59 to digital control upgrades.

A presentation on CCF in July 2016 [79], included the following statements:

> "Because of the lack of clarity of the scope of BTP 7-19 and the limited methods dealing with CCF, as well as the onerous ISG-06 process, submittal to the NRC for approval (i.e., via the License Amendment Request process) would create unnecessary cost and schedule impacts as well as regulatory uncertainties associated addressing CCF make the project unfeasible." "Direction is now to use chillers with first of a kind analog controls which are expected to not be as reliable or efficient as the digital controls."

The draft guidance in Section 5.5 of NEI 96-07 Appendix D, addresses an example replacement of a safety related control room chiller analog control system with a digital system. The chiller digital upgrade described in the example is acknowledged to result in a CCF concern due to operation of the digital control systems with identical software. The 10CFR50.59 screening conclusion was adverse, but the evaluation concluded a hardware or software related CCF was unlikely based upon the supporting design analysis and testing conducted by the change process. Therefore, the change was concluded not to constitute an unreviewed safety question, and could be implemented under 10CFR50.59 instead of a License Amendment Request.

10CFR50.59 screening questions for changes to the licensed unit include, "Does the proposed activity involve a modification, addition to, or removal of a SSC such that the design function of the SSC, as described in the UFSAR, is adversely affected?" The guidance in Appendix D notes an adverse impact on the independence of the chillers described in the UFSAR will result from the analog to digital control upgrade (i.e., a "Yes" response to the screening question). The adverse impact is associated with the use of identical software in each digital control system, which creates an adverse impact on the independence of the two chiller trains. Separation and redundancy are both maintained, but the independence of the two trains is adversely affected. The same controller is not credited with controlling each train, but the two separate controllers each run the same software, which creates a commonality that did not previously exist and therefore the creation of a new type of malfunction not previously considered.

The 10CFR50.59 evaluation will subsequently determine if the magnitude or likelihood of the adverse impact is acceptable or not, which is the determining factor related to the change being an unreviewed safety question.

An NEI presentation on the chiller control replacement example in 96-07 Supplement D, Section 5.5, is captured in NRC ADAMS document ML16231A314 [60]. This presentation included a tabletop summary discussion of the 10CFR50.59 screening and subsequent evaluation question results.

Screening criterion 2 for the 10CFR50.59 process asks if "more than a minimal increase in the likelihood of occurrence of a malfunction" will result from the change being reviewed. To avoid more than a "minimal increase" in the likelihood of malfunction associated with a digital control system, the response credits the following:

- Common Cause Failure (CCF) issues associated with the operating environment (EMI/RFI susceptibility, seismic, temperature, humidity, and radiological) for the digital controls are addressed by the design process ensuring the equipment is suitable for the range of possible field service conditions.
- Critical Digital Review (CDR) and Failure Modes Effects Analysis (FMEA) are credited with addressing hardware design for potential hazards and failure modes.
- The overall CDR, Software Requirements Specification (SRS), Software Design Document (SDD), Software Verification and Validation Report (SVVR), Hazards Analysis, and FMEA are credited with ensuring the likelihood of software failure is low enough to be considered acceptable. The performance of Factory Acceptance Testing (FAT) via operation of a chiller package utilizing the chiller specific hardware, firmware, and software is also credited by the reliability conclusion.

The determination that there will be no more than a "minimal increase" in the likelihood of a malfunction of the chiller associated with a digital control upgrade therefore directly results from the aggregate combination of design analysis and testing applied by the modification process.

There is regulatory acknowledgment of the difference between safety systems and protection systems. A graded approach for auxiliary support systems (e.g., control room chillers) is being pursued, however, until new guidance is approved all evaluations are performed against existing guidance.

CCF can also be addressed by actions to mitigate or cope with the impact. Inclusion of a manual bypass mode to perform basic functions such as an override start that does not depend on digital controls could be included in the design and may sufficiently address existing CCF concerns.

4.2.3 Commercial Grade Dedication

The purchase of a safety related components must include either manufacturing (including controls and software) under an Appendix B QA program, or purchase as a commercial grade system that was dedicated under the requirements of industry accepted CGD practices (i.e., EPRI 3002002982 [80]). Since there no safety related original equipment manufacturers (OEMs) for chiller systems, including applicable digital controls, CGD is the only available option [69]. The nuclear industry relies heavily upon third-party organizations with extensive experience and expertise for CGD of chiller equipment and related digital control systems.

The topic of Commercial Grade Dedication is far reaching and well beyond the scope of this report. For guidance and information on the topic, the reader is directed to EPRI Report 3002002982, *Guideline for the Acceptance of Commercial-Grade Items in Nuclear Safety-Related Applications*. [80] This report supersedes EPRI reports NP-5652 [2] and TR-102260 [24], and provides the basic outline for the performance of CGD.

Additional guidance for accepting digital devices may be found in the following EPRI documents:

- *Commercial-Grade Digital Equipment for High-Integrity Applications: Oversight and Review of Evaluation and Acceptance Activities*, 1025283 [25]
  - Provides supplemental guidance for digital CGD to that in TR-106439 [21]
  - Tool to assist with oversight of CGD vendor to ensure a quality product
- *Evaluating Commercial Digital Equipment for High-Integrity Applications: A Supplement to EPRI Report TR-10643*9, TR-107339 [92]
- *Guideline on Evaluation and Acceptance of Commercial-Grade Digital Equipment for Nuclear Safety Applications*, TR-106439, [21] and the NRC's SER "Review of EPRI Topical Report TR-106439"
- *Generic Requirements Specification for Qualifying a Commercially Available PLC for Safety-Related Applications in Nuclear Power Plants*, TR-107330 [93]
- *Handbook for Evaluating Critical Digital Equipment and Systems*, 1011710 [18]
- *Handbook for Verification and Validation of Digital Systems*, TR-103291 [23]
- *Guidelines for the Technical Evaluation of Replacement Items in Nuclear Power Plants (Revision 1)*, 1008256 [1]

EPRI has conducted Commercial Grade Dedication Summit meetings to discuss current and emerging issues and challenges to implementation of commercial grade dedication.

A presentation by an industry expert in CGD provided the following insights regarding the verification and validation (V&V) actions associated with dedication of a safety related chiller digital control system [44]:

- Industry V&V requirements are complex and difficult to implement on a generic basis
- Plant/customer expectation that V&V process and documents will be project specific
- Nuclear chiller controls V&V specification requirements are inconsistent across the Industry, both nationally and internationally
- Nuclear chiller controls V&V specification requirements are often not tied to plant licensing commitments
- Nuclear chiller V&V specification requirements are often dependent upon plant digital expert

- Nuclear chiller controls V&V specifications often invoke conflicting requirements
- Chiller replacement/upgrade projects often implemented by third party engineering firms that may not be cognizant of industry or plant V&V/digital dedication requirements
- Open and constant communications between the supplier, engineering design firm and utility personnel are key to project success…. TEAM attitude is imperative

4.2.4 Configuration Management

The level of configuration control applied in the nuclear industry to components, sub-components, and software/controls coding far exceeds what exists in most other commercial and industrial applications. The equipment manufacturers are not typically well positioned to support the configuration control needs of the nuclear power industry, particularly in light of the dynamic environment that exists for electronic equipment, which as noted in Section 4.2.1 is in a nearly continuous state of change.

This disconnect is certainly not exclusive to chillers, but it has been found to be a major issue with chiller replacement projects throughout the industry. Most projects have reported that electronic parts, software versions, and the entire control system have been changed by the manufacturer between when the products were selected for purchase and when the project was completed. The rapid rate of parts and control software changes results in the frequent need for resource intensive engineering evaluations and in some cases testing of replacement parts or software to verify their acceptability.

In commercial industry applications, these changes are often invisible to the end-user. Service technicians routinely perform part and component replacements and install software updates. In most cases, a suitable replacement part (as determined by the vendor/manufacturer) remains available to support the equipment, but the acceptability of the latest parts change per the commercial grade vendor’s review method is not consistent with the level of review and range of considerations applied for nuclear safety related applications.

Configuration or change control processes must be discussed, understood and agreed upon during the bid evaluation phase. This will help ensure the vendor is aware of and prepared to initiate the necessary level of control/tracking of changes during the product manufacturing and testing phases. These controls must include changes to the software version used during the qualification and factory acceptance tests. Drawings depicting the chiller control panel switch settings need to be generated prior to factory testing and field verified against the tested equipment (both as-found and as-left verifications may be prudent). These drawings will subsequently convey to site drawings or inclusion into site procedures in order to ensure proper control panel configuration is maintained.

Examples of previous related problems encountered include the following"

> "…after the initial software installation, vendors changed software without testing it or notifying the utility of the change."
>
> "…software supplier loaded new software into a programmable logic controller (PLC) subsequent to the software revision. The PLC software loading procedure did not specify any subsequent checks."

EPRI Report 1022991 and INPO document 12-014, Software Quality Assurance, Rev. 1, provide guidance related to the control of software such as that used for safety related chiller digital controls [101,89]. These requirements are likely to have been incorporated into site procedures, although a reconciliation of the key recommendations against existing procedures applicable to the project would be a good practice to ensure the latest industry guidance and recommendations are followed by the project.

4.2.5 Cyber Security

Cyber security is an active and evolving issue for the nuclear industry. Several EPRI reports provide effective technical guidance for integrating cyber security into the design and procurement processes. These include:

- *Technical Guideline for Cyber Security Requirements and Life Cycle Implementation Guidelines for Nuclear Plant Digital Systems*-1019187 [28]
- *Cyber Security Procurement Methodology, Rev. 1*- 3002001824 [29]
  - *Cyber Security Procurement Methodology Training Module*, 3002002499 [94], is available to augment 3002001824
- *Cyber Security Technical Assessment Methodology, Vulnerability Identification and Mitigation*; 3002008023 [100]

These resources aide industry personnel in the technical decisions required to establish effective cyber security and achieve safe and effective digital designs under the current regulation.

Nuclear Energy Institute (NEI) 08-09, Revision 6 [38], dated April 2010, provides the industry implementation plan to meet NRC requirements of 10 CFR 73.54 and guidance in Regulatory Guide 5.71 [56]. In a letter dated May 5, 2010, the NRC found that NEI 08-09, Revision 6, "would be acceptable for use by licensees to comply with the requirements of 10 CFR 73.54." The actions the industry took in this binding initiative were implemented at all operating U.S. nuclear power reactors, with NRC endorsement, and remain the foundation for current industry programs.

Section 54, *Protection of Digital Computer and Communication Systems and Networks*, of Title 10, Part 73, *Physical Protection of Plants and Materials*, of the Code of Federal Regulations rulemaking and the new Federal Energy Regulatory Commission (FERC) order 706B require assurance that digital systems are protected from cyber attacks. 10 CFR 73.54 requires that licensees provide the following:

- High assurance that digital computer and communication systems and networks are protected against cyber attacks, up to and including the design basis threat
- A cybersecurity plan for NRC review and approval—Current applicants for an operating license or a combined license must submit, or amend their applications to include, a cybersecurity plan.

Since chillers typically do not communicate with other systems in the plant and may not interface with the plant monitoring system, the risk of outside code being introduced in the plant by a chiller digital control system is low. The control of laptops, if used for troubleshooting, must address cyber security processes applicable to the station, often by the use of a dedicated laptop with restricted access to ensure it remains free of potential adverse software.

4.2.6 Trips and Interlocks – Robustness of Design Review

Digital control systems provide an expanded opportunity to improve operation, monitoring/diagnostics, fault tolerance, and reliability of chillers. The digital control capabilities are typically much greater than what is being utilized in the design. In addition, the number of monitored parameters and amount of available data also exceeds that in an analog system. This introduces the opportunity to “improve” the design by adding additional interlocks and features intended to protect a part or function, and in so doing the added complexity of the control system may decrease reliability.

Equipment manufacturers must determine the proper balance between equipment start/run reliability and equipment protection when determining the digital control inputs to be used as trip inputs and start interlocks. The selection of which parameters monitored by the digital controller warrant inclusion as a trip input or as a start permissive input, as well as the trigger thresholds established for those parameters, may have been selected based upon a customer base that lacks the nuclear industry’s focus on operational reliability. Accordingly, a careful review of the start-run permissives and the equipment trip inputs, and the “setpoint” defined for each parameter, is recommended. Comparison of the quantity of inputs and their settings to the existing analog chiller control logic may be informative when evaluating if the changes in control are more likely to increase or decrease reliability.

Clearly it is not desirable to allow safety related equipment or equipment important to power generation to be run to failure, particularly when diagnostic monitoring was available to provide advance warning. However, adding new trip functions or new required start permissives should be evaluated against operating experience regarding the need for the added complexity (i.e., satisfactory operation w/o the feature for decades with the analog controls) and/or if a warning alarm would suffice. When there is not an imminent sustained threat to equipment failure, an alarm may be the more appropriate response. Similarly, changes to the setpoints for trip or start-run permissive inputs should also be reviewed if the change reduces or improves reliability.

The above review comments should also be balanced against a preference to avoid changing standard vendor control settings, software, firmware, etc. Such changes increase the potential for future errors or problems due to receiving/installing a device, software update, etc. that does not include the site-specific changes. The potential for unintended consequences also exists, with the introduction of new problems or vulnerabilities which were not recognized due to the singular focus taken toward the review. Operating a chiller with different control logic than all other installations removes some degree of comparison capability between other users and their experiences, as well as impacting troubleshooting if the problem cannot be duplicated on the supplier's equipment due to the problem being unique to the equipment's control software.

As noted in Section 4.1, another design consideration is to include the capability to manually override the digital control to operate the chiller with a backup analog control system. The analog controls could include start-run permissives as well as trip inputs. Such designs have been included in some recent nuclear chiller installations.

Previous EPRI reports have referred to this as "dependability characteristics", which are described as being associated with the reliability of the device over the entire range of operating conditions and event sequences. The ability to perform all safety functions and handle anticipated as well as unexpected inputs and fault conditions [80].

While not nuclear related, EPRI report 1017083, Case Study – Chiller Shutdowns Caused by Sensitivity of Control Relays to Voltage Sags, [81] documents an example of a chiller digital control system with inappropriately sensitive (per IEEE standards) protective relay settings for voltage sags that were resulting in repeated shutdown of large chillers.

4.2.7 Operating Environment

The chiller specification must describe the operating environment for the chiller assembly location, and the control cabinet operating environment, if located separately. The description should include:

- Indoors/outdoors
  - If outdoors, include description of weather and sunlight exposure (if coastal region note salt issues)
- Temperature range
- Humidity
- Air cleanliness/quality

- RFI/EMI conditions
- Post-accident or design basis operating environment extremes (for safety related)
- Radiation fields (normal, outage, accident)

Environmental and other conditions which may not have been of significant concern for an analog control system must be more carefully considered for digital systems. Vendors have been able to relocate the control panel away from the chiller skid (60 ft. noted in one example) to provide a more compatible environment for a digital system. Relocation of the control panel is a possible means to reduce impacts to the electronic components housed in it, but impacts to the instruments and devices at the chiller assembly must also be addressed.

It is important for the engineering package to identify the design features that are specifically relied upon by digital control system for protection and proper functioning. Similarly, features relied upon to achieve the expected service life should also be noted. Examples could include local ventilation for control panels or shielding to avoid interference or damage from sunlight, EMI, RFI, radiation, etc. Identifying these features assists in understanding potential operability impacts for safety related chiller controls, and for establishing appropriate periodic inspections and/or tests, and preventive maintenance actions and their intervals to ensure these features are properly maintained.

4.2.8 Digital Controls Training Considerations

Training for the new digital controls should include operations, maintenance and engineering personnel. The initial training can be conducted by the vendor in many cases, and may be at the testing facilities used for the new equipment. If the project involves chiller replacement involving new digital controls, then the project often purchases a spare chiller for training purposes which may be the chiller assembly used for mock-up testing and seismic qualification tests (safety related chillers). Digital control upgrade projects often include purchase of a spare control panel assembly with software (and a dedicated laptop) to simulate the chiller function to support training needs for both initial equipment turnover as well as on-going training needs for maintenance and other departments.

It is beneficial for the training actions to simulate (or perform if possible) planned preventive maintenance actions, troubleshooting evolutions, as well as monitoring actions.

4.3 Embedded Digital Technology

Equipment with firmware or embedded digital technology are becoming increasingly prevalent and may include parts such as instrumentation, electrical relays and breakers. Thus, digital issues may need to be addressed associated with component level replacements even if the chiller controls remain analog. The procurement of integrated equipment skids such as a chiller system containing a large number of components and sub-assemblies, increases the potential for unintended or unrecognized use of digital components by the supplier or a sub-supplier.

The NRC defined an embedded digital device in RIS 2016-05 [62], as “a component consisting of one or more electronic parts that requires the use of software, software-developed firmware, or software-developed programmable logic, and that is integrated into equipment to implement one or more system safety functions.” The document defined firmware as including but not limited to “devices such as programmable logic devices, field programmable gate arrays, application specific integrated circuits, erasable programmable read only memory, electrically erasable programmable read only memory, and complex programmable logic devices.”

The IEEE standard 7-4.3.2-2015 [33] defines a Programmable Digital Device (PDD) as “any device that relies on software instructions or programmable logic to accomplish a function. Examples include a computer, a programmable hardware device, or a device with firmware.”

Issues to be addressed for the digital technology equipment may include:

- Identification that the component includes digital technology is necessary
- Potential hazard recognition, including software common cause failures if safety related
- EMI/RFI issues must be addressed
- Other environmental impacts such as operating temperature, radiation exposure, moisture, etc.
- Environmental qualification considerations (if safety related)
- Programming/Software configuration control (and QA if safety related)
- Procurement, specification, and testing requirements

Utility procurement guidelines and procedures should include content addressing the purchasing of electrical equipment and instruments regarding the presence of embedded digital technology.

Recent Industry Examples:

There have been continued instances of problems encountered with devices containing embedded digital technology, involving both safety related and non-safety related chiller replacement projects. Two examples are noted below:

1. Molded case circuit breakers (MCCBs) were supplied with replacement safety related chillers containing inappropriate trip settings, which were not detected during testing evolutions [77]. The utility subsequently reported the chiller had been inoperable since installation due to skid mounted molded case circuit breaker trip setpoints being too low. The instantaneous trip setting for the MCCBs were changed from 5 times to 8.75 times the breaker's nominal 400 amperage. The short time trip settings for the chiller’s main supply breaker was also changed from the 6x tap to the 8x tap.
2. Following replacement of a large non-safety related chiller set, the chiller failed to start after performing an annual preventive maintenance (PM) task on a protective relay. The newly installed relay would not allow the chiller to start due to the site adding program inputs for a function that had been preprogrammed into the relay from the vendor, which resulted in a duplicated function and prevented the chiller from starting [78].

5

CHILLER HARDWARE REPLACEMENT

This section provides supplemental information, lessons learned and project and operating experience based additional input for consideration in the chiller hardware selection and design process.

If an overview of basic compressor designs with a summary description of major chiller components is desired, see EPRI report 1007361, Chiller Performance Monitoring and Troubleshooting Guideline, chapter 3 [8].

It is not the intent of this report to guide the user through the overall technical selection process or review of the positive/negative characteristics of reciprocating, centrifugal, screw or scroll compressor types. There are various technical resources available to assist with the technical evaluation. Utilities, and the engineering organizations supporting them, have the experience and expertise in HVAC chiller equipment sizing and selection to properly select the chiller design that is optimum for their site-specific application.

5.1 Compressor and Refrigerant Selection

The chiller selection decision involves consideration of the cooling load, cooling source (i.e., water cooled or air cooled), available space for installation (and rigging), electrical load limitations (i.e., emergency diesel generator capacity margin), and range of operating conditions/load in the selection process. Site experience with operation and maintenance of a given compressor type and other variables may also influence the final selection.

Complete replacement may be required due to mechanical failure, lack of parts and support, refrigerant, and other issues. A larger tonnage chiller could be required due to changes in refrigerant type. This increase in chiller capacity could potentially result in electrical impacts such as diesel generator load capacity, breaker sizing, cable sizing, and related items, although efficiency gains available with replacement equipment may outweigh the increase in chiller tonnage rating such that electrical demand is not increased. The load reduction analysis options discussed in Section 5.1.2 represent another option to reduce cooling load and potentially the associated project scope, schedule, and cost impacts.

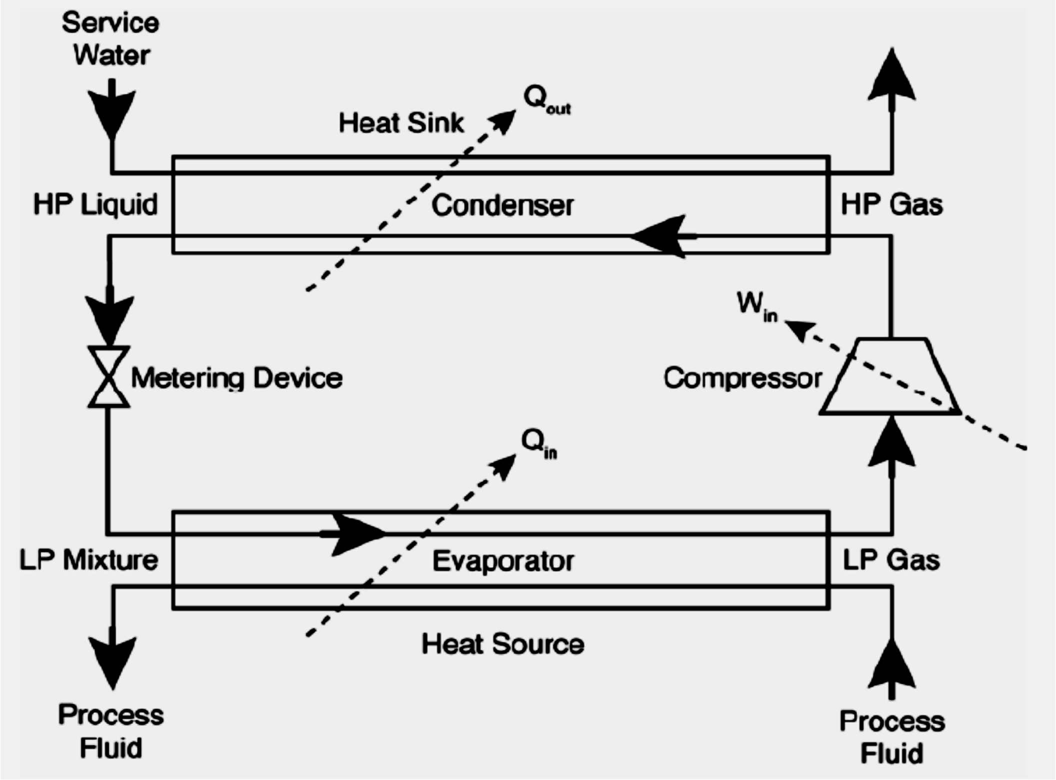

Figure 5-1
Basic Refrigeration Cycle

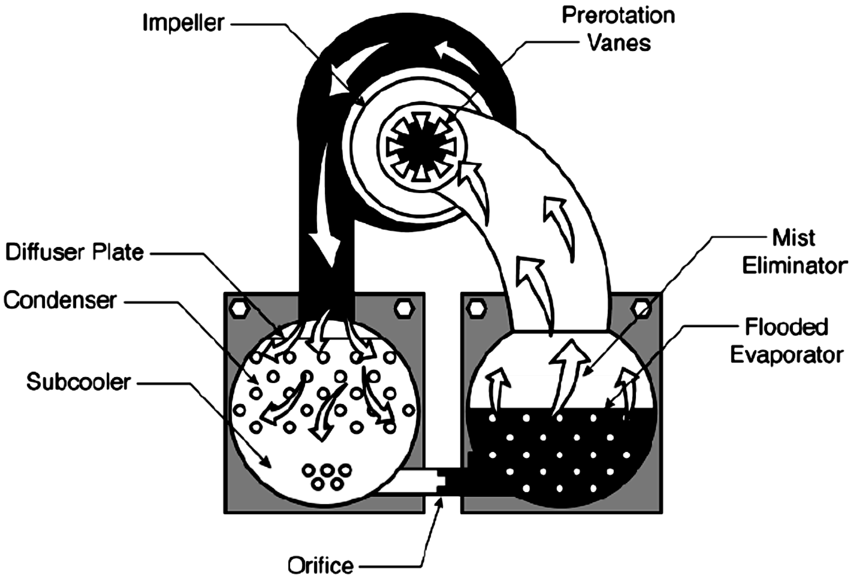

Figure 5-2
Simplified Diagram of a Centrifugal Compressor Refrigerant Cycle

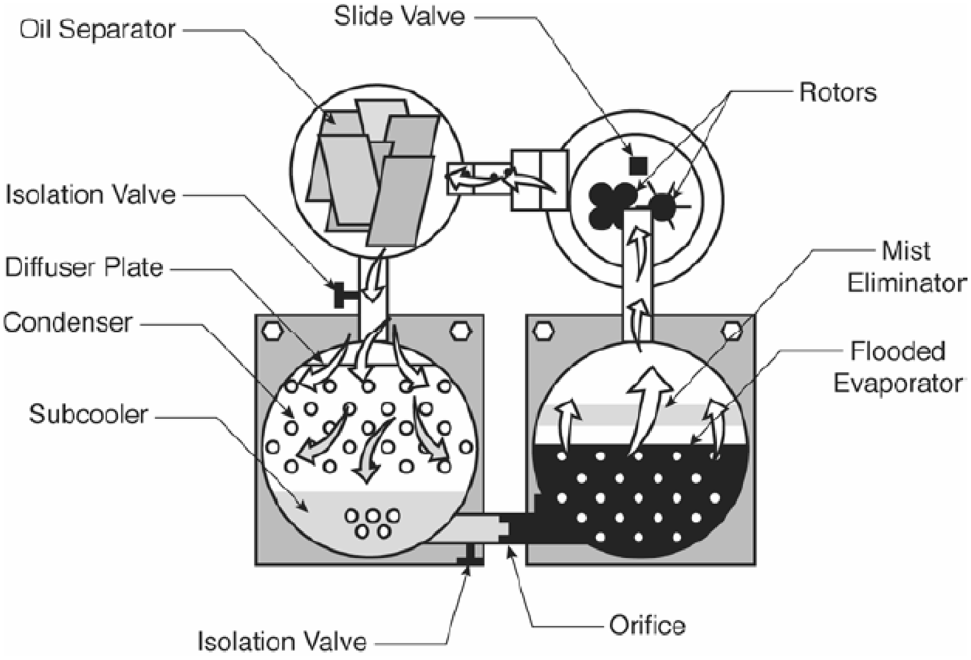

Figure 5-3
Simplified Diagram of a Screw Compressor Refrigerant Cycle

As noted in Section 2.2.6, the selection of a refrigerant type and chiller design are directly related and are effectively part of the outcome of the project scoping report versus an input. This selection requires consideration of various factors such as thermal efficiency, environmental and personnel safety, material compatibility, and vendor/industry/site experience. A long-range refrigerant management plan for the station, as discussed in Section 5.1.1, can help direct decisions regarding the selection of refrigerant types for replacement chillers.

Refrigerants:

As noted in Section 2.2.6, refrigerants used in new chillers have been changing for decades. The past phasing out of both CFCs and HCFCs are now being followed by plans to discontinue use of HFC refrigerants in favor on new compounds that avoid ozone depletion as well as global warming potential as a greenhouse gas.

Regulation of chiller refrigerant began with ozone depletion concerns. The Montreal Protocol established dates to phase out the production of refrigerants based on their ozone depletion. Chlorofluorocarbon (CFC) refrigerants, such as R-11 and R-12, had the greatest adverse impact on ozone and were classified as Class I ozone depleting substances. The CFC refrigerants were phased out of production first (by 1996). Many of the CFC refrigerants were replaced with hydrochlorofluorocarbons (HCFCs), such as R-22 (also used in several refrigerant blends including R-410A and R-402A), R-123 and R-124. The HCFCs have a much lower ozone depletion impact than CFCs, and are Class II ozone depleting substances. Due to their lower ozone depletion impact, the HCFC phase-out of production and import of these materials was targeted for a later and longer time period starting in 2004 and completing in 2030 (for developed countries) [76].

The hydrofluorocarbon (HFC) refrigerants, such as R-134a and R-410A, have been determined to have no ozone depletion impact and are therefore not restricted by the Montreal Protocol. However, the HFC refrigerants were determined to pose a concern as a greenhouse gas. The Kyoto Protocol of 1997 established reduction targets for greenhouse gases, which included HFCs. The subsequent phase-out of HFCs to reduce their potential global warming impact is underway. The United States Environmental Protection Agency (EPA) has proposed phase-out of new chiller use of HFCs by 2024. Amendments to the Montreal Protocol have been proposed in 2016 to freeze the production and consumption of HFCs in the U.S. and the European Union by 2018, and reduce them to 15% of 2012 levels by 2036.

Alternative refrigerants have continued to be developed to minimize both ozone depletion and global warming concerns, such as the hydrofluoroolefins (HFOs) and blends which are currently used in automotive applications. "Next generation" HFO refrigerants are available that have ultra-low global warming potential and have no foreseeable regulatory restrictions. Both the replacement refrigerants and associated chiller equipment technology are available to support the proposed and pending changes. However, the evaluation of replacement refrigerants for nuclear safety related service applications will require significant field experience, test data, and understanding of thermal properties, material interactions, and potential safety concerns.

Chillers operating with obsolete or phased-out refrigerants have remained viable due to the regulations that required discontinuation of the production of a refrigerant allowing it to remain in use via recovery, recycling, and inventory stockpiling. These actions have been found to provide an effective means to continue operating chillers with refrigerants whose production was been phased out decades ago [76].

A summary of past and future refrigerant phase-outs as well as conversions is noted below [76]:

- R11, R12, R113, R114, R115, and R500 refrigerants were phased out in 1996
- Some sites converted R12 to R134a and R11 to R123
- No conversions are available for R113, R114, R115, and R500
- R22 and R123 phase-out is in 2020
- R134a phase-out is expected in 2024 (pending final rulings or orders)
- Conversion of R123 to R514A is projected to result in 0.25% efficiency loss
- Conversion of R134a to R513A is projected to result in 4% efficiency loss

Refrigerant Conversion Comments:

While suitable "next generation" refrigerants have been identified for possible conversion of low and medium pressure machines, the replacement options for higher pressure refrigerants are projected to be slightly flammable. This could introduce significant safety evaluation issues for refrigerant conversions of some chillers, pending site specific applications.

It is important to evaluate the impact of a refrigerant change on the performance and reliability of a safety related chiller over the full range of design conditions, and not assume impacts at lower loads are conservatively bounded by the full-load derating. Differences in the refrigerant boiling points and properties result in equipment performance impacts beyond just heat transfer capability and efficiency. Performance impacts for refrigerant conversions may be stated in terms of the full-load capability of the chiller, but may not reflect performance problems impacting chiller stability/reliability at low loads. A station has reported that in addition to the planned/expected performance derating associated with a refrigerant conversion, they have also experienced greater problems with oil migration, oil recovery, and foaming issues at low/partial load operation. Since nuclear safety related chillers tend to be over-sized to a greater extent than non-safety related chillers, as discussed in Section 5.1.2, their normal operating window is in the low/partial load condition. Some replacement refrigerants utilize a blend of multiple refrigerants in an effort to replicate performance of an obsolete refrigerant. Periodic sampling/testing of the blend may be needed to ensure the refrigerant ratio remains within allowable limits.

Refrigerant Leakage Reporting:

Changes to Section 608 of the U.S. Clean Air Act for reporting and record keeping requirements for refrigerant leakage and releases are pending. New requirements to track leakage of HFCs, lower leakage reporting thresholds, required leakage inspections, as well as requirements to replace equipment if the system has leaked >75% of its charge for 2 consecutive years. Thus, an increased emphasis on equipment leak tightness will be needed to reduce overhead costs associated with leak tracking, reporting, and the possibility of regulatory driven equipment replacement [76].

5.1.1 Refrigerant Management Plan

The station and the utility may have a refrigerant management plan dealing with the long-range plan for refrigerant obsolescence, inventory, and usage. To the extent such plans exist, they should provide input and guidance to the chiller replacement/upgrade project. If such plans have not been established, then establishing them in conjunction with the project scoping is a consideration.

In addition to the long-range refrigerant management plan noted above, the development of an integrated site plan to address critical chiller reliability, obsolescence, and replacement is also a beneficial practice. To the extent such plans exist, they should provide input and guidance to the chiller replacement/upgrade project. If such plans have not been established, then establishing such a plan as part of or in conjunction with the project scoping report could be considered. An integrated plan could address variables such as:

- Critical chiller composite list (both safety related and non-safety related)
- Refrigerant: Types used, availability, stockpiled inventory and use rate
- Vendor/Manufacturer Consistency: training, maintenance procedures, parts, familiarity, technical support
- Obsolescence/Support/Parts: Mechanical and Electrical/Instruments/Software/Controls

A long range chiller plan, with associated management approval and integration with the site's capital planning process should assist in the prioritization and scheduling of chiller upgrade and replacement projects. The plan will require periodic updates to reflect changes in vendor support, parts availability, funding, schedules, equipment reliability, and industry experience.

5.1.2 Cooling Load – Limits and Min/Max Range

The cooling load for the application impacts the type of chiller selected, as well as size, cost, electrical demand, and related factors. The extent to which the stated cooling load matches actual operating conditions during warm weather periods will vary according to the safety classification of the chiller. Properly specifying the full range of operating conditions and loading is also important, and is absolutely vital for safety related applications to ensure the optimum compressor type and load control options are selected.

Chiller efficiency is a significant consideration for most commercial and industrial applications, due to operating costs, but is primarily of interest in nuclear applications only for safety related service. For safety related chillers the interest in efficiency is not operating cost due to electric power usage, but emergency diesel generator loading considerations. Diesel electrical loading margin at many stations has become constrained and there may be considerable interest in margin recovery if chiller power demand can be reduced. The efficiency of replacement chiller hardware typically has improved over what is currently installed, and a change of compressor types may also provide improvements in electrical load per ton of cooling. The replacement HFO refrigerants are less efficient than the previously used CFC, HCFC, or HFC refrigerants. However, in most cases the reduction in replacement refrigerant efficiency is outweighed by efficiency gains with other components, resulting in a net efficiency improvement for the replacement chiller.

Options to reduce the required capacity or size (i.e., cooling requirements) of the replacement chiller typically involve one or more of the following approaches:

1. Reanalysis – most likely to be beneficial for safety related chillers
2. Testing of existing chiller (determine heat load and efficiency)
3. Adjust/relax limits at temperature extremes (i.e., room temperature, etc.)

Reanalysis:

Significant conservatism typically exists in the room heat load calculations performed for nuclear plant control rooms and other facilities. The cooling load calculation methods in the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) Fundamentals Handbook [102] have evolved over the subsequent years, as have the recommended input for heat loads, which have combined to reduce assumed heat loads in current analysis of the same structures. Opportunity may exist to reduce the extent of conservatism in the original heat load analysis with more detailed and accurate information, while still maintaining an appropriate amount of margin in the design.

Reducing excess conservatism to provide more accurate maximum heat load not only reduces the size of the chiller and associated diesel generator load and cooling water flow requirements, but may also improve the reliability of the replacement chillers by allowing smaller, more closely matched to actual load, chillers to be purchased. A chiller that is better matched to its actual load is likely to experience more stable operation, be less prone to trips and may have less wear-and-tear than one operating near the lower extreme of its control range [42]. Cycling of oversized chillers has been a contributor to failures and accelerated damage rates. NRC Information Notice 94-82 [43], *Concerns Regarding Essential Chiller Reliability During Periods of Low Cooling Water Temperature*, is directly related to this issue (see Section 14).

All safety related chillers must be oversized due to the need to ensure safety function (i.e., cooling) capability under the most limiting combination of environmental and operating conditions. Performance analysis and sizing of the equipment assumes the design limiting or worst case condition for condenser flows, fouling factors, cooling water temperature, and tube plugging/blockage. Each of these parameters is independently maintained with margin against the design limit, which results in oversizing with a perfectly matched heat load analysis. There are limits to the practical extent to which conservatism in the sizing of safety related chillers can be reduced while still bounding design conditions. The use of simplified and less accurate input assumptions, which result in increased chiller sizing well beyond actual loads, has been found to be detrimental to chiller reliability and maintenance service life. The heat load calculation often is the largest and most cost-effectively addressed cause of chiller over-sizing.

Chiller Testing:

Performance testing to determine the actual heat load being rejected by a chiller can provide useful information for the replacement project scoping. Utility personnel may not have information on the heat duty removed by the chillers they are monitoring or the range between minimum and maximum loading. Determining the amount of heat rejected by a water cooled condenser or picked up by a chilled water system may be obtainable, depending upon access constraints. The heat rejected by the condenser reflects both the heat removed from the space being cooled and the energy added by the chiller. The efficiency of the chiller can be expected to be lower at partial load (which is a given condition for a safety related chiller), but chiller efficiency can also be reduced by degraded/malfunctioning components. Obtaining additional data and performance of a more elaborate test may be justified.

More sophisticated field thermal performance testing of chillers as well as testing of control room heat-up following a loss of normal cooling have been conducted at nuclear plants. This information may be beneficial for chiller load analysis, updates to room heat load analysis, as well as dynamic heat-up rates. The dynamic heat-up analysis could be used to support increased operator response time for loss of cooling (i.e., both trains OOS), such as to support an LAR to allow restoration time for one train of cooling in the event both trains were OOS, as discussed in Section 2.2.3.

Obtaining performance data which reflects the actual house loads the chiller has supported over an operating cycle, with seasonal variations, can provide valuable insight to the vendor regarding the range of actual operating load compared to the design specified load requirement.

Limit Adjustment:

Changes to both the normal chilled water temperature and maximum chilled water temperature may allow selection of a slightly smaller chiller (i.e., sized more appropriately for actual load) while still bounding the extremes of the conservative analysis and design basis conditions. The design chilled water temperature and requirements for it to remain at the design value under worst-case loading and conditions have been found in some cases to have been unnecessary design constraints for satisfactory performance of the safety function. Analysis showed room temperatures remained acceptable for equipment qualification as well as personnel occupancy with higher chilled water temperatures under design limiting conditions.

Operating Range Considerations:

The range of operating conditions and loading must be clearly defined. As previously noted, safety related chillers are always over-sized, the extent of which varies.

For water cooled condensers, the range of cooling water temperature variation is of interest. This is particularly true when the condenser is cooled by an open cooling water system (e.g., "raw water") versus a closed cooling water system. In addition to the maximum condenser cooling water temperature, the minimum temperature should be considered as well. Numerous problems have occurred associated with chiller reliability when operating with low cooling water temperatures, as noted previously and in Section 14. The ability to maintain stable and reliable chiller control with low condensing water temperatures should be carefully considered. Testing should be used to validate control stability with low cooling loads and minimum cooling water temperatures.

The maximum condenser cooling water temperature at the guaranteed minimum flow (and maximum fouling and number of plugged tubes) determine the required chiller condenser size. Safety related chillers must address the maximum temperature for the Ultimate Heat Sink (UHS) whether the condenser is cooled directly by an open cooling water system, or by a closed cooling water system that subsequently rejects its heat to an open cooling water system. Stations with a recirculating UHS may have peak water temperatures following a design basis event that are significantly higher (i.e., +15-20°F) than the temperatures experienced during normal plant operation. Numerous stations have had to increase their maximum UHS temperature limit above the original design value. Accordingly, it may be prudent to evaluate the impact of a condenser cooling water temperature 2-3°F higher than the site's existing peak UHS temperature as an alternate analysis case, unless the current peak UHS temperature is expected to remain bounding over the chiller's projected service life. The existing UHS temperature limit should be used as the design point analysis condition, but alternate conditions can be requested in the specification.

The ability of safety related chillers to operate at low cooling loads with excessive condenser cooling capability (e.g., <40°F water) should be carefully considered in the chiller selection process. The minimum load range of the compressor, the mechanisms utilized by the design to operate at minimum load, how the compressor functions below the minimum load value (i.e., stop/start operation), and industry experience problems with low temperature/low-load operation should all be reviewed, discussed with the vendors, and meeting the described/agreed upon low load conditions included in the bid specification and testing requirements.

5.2 Sub-Components

The project must determine the proper balance between specifying the performance requirements and limitations for the overall assembly, leaving the vendor significant latitude in selecting/specifying the sub-component details, versus also defining/specifying details for the various sub-components on the skid. Considerations regarding this balance are noted in Section 5.2.1

For safety related chiller applications, there are numerous electrical, mechanical, and structural design requirements that must be retrofit onto the commercial equipment and will apply to each of the sub-components that support the safety function. The commercial grade dedication process utilized for the chiller is summarized in Section 4.2.3. Specialized vendors are routinely relied upon for this service.

Various service conditions may warrant detailed design requirements for the chiller sub-components for both safety related and non-safety related chillers. Examples of such service conditions include:

- Outdoor location of non-safety related chillers may influence materials, design (i.e., severe duty rating), sealing, use of coil coatings to improve corrosion resistance, or relocation of controls/panels away from the skid to a nearby building.
- Open cooling water supplied to the chiller condenser, depending upon water quality and treatment (e.g., salt or brackish water, high suspended solids, biologics, etc.) will influence materials and design margins for the condenser as well as the type, materials, and location of components used to regulate low-load operation (e.g., flow control valves). Frequent access for cleaning may impact the location, clearances, physical size, and use of marine waterboxes for ease of cleaning (with added impact to connecting cooling water piping design).

5.2.1 Custom Specified or Vendor Standard

There are positive and negative aspects regarding detailed specification of separate components in the chiller assembly or skid. Positive aspects include the ability to clearly define fabrication details, materials, testing, and other aspects to obtain high quality and long service life components for the application. The incorporation of site-specific as well as industry operating experience can provide useful improvements to components to ensure their performance in a nuclear plant environment, with the applicable monitoring and periodic testing actions, will meet the reliability needs of the station. Most commercial and many industrial applications are much more tolerant of occasional chiller failures than nuclear plant critical service applications. The comparative ease of access, cost of maintenance/repairs, and availability of chiller vendor service contracts results in a normalization of design reliability around this tolerance level since those customers represent effectively the entirety of the market share.

Some standardization practices may not be supportive of improved reliability over the entire range of operating loads desired by a nuclear plant installation. Because large chillers can be significant energy consumers there has been an understandable focus on improving efficiency. Some design features involving refrigerant bypass/recirculation may support reliable operation over a wider load range but at the expense of net efficiency. Design changes by chiller manufacturers have included an emphasis of maximizing efficiency, which may have narrowed the acceptable range of operation or reliability at low load conditions. Specifying part-load optimization of the chiller may improve the control stability at lower cooling loads.

The selection of standardized chiller assembly designs typically provides a higher confidence in the long-term reliability of the equipment matching performance seen in other commercial and industrial services, and should improve spare part availability as well as vendor technical support. The value of a "proven" or standardized design includes having previously addressed problems and issues with individual components/parts or the interactions between components or instruments. The new design of any highly integrated equipment assembly typically encounters some degree of trouble-shooting and problem solving to achieve consistent reliable operation. Changes to major and minor components and sub-components must be reviewed carefully not in context of the individual component but how it integrates with all of the other interacting components in the chiller assembly. The complexity of such an evaluation may exceed the design team's ability to fully perform due to limited information related to that purpose. In which case, greater reliance is required on testing evolutions to verify chiller performance.

5.2.2 Motor

The compressor motor is one of the key components of the chiller assembly. 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, resulting in higher costs for repairs and added difficulty in performing some predictive maintenance monitoring actions. A semi-hermetic compressor contains the compressor and the motor in a bolted housing and is available for servicing. Both the hermetic and semi-hermitic motor designs benefit from motor cooling provided by the chiller and the avoidance of dust/dirt buildup with the associated periodic cleaning maintenance, as well as elimination of couplings and shaft seal maintenance (and refrigerant leakage potential) for open-drive motors.

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 [11]. The seals for an open-drive compressor are a potential source of refrigerant leakage, which should be considered in context of the proposed changes in leakage reporting described in Section 5.1, as applicable to the refrigerant type selected.

The range of air temperature, humidity, and cleanliness at the installation location are all typically included in the purchase specification and influence the selection of the best choice of motor design for the service conditions.

Figure 5-4
Example of Centrifugal Chiller with Hermetically Sealed Motor

Motors for safety related applications may have additional design and qualification considerations, such as environmental qualification (EQ) (depending upon the chiller location), seismic qualification, as well as the effects of voltage and frequency variations associated with operation using emergency diesel generator backed power. Considerations for both safety related and non-safety related applications include ease of maintenance, robustness of design (bearings, lubrication, safety factor/windings, etc.). The range of air temperature, humidity, and cleanliness at the installation location are all typically included in purchase specifications. The vibration level associated with the type compressor should be considered in context of the need for vibration isolators or other mounting details to minimize potential vibration related damage. Information on the natural frequencies and vibration analysis for the motor/compressor set and overall skid is of interest.

The use of a safety related motor specification for non-safety related chillers in critical service applications has been used to improve quality control. Inspection, hold or witness points during the motor manufacturing and/or testing phases have been included in specifications to ensure quality and performance prior to receipt by the chiller supplier. EPRI reports 3002000809 [5], *Guide for the Specification of Replacement and Spare AC Squirrel-Cage Induction Motors Having Voltage Ratings Up to 600V*, and 1020625 [6], *Guidance for the Replacement of Large Electric Motors at Nuclear Power Plants*, include additional information specific to the specification and purchase of replacement electric motors.

The use of a variable frequency drive is an additional option associated with the drive and controls. This option introduces some benefits as well as significant added complexity to the design and testing. The availability of comparable nuclear experience would also be limited.

5.2.3 Cooling Water Quality and Material Selection

The condenser tube material selection is of increased importance if supplied by an open cooling water system. Open cooling water systems result in much greater susceptibility to ID pitting and corrosion issues as well as fouling considerations. Copper alloy tubes are commonly used with minimal issues in closed cooling water systems, but have had much more widely varied reliability and service life in open cooling water systems [4]. EPRI reports 3002000542 [7], *Guidance for Replacing Shell-and-Tube Heat Exchangers at Nuclear Power Plants*, and 1025275 [9], *Guidelines for Replacement Materials for Service Water Systems*, provide additional insights regarding heat exchanger tube material selection and specification for open cooling water systems.

If the chiller vendor/supplier will be responsible for tube material selection, the specification should include chemical analysis of the water quality in both the evaporator and condenser, as well as the bounding limits for potentially detrimental chemicals/materials in the water supply either based on chemistry procedure limits for closed water systems, or monitoring results for open cooling water systems. Instrumentation, if it will be in contact with the water sources, must also be compatible with the specified water quality.

Tube plugging limits desired to support maintenance and equipment aging/degradation must be specified by the purchases. Smaller limits of $\leq$5% are typically suitable for closed water systems (i.e., component cooling water and chilled water). Larger limits may be prudent for open cooling water systems, pending water quality, tube material, and macrofouling experience with the system.

5.3 Design Basis Input Changes

Since this report addresses replacement of an existing chiller, the information from the original purchase specification or procurement documents (non-safety related) should be available. Accordingly, the design inputs for the chiller should be reviewed, if available.

Safety related chillers may warrant review of the originally specified design requirements and conditions to ensure they are consistent with the station's current design and licensing basis. Improvements to existing design, such as the elimination of manual operator actions to restart the chiller following a power disturbance, have been achieved in some cases.

5.3.1 Electrical Design Additional Considerations

The use of a more efficient chiller design may allow a replacement chiller to provide the same amount of cooling as the original chiller with a lower electrical load. This may restore margin to the electrical load analysis for the emergency diesel generators. If the original chiller was marginal in size and a larger capacity unit is selected, then the use of more efficient units may avoid or minimize impact on diesel generator load margin. As noted in Section 5.2.1, newer chiller designs may have achieved part of their efficiency gain at the expense of features that supported operation at low/partial loads. Since almost all safety related chillers are required to be significantly over-sized relative to normal loading, the ability to operate at reduced load should be carefully considered in the design. Similarly, if features are added to the base chiller design to accommodate a wider range of operating load, they should be carefully reviewed (and possibly validated with testing) with respect to their impact on rated efficiency at the design load case.

Chiller overhauls, particularly those involving conversion from an obsolete to a replacement refrigerant will need to carefully evaluate the potential loss of efficiency and associated re-rating of the chiller.

Increases in chiller sizing that result in greater electrical loading than the existing equipment require impact reviews for breaker/switchgear sizing, cable sizing, protective relays, and similar items in accordance with the site’s modification review process.

The replacement of safety related chillers should consider the impact of voltage and frequency variations allowed by the site’s license basis when vital power is supplied by diesel generators. A review of design and license basis documents as well as industry response documents for this issue, such as WCAP-17308-NP [57], is necessary to ensure the purchase specification accurately reflects the appropriate range of design basis conditions applicable to system operation.

Additional electrical design and/or field equipment lessons learned from chiller replacement projects include:

- Maintaining the locations for electrical connection points can avoid need for new conduit runs and cable pulls or splices.
- Ensure the electrical cable insulation is adequately protected from or designed to withstand abrasion and similar damage where it enters motor terminal box.
- Overhaul, inspection, testing, or replacement of the motor starter, breaker/switchgear, and associated electrical supply components in conjunction with the chiller replacement or overhaul project are recommended to rebaseline the service life clock for the electrical supply equipment.

5.3.2 Mechanial Design Additional Considerations

In addition to the mechanical design related topics previously discussed in Sections 5.1 and 5.2, the following topics are noted for consideration.

Condenser Cooling Water Flow Range

Differences exist between the design point condenser cooling water flow and normal system flow for safety related versus non-safety related chiller applications. For non-safety related chillers, the design point flow is likely to represent the normal maximum available flow for summer or most-limiting conditions. This is consistent with most process industries and commercial applications. The design point flow for a safety related chiller represents a guaranteed minimum available flow for design calculations. Actual available flow is typically maintained much higher, particularly for open cooling water systems, due to the guaranteed flow bounding the effects of flow measurement accuracy, pump degradation, alternative system alignments/loads, strainer clogging, minimum pump bay levels, and/or other variables. This higher normally available condenser cooling water flow may influence tube velocity considerations (e.g., erosion/corrosion damage to copper alloy tubes), tube-side pressure drop (e.g., partition plate differential pressure), and cooling water control valve sizing (if used for condenser pressure/temperature control). Accordingly, specifications for safety related chillers should include in addition to the design point condenser cooling water flow the expected normal and maximum flow conditions supplied to the chiller.

Condenser Fouling Factor

The fouling factor in the replacement specification for the chiller condenser cooling water is often unchanged from the original specification. Safety related chillers that are cooled by an open cooling water system (i.e., Essential Service Water) may be subject to regulatory commitment actions (such as NRC Generic Letter 89-13 [103] in the U.S.) to ensure the required heat removal capability is maintained. The project team should verify that the fouling factor specified for the replacement chiller is consistent with the fouling factor used elsewhere in the system. If the design fouling factor specified for the replacement chiller is lower than what is generally used for other heat exchangers in the open cooling water system, then a technical basis or justification is recommended to document how the lower fouling factor will be maintained.

Cooling Water Control Valves

The water regulator modulates the quantity of the water passing through a water-cooled refrigerant condenser in response to the condensing pressure. The regulator consists of a valve and actuator, which may be electric, pneumatic, or may utilize other means of valve stem movement control. A three-way regulator or bypass valve is similar to the two-way valve except it has an additional port to bypass water around the condenser.

The selection of the design and materials for the regulator or bypass valve are influenced by the cooling water system being open or closed. Few problems are likely to be encountered with closed cooling water service. Open cooling water system water quality varies significantly between stations, according to the water source and system design. If the condenser is cooled with an open cooling water source, it is vital that the design and operation of a cooling water control valve carefully consider the potential for fouling/clogging of the valve with macrofouling debris and/or the condenser by debris or sedimentation. Macrofouling should consider both external sources common to the water source as well as intra-system sources such as detached corrosion nodules, according to station history/experience. A wide variety of valve trim/cage assembly designs exist, with different macrofouling susceptibilities. Valves with multiple small openings are more readily clogged versus designs with progressively larger openings as the valve stroke proceeds towards full-open. The strainer opening size for once-through open cooling water systems is a design constraint to be recognized for downstream components as well.

Chilled Water

System designs using chilled water need to evaluate chiller replacement impacts to the chilled water system. The chilled water system design parameters of flow and design supply temperature need to be communicated in the specification. The available range of chilled water flow should be noted. The chilled water system pressure drop in the chiller assembly (i.e., evaporator and piping) must be considered against available system margin and controls. Other changes associated with the modification could include revised heat load analysis, chilled water control temperatures, and other variables beyond the chiller assembly.

Chiller Vibration:

Chillers are often a high vibration equipment skid. INPO document IERL4-14-30 [88], Analysis of Vibration-Induced Piping and Tubing Leaks, warrants consideration during the design phase as well as the installation and testing phases. Points of interest for chiller projects include, but are not limited to:

- Most piping or tubing leaks occurred due to failure to address susceptibility to vibration-induced fatigue in the design, testing, or field installation.
  - Long segments without sufficient support
  - Cantilevered connections not checked for vibration
- The modification process did not require formal inspection and documentation of vibration in the range of design operating modes during post-modification testing.
- Vibration analyses did not include connected small-bore piping or tubing
- Tubing wall thickness selection did not consider vibration, resulting in failures from “normal” system vibrational effects.
- Copper tubing has been replaced after vibration related failures with stainless steel tubing
- Post-modification inspections should include observation for vibration during all modes of operation, where practical.

An example of an incident related to the above involved chiller instrument tubing which was inadequately field supported, resulting in leakage and past operability concerns [74]. Some of the content of interest includes:

- A 22 drop per minute oil leak was discovered on instrument tubing for Essential Chiller A Compressor Low Oil Pressure Switch
- The tubing had been tie-wrapped to adjacent piping. Friction from normal system vibration had worn through the tubing at the contact point.
- A previous change to the chiller assembly added isolation valves for the pressure switches and field routing of new tubing. The package specified "field routing" of tubing and did not address tubing supports.
- The design input step for supports was incorrectly dispositioned as not applicable. As a result, no tubing support requirements were specified, no clearance requirements to adjacent components were specified, and no post-installation inspections of acceptable tubing attachment or vibration was specified

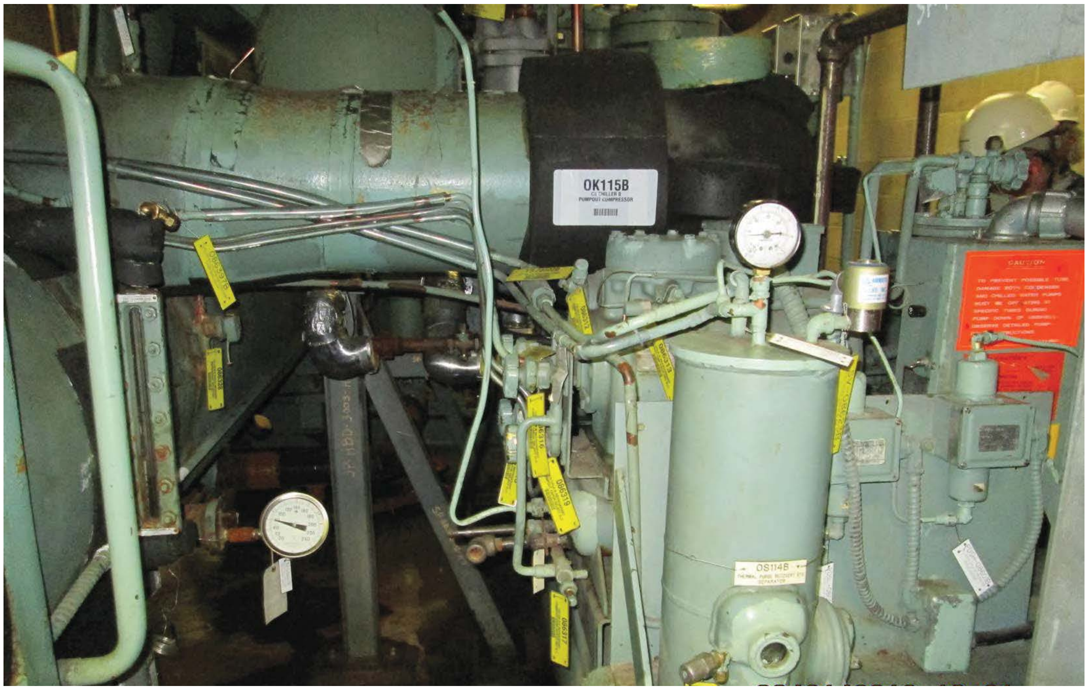

Figure 5-5
Poorly Routed and Supported Chiller Tubing Prior to Refurbishment

Figure 5-6
Chiller Tubing After Refurbishment

5.3.3 Civil Design Additional Considerations

A review of civil design attributes involving weight, anchorage and rigging plans is applicable to both safety related and non-safety related chiller replacements. Safety related chillers must also address changes to the seismic design analysis and qualification, pipe stress analysis changes for piping changes and/or nozzle loading, as well as seismic two-over-one (II/I) reviews for the rigging path or new installation location, if applicable. If the interfacing safety related piping systems (e.g., system providing condenser cooling water) are to remain operable during the replacement, then pipe stress operability may require review for the temporarily disconnected piping. EPRI guidance is available in reports such as TR-105849 and TR-112579 [15,16].

The connection interfaces to the chiller assembly are an important consideration. The pipe size, schedule/rating, material, location/orientation, and joint type (i.e., welded, flanged, threaded, etc.) must all be matched or changes addressed. For non-safety related chillers, there is much greater likelihood a "pre-packaged" or standard chiller assembly will be selected, in which case the interconnections to plant piping are modified to match the standard connections for the purchased unit. Safety related chillers may use standard equipment, but the chiller assembly/skid may need to be customized and can more readily be configured to match the existing plant connection configurations. This may involve design iterations to balance considerations of adjustments necessary to support the rigging plan, the new chiller equipment selected, and desire to minimize the need to modify and reanalyze safety related piping connection points.

The cost of seemingly minor connection relocation for safety related piping has been found to be significant for some projects. Pipe stress reanalysis may require the use of different (i.e., current) guidance/methods and changes to software models due to obsolescence. These changes may result in unacceptable nozzle loads requiring modification of pipe supports extending some distance from the chiller. Congestion of piping, electrical conduit and cable trays, HVAC ducts, and other interferences in the vicinity of the needed changes may result in cost and schedule impacts to the project due to the associated piping and pipe support modifications.

The condition of interfacing open cooling water piping also warrants review. This review should consider the piping materials, water quality, and station experience.

Ease of installation should be addressed in the replacement chiller design, based upon how and where it will be installed. Layouts, lift/rigging plans, and space limitations should be communicated to manufacturers so appropriate features can be included in the design to facilitate handling and installation. Walkdowns provide a way to share installation issues with potential vendors during the design/bid phase of the project. Examples of design features that can enhance the ease of installation of a chiller include:

- Coordinating the location of lifting and rigging points on the chiller assembly with the rigging plan.
- Ensuring outline drawings establish the exact location of nozzles and supports (review original setting plan documents, perform laser survey, compare results to drawings, etc.)
- Marking the center of gravity
- Adding features to assist with the movement and transport of the chiller

As noted in Section 2.2.4, the rigging plan for installation of replacement chillers must be evaluated in the project scoping phase to identify the extent of interference removal and/or redesign of the chiller assembly. Figures 2-2, 2-3, and 2-4 in Section 2.2.4 depict replacement chiller assemblies fabricated in sections to limit the amount of interferences to be addressed.

Some of the rigging and lifting devices necessary to support installation of the replacement chillers could be left as permanent changes to support future maintenance needs for equipment overhaul.

5.4 Operating Environment/Conditions

The description provided in the original chiller specification for the operating environment such as indoors/outdoors, temperature range, humidity, etc. can be updated to reflect any changes to the design parameters. If the chiller is being relocated, then the conditions applicable to the new location must be provided in the specification.

Non-safety related chillers may be located in an outdoor environment. In addition to temperature, humidity and water ingress considerations, outdoor locations should address sunlight exposure issues. In addition to the adverse impacts to control panels discussed in Section 4.2.7, degradation of plastics, insulation and other materials have resulted from sunlight exposure. Motors located outdoors or other areas with elevated ambient temperatures may require severe duty ratings to ensure adequate cooling and winding life. Clogging of air flow passageways is another consideration for outdoor equipment, which can be from a variety of air borne materials, insects, spiders, etc. Coastal stations may need to address added corrosion concerns and electrical contact issues resulting from salt residue in wind, storms, etc.

Additional location considerations for the replacement project include:

- Physical protection may be warranted for tubing, instruments, display panels or other parts, if the chiller is located near high traffic, outage lay-down/staging locations or other potential sources of incidental/inadvertent contact.
- Noise levels associated with chiller operation may be a consideration if the chiller is near a normally or frequently attended location. Changes in operating noise level in the selected location (i.e., may be higher than in vendor test shop) should be considered with respect to hearing protection needs/postings in the area as well as personnel ability to hear speakers, alarms, annunciators, or other audible messages.

5.5 Obsolescence – Life Cycle Management

Obsolescence issues for the chiller hardware are fortunately not as dynamic or fast-paced as those encountered with controls, but remain an important life cycle management consideration for a chiller replacement project. Vendors/suppliers may not agree to long-term (or short-term) guarantees of parts availability.

Historical practice often left these issues to the maintenance organizations with support provided by engineering and procurement groups. Projects that address life cycle management related issues such as preventive maintenance actions, projected rebuild or major repair frequencies, parts identification (and availability for long-lead items), as well as agreement on warehouse inventory stocking levels provide the station the ability to take over operational as well as long-term maintenance ownership of the replacement equipment.

5.6 Maintenance, Operations and Training Considerations

Accommodating access for chiller is a consideration to be addressed to the extent practical. As noted in Section 5.3.3, non-safety related chillers are more likely to be purchased as a standard prefabricated assembly, which affords little opportunity for changes to accommodate maintenance access. Safety related chiller assemblies are more likely to be customized and therefore can more readily incorporate changes for ease of maintenance. The following represent examples of communications and considerations related to ease of operating, monitoring, and maintaining the chiller:

- Request input from operations and maintenance personnel regarding access issues with the existing chillers to obtain insight for improvements.
- Valve location, to the extent possible, as well as handle or handwheel orientation should allow ease of operation.
- Provide clearance/minimize interferences for removal/replacement of major components such as compressors and motors
- Maintain clearance around the chiller for access. If one side of the chiller is to be against a wall, ensure the placement and orientation of valves, instruments, etc. reflect the lack of access to that side of the chiller.
- Require any special tooling necessary for the installation, operation or maintenance of the chiller, including sub-components, to be identified and provided by the vendor.
- Safety guards may be customized to include transparent sections for visual access or hinged windows to allow insertion of monitoring probes.
- Specialized instruments or connections to support performance monitoring by operations, maintenance, chemistry, or engineering. Examples could include motor testing, actuated valve testing, oil analysis, sampling, thermal performance testing, vibration monitoring, etc.
- The number and size of vents and drains for evaporator and condenser filling/venting activities.
- Route pipe in the overhead when possible, away from walking/working areas.

Considerations for the training of operations, maintenance and engineering personnel for the new equipment, controls, etc., should include the initial training needs for turn-over of the equipment as well as on-going training needs. Vendors may be able to provide training videos or conduct training courses for the equipment. The chiller assembly used for mock-up testing and seismic qualification shaker testing (safety related chillers) could be retained as a maintenance training tool.

6

DEVELOPING BID SPECIFICATIONS AND REQUESTS FOR PROPOSALS

The specific technical inputs that both define and constrain the design are discussed in Sections 2, 4 and 5. This section addresses more general aspects of the bid specification development and request for proposal.

An earlier EPRI report [27] dealing with digital upgrades states, "*…studies of software based systems have concluded that a large fraction of the problems characterized as software errors are more correctly attributed to* ***problems in the requirements specifications, such as errors, omissions, inconsistencies, and ambiguities****. The experience of nuclear utilities seems consistent with this review, in part, from ill-defined and inadequately verified requirements*." The applicability of this statement extends beyond software and digital control systems to the overall component as well. Chiller replacement projects have encountered significant delays, difficulties and problems at least partially attributable to inadequate specifications.

Achieving a high quality component that is capable of functioning properly over the full range of operating conditions is not assured solely by a detailed specification, but it may easily fail to be achieved solely due to an inadequate specification.

6.1 Bid Specifications

The original specification is likely to be of only limited use for the hardware, and likely to be of even less usefulness regarding the controls. Older specifications may refer to designs and materials that are no longer relevant. The previously specified service conditions and requirements may not reflect current system design or operating conditions, or only specified the maximum load performance requirement. A new specification or a comprehensive revision to the existing specification should be assumed by the project team.

The early phases of a chiller replacement project are likely to require multiple rounds of iterative processes to develop the technical and testing requirements for the replacement chiller and/or associated controls. This begins in the project scoping phase which may yield a specification outline, followed by extensive vendor communication to select the chiller design, type of controls, and testing to be performed in order to prepare the initial draft specification for the request for proposal bid phase. A subsequent round of specification changes may be needed to incorporate vendor exceptions, comments, feedback, and agreed upon details prior to the procurement phase. Perceived schedule pressure combined with a potential comfort level with a vendor "knowing" what is needed may result in the final specification having an inadequate level of detail. Extensive communication between the project team and vendor is necessary and beneficial, but it is also necessary to capture key details that have been discussed, described, and agreed upon by the two parties in the specification and/or purchase documents.

Emphasis on the chiller's ability to perform over entire range of operating conditions is needed, particularly for safety related chillers, as discussed in previous sections. Vendor testing to validate this performance capability also needs to be clearly identified. With multiple components in a chiller assembly required to function as an integrated system, reliability is dictated by the "least common denominator", in other words reliability of the whole is only as good as the LEAST reliable component in the assembly. Reliability should consider the off-normal operating conditions, frequency and duration of service and standby periods, response to faults or problems, and the consequences of component failure for the specific application.

6.1.1 Technical Requirements and Operating Conditions

The technical requirements in the replacement chiller specification should include:

- Performance requirements include cooling load, flow rates, condenser cooling means (air or water) with associated temperature ranges, fouling factor, and available flow for water cooled condensers.
- The full range of load conditions, temperatures, and flows to be reliably accommodated by the design should be included (not just maximum load, maximum temperatures, etc.)
- Design pressure and temperature for the interfacing fluid systems (i.e., condenser cooling water, chilled water, etc.) should be provided to ensure the ratings for chiller equipment meet or exceed those values.
- Tube plugging limit for the heat exchangers should be specified
- Dimensional constraints for both the installed location and rigging path.
- Water quality, including ranges, for condenser cooling water and chilled water (if applicable)
- Special material requirements, such as to handle water quality/treatment issues with open cooling water source, should be identified based on site experience
- Electrical supply and connections information
- Controls requirements (see Section 4)
- Special sub-component requirements (See Section 5)
- Safety related design requirements, as applicable, such as seismic, EQ, accident response and conditions, etc.
- Service environment (see Sections 4.2.7 and 5.4)

Other technical procurement requirements that might be specified include the following:

- Special manufacturing/fabrication processes
- Coating requirements
- NDE
- Storage and staging requirements to prevent degradation
- Request for spare and replacement part information
- Means of design verification
- Plant-specific drawings/supplier drawings and revision level
- Shelf life requirements (replacement gaskets or coating repair materials)
- Accommodations for special lifting and handling (e.g., lifting lugs, trunnions, or holes)

The level of detail appropriate in the technical description is affected by:

- The role of the supplier in the equipment design
- The complexity of the design
- The chiller safety classification/function

The project team should work closely with the system engineer (and component engineer if applicable) as well as maintenance and operations personnel in developing the range of service conditions for the specification as well as for input on performance and reliability problems encountered with the chiller being replaced (and other chillers at the site).

Sections 4 and 5 include additional detail and considerations regarding the technical requirements, operating environment, interface, and control parameters for the chillers.

Safety-related chillers may invoke requirements from regulatory accepted design standards, such as ANSI/ASME AG-1 [98] and/or ASME Section III [99] in the U.S., for the design, fabrication, construction, and testing requirements. The applicability of the design standards may vary according to the design and licensing basis for the station and existing equipment.

6.1.2 Quality Requirements

The quality requirements specified for a replacement chiller should be commensurate with the component's quality classification and failure risks. The quality requirements should be clearly defined in the purchase specification. These requirements translate into the necessary supplier controls over manufacturing, design, and purchasing activities as well as CGD processes that govern adherence to the specified technical requirements. The specification should also delineate QA program responsibilities between the project team and various organizations in the supply chain.

Quality requirements do not take the place of or substitute for technical requirements. Chillers may fabricated or dedicated under an acceptable quality program but may also be technically inadequate for the application.

Specific quality requirements may focus resources on design attributes critical to the chiller's performance and reliability. The purchase specification may request the manufacturer to identify design options and quality control test/inspection actions to improve reliability. Acknowledging that reliability improvement options will be weighted in the bid evaluation process can incentivize the vendor to maximize quality/reliability instead of minimizing cost in order to be awarded the purchase contract.

To ensure appropriate quality requirements are passed on and specified correctly throughout the supply chain, it is necessary to understand the chiller vendor's use of sub-suppliers for materials and components.

The licensee's specific quality commitments for CGD from its QA program and UFSAR, as applicable, should be included.

Quality requirements in the procurement specification typically include the following:

- QA program documents submitted for project team review.
- Frequency and types of supplier audits is specified or requested from the CGD vendor.
- Source inspections and the witnessing of tests is specified for processes affecting design or performance attributes for which the quality cannot be readily confirmed by other methods. (For guidance on available methods, see ANSI N45.2.13) Suppliers should be aware of the frequency of inspections and the degree of inspector access during manufacturing. Industry experience should guide for the scope and frequency of verification activities.
- The scope of verification activities performed upon receipt of the chiller should be described to allow the supplier to coordinate resources needed for the receipt inspections.
- Other special quality requirements may include:
  - Personnel qualification and certification
  - Requests for sub-supplier inspection/audit/surveillance/sampling controls
  - Cleanliness verification requirements

The following items warrant consideration for their impact on the ability of a supplier to fully comply with the procurement specification:

- Recent changes in senior management
- Changes within the QA organization
- Designation of a new QA manager
- Recent acquisition of the supplier by a larger organization
- Negative recent industry experience or regulatory violations involving the supplier's quality

6.1.3 Supplier Documentation

In general, supplier documentation is required to furnish the project team objective evidence that the technical and quality requirements have been met. Documentation should be considered a tool in the verification of an item's technical adequacy and quality compliance, but it should not be used without confirmation of its validity.

Supplier documentation requirements should correlate with the specified technical and quality requirements and be specific as to content. Care should be taken not to request excessive documents or test reports that are unlikely to be of future value for reference information.

Certificates of conformance should not rely solely on generalized statements such as "This item meets the requirements of the purchase document." The documentation should contain specific statements enabling the purchaser to verify specified requirements. The project team should be involved in the acceptance process.

The range of supplier documentation typically includes, as applicable, the following:

- Supplier drawings, procedures, and specifications
- As-built dimensional drawings
- Instruction manuals (including maintenance recommendations)
- Certified material test reports
- Nondestructive test reports
- Personnel certifications and qualifications
- Inspection reports
- QA manuals
- Certificates of conformance/compliance
- Recommended spare/replacement parts lists
- Factory Acceptance Testing (FAT) results
- Seismic qualification test results (as applicable)
- Software V&V
- Control system mock-up test results (as applicable)
- Performance testing results (if specified)

A submission schedule should be provided to inform the supplier when each document is to be submitted to the project team for review. Retention time of records may be specified as well as the quality and legibility of the records.

6.1.4 Special Procurement Requirements

Additional special requirements in the bid specification may include:

- Access requirements for inspection/audit/surveillance
- Performance of sub-supplier's inspection/audit/surveillance/sampling
- Special processes and/or cleanliness requirements

6.2 Request for Proposal

At this stage of the project, the project team should have completed a conceptual design study and have a basic understanding of the type of replacement chiller to be installed and the related system performance parameters. The project team should compile known design basis and system operating parameters and communicate them to potential suppliers in a request for proposal, or what is commonly referred to as a *bid specification*.

The project team should communicate the following information to potential bidders:

- The scope of work (equipment only, equipment and installation, and so on).
- The design and performance parameters for the existing chiller.
  - Identify information that exceeds design basis requirements
  - Identify the full range of loading and operating conditions for which the chiller is to properly operate. This includes min/max of temperatures, flows, fouling, heat load, electrical frequency and voltage, etc.
- The bid specification for the replacement chiller, including:
  - The anticipated supplier interface, including walkdown planning, pre-bid meetings, and bid submittal schedule.
  - A schedule for replacement.
- Commercial terms and conditions (fixed price, progress payments, time and material, incentives and penalties, etc.).

6.3 Installation and Construction Specification

The need for an installation/construction specification, and its level of detail and scope, will vary according the complexity of the installation, outage schedule impacts, and the organization performing the replacement. For less complex applications where the project team will install the chiller, work package instructions developed per existing site procedures may suffice.

The installation and construction are not typically performed by the chiller vendor.

The following issues may warrant inclusion in the installation/ construction specification:

- Scope/boundaries of components to be removed (typically communicated on drawings)
- Sequence of removal/installation steps
- Description of interface points and work associated with connecting interfaces
- Description of modifications (temporary and permanent) on adjacent systems or components
- Plan/section drawings, schematics, and movement diagrams depicting the removal of the old chiller and the installation of the replacement
- Lifting and rigging plans for both the old and new chillers
  - Special lifting/handling requirements
- Quality Control (QC) inspections required during the installation of the new chiller
- Post-installation tests required, and acceptance criteria
- Personnel qualification requirements for labor, inspectors, and riggers used for installation
- Special tools or scaffolding required to install the new chiller
- Codes and standards applicable to the installation work
- Personnel safety and ALARA issues
- Requirements for the submission of an installation plan and schedule
- Description of organizational interfaces and roles/responsibilities among organizations comprising the installation team
- Storage/staging requirements (power, air, lighting, and so forth)
- Reference to applicable procedures of the installation contractor

Many of the preceding installation issues are discussed in more detail in Section 12 of this report. They are listed here to support communication of issues resolved between the project team and the chiller vendor in the specification document(s).

7

SUPPLIER QUALIFICATION AND SELECTION, BID EVALUATION, AND PURCHASING

7.1 Supplier Selection and Qualification

In general, the selection of a supplier should be based on their ability to provide items in accordance with the procure document requirements. Engineering should perform sufficient research of potential suppliers to assess their technical and manufacturing capabilities. Industry experience with the potential suppliers should be investigated. This research should result in a manageable number of potential bidders and should help optimize the bid evaluation process.

To understand each supplier’s capabilities, it is important to specify the technical requirements for the replacement chiller and to ensure the bidders understand the quality expectations.

7.1.1 Selection of Procurement Sources

Section 4 of ANSI N45.2.13 recommends that supplier selection be based on evaluation of their ability to provide items in accordance with the procurement document requirements. The standard also requires that procurement source evaluation and selection measures include integrated actions involving one or more organizations (such as engineering, construction, manufacturing, operations, purchasing, and QA) based upon the item being procured.

Methods to be used in evaluating supplier sources and the results should be documented and include one or more of the following:

- An evaluation of the supplier’s history of providing satisfactorily performing products
- The supplier’s current quality records, supported by documented qualitative and quantitative information that can be objectively evaluated
- The supplier’s technical and quality capability as determined by a direct evaluation of its facilities and personnel, plus the implementation of the supplier’s QA program

7.1.2 Supplier Qualification Status

ANSI N45.2.13 states in part that the licensee is responsible for the “evaluation of supplier’s quality assurance program to assure that it is appropriate and satisfies the requirements for the items or services being purchased”.

If the chiller is being procured from a supplier with whom the licensee has experience, the project team should verify the supplier's qualification status by reviewing the approved suppliers list (maintained by the QA organization). The QA organization should be consulted regarding actions needed for a new supplier.

7.1.3 Supplier Quality Program Capabilities

The project team should confirm the supplier has the technical capabilities to meet the specification requirements and QA programs to ensure those capabilities are implemented consistently. Project teams should recognize the potential variations between supplier QA program capabilities. Furthermore, a supplier's commitment to a given QA program does not guarantee reliable performance of the manufactured component. If the supplier's QA program does not meet the licensee's requirements, the project team is responsible for addressing the shortcomings to achieve the necessary level of QA, or another supplier should be selected.

The results of a supplier evaluation should be made available to engineering for review. The supplier evaluation confirms the supplier has the necessary technical capabilities and QCs, and they are being implemented properly.

Section 2 of ANSI N45.2.13 recommends that measures to control procurement of a replacement component are established and include appropriate planning. The ANSI standard, which looks at many key elements of the process involved in replacing a major plant component, states in part:

> Planning shall result in the documented identification of methods to be used in procurement activities, sequence of action and milestones indicating the completion of these activities, and the preparation of applicable procedures prior to the initiation of each individual activity listed below. Planning shall provide for the integration of the following:
>
> - Procurement document preparation, review and change control
> - Selection of procurement resources
> - Bid evaluation and award
> - Purchaser control of supplier performance
> - Verification (surveillance, inspection, or audit) activities by the purchaser
> - Control of non-conformances
> - Corrective action
> - Acceptance of item or service
> - Quality assurance records
> - Audit of procurement program

Another factor not explicitly described in ANSI N45.2.13 that should also be considered is the division of QA programmatic responsibilities between the project team and various organizations in the supply chain. These factors are discussed in more detail in the following section.

7.2 Bid Evaluation and Award

7.2.1 General Guidance

Section 5 of ANSI N45.2.13 states in general that each licensee should establish a documented system for reviewing and evaluating bids and awarding of contracts. This process should be used to evaluate the bids for a replacement chiller. Figure 7-1 illustrates the general process for supplier selection and bid evaluation that is implemented by many utilities.

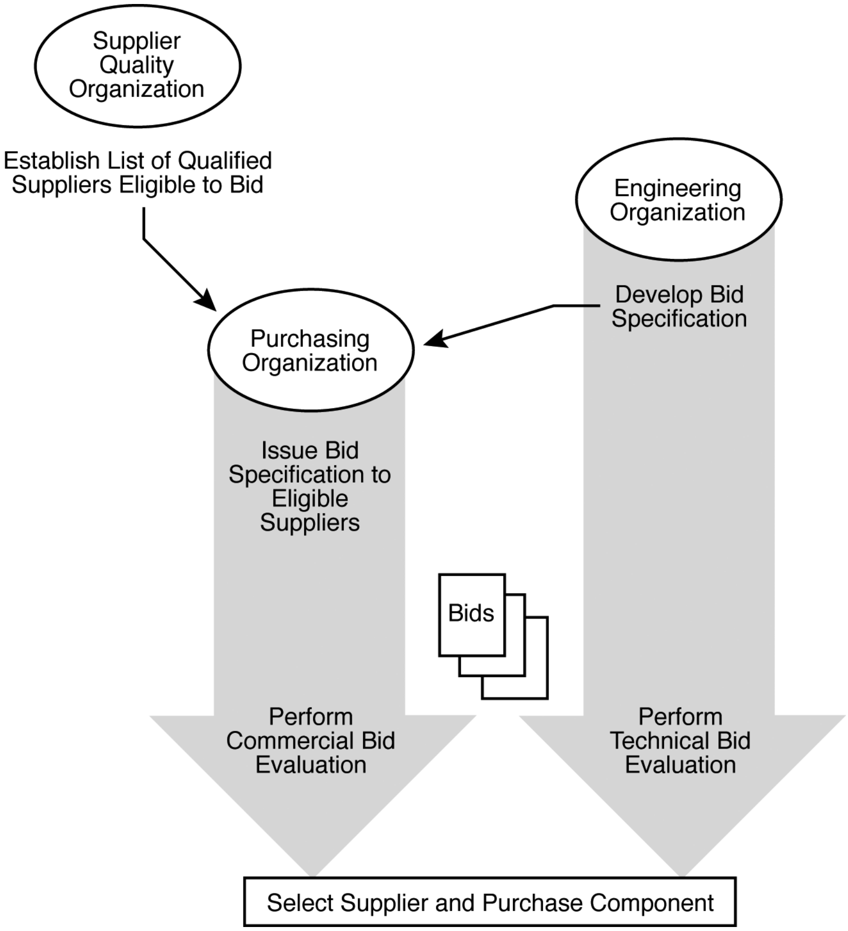

Figure 7-1
Supplier Selection and Bid Evaluation

Figure 7-1 illustrates that the licensee's QA organization is typically responsible for the initial qualification and screening of potential suppliers. After requests for proposals are issued, the bid evaluations are performed jointly by the licensee's purchasing organization and engineering organization. In most cases, the engineering organization evaluates the technical aspects of each bid, and the purchasing organization evaluates the commercial terms and price of each bid.

Bid evaluations should be made by individuals or organizations designated to evaluate the following subjects, as applicable to the type of procurement and replacement component:

- Technical considerations
- QA requirements (such as the supplier's quality program capabilities, establishment of witness hold points, and manufacturing surveillance)
- Supplier's personnel
- Supplier's production capability
- Supplier's past performance
- Alternate designs for consideration
- Evaluations of exceptions to the bid
- Schedule adherence
- Operating experience

Although not quality-related, other factors that might be considered include the following:

- Equipment purchase price and price adjustments
- Supplier experience/reputation/recognition in the nuclear industry
- Manufacturing facility location
- Ease of doing business
- Commercial terms and conditions
- Warranties

7.3 Purchasing Issues and Considerations

The project team should recognize that not all issues will be presented and resolved during the bid evaluation phase, and some may arise after the contract has been awarded. The issues noted in Sections 7.3.1–7.3.4 are also included in Section 3 of this report with respect to the overall project management responsibilities of the project team. They are reiterated here to emphasize the importance of resolving them prior to the start of fabrication.

7.3.1 Licensee Schedule Demands

One of the first nontechnical issues that should be addressed early in the procurement process is the schedule for the design, manufacturing, testing, receiving, and installation of the replacement chiller. All licensees have a process for planning and scheduling work activities, but for a chiller replacement project, the process is much more extensive than planning and scheduling routine maintenance activities.

7.3.2 Manufacturing Lead Times

Another major issue affecting the selection of a supplier and, subsequently, the procurement of the replacement chiller is the manufacturing lead time. The manufacturer must either custom manufacture or adjust an existing standard chiller design for the purchaser's procurement specification requirements. Large chiller lead times of 9–12 months have been reported.

The project team should determine if the supplier is capable of meeting the desired delivery dates as part of the initial qualification of the primary supplier (and sub-suppliers). Guaranteed lead times should be negotiated as part of the commercial terms. By the time a supplier has been selected and a purchase order placed, the project team should need only to confirm lead times with the supplier to ensure the chiller can be delivered to meet the demands of the site.

Manufacturing lead times can vary because of influences beyond either the manufacturer's or owner's control. The user of this report should recognize that premiums might be required to expedite delivery of the replacement chiller.

7.3.3 Commercial Terms and Conditions

Negotiating commercial terms and conditions is typically not an engineering function. Purchasing organization normally resolve these types of issues. Special commercial considerations can include the following:

- Delivery, title, and risk of loss
- Performance incentives
- Warranty limitations
- Limitations of liability
- Indemnity
- Resolution of non-conformances and arbitration process
- Component cost
- Transfer/shipping/routing of the chiller
- Transfer of responsibility during shipment, receipt, storage/staging, and installation
- Type/schedule/frequency of document reviews
- Quantified level of oversight by the project team
- State laws
- Type of contract, payment terms, and invoicing
- Performance warranty

7.3.4 Procurement Document Preparation, Review, and Change Control

The development of the procurement specification should be a continuation and refinement of the bid specification. The procurement specification should be finalized upon completion of the bid evaluation and qualification and selection of the replacement heat exchanger supplier (see Section 6 for detailed guidance).

Consistent with licensee procedures and their regulatory bases, the project team should verify applicable regulatory requirements, design bases, and other requirements necessary to ensure adequate quality are included or referenced in the chiller procurement documents.

The engineering organization should ensure the procurement specification translates the design requirements into procurement requirements.

When the supplier has been selected, the project's engineers should refine the specification as needed to clearly communicate technical and quality requirements. The supplier's capabilities to meet these requirements should also be documented. Additional guidance is provided in Section 3 of ANSI N45.2.13.

7.4 Exceptions to the Purchase Order

Purchase orders awarded through competitive bidding are less likely to have the manufacturer take exceptions to the requirements. The bid process provided an opportunity to evaluate and resolve issues prior to the purchase order being awarded. Technical or commercial exceptions to purchase order requirements are more common when the purchase order is awarded sole-source, without competitive bidding. In these cases, the vendor/manufacturer is seeing the purchase requirements for the first time when the purchase order is awarded.

7.4.1 Technical Exceptions

The project's engineering organization should lead in resolving technical exceptions. Input from maintenance and operations may assist in reaching a feasible solution to the issue. Purchasing agents or non-technical employees are not responsible for resolving technical exceptions.

Technical exceptions that can arise during the specification and procurement of a replacement chiller could include the following requirements:

- Performance requirements
- Technical requirements:
  - Requirements in industry codes and standards
  - Physical and chemical material properties, in accordance with ASTM and/or ASME
  - Dimensional requirements, including tolerances
- Special manufacturing/fabrication processes

- Requested drawings/details (proprietary designs)
- Software content for control systems (proprietary designs)
- Shipping, packaging, and storage requirements
- Request for spare and replacement part information
- Means of design verification
- Shelf life requirements
- In-storage maintenance requirements

7.4.2 Commercial Exceptions

The station's/utility's purchasing procedures and processes should address actions and responsibilities for resolving commercial exceptions to the purchase order. In some cases, input from the project team members may help resolve a commercial exception.

7.5 Acceptance Planning

Ideally, acceptance planning should begin during the specification and procurement of the replacement chiller. This affords the project team the opportunity to plan the types of schedules for verifications with the selected manufacturer (and third-party organizations, if needed) in advance of final design and fabrication. After the supplier and final chiller design have been selected, however, the project team should finalize the scope and frequency of acceptance activities, including any of the following:

- Additional or ongoing audits of organizations in the supply chain
- Source verification activities (hold and witness points) which may be at the vendor facility
- Receipt test/inspection activities
- Post-installation tests/inspections

Section 10 of ANSI N45.2.13 states in part that the licensee shall:

> "Establish the method of acceptance of an item or service being furnished by the supplier. Prior to offering the item or service for acceptance, the supplier shall verify that the item or service being furnished complies with the procurement requirements. Where required by code, regulation or contract requirement, documentary evidence that items conform to procurement documents shall be available at the nuclear power plant site prior to installation or use of such items regardless of acceptance methods."

When a major component like a chiller is replaced, it is recommended that all of the acceptance activities listed previously be used to some extent due to the complexity of the item. Of these methods, source verification involves acceptance during the fabrication of the replacement item and is discussed in more detail in this section.

Section 6 of ANSI N45.2.13 states in general, that a licensee should retain the responsibility of monitoring and evaluating supplier performance to the procurement document requirements. The methods provided might include the following:

- Establishing an understanding between the project team and the supplier of the provisions and specifications of the procurement documents
- Requiring the supplier to identify planning techniques and processes to be used in fulfilling procurement document requirements
- Reviewing documents that are generated or processed during activities that fulfill procurement requirements
- Identifying and processing necessary change information
- Establishing a method for exchanging information contained in the procurement document between the project team and the supplier

Depending on the complexity or scope of the replacement chiller, the project team should initiate pre- and post-award activities. These activities, which can take the form of meetings or other forms of communication, establish the following:

- An understanding between the project team and the supplier of the procurement requirements
- The intent of the project team in monitoring and evaluating the supplier's performance
- The planning, manufacturing techniques, tests, inspections, and processes to be used by the supplier in meeting procurement requirements

Project team notification points, including hold and witness points, should be identified and documented based upon mutual agreement between the supplier and the project team. These activities should be implemented as early as practicable in the procurement process. The depth and necessity of pre- and post-award activity depends on the uniqueness, complexity, procurement frequency with the same supplier, and past supplier performance for the specific component covered by the procurement document.

7.6 Supplier Certificates and Documentation

7.6.1 Supplier Certification

After a supplier's QA program capabilities and implementation have been evaluated and found to be acceptable and contractual terms have been established, the project team can request certification from that supplier as objective evidence that the specified QCs were implemented and that purchase requirements have been met.

Section 6 of this report discusses the types of quality requirements that can be specified for a replacement component and the types of documentation typically furnished by the manufacturer.

ANSI N45.2.13 provides the following guidance regarding the receipt of a supplier's certificate of conformance:

> Where not precluded by other requirements, documentary evidence may take the form of written certificates of conformance which identify the requirements met by the items. Where certificates of conformance are used, the following minimum criteria shall be met:
>
> a. The certificate should identify the purchased material or equipment, such as by the purchase order number.
>
> b. The certificate should identify the specific procurement requirements met by the purchased material or equipment, such as codes, standards, and other specifications. This may be accomplished by including a list of the specific requirements or by providing, on-site, a copy of the purchase order and the procurement specifications or drawings, together with a suitable certificate. The procurement requirements identified should include any approved changes, waivers, or deviations applicable to the subject material or equipment.
>
> c. The certificate should identify any procurement requirements that have not been met, together with an explanation and the means for resolving the non-conformances.
>
> d. The certificate should be attested to by a person who is responsible for this quality assurance function and whose function and position are described in the purchaser's or supplier's quality assurance program.
>
> e. The certification system, including the procedures to be followed in filling out a certificate and the administrative procedures for review and approval of the certificates, should be described in the purchaser's or supplier's quality assurance program.
>
> f. Means should be provided to verify the validity of supplier certificates and the effectiveness of the certification system, such as during the performance of audits of the supplier or independent inspection or test of the items. Such verifications should be conducted by the purchaser at intervals commensurate with the supplier's past quality performance.

Receipt of supplier documentation in general, and a certificate of conformance in particular, should be an integral part of the acceptance plan for the replacement chiller. However, acceptance of any major plant component based solely on the receipt of supplier documentation is not recommended. Instead, the project team should consider using all of the means available to ensure that the chiller is conforming to its design requirements and that it will perform all of its design and safety functions. These acceptance methods, detailed in ANSI N45.2.13, should be considered during the development of the specification, during the bid evaluation, and throughout fabrication, receipt, and installation.

7.6.2 Supplier Documentation

The project team's engineering personnel should interface closely with the supplier so that the design is suitable for the chiller's intended service conditions. Design interface should result in a qualified and suitable final chiller design, and the supplier should be required to furnish the documents necessary to demonstrate the suitability of the design as well as supporting information regarding its installation, operation, and maintenance. These documents, which constitute design outputs from the supplier and inputs to the design modification process, are usually requested by the project team in the final procurement specification. They might include any of the following:

- Supplier drawings, procedures, and specifications
- As-built dimensional drawings
- Supplier instruction manuals (including maintenance recommendations)
- Certified material test reports
- Nondestructive test reports
- Personnel certifications and qualifications
- Inspection reports
- QA manuals
- Certificates of conformance/compliance
- Recommended spare/replacement parts lists
- Software reports
- Electrical connection, schematic, control, and logic drawings
- Factory acceptance test reports
- Motor baseline tests
- Heat exchanger tube baseline NDE reports and inspection data
- Vibration analysis data
- Seismic qualification reports
- Commercial Grade Dedication package

8
FABRICATION OVERSIGHT

8.1 Establishing Witness and Hold Points

As noted in Sections 6 and 7, witness and hold points communicate to the manufacturer what attributes need to be verified before fabrication resumes and at what point in the manufacturing process those critical attributes can be verified most effectively. Although included in the bid specification and considered during the bid evaluation, the witness and hold points should be revisited after supplier selection and prior to fabrication. The project team should finalize the scope of oversight activities and ensure appropriate individuals are designated and authorized to approve the activities witnessed during hold points.

System engineer and maintenance personnel involvement with vendor testing is beneficial, including reviews of test plans and observing selected test activities.

8.2 Manufacturing Surveillance

Manufacturing surveillance is a vital step in ensuring the quality of the replacement component. When acceptance planning requires licensee source verification, it should be implemented to monitor, witness, or observe manufacturing at the organization in the supply chain that is best qualified to evaluate the activities. Source surveillance might require the assignment of personnel to a supplier’s facility.

Manufacturing surveillance is a type of source verification that affords the project team an opportunity to observe a special process that renders or imparts a critical attribute to the replacement chiller. Processes that are often observed can include any of the following:

- Welding
- Assembly
- Machining
- Testing

The level of manufacturing surveillance should be based on the following factors:

- Unique and highly specialized components tend to require more surveillance to ensure that the unique design features conform to the established, qualified design.
- Adequate supplier certification/capabilities can eliminate the need for additional surveillance by the project team. Conversely, if the supplier's capabilities are lacking, the project team should consider increased surveillance activities to confirm the component conforms to its design requirements.
- Design functions and reliability of the replacement component.

8.3 Witnessing Tests and Inspections

Similar to manufacturing surveillance, source inspection should be implemented in accordance with plans to perform inspections, examinations, or tests at predetermined points. Source inspection might require the assignment of personnel to a supplier's facility. The tests and inspections listed in this section should be considered when replacing a major plant component like a chiller and might be required by codes, standards, or the owner's procedures.

Typical customer oversight activities during fabrication/assembly/testing of a chiller might include any of the following:

- Pre-inspection meeting
- Seismic qualification testing (if applicable)
- Software tests (if applicable)
- Performance tests
- Documentation review/approval necessary for fabrication activities (drawings, calculations, inspection and test plan, procedures, and so on)
- Observation of special packing requirements (typically for international shipments)

Tests that may be performed after installation of the chiller include the following:

- In-service leak test
- Motor and compressor vibration analysis
- Performance tests

See Section 12.8 of this report for information regarding the scope of post-installation testing.

Project team members typically witness the Factory Acceptance Test (FAT) for the chiller. The performance parameters identified in the specification should be validated or demonstrated by the test scope. Acceptance criteria for the test results must be identified and agreed upon prior to the tests. Examples of testing oversight common for chiller projects include:

- Minimal and full load operation
- Baseline vibration profile (attendance or performed by site vibration program owner)
- Control system testing. (extensive testing may be involved for digital control systems)
- Safety shut down switch functions
- Site acceptance testing should also fully check the functioning of the chiller.
  - The vendor will typically be present for initial testing of the chiller in the plant, but it should addressed in the specification.

8.3.1 Establishing Acceptance Criteria

Prior to witnessing—or in some cases, prior to actually conducting—the test or inspection, the project team should coordinate with the chiller vendor/manufacturer to establish the mutually agreed upon acceptance criteria. The test/inspection should verify that the manufactured chiller or sub-component conforms to its required design values.

8.3.2 NDE

The project team should be aware of NDE required by the applicable material standards for the parts used to fabricate the replacement component. Additionally, the project team should determine which, if any, of these examinations/evaluations should be witnessed during source inspection. The scope of NDE will vary among components, and requirements should be specified in the procurement specification.

8.3.3 Shop Testing/In-Process Testing and Inspection

In the design and fabrication of a large, complex component like a chiller, the manufacturer performs numerous in-process tests as the subcomponents are produced and as the chiller assembly is integrated. These tests and inspections are typically performed at the manufacturer's facility, thus the term *shop testing* is used to refer to these types of verification activities. The in-process test or inspection is a means for the manufacturer to verify the acceptability of certain attributes of the sub-components and chiller that might otherwise be difficult or costly to verify once the entire component is fully assembled. They are also performed to verify the acceptability of subcomponents prior to being installed in the chiller assembly. Based on the function of the subcomponent and its significance to the chiller performance, the project team should establish a way to perform the verification actions as the subcomponent is being installed.

8.4 Manufacturer Non-Conformances

ANSI N45.2.13 Section 8 states in general that the project team and the supplier should establish and document measures for the identification, control, and disposition of items that do not meet procurement document requirements. The requirements for handling non-conformances are not limited to non-conformances discovered after receipt of the item, and as such the requirements apply to any uncorrected non-conformances discovered during the manufacture of the chiller and sub-components.

The project team should establish the most appropriate process/procedure for handling non-conformances discovered in the replacement chiller as part of the commercial terms and conditions of the procurement specification or purchase documents. In general, nonconforming items should not be released for shipment, unless agreement is reached for the item to be corrected at the station.

Non-conformances should be handled using a graded approach in which the project team is involved in resolving only those non-conformances that reach the threshold as determined in the final procurement specification. However, the project team should be made aware of and monitor all non-conformances arising during fabrication. Manufacturing non-conformances should be addressed in accordance with the following sequence of actions:

1. Review the type and extent of the non-conformance.
2. Notify the project team of the non-conformance (if occurring without the licensee present).
3. Oversee the licensee's acceptance of the disposition of the nonconformance.
4. Verify that the nonconformance was dispositioned properly.
5. Maintain records as appropriate.

8.5 Required Documentation

As noted in Section 6, the project team should specify the types of documentation needed to ensure that technical and quality requirements have been met by the manufacturer and other organizations in the supply chain, as applicable. Documentation should be considered a tool in the verification of an item's technical adequacy and quality compliance, but it should not be used without confirmation of its validity.

The types of supplier documentation specified should include, as applicable, the following:

- Supplier drawings, procedures, and specifications
- As-built dimensional drawings
- Supplier's instruction manuals (including maintenance recommendations)
- Certified material test reports
- Nondestructive test reports

- Personnel certifications and qualifications
- Inspection reports
- QA manuals
- Certificates of conformance/compliance
- Recommended spare/replacement parts lists
- Electrical drawings (connection, schematics, logic, etc.)
- Software (as applicable)

Receipt can take place during fabrication, final product testing, or receipt of the complete replacement chiller. In some cases, documentation specific to an assembly or subcomponent is received separately based on requirements in the design/procurement specification.

8.5.1 Review of Vendor Documents

The reviews of manufacturer's documents by the project team engineers should verify all dimensions are consistent on all drawings, in all specifications, and calculations submitted by the manufacturer. The dimensions specified for the chiller skid and connection points must be checked to ensure installation and fit-up issues are avoided and that they comply with the specification.

Mistakes may occur when information is copied from calculation sheets to drawings or from one drawing to another. Details may not be consistent between the overall chiller assembly drawing and other drawings of individual subcomponents. Another common source of error involves failure to reflect details revised on one drawing in other affected documents.

While manufacturers are typically familiar with applicable standards and Code requirements, this may not be true for additional requirements in the purchase specification. A careful review is warranted for all details or requirements required by the specification which are tighter or more restrictive than those required by the applicable codes and standards.

8.5.2 Review of Vendor Computer Programs

The extent of vendor computer/software programs used in digital control systems is per guidance documents in Section 4 of the report and EPRI report 3002002289 [26].

8.6 Cleanliness Requirements and Special Controls

The project team should determine the cleanliness requirements for the replacement chiller with input from the chemistry department for interfacing systems cleanliness requirements, such as for the shell and tube sides of heat exchangers.

The project team should make certain that appropriate inspection and verification steps are established prior to shipment and upon receipt of the equipment. Site foreign material exclusion procedure guidance will apply once the chiller assembly is received. Similar processes applied by the vendor should be reviewed/accepted by the project team.

Reference EPRI report 3002000542, *Guidance for Replacing Shell-and-Tube Heat Exchangers at Nuclear Power Plants*, [7] sections 7.6.2 and 7.6.3, for information on cleanliness requirements that may be applied to the heat exchangers supplied with the chiller assembly.

The specification should describe inert gas (i.e., nitrogen or similar) blankets for shipping as well as cleanliness and sealing requirements for electrical components.

9

SHIPPING

ANSI N45.2.2 Section 4 covers the requirements for loading and shipping items like a chiller. The standard describes environmental protection during transit, procedures to minimize damage in transit, precautions required when handling items during loading and transit, and identification and inspection of overseas shipments.

9.1 Shipping and Packaging Considerations

The need for physical protection because of movement or contact with other items during transit should be reviewed with the vendor prior to shipment. The following issues should be considered when determining the type and amount of packaging for a replacement chiller during shipping:

- The manufacturer's recommendation for packaging during shipment
- The physical size, weight, and overall configuration of the replacement chiller
- The shipping method
- The chiller's susceptibility to damage during shipment, including electronic parts
- Security requirements and inspections at points of shipment, entry, and/or receipt
- The possibility of theft and vandalism during shipment

In general, the mode of transportation used should be consistent with the protection classification of the item and with the packaging methods employed. Section 4.2 of ANSI N45.2.2 provides additional guidance on selecting and using open carriers, closed carriers, and special shipments.

ANSI N45.2.2, Section 4.2.2 states in general that the conveyance used for transport should be certified to be structurally adequate to take the loads imposed during loading, while en route, and during unloading. Prior to shipment, to ensure safe transit, the project team should investigate the route. The following additional transport issues may apply:

- State or local transportation routing requirements
- Need for escorts

For domestic transport, it is standard for a skid-mounted chiller to be shrink-wrapped, with its connection openings adequately covered and protected. For overseas shipments, the chiller can be containerized with bracing or export-crated (i.e., completely boxed).

Special coatings are typically not needed for exposed surfaces unless they are unpainted carbon steel. However, an assessment should be done. Consideration should be given to nitrogen purge/blanketing for the cooling water sides of heat exchangers, and other fluid systems not filled with their normal fluids. The use of sensing devices such as accelerometers during shipment can be discussed with the vendor. If used, acceptance criteria and response actions should be agreed upon in advance. A pressure gauge can provide monitoring capability for the nitrogen purge, if applicable.

Terminology used in the purchase specification related to shipping requirements, such as "suitably plugged" and "suitably protected", should be adequately defined. It is recommended to use specific wording for cleanliness criteria, preparations for short or long-term outdoor storage, acceptable covers for connection points, cabinets and other areas to be protected. The guidance in ASME NQA-1 Subpart 2.2 is a source for shipping details [32].

Section 4.5 of ANSI N45.2.2 provides guidance regarding shipments from countries outside the United States. Care should be taken to see that current Department of Homeland Security requirements are met.

9.2 Lifting/Handling Issues

When lifting and handling a chiller skid, the following should be considered:

- Loading. The weight, lifting points, or center of gravity indicated on the skid should be used to ensure proper handling during loading, transfer between carriers, and unloading.
- Rigging. Rigging requirements should be established by the project team prior to transport and handling of the chiller skid.
- Sealed openings should be inspected after loading to ensure all closures remain intact. Materials used for resealing should comply with applicable standards or procedures.
- The bracing and tie-down methods to be used should be specified.

If lifting lugs are provided, always use proper rigging rated above the published weight of the chiller assembly. The project team should confirm that heavy load issues and structural concerns are addressed in the handling plan for the new chiller. A detailed routing plan (i.e., load path) identifying the entire route of travel of a "heavy load" through the plant should be developed in accordance with site procedures. This plan should address the movement and transport of the chiller from the point it is off-loaded at the site until it is installed.

The project team should verify all points along the heavy load travel path are structurally sufficient to support the weight of the chiller. Documentation of analysis of the structural adequacy of the load path should be as required by site procedures. Additional support or rigging attachment structures may be needed either temporarily or permanently.

EPRI report *Lifting, Rigging, and Small Hoist Usage Program Guide,* is an available reference for lifting and handling requirements [13].

10

RECEIPT INSPECTION

As noted in Section 7 of this report, receiving inspection should be an integral part of the acceptance plan when replacing a chiller. The receiving inspection plan should verify the specified physical characteristics and that the replacement chiller is not damaged during shipment. ANSI N45.2.13 Section 7 [31] states:

> "When planning requires (licensee) receipt inspection, it shall be implemented and coordinated with source verifications performed. During receiving inspection, emphasis shall be placed on assuring that items have not sustained damage in shipment that would influence subsequent fabrication, construction, installation or end use. Sampling may be utilized during receiving inspection when conducted in accordance with established procedures or recognized standards. These measures shall also include provisions for dispositioning (i.e., accept, reject or hold) and handling of items received and services performed."

Receipt inspection should supplement the QA and verification actions performed prior to and during manufacture of the chiller to verify purchase order requirements are met.

10.1 Inspection Attributes

The inspection attributes can be instructions to verify the receipt of supplier documentation, as described in the procurement specification. In most cases, the supplier documentation provides objective evidence that certain physical and/or performance attributes of the replacement chiller have been verified as conforming to the manufacturer's design. The project may specify verification of physical or performance attributes through tests or inspection.

10.1.1 Documentation Review

ANSI N45.2.13 Section 7 states in part:

> "Receiving inspection measures shall include provisions for receiving documentation (such as drawings, certifications, test results and other materials) offered as objective evidence in satisfaction of requirements."

Receipt acceptance activities for the chiller primarily ensure appropriate and accurate documentation has been received in accordance with the procurement specification. Section 8.5.1 includes documentation review comments.

10.1.2 Testing and Inspecting

It is uncommon for physical and/or performance attributes of the chiller to be verified during a receiving inspection because the supplier (through audit or source verification) should have already verified them.

The project may specify testing or inspection of supporting items, such as:

- Spare/replacement items
- Consumables used during installation (weld rod, lubricants, etc.)

Similar to testing and inspecting the chiller, if receiving activities verify physical or performance attributes of auxiliary items (e.g., relief valves), the project team should establish acceptance criteria.

10.2 Site Testing and Inspection

Testing and inspecting requirements when receiving a chiller should be determined as early in the procurement process as possible through close coordination between engineering and QA.

Testing of subcomponents may include baseline NDE testing of the heat exchanger tubes and motor testing. These inspections may be performed at the chiller vendor facilities or after receipt at the site.

11
STORAGE AND STAGING

11.1 Storage Level Determination and Requirements

Station or utility procedures/processes are relied upon for the necessary controls to package, ship, receive, store, and handle incoming components and replacement parts. This guidance many have been taken from ANSI N45.2.2 [31] for U.S. nuclear licensees, with Section 2.7 of the ANSI standard providing detailed guidance on classifying a procured item with respect to protective measures to prevent damage, deterioration, or contamination of the item. For chillers, the storage level varies.

EPRI's *Packaging, Shipping, Storage, and Handling Guidelines for Nuclear Power Plants* [14] provides additional guidance that can be helpful when replacing a key plant component.

As part of the project planning, the project team should evaluate the adequacy of available storage/staging facilities and practices for larger components like chiller assemblies.

11.2 In-Storage Maintenance Activities

Depending on the length of time the replacement chiller will be in storage/staged prior to installation, the project team should determine the need for in-storage maintenance actions. The project team should coordinate with the manufacturer to determine what requirements might apply and how often these activities should be performed. EPRI's *Packaging, Shipping, Storage, and Handling Guidelines for Nuclear Power Plants* [14] stresses the need to consider in-storage maintenance requirements as a factor when determining the most appropriate packaging, shipping, storage, and handling of items.

For long-term storage, it may be appropriate to have the chillers shipped with a nitrogen versus refrigerant charge, or to remove the as-supplied refrigerant charge and install a nitrogen charge in the chiller equipment.

11.3 Licensee Lifting and Handling Capabilities

The project should address how the chiller will be moved from its mode of transport to its storage/staging area. Special lifting and rigging may be necessary. Detailed guidance is provided in the EPRI report *Lifting, Rigging, and Small Hoist Usage Program Guide* [13] and the manufacturer is an important source for lifting guidance. Site procedures should be used to determine lifting/handling methods, develop a lift plan, and to move the equipment to its storage/staging area.

11.4 Materials Management

An issue to be addressed by the project is ensuring the replacement chiller and its spare parts are controlled and tracked in accordance with site processes. In most cases, this will entail verifying the chiller and the associated subcomponents have been assigned equipment identifiers and the spare items have been assigned unique stock codes referenced to the equipment identifier.

Inventory unique to the replaced chillers should be removed from the system and disposed of if it cannot be used on other components. These stock codes/identifiers should be deactivated to avoid automatic reorder of obsolete parts and to avoid spare parts applicable to the replaced chiller being pledged against future maintenance work packages.

12
INSTALLATION

12.1 Pre-Installation Requirements

12.1.1 Optimum Access Route

As noted in Section 2.2.4, the project team should evaluate the access routes from the storage/staging area to the final location. The evaluation should consider:

- Structural adequacy of the load path
- Need for special lifting/handling equipment
- Impact of routing on plant equipment and any modifications needed to address interferences resulting from moving the replacement chiller into place
- Personnel safety and ALARA considerations
- Ability to change the orientation of the chiller during routing

12.1.2 Lifting and Rigging Requirements

Sources of lifting guidance include the manufacturer and a heavy load rigging contractor, if used. The lifting guidance must be implemented per the site's lifting and rigging requirements.

EPRI report 1007914, *Lifting, Rigging, and Small Hoist Usage Program Guide,* [13] provides generic information for lifting/rigging requirements. The first step is to confirm technical personnel have adequately planned and evaluated the lift. Under no circumstances should a lift rely solely on one individual's knowledge and/or experience. The verification of personnel qualifications and certifications is essential for implementation.

The report stresses that safe and effective lifting should be planned and evaluated. Typically, the evaluation includes the following as a minimum:

1. Determine the load weight.
2. Determine the load's center of gravity.
3. Establish the means to stabilize the load.
4. Consider the availability and use of special load-handling equipment (trunnions).
5. Consider clearances available and the load path.

6. Consider structural requirements for the load path.
7. Consider heavy loads issues.
8. Consider past history of similar lifts and lessons learned.

Each step of the process is detailed in the report. The consequences of a load drop should be considered when determining the factor of safety and degree of redundancy applied to the rigging evaluation.

12.1.3 Developing a Lift Plan

The lift plan can vary depending on the lift complexity, weight, criticality of lifted equipment, and load drop consequences. Lift plans may vary in the level of detail and degree of utility engineering involvement. Some lift plans are applicable to a single lift, while others are generic to a particular type of lifting/rigging equipment. Lift plans can be grouped as:

- Pre-engineered lift plans with significant engineering involvement
- Pre-planned lifts that are primarily driven by the scope of the work order
- Field-planned lift plans developed by craft personnel
- At-the-job lift plans developed for a particular lift

The lift plan might include a checklist and sketches or drawings to convey the conduct of the lift.

12.2 Interferences

Interferences should be identified in the project design phase. The use of optical scanning technology and three-dimensional models can assist in identifying and addressing interferences.

Cases of the physical plant not precisely matching design drawings have occurred, resulting in unexpected interferences. Field verification of any close-fit tolerances is a good project practice. The use of optical or laser scanning technology for field connection points and the as-built replacement chillers can identify potential fit-up issues or close proximity items in the rigging path.

12.3 Plant Conditions for Installation (On-Line Versus Outage)

Major chiller replacements in nuclear power plants may be performed with the unit on-line or in an outage, depending upon the specific system and station design, impacts to multiple units, and other similar considerations. If an on-line replacement is planned, careful review of the potential impacts to operating equipment and systems must be included with the project risk assessment. Section 2.2.3 includes additional schedule considerations and potential risk mitigation options for safety related chiller replacement projects.

12.4 Installation Expertise

As noted in Section 6, during the design/specification phase the project team should determine who is best suited to install the replacement chiller. In some cases it may be beneficial for the manufacturer's technical representative to be present during the installation activities.

12.5 Installation

12.5.1 General Guidance

The sequence of installation steps should be closely coordinated between the project team, the manufacturer, and the installer. The sequencing should include the following:

1. All necessary demolition work of existing equipment
2. Mechanical/electrical/I&C interface disconnects, protection, and rerouting, as needed
3. Design modification of existing SSC to accommodate the new chiller
4. Handling of the new component as it is moved through its access route
5. Chiller placement
6. Interface reconnections
7. In-process testing and inspection
8. Integration of activities into overall outage work schedule (a readiness review addressing the feasibility of the sequence is recommended)

12.5.2 Key Installation Issues

In most cases, installation issues are addressed in the procurement/design specification or the construction/installation specification. Key installation issues during chiller replacement include:

- Foundation preparation information may be provided by the manufacturer in the setting plan.
- Foreign material precautions should be in accordance with site foreign material exclusion (FME) controls, before connecting piping to confirm foreign objects are not in the pipes or components.
- Working space around the equipment should be sufficient for operations and maintenance.
- The design should ensure stresses from the pipe connections are within design analysis limits.
- Instrumentation on the chiller equipment should include instructions addressing installation, calibration, and testing.
- Scaffolding required should be coordinated with the work planners.
- Insulation should be installed, to the extent practical, prior to the installation.

Additional comments and considerations related to chiller installation are in Sections 5.3.3, 5.4, and 5.6.

12.6 Special QC Requirements

The project team should coordinate QC activities with the QA organization during the design and specification phase. Industry codes and standards may require certain QC actions during the installation. The equipment manufacturer and the installation contractor might also prescribe certain QC actions.

Activities requiring QC actions and documentation of satisfactory completion may include:

- NDE
- Witness and hold points for inspection and testing during the fabrication and/or installation processes
- Foreign material exclusion and control plans

12.7 Personnel Safety and ALARA

The project team should address personnel safety and ALARA issues during installation of the replacement chiller. Issues when replacing a major plant component may include:

- ALARA—minimizing radiation exposure
- Special shielding and personnel protection
- Working in proximity to equipment being lifted
- High temperature/humidity environment

The project team should ensure that personnel involved in the installation of the replacement component meet all applicable OSHA requirements.

12.8 Post-Installation Testing

The project team should ensure post-installation testing is conducted in accordance with the installation specification and/or the manufacturer's recommendations. The project team and manufacturer should work closely to establish the following:

- System operating conditions under which the chiller will be tested
- Acceptance criteria for performance
- The type of post-installation test(s) to verify performance
- Procedures and instructions for conducting the post-installation tests

- Qualification requirements for personnel conducting the prescribed tests
- Means of measuring the results of the post-installation test(s)
- Benefits of pre-service inspections and/or in-service inspections
- Instrumentation and calibration requirements

Post-installation tests and inspections conducted on chillers may include any of the following:

- Leak tests
- Thermal performance test
- Trip and alarm tests for setpoint and function
- Flow testing of condenser cooling water, chilled water, etc.
- Operational tests (including surveillance testing, if applicable)

Tests and inspections may also be required following the restoration of interferences removed to allow chiller installation.

13

MAINTENANCE STRATEGY

As previously noted in Sections 2.2.6 and 5.1, a long-range refrigerant management plan is a useful tool to assist stations and utilities with their use of existing and replacement refrigerant types, sharing plans between plants, availability changes, and the selection of refrigerant types for replacement chillers.

In addition to the long-range refrigerant management plan, an integrated site plan to address critical chiller reliability, obsolescence, and replacement is also a beneficial practice. To the extent such plans exist, they should provide input and guidance to the chiller project as well as to the chiller maintenance planning. If such plans have not been established, then establishing such a plan as part of or in conjunction with the project scoping report could be considered. An integrated plan could address variables such as:

- Critical chiller composite list (both safety related and non-safety related)
- Refrigerant: Types used, availability, stockpiled inventory and use rate
- Vendor/Manufacturer Consistency: training, maintenance procedures, parts, familiarity, technical support
- Obsolescence/Support/Parts: Mechanical and Electrical/Instruments/Software/Controls

A long range chiller plan, with associated management approval and integration with the site's capital planning process should assist in the prioritization and scheduling of chiller upgrade and replacement projects. The long-range chiller plan may also incorporate major maintenance schedules for the important chillers at the station.

13.1 Preventive Maintenance Changes

Chillers include a variety of components which are subject to degradation and require Preventive Maintenance (PM) to provide acceptable reliability. All nuclear utilities are expected to already have a PM program, which has been applied to the chiller being upgraded or replaced. Changes to the existing PM basis may be warranted for the replacement chiller due to changes in design, materials, margins, etc. Guidance for PM of Digital control equipment is available in EPRI report 3002000502 [30].

The project team should coordinate with the site PM group, system engineers, maintenance, and component engineers to determine the appropriate changes to the PM tasks for the replacement chiller. Obtaining industry experience input from other stations with the same or similar chillers provide useful experience based information for such decisions. Sufficient review of the differences in the application, location, duty cycle, service load, materials, water quality, etc. is needed between the other station(s) and the current installation.

13.1.1 EPRI PM Templates

Separate EPRI PM templates are provided for screw compressor chillers and centrifugal compressor chillers, as shown in Figures 13-1 and 13-2, respectively. Additional EPRI PM templates exist for sub-components on the chiller skid such as general shell-and-tube heat exchangers, and motors (medium and small voltage), as shown in Figures 13-3, 13-4, and 13-5, respectively. The station or utility may have developed their own PM templates that are used as the basis document. Comments regarding application of the PM templates and other PM actions are noted as follows:

- PM templates are normally viewed as a generic starting point for actions, which are adjusted/changed based upon a documented justification which considers the results of maintenance performed, inspections, monitoring data, applicable industry experience, and additional features or details not reflected on the template, but relevant to the task being performed.
- Past experience at the station with similar type chiller equipment or at other stations with the same (or nearly the same) equipment that have been used to justify longer or extended maintenance intervals should initially be viewed as “one-off” comparisons, that warrant consideration but require additional justification or explanation before incorporating the extended maintenance period for a replacement component.
- Sub-component PM interval tasks should be synchronized to the extent practical to minimize the out-of-service or unavailability time for the equipment and maximize efficiency of site resources supporting the maintenance.
- Shorter initial intervals for some actions may be warranted until PM results are available to confirm the expected condition. Examples could include tasks such as vibration analysis, heat exchanger tube NDE, and motor monitoring.
- PM tasks may need to be added for items or design features relied upon by a new digital control system for proper operation or service life.
- Changes to the condenser cooling water flow control design may warrant an early open/inspect period for the heat exchanger, if cooled by an open cooling water system with suspended solids and/or a history of macrofouling debris.

	Critical				Non-Critical			
	HI	LO	HI	LO	HI	LO	HI	LO
	Severe		Mild		Severe		Mild	
	CHS	CLS	CHM	CLM	NHS	NLS	NHM	NLM
Calibration	2Y	2Y	2Y	2Y	AR	AR	AR	AR
External Inspection	3M	3M	3M	3M	6M	6M	6M	6M
Glycol Analysis	6M	6M	6M	6M	6M	6M	6M	6M
Internal Inspection - Compressor	10Y	10Y	10Y	10Y	10Y	10Y	10Y	10Y
Internal Inspection - Heat Exchangers	2Y	2Y	2Y	2Y	2Y	2Y	2Y	2Y
Oil Analysis	1Y	1Y	1Y	1Y	1Y	1Y	1Y	1Y
Operator Rounds	1S	1S	1S	1S	1D	1D	1D	1D
Overhaul	AR	AR	AR	AR	AR	AR	AR	AR
Refrigerant Analysis	1Y	1Y	1Y	1Y	1Y	1Y	1Y	1Y
System Testing - Functional Tests	AR	AR	AR	AR	AR	AR	AR	AR
System Testing - Performance Tests	2Y	2Y	2Y	2Y	AR	AR	AR	AR
Vibration Analysis	1Y	1Y	1Y	1Y	1Y	1Y	1Y	1Y

Figure 13-1
EPRI PM Template for Screw Chillers [19]

	Critical				Non-Critical			
	HI	LO	HI	LO	HI	LO	HI	LO
	Severe		Mild		Severe		Mild	
	CHS	CLS	CHM	CLM	NHS	NLS	NHM	NLM
Calibration	2Y	2Y	2Y	2Y	AR	AR	AR	AR
External Inspection	3M	3M	3M	3M	6M	6M	6M	6M
Glycol Analysis	6M	6M	6M	6M	6M	6M	6M	6M
Internal Inspection - Compressor	10Y	10Y	10Y	10Y	10Y	10Y	10Y	10Y
Internal Inspection - Heat Exchangers	2Y	2Y	2Y	2Y	2Y	2Y	2Y	2Y
Oil Analysis	1Y	1Y	1Y	1Y	1Y	1Y	1Y	1Y
Operator Rounds	1S	1S	1S	1S	1D	1D	1D	1D
Overhaul	AR	AR	AR	AR	AR	AR	AR	AR
Refrigerant Analysis	1Y	1Y	1Y	1Y	1Y	1Y	1Y	1Y
System Testing - Functional Tests	AR	AR	AR	AR	AR	AR	AR	AR
System Testing - Performance Tests	2Y	2Y	2Y	2Y	AR	AR	AR	AR
Vibration Analysis	1Y	1Y	1Y	1Y	1Y	1Y	1Y	1Y

Figure 13-2
EPRI PM Template for Centrifugal Chillers [19]

	Critical				Non-Critical			
	HI	LO	HI	LO	HI	LO	HI	LO
	Severe		Mild		Severe		Mild	
	CHS	CLS	CHM	CLM	NHS	NLS	NHM	NLM
Cleaning	2Y	4Y	AR	AR	AR	AR	NR	NR
NDE Inspection	4Y	4Y	8Y	12Y	AR	AR	NR	NR
Operator Rounds	1S	1S	1S	1S	1D	1D	1D	1D
Performance Monitoring	3M	AR	3M	AR	AR	AR	NR	NR
Replacement	AR	AR	AR	AR	AR	AR	AR	AR
System Engineer Walkdown	3M	3M	3M	3M	3M	3M	3M	3M
Tube Side Internal Inspection	2Y	4Y	8Y	12Y	AR	AR	NR	NR

Figure 13-3
EPRI PM Template for General Shell-and-Tube Heat Exchangers [19]

	Critical				Non-Critical			
	HI	LO	HI	LO	HI	LO	HI	LO
	Severe		Mild		Severe		Mild	
	CHS	CLS	CHM	CLM	NHS	NLS	NHM	NLM
Electrical Tests - Off-line	2Y	4Y	2Y	4Y	4Y	4Y	4Y	4Y
Electrical Tests - On-line	6M	1Y	6M	1Y	1Y	2Y	1Y	2Y
Mechanical Refurbishment	AR	AR	AR	AR	AR	AR	AR	AR
Mechanical Tests - Off-line	2Y	4Y	2Y	4Y	3Y	5Y	3Y	5Y
Mechanical Tests - On-line	3M	6M	3M	6M	6M	1Y	6M	1Y
Oil Analysis And Lubrication	6M	6M	6M	6M	1Y	1Y	1Y	1Y
Operator Rounds	1S	1S	1S	1S	1D	1D	1D	1D
Refurbishment	10Y	15Y	10Y	15Y	10Y	20Y	10Y	20Y
System Engineer Walkdown	3M	3M	3M	3M	3M	3M	3M	3M
Thermography	6M	6M	6M	6M	6M	6M	6M	6M
Vibration Monitoring	3M	3M	3M	3M	6M	6M	6M	6M

Figure 13-4
EPRI PM Template for Medium Voltage (<15kV) Motors [19]

	Critical				Non-Critical			
	HI	LO	HI	LO	HI	LO	HI	LO
	Severe		Mild		Severe		Mild	
	CHS	CLS	CHM	CLM	NHS	NLS	NHM	NLM
Acoustic Monitoring	3M	3M	3M	3M	AR	AR	AR	AR
Bridge Test Over 20HP	3Y	3Y	3Y	3Y	NR	NR	NR	NR
Motor Performance Testing	3Y	3Y	3Y	3Y	NR	NR	NR	NR
Oil Analysis And Lubrication	6M	6M	1Y	1Y	NR	NR	NR	NR
Operator Rounds	1S	1S	1S	1S	1S	1S	1S	1S
Refurbishment	AR	AR	AR	AR	AR	AR	AR	AR
System Engineer Walkdown	3M	3M	3M	3M	3M	3M	3M	3M
Thermography	6M	6M	6M	6M	1Y	1Y	1Y	1Y
Vibration Monitoring	3M	3M	3M	3M	1Y	1Y	1Y	1Y

Figure 13-5
EPRI PM Template for Low Voltage (<600V) Motors [19]

13.1.2 Digital Equipment PM

Existing I&C calibration PMs should be reviewed for continued need following a change from analog to digital controls. Changes to PM tasks for the electronics involved with a digital control should be discussed with the vendor/supplier.

As noted in Section 4.2.7, it is important for the engineering package to identify the design features that are specifically relied upon by digital control system for protection and proper functioning. Similarly, features relied upon to achieve the expected service life should also be noted. Examples could include local ventilation for control panels or shielding to avoid interference or damage from sunlight, EMI, RFI, radiation, etc. Identifying these features assists in understanding potential operability impacts for safety related chiller controls, and for establishing appropriate periodic inspections and/or tests, and preventive maintenance actions and their intervals to ensure these features are properly maintained.

13.2 Spare Parts

As previously noted in Section 4.1.1, 4.2.1, and 5.5, the maintenance strategy should be considered during the specification development phase for the replacement chiller and decisions made regarding the quantity of electronic parts, software, and other items with the original equipment purchase. A change in how spare parts inventory are weighted/evaluated may be needed in recognition of the level of configuration control applied in the nuclear industry, the resources necessary to evaluate/approve changes to electronic parts, and the rate at which electronic equipment models change and become obsolete. The purchase of the projected quantity of digital control panels, circuit boards and related parts necessary to support the expected service life of the component, at the time of initial equipment purchase warrants consideration by the project team and site. As noted in Section 4.2.1, several utilities have reported experience with controls hardware and software not only changing models/revision, but becoming fully obsolete and no longer available before completion of the project. The number of spare parts should consider the owner's experience, vendor input, the criticality of the item, and the system application.

Disposal of spare parts that are no longer applicable to site equipment is a project responsibility.

The design specification for the replacement chiller should include the vendor submittal to the utility of design information such as materials and dimensions/tolerances for spare/replacement parts necessary for normal maintenance.

The manufacturer's recommendations for spare part shelf life should be provided. EPRI's *Packaging, Shipping, Storage, and Handling Guidelines for Nuclear Power Plants* [14] provides guidance applicable to long-term storage of parts.

13.3 Condition Monitoring

The project team should discuss with site engineering the extent of condition monitoring performed on the chiller. Increased monitoring during the first cycle of operation is always prudent for a replaced component.

13.4 Training

Operations and Maintenance training departments should be involved with chiller projects performing digital upgrades. Training costs should be included in the project cost estimates and vendor contracts. The chiller maintenance team should receive extensive vendor training to become familiar with the machine to understand symptoms, causes, troubleshooting techniques, adjustments and repairs for the new equipment. Digital controls provide more information on the causes of the malfunctions or failures than analog control systems, but until experience is gained, this additional information may also result in false alarms, misdiagnosis, or other new problems not been previously observed or evident.

As noted in Sections 4.2.8 and 5.6, training for the new digital controls should include operations, maintenance and engineering personnel. The initial training can be conducted by the vendor in many cases, and may be at the testing facilities used for the new equipment. If the project involves chiller replacement with new digital controls, then a spare chiller for training purposes (which may be the chiller assembly used for mock-up testing and seismic qualification tests if safety related) is often purchase. Digital control upgrade projects often include a purchase of a spare control panel assembly with software to simulate the chiller function to support training needs for both initial equipment turnover as well as on-going training needs for maintenance and other departments.

It is beneficial for the training actions to simulate (or perform if possible) planned preventive maintenance actions, troubleshooting evolutions, as well as monitoring actions.

Technical Manuals

Chiller technical manuals from the vendors are now available in digital as well as the hard copy format and are much more detailed. The quality of the pictures and text remain in “new” condition, avoiding legibility problems experienced in the past with hard copies.

14
INDUSTRY EXPERIENCE

14.1 Industry Experience with Chiller Reliability

Example cases resulting from, or of interest to chiller replacement projects are noted below. In addition to the below example cases, EPRI report 1015075 [11] provides a listing of chiller related Licensee Event Reports.

Case #1:

What Happened: A new 700 ton, water cooled, external drive chiller was installed at a plant with both vendor and site acceptance testing completed. After approximately 2000 operating hours, motor vibrations increased to a point that the chiller was required to be removed from service.

Cause: The motor rotor was not correctly manufactured. The rotor plates had begun to separate resulting in numerous rotor hot spots and shaft distortion which caused excessive vibration capable of seal damage and eventual chiller failure.

Fix: A temporary balance was performed which restored chiller to service. With chiller vendor assistance, the motor fabrication process was upgraded, which included new equipment, a new vacuum chamber, a change in metal supplier, and a new coil winding process. These changes succeeded in providing the quality improvements needed to support long-term service life. The original chiller motors required replacement and spares were provided.

Case #2:

What Happened: The plant common switchgear breaker tripped resulting in the loss of 5 chillers. The remaining chillers were started but containment temperatures were increasing. Several hours later the problem was found and isolated, allowing four chillers to be returned to service.

Cause: An internal motor lead in a new chiller shorted against the motor housing. The new chiller motor checks were satisfactory, but the insulation on the motor leads was found to be softer than normal for electrical cables. The motor lead insulation was in contact with the edge of the motor housing at the exit of the junction box, allowing the insulation to wear through over time due to chiller vibration. The insulation vibration wear eventually resulted in a direct short to ground. Damage to the remote starter panel also resulted from the short.

Fix: The motor leads were replaced and more insulation was installed on the internal motor housing. Leads were restrained to avoid contact with the side of the housing. The chiller was out of service for an extended time period removing redundancy and increasing operational risk.

Case #3:

What Happened: New chiller shut down for due to a failed flow sensor.

Cause: The water chemistry in the condenser corroded through the water flow sensor causing a flow switch failure and loss of condenser flow signal which shut down the chiller.

Fix: Initially the flow switch was replaced and failure reoccurred within several months for the same reason. This became a repetitive failure which lead to the failure of the control board. A design change was required to change the flow sensor type/material to be compatible with system water chemistry. (NOTE: The condenser flow sensor as a trip initiator rather than an alarm is a potential example of reduced reliability discussed in Section 4.2.6, since an actual loss of adequate condenser flow would rapidly be detected by refrigerant cycle pressure changes.)

Case #4:

What Happened: Replacement chillers included an automatic trip feature that required local resetting. Operations procedures did not address the need to local reset the chillers for them to restart after a loss of power. Station received a Green, non-cited violation of 10 CFR 50, Appendix B, Criterion III, “Design Control,” for failure to verify the adequacy of the design of the control room HVAC system.

Case #5:

What Happened: Tubing leak resulted in chiller inoperability

Cause: Chiller instrument tubing was inadequately field supported, resulting in a 22 drop per minute oil leak which resulted in the safety related chiller being declared inoperable and subsequent past operability concerns [74]. Some of the content of interest includes (repeated from Section 5.3.2):

- The tubing had been tie-wrapped to adjacent piping. Friction from normal system vibration had worn through the tubing at the contact point.
- A previous change to the chiller assembly added instrument isolation valves and specified “field routing” of tubing without addressing tubing supports, clearance requirements to adjacent components, and without post-installation inspections of tubing for vibration or fretting concerns

Case #6:

What Happened: Low Oil Level Trip Renders Chiller Non-Functional

The past operability review determined a safety related chiller had been non-functional due to a vulnerability resulting in a low oil level condition. The chiller tripped on low oil level following surveillance testing. The cause was stated as low superheat, causing liquid flood-back to the compressor and a low evaporator heat load causing insufficient oil return from the evaporator.

The chiller had been replaced with a new design 2 years previously, and was determined to have been vulnerable to the low oil level condition since original installation. The 10CFR50.59 review for the chiller replacement stated,

- "functions….will be performed identically by the replacement chillers"
- "All plant-specific conditions of approvals specified in the NRC SER have been satisfied for the replacement chiller application"
- "the potential for software common mode failure has been carefully considered. The application software has been developed by (the supplier) under its plans, procedures, QA and V&V, and tested extensively at the factory. On this basis, the potential for a software common mode failure that could disable all chillers is concluded to be highly unlikely, no more likely than the potential for common cause failures in the original chiller equipment."

Contrary to the above, the digital control settings were found after-the-fact to include inappropriately low over-current trip setpoints. In addition, the skid mounted molded case circuit breaker (MCCB) setpoints were found to be too low, resulting in chiller trips in response to a loss-of-offsite power, which is a standard event assumed per design basis and in conjunction with design basis accidents.

Corrective actions to resolve the conditions included valve adjustments to optimize superheat, changes to the condenser cooling water valve throttle position to enhance compressor discharge pressure control, and software changes to modify the hot gas bypass function, limit minimum compressor unloading, and revise the permissive for securing the lag compressor to reduce the run time at minimum loads during transients.

The associated regulatory violation noted that software design deficiencies were caused from the field changes implemented to correct previous software design flaws found after chiller installation. The violation report concluded "*the chiller's design process and implementation history increased the likelihood of automation flaws and the possibility that these flaws could generate software common cause failures (CCF). The licensee's 10 CFR 50.59 process for implementing this modification without a license amendment relied on compliance with and application of the design processes specified in the quality standards*".

The below items were identified as issues:

- Management activities did not ensure the implementation of the specified design quality and practices addressed in the applicable quality standards.
- The design failed to implement the full scope of specified applicable life cycle activities.
- The chiller functional and software requirements specifications were not well defined and complete, thus they did not contain specific requirements necessary to address fast power transfer as identified in the LER.
- The software specification did not address applicable functional requirements from 10 CFR 50.55a, for newly designed digital SSCs (i.e., IEEE 603-1991).
- The verification and validation (V&V) activities did not meet performance and independence specifications.
- V&V did not ensure that the functional requirements were well defined and complete.
- The as-built design did not provide a diverse means of operating the chillers as required by the PO.

Case #7:

What Happened: A safety related chiller tripped due to excessive oil addition

Cause: The low refrigerant pressure trip was caused by excess oil in the evaporator. Approximately six gallons of excess oil were removed from the chiller to restore proper level. Oil addition/removal was performed “as needed” without being tracked. Chiller operating instructions did not require sufficient run times for the standby/swing chiller for oil reclaim. Short periods of operation with low cooling loads resulted in oil collecting in the evaporator. Oil continued to be added to the system to maintain normal level which eventually resulted in excessive oil quantity in the system affecting evaporator function and a chiller trip.

Operating procedures were revised regarding chiller operation for oil reclaim and guidance on required oil levels for chiller start. Trending of oil addition/removal data was also initiated.

Case #8:

What Happened: A safety related chiller was declared inoperable due to inadequate oil level associated with low load operation

Cause: The low oil level condition occurred on 3 separate occasions over a 2 month period (winter) in spite of oil being added to the system following each occurrence. Similar to Case #7 the low oil level and repeated oil additions were due to oil accumulation in the evaporator associated with very low-load operation.

The station changed procedures for chiller operation, and processes for monitoring oil addition as well as oil recovery from the evaporator during low-load periods.

Case #9:

Examples of operational and maintenance issues with a specific chiller at a station as described in Section 24 of EPRI report 1003059 [10] are noted below (repeated from Section 2.2.5):

- Re-occurring mechanical maintenance problems were characterized as:
  - Low system heat load causes the operating chiller to cycle on and off
  - Chiller performance problems due to air-in leakage (approximately 2 per year),
  - Chiller motor cooler cartridge leakage
  - Purge system leakage, typically requires a float switch replacement and flushing (approximately 1 occurrence per year per chiller).
- Corrosion products have been observed in the oil and are believed to emanate from the condenser and evaporator surfaces. A clean-up system was added to chiller C and significantly reduced the amount of corrosion products and eliminated the need to periodically replace the jet pumps and other close tolerance parts. …the corrosion products are increasing in chiller B.
- The idle chillers are prone to oil migration problems and air in-leakage (refrigerant circuit is maintained at a vacuum).
- The available workspace around the chillers was characterized as tight. Often several crafts need to work in parallel and the tight space reduces efficiency.
- Vibration testing continues to show a vibration noise in chiller A. The noise is attributed to a gear set. The signature has not noticeably changed for several years and the oil analysis does not show any symptoms of gear wear. The vendor does not believe the noise is a concern.

Case #10:

Examples of vibration-induced piping and tubing leaks, which include some involving chillers, are described in INPO Event Report 14-30 [88]. Points of interest for chiller projects include, but are not limited to:

- Most piping or tubing leaks occurred due to failure to address susceptibility to vibration-induced fatigue in the design, testing, or field installation.
  - Long segments without sufficient support
  - Cantilevered connections not checked for vibration
- The modification process did not require formal inspection and documentation of vibration in the range of design operating modes during post-modification testing.
- Vibration analyses did not include connected small-bore piping or tubing

- Tubing wall thickness selection did not consider vibration, resulting in failures from "normal" system vibrational effects.
- Copper tubing has been replaced after vibration related failures with stainless steel tubing
- Post-modification inspections should include observation for vibration during all modes of operation, where practical.

14.2 Related NRC Information Notices

The following NRC generic communications are of potential interest for chiller upgrade/replacement projects. Any needed actions to address potential concerns associated with the information for existing plant chillers would have been performed previously. The project should ensure any potential applicability to the replacement chillers is addressed.

NRC Information Notice 94-82: Concerns Regarding Essential Chiller Reliability During Periods of Low Cooling Water Temperature [43]:

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 96-01: Potential for High Post-Accident Closed-Cycle Cooling Water Temperatures to Disable Equipment Important to Safety: [95]

This notice, describes the potential loss of control room chillers following a large primary coolant system pipe rupture or a main steamline break inside containment. The heat load rejected to the closed cooling water (CCW) system could result chiller condenser pressure exceeding rupture disc pressure and subsequent loss of refrigerant charge.

NRC Information Notice 85-89 [97] primarily addressed the loss of solid-state instrumentation following a failure of control room cooling. The incident resulted in numerous spurious alarms. Previously, the same plant had experienced similar behavior and numerous component failures and degradation due to high temperature in control cabinets. The plant had previously reported that their chillers developed oil level problems when loaded at less than full capacity. The heat load calculated during plant design was greater than the actual heat load, resulting in oversized chillers.

NRC Information Notice 2014-11, Recent Issues Related to the Qualification and Commercial Grade Dedication of Safety-Related Components, [96] does not directly reference any issues involving chillers, but is of potential interest for safety related chiller projects. The project team could request review of the document with CGD vendors during the bid communications and evaluation process regarding actions they have taken in response to avoid similar issues.

15

REFERENCES

1. *Guidelines for the Technical Evaluation of Replacement Items in Nuclear Power Plants (Revision 1)*. EPRI, Palo Alto, CA: July 2006. 1008256.
2. *Guideline for the Utilization of Commercial Grade Items in Nuclear Safety Related Applications (NCIG-07).* EPRI, Palo Alto, CA: 1988. NP-5652.
3. *Guidelines for Reverse Engineering at Nuclear Power Plants*. EPRI, Palo Alto, CA: 1998. TR-107372.
4. *Materials Handbook for Nuclear Plant Pressure Boundary Applications.* EPRI, Palo Alto, CA: 2006. 1014481.
5. *Guide for the Specification of Replacement and Spare AC Squirrel-Cage Induction Motors Having Voltage Ratings Up to 600V*. EPRI, Palo Alto, CA: May 2013. 3002000809.
6. *Guidance for the Replacement of Large Electric Motors at Nuclear Power Plants;* EPRI, Palo Alto, CA. March 2010. 1020625.
7. *Guidance for Replacing Shell-and-Tube Heat Exchangers at Nuclear Power Plants;* EPRI, Palo Alto, CA. 2014. 3002000542.
8. *Chiller Performance Monitoring and Troubleshooting Guide;* EPRI, Palo Alto, CA. 2002. 1007361.
9. *Guidelines for Replacement Materials for Service Water Systems*. EPRI, 2012. 1025275.
10. *Life Cycle Management Planning at V.C. Summer Nuclear Plant: Main Condenser, Radiation Monitoring System, and Nuclear Safety-Related HVAC Chilled Water*; EPRI, Palo Alto, CA. 2001. 1003059.
11. *Plant Support Engineering: Life Cycle Management Planning Sourcebooks – Chillers;* EPRI, Palo Alto, CA. December 2007. 1015075.
12. *Electric Chiller Handbook*. EPRI, Palo Alto, CA: 1996. TR-105951-R1.
13. *Lifting, Rigging, and Small Hoist Usage Program Guide*. EPRI, Palo Alto, CA. 2003. 1007914.
14. *Packaging, Shipping, Storage, and Handling Guidelines for Nuclear Power Plants*. EPRI, Palo Alto, CA: 1997. TR-107101.
15. *Plant Support Engineering: Generic Seismic Technical Evaluations of Replacement Items for Nuclear Power Plants Item Specific Evaluations – TR-105849 Rev.1*. EPRI, Palo Alto, CA: 2008. 1016694.
16. *Critical Characteristics for Acceptance of Seismically Sensitive Items (CCASSI)*; EPRI, Palo Alto, CA. March 2007. TR-112579.

17. *Methods for Assuring Safety and Dependability When Applying Digital Instrumentation and Control Systems*, EPRI, Palo Alto, CA: 2016. 3002005326.
18. *Handbook for Evaluating Critical Digital Equipment and Systems*. EPRI, Palo Alto, CA: Nov. 2005. 1011710.
19. *EPRI Preventive Maintenance Basis Database,* pmbd.epri.com.
20. *Guideline on Licensing Digital Upgrades – TR-102348 Revision 1, NEI 01-101: A Revision of EPRI TR-102348 to Reflect Changes to the 10 CFR 50.59 Rule*; EPRI, Palo Alto, CA: 2002. 1002833.
21. *Guidelines on Evaluation and Acceptance of Commercial Grade Digital Equipment for Nuclear Safety Applications*; EPRI, Palo Alto, CA: 1996. TR-106439.
22. *Effects of Digital Instrumentation and Control Defense-in-Depth and Diversity on Risk in Nuclear Power Plants*; EPRI, Palo Alto, CA. December 2009. 1019183.
23. *Handbook for Verification and Validation of Digital Systems*; EPRI, Palo Alto, CA. December 1998. TR-103291-CD.
24. *Supplemental Guidance for the Application of EPRI Report NP-5652 on the Utilization of Commercial Grade Items;* EPRI, Palo Alto, CA; 1994. TR-102260.
25. *Commercial Grade Digital Equipment for High-Integrity Application: Oversight and Review of Evaluation and Acceptance Activities*; EPRI, Palo Alto, CA. 2013. 1025283.
26. *Guideline for the Acceptance of Commercial*-Grade Design and Analysis Computer Programs Used in Nuclear Safety-Related Applications: Revision 1 of 1025243; EPRI, Palo Alto, CA. Dec. 2013. 3002002289.
27. *Requirements Engineering for Digital Upgrades: Specification, Analysis, and Tracking*; EPRI, Palo Alto, CA. TR-108831.
28. *Technical Guideline for Cyber Security Requirements and Life Cycle Implementation Guidelines for Nuclear Plant Digital Systems*; EPRI, Palo Alto, CA. Oct. 2010. 1019187.
29. *Cyber Security Procurement Methodology, Rev. 1*; EPRI, Palo Alto, CA. Dec. 2013. 3002001824.
30. *Preventive Maintenance Practices for Digital Instrumentation and Control Systems*; EPRI, Palo Alto, CA. August 2013. 3002000502.
31. *Quality Assurance Program Requirements for Nuclear Power Plants*. American National Standards Institute, Washington, D.C.: ANSI N45.2, various editions.
32. *Quality Assurance Requirements for Nuclear Facility Applications*. ASME, NQA-1.
33. *Criteria for Digital Computers in Safety Systems of Nuclear Generating Stations*; IEEE 7-4.3.2, 2015
34. *Standard for Developing Software Life Cycle Processes*; IEEE 1074-2006
35. *IEEE Standard Criteria for Safety Systems for Nuclear Power Generating Stations*; IEEE 603-2009

36. *Transmittal of TSTF-553, Revision 0, "Add Action for Two Inoperable CREATCS Trains"*; October 31, 2015 (ADAMS ML15304A002)
37. *Request for Additional Information: Traveler TSTF-553, Revision 0*; February 23, 2016 (ADAMS ML16028A453)
38. *Cyber Security Plan for Nuclear Power Reactors*; NEI 08-09, Rev. 6, April 2010
39. Regulatory Issue Summary (RIS) 2002-22, *Use of EPRI/NEI Joint Task Force Report, "Guideline on Licensing Digital Upgrades"*. NRC, Nov. 2002
40. NRC Information Notice 2014-11: *Recent Issues Related to the Qualification and Commercial Grade Dedication of Safety-Related Components*
41. Response to Request for Additional Information Regarding TSTF-553, Revision 0; May 2016 (ADAMS ML16215A129)
42. *HVAC Equipment Aging and Reliability Issues At Commercial Nuclear Power Plants*; 28th Nuclear Air Cleaning Conference; Deep Ghosh, PE; Southern Nuclear and Robert Campbell, PE; Tennessee Valley Authority
43. NRC IN 94-82: *Concerns Regarding Essential Chiller Reliability During Periods of Low Cooling Water Temperature*
44. *Verification and Validation of Nuclear Chiller Digital Controls*, James M. Dean; NPEC 2011 Summer Meeting; July 27, 2011
45. NUREG-0800, Standard Review Plan, Branch Technical Position 7-14, *Guidance on Software Reviews for Digital Computer-Based Instrumentation and Control Systems*, Revision 6, August 2016
46. NUREG-0800, Standard Review Plan, Branch Technical Position 7-18, *Guidance on the Use of Programmable Logic Controllers in Digital Computer-Based Instrumentation and Control Systems*, Revision 6, August 2016.
47. NUREG-0800, Standard Review Plan, Branch Technical Position 7-19, *Guidance for Evaluation of Diversity and Defense-in-Depth in Digital Computer-Based Instrumentation and Control Systems*, Revision 7, August 2016.
48. *Criteria for Use of Computers in Safety Systems of Nuclear Power Plants*; NRC Regulatory Guide 1.152, Rev. 3, July 2011.
49. *Verification, Validation, Reviews, and Audits for Digital Computer Software Used in Safety Systems of Nuclear Power Plants*; NRC Regulatory Guide 1.168; Revision 2, July 2013
50. *Configuration Management Plans for Digital Computer Software Used in Safety Systems of Nuclear Power Plants*; NRC Regulatory Guide 1.169; Revision 1, July 2013
51. *Test Documentation for Digital Computer Software Used in Safety Systems of Nuclear Power Plants*; NRC Regulatory Guide 1.170; Revision 1, July 2013.
52. *Software Unit Testing for Digital Computer Software Used in Safety Systems of Nuclear Power Plants*; NRC Regulatory Guide 1.171; Revision 1, July 2013.

53. *Software Requirement Specifications for Digital Computer Software and Complex Electronics Used in Safety Systems of Nuclear Power Plants*; NRC Regulatory Guide 1.172; Revision 1, July 2013.
54. *Developing Software Life Cycle Processes for Digital Computer Software Used in Safety Systems of Nuclear Power Plants*; NRC Regulatory Guide 1.173; Revision 1, July 2013.
55. *Guidelines for Evaluating Electromagnetic and Radio-Frequency Interference in Safety-Related Instrumentation and Control Systems*; NRC Regulatory Guide 1.180; Rev. 1, Oct. 2003 (reviewed June 2011)
56. *Cyber Security Programs for Nuclear Power Plants*; NRC Regulatory Guide 5.71, Rev. 0, Jan. 2010 (reviewed April 2015)
57. WCAP-17308-NP, *Treatment of Diesel Generator (DG) Technical Specification Frequency and Voltage Tolerances*
58. *Request for Additional Information for TSTF-553, Revision 0*; August 2016 (ADAMS ML16215A125)
59. NEI 96-07, Appendix D, *Supplemental Guidance for Application of 10 CFR 50.69 to Digital Modifications*, Draft Revision 0, April 2016 (reference NRC ADAMS document ML16126A197)
60. *Tabletop of NEI 96-07, Appendix D, Section 5.5, Example 4: Chiller Controls Replacement*; August 24, 2016 (reference NRC ADAMS document ML16231A314)
61. *Industry Comments on NRC Preliminary Draft of Integrated Action Plan to Modernize Digital Instrumentation and Controls Regulatory Infrastructure*; April 22, 2016 (NRC ADAMS document ML16118A279)
62. NRC Regulatory Issue Summary 2016-05, *Embedded Digital Devices in Safety-Related Systems*; April 29, 2016
63. *Digital Equivalency Evaluation: Screening Checklist and Considerations*; EPRI, Palo Alto, CA; December 2015. 3002007023.
64. NUREG-0800, Standard Review Plan
    a. Section 7.0; *Instrumentation and Controls – Overview of Review Process*; Revision 7, August 2016
    b. Appendix 7.0-A, *Review Process for Digital I&C Systems*; Rev. 6, Aug. 2016
    c. Section 7.1, *Instrumentation and Controls – Introduction*; Rev. 6, Aug. 2016
    d. Section 7.1-T, *Table 7-1 Regulatory Requirements, Acceptance Criteria, and Guidelines for I&C Systems Important to Safety*; Revision 6, Aug. 2016
    e. Appendix 7.1-A, *Acceptance Criteria and Guidelines for Instrumentation and Controls Systems Important to Safety*; Revision 6, August 2016

   f. Appendix 7.1-B, *Guidance for Evaluation of Conformance to IEEE 279*; Rev. 6, August 2016
   g. Appendix 7.1-C, *Guidance for Evaluation of Conformance to IEEE 603*; Rev. 6, August 2016
   h. Appendix 7.1-D, *Guidance for Evaluation of the Application of IEEE Std 7-4.3.2*; Rev. 1, August 2016

65. NRC Interim Staff Guidance (ISG), Digital Instrumentation and Controls; DI&C-ISG-01, Revision 0 (Dec. 2007); *Cyber Security*
66. NRC Interim Staff Guidance (ISG), Digital Instrumentation and Controls; DI&C-ISG-02, Revision 2; *Diversity and Defense-in-Depth Issues*; (NOTE: ISG-02 has been superseded by BTP 7-19, Rev. 6)
67. NRC Interim Staff Guidance (ISG), Digital Instrumentation and Controls; DI&C-ISG-06, Revision 1 (Jan. 2011), *Licensing Process*
68. NRC Staff Requirements Memorandum (SRM) to SECY-93-087; July 21, 1993
69. *Regulatory Requirements for Digital Chiller Controls*; Ray Herb, Southern Nuclear Operating Company, 2015 NHUG meeting presentation
70. *Watts Bar Nuclear Plant Unit 1 – Technical Specifications Change – Main Control Room Chiller Completion Time Extension;* Feb. 24, 2010 (ADAMS ML100570414)
71. *Response to Request for Additional Information Concerning Technical Specifications Change WBN-TS-09-16 – Main Control Room Chiller Completion Time Extension*; Nov. 5, 2010 (ADAMS ML103120455)
72. *Watts Bar Nuclear Plant, Unit 1 – Issuance of Amendment Regarding the Main Control Room Chiller Completion Time Extension*; Feb. 8, 2011 (ADAMS ML110190280)
73. *LER 2012*-004, *Supplemental Information; Essential Chiller Oil Leak Creates Unanalyzed Past Operability Condition*; (ADAMS ML12174A161)
74. Inspection Report 2013008, Virgil C. Summer Nuclear Station – NRC Evaluation of Changes, Tests, and Experiments and Permanent Plant Modifications; Jan. 2, 2014 (ADAMS ML14002A205)
75. Inspection Report 2015003, Columbia Generating Station; November 12, 2015 (ADAMS ML15316A834)
76. *Refrigerant Update – The Next Transition Has Begun*; Mike Thompson, Trane – Ingersoll Rand, presentation at 2016 NHUG Conference
77. LER 2013-003, *Trip Setpoint Renders Chiller and Control Room Emergency Filtration Inoperable*; (ADAMS ML13235A311)
78. *Turbine Building Chiller Replacement Project*; Andy Ralph, Duke Energy, presentation at 2016 NHUG conference
79. *NEI CCF Tabletop, Part 1*; presentation July 11, 2016 (ADAMS ML16192A003)

80. *Guideline for the Acceptance of Commercial-Grade Items in Nuclear Safety-Related Applications, Revision 1 to EPRI NP-5652 and TR-102260*; EPRI, Palo Alto, CA. September 2014. 3002002982
81. *Chiller Shutdowns Caused by Sensitivity of Control Relays to Voltage Sags – Case Study*; EPRI, Palo Alto, CA; 2007. 1017083
82. *Digital Control System Problems:* INPO OE Digest 2006-13
83. *Digital Instrumentation and Control Computer-Based Training Modules 2013*; EPRI, Palo Alto, CA; December 2013. 3002000531
84. *Computer Based Training (CBT) – Digital Design Guide 2015*; EPRI, Palo Alto, CA. October 2015. 3002005327
85. *Digital Instrumentation and Control Design Guide*; EPRI, Palo Alto, CA. October 2014. 3002002989.
86. *Ensuring Engineering Quality in Digital System Projects, Rev. 1*; INPO, report 10-008, March 2015.
87. *Microprocessor-Based Digital Hardware Related Events*; INPO Topical Report TR8-64. July 2008
88. *Analysis of Vibration-Induced Piping and Tubing Leaks (2010 through 2013)*; INPO Event Report 14-30. June 5, 2014.
89. *Nuclear Power Plant Software Quality Assurance, Revision 1*; INPO, 12-014. April 2015.
90. *Digital Thoughts*; S. Jason Remer, Director Plant Life Extension, Nuclear Energy Institute, presentation at May 2016 INPO Digital Workshop
91. Title 10 Code of Federal Regulations (CFR) 50.55a(h)(2)
92. *Evaluating Commercial Digital Equipment for High-Integrity Applications: A Supplement to EPRI Report TR-106439;* EPRI, Palo Alto, CA. December 1997. TR-107339.
93. *Generic Requirements Specification for Qualifying a Commercially Available PLC for Safety-Related Applications in Nuclear Power Plants;* EPRI, Palo Alto, CA. TR-107330.
94. *Cyber Security Procurement Methodology Training Module Rev. 14.00*; EPRI. Palo Alto, CA, May 2014. 3002002499.
95. NRC Information Notice 96-01: *Potential for High Post-Accident Closed-Cycle Cooling Water Temperatures to Disable Equipment Important to Safety*
96. NRC Information Notice 2014-11: *Recent Issues Related to the Qualification and Commercial Grade Dedication of Safety-Related Components*
97. NRC Information Notice 85-89: *Potential Loss of Solid State Instrumentation Following Failure of Control Room Cooling*
98. *Code on Nuclear Air and Gas Treatment*; ASME, AG-1 2015
99. Boiler and Pressure Vessel Code (B&PVC); ASME, various editions

100. *Cyber Security Technical Assessment Methodology: Vulnerability Identification and Mitigation: Vulnerability Identification and Mitigation*. EPRI, Palo Alto, CA: 2016. 3002008023.

101. *Guideline on Configuration Management for Digital Instrumentation and Control Equipment and Systems*. EPRI, Palo Alto, CA: 2011. 1022991.

102. ASHRAE Handbook – Fundamentals; ASHRAE, various editions

103. NRC Generic Letter 89-13, Service Water System Problems Affecting Safety Related Equipment, July 18, 1989

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