PNL-8614
Vol. 2

Aging Assessment of Essential HVAC Chillers Used in Nuclear Power Plants

D. E. Blahnik, PNL
T. W. Camp, L&GP, Inc.

September 1996

Prepared for
Division of Engineering Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
NRC JCN B2865

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle

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PNL-8614

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE MEMORIAL INSTITUTE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831;
prices available from (615) 576-8401.

Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161

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Abstract

The Pacific Northwest Laboratory conducted a comprehensive aging assessment of chillers used in the essential safety air-conditioning systems in nuclear power plants (NPPs). The chillers used, and air-conditioning systems served, vary in design from plant to plant. The review of operating experience indicated that chillers experience aging degradation and failures. The primary aging factors of concern for chillers include vibration, excessive temperatures and pressures, thermal cycling, chemical attack, and poor quality cooling water. The evaluation of Licensee Event Reports (LERs) indicated that about 38% of the failures were primarily related to aging, 55% were partially aging related, and 7% of the failures were unassignable. About 25% of the failures were primarily caused by human, design, procedure, and other errors. The large number of errors is probably directly related to the complexity of chillers and their interfacing systems. Nearly all of the LERs were the result of entering plant Technical Specification Limiting Condition for Operation (LCO) that initiated remedial actions like plant shutdown procedures. The trend for chiller-related LERs has stabilized at about 0.13 LERs per plant year since 1988. Carefully following the vendor procedures and monitoring the equipment can help to minimize and/or eliminate most of the premature failures. Recording equipment performance can be useful for trending analysis. Periodic operation for a few hours on a weekly or monthly basis is useful to remove moisture and non-condensable gases that gradually build up inside the chiller. Chiller pressurization kits are available that will help minimize the amount of moisture and air ingress to low-pressure chillers during standby periods. The assessment of service life condition monitoring of chillers indicated there are many simple to sophisticated methods available that can help in chiller surveillance and monitoring. These methods will help prevent accelerated degradation and failures in chillers. A predictive maintenance program with effective service life condition monitoring will be helpful in reducing the number of Technical Specification LCO entries and LERs, and possibly eliminate them altogether. New refrigerant handling and storing procedures and guidelines should be accommodated.

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Summary

The Pacific Northwest Laboratory (PNL)[(a)] conducted an aging assessment of chillers used in essential safety heating, ventilating, and air conditioning (HVAC) systems of nuclear power plants (NPPs). This report, Volume 2, covers the second phase of the study. Searches of traditional nuclear plant databases provided limited information on chillers. Plant visits to obtain maintenance and failure data were not performed. The available database information was augmented by non-nuclear chiller operating experience.

Centrifugal chillers in the 75- to 750-ton refrigeration capacity range are the predominant type used in essential nuclear plant HVAC systems. Other, less-used types include rotary, screw, and reciprocating chillers. The chillers used, and HVAC systems served, vary in design from plant to plant. It is difficult to select a generic design. This study focused on centrifugal packaged chillers.

The review of operating experience indicated that chillers experience aging degradation and failures. The primary aging factors of concern for chillers include vibration, excessive temperatures and pressures, thermal cycling, chemical attack, and poor quality cooling water. Aging is accelerated by moisture, non-condensable gases (e.g., air), and other contamination within the refrigerant containment system. Excessive start/stop cycling and under-loading of chillers can promote rapid aging. Aging is also accelerated by corrosion and fouling of the condenser and evaporator tubes. The principal cause of chiller failures is lack of monitoring (Blahnik and Klein 1993). It is important to record and trend the operating temperatures and pressures on a daily basis and routinely analyze the lubricant oil and refrigerant chemistry. Human errors and omission of scheduled maintenance also contribute to the failures. Failures due to design and manufacturing discrepancies usually occur during the original start-up, shakedown, or first year of operation for a particular new chiller model.

The Phase II evaluation of Licensee Event Reports (LERs) indicated that about 38% of the failures were primarily related to aging, 55% were partially aging related, and 7% of the failures were unassignable. About 25% of the failures were caused primarily by human, design, procedure, and other errors. The large number of errors is probably directly related to the complexity of chillers and their interfacing systems. Nearly all of the LERs were the result of entering a plant Technical Specification Limiting Condition for Operation (LCO). LCOs are the lowest functional capability or performance levels of equipment required for safe operation of the plant. When an LCO is exceeded, remedial actions, such as plant shutdown procedures, are required to be taken within a specified period of time. In thirteen chiller-related LCO cases power reduction was started, and in three cases the plant was completely shut down. There likely were more such cases that were not listed in the brief LER summaries reviewed. In one case two adjacent plants had to start shutdown procedures because they shared common essential chillers that had failures.

The trend for chiller-related LERs has stabilized at about 0.13 LERs per plant year since 1988. Based on the two plants that provided detailed chiller failure data in the Phase I study (Blahnik and Klein 1993), there are probably one to two orders of magnitude more failures causing a chiller trip, than indicated by the LERs. There may be an additional order of magnitude more failures that are minor and do not cause a chiller to trip. LERs report a situation where both redundant chillers are inoperable at the same time.

Most failures may be eliminated or minimized by carefully following vendor procedures and monitoring equipment. Equipment performance should be recorded and trended. The staff performing routine maintenance should be well-trained. Major overhauls and maintenance that require opening the refrigerant containment region should be performed carefully by well-trained and experienced technicians. It may be preferable to use service company technicians who routinely tear down and overhaul chillers. A small amount of contamination or a damaged or misaligned part can cause major problems during operation of

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(a) Operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

a chiller. It is crucial at all times to keep equipment internals very clean and prevent the leakage of water, air, and other contaminants into the sealed refrigerant containment system.

Periodic operation for a few hours on a weekly or monthly basis is necessary to remove moisture and non-condensable gases that gradually build up inside the chiller. Moisture and non-condensable gases accelerate aging in chillers. A few hours of operation will help to provide the stable operation needed to evaluate the operating parameter performance, especially if the chiller is required to operate as an emergency standby unit. This will provide some approximate trendable information about degradation occurring during standby. If multiple chillers are available, alternate operation and balancing their hours of operation are recommended.

Chiller pressurization kits are available that will help minimize the amount of moisture and air ingress to chillers during standby periods. These kits are especially beneficial for low-pressure chillers (use R-11/R-123 refrigerant) that operate and stand by with the refrigerant below or near atmospheric pressure. In many cases the chillers can be upgraded and/or converted to new refrigerants by installing adaptor equipment packages provided by the manufacturers or chiller vendors. The upgrades will help reduce failures and improve machine reliability.

The assessment of service life condition monitoring of chillers indicated there are many simple to sophisticated methods available that can help in chiller surveillance and monitoring. These methods will help to prevent accelerated degradation and failures in chillers. The most effective chiller monitoring methods are refrigerant/lubrication oil leak detectors, periodic refrigerant/lubricant chemical analysis, vibration analysis, tube eddy current testing, and infrared thermal analysis. The ultimate method is a computerized monitoring system that will continually monitor the chillers and their interfacing systems.

Review of numerous maintenance manuals provided by the centrifugal chiller manufacturers indicated that the maintenance requirements for chillers are well prepared and thorough. The operation manuals provided by the manufacturers are also excellent, and they provide warnings and guidelines that, if followed, will prevent accelerated aging and degradation of the chillers. Using the manuals will also help prevent unnecessary LERs, LCOs, chiller shutdown trips, and aid in startups.

A predictive maintenance program with effective service life condition monitoring will be helpful in reducing the number of LERs and LCOs and possibly eliminating them altogether. This study indicated that such programs and equipment are available and should be used with chillers and other NPP equipment. Literature indicated that some plants have successfully implemented similar programs. The programs enhance trouble-shooting, root cause analysis, and corrective action.

Changes in environmental regulations are anticipated to impact the choice and use of refrigerants in chillers. Changes in refrigerants may impact the performance and aging of chillers. Three options for accommodation include:

- Improve the existing chiller's tightness to prevent CFC refrigerant leakage.
- Convert the existing chillers to use non-CFC refrigerants.
- Replace the existing chillers with new chillers using non-CFC refrigerants.

The option selected should depend on the results of a careful safety, facility, cost, schedule, and risk study. Many plants have access problems for chiller replacement, and the facility ventilation systems may be impacted. New refrigerant handling and storing procedures and guidelines should be accommodated.

Discussions with representatives of chiller, refrigerant, and lubrication oil manufacturers have indicated that the HVAC industry has resolved most of the problems associated with the new refrigerants. New chillers and retrofit kits are well designed and have worked satisfactorily. Operation and maintenance (O&M) requirements have changed slightly. Time will tell if there are any accelerated degradation problems, but none are expected at this point in time.

The essential (safety-related) chillers are important to cool the Control Room and other safety-related equipment rooms. The cooling is needed to prevent degradation and failure of safety-related equipment, to protect personnel, and to prevent or mitigate events and accidents. Control of temperature and humidity in these rooms is very important. Therefore, the essential chillers play an important role in nuclear plant safety. This report addresses the steps necessary to understand and manage the chiller aging process and provides recommendations that will help the essential chillers perform safely and reliably.

Acknowledgments

The authors of this report acknowledge the support and technical guidance of Dr. J. J. Burns, Mr. J. P. Vora, and Mr. S. K. Shaukat of the Nuclear Regulatory Commission during the course of this research under the Nuclear Plant Aging Research Program. Information on Licensee Event Reports was provided by G. A. Murphy of Oak Ridge National Laboratory. Chiller failure data was provided by D. E. Stouppe of The Hartford Steam Boiler Inspection and Insurance Company. Chiller refrigerant conversion information was provided by E. M. Clark of E.I. DuPont de Nemours & Company. Technical assistance was provided by personnel from The Trane Company, Carrier Corporation, and York International Corporation. Chiller condition monitoring reports were provided by E. C. Hart of Systems Engineering Associates Company, W. H. Frazier, III of Tubular Technologies, and G. N. Thoen of HEATSCAN. Staff from the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, the Air-Conditioning and Refrigeration Institute, and the Underwriter's Laboratory also provided valuable assistance.

The authors also wish to thank the following PNL staff for their contributions to this report: Dr. R. P. Allen for project management support and technical guidance; Dr. A. B. Johnson, Jr. for his contribution on chiller corrosion and general support; H. D. Steele for providing assistance in the review of PNL chiller work activities; and J. R. Coblentz who performed an extensive literature search on chillers.

Acronyms

ANS	American Nuclear Society
ARI	Air-Conditioning and Refrigeration Institute
ARTI	Air-Conditioning and Refrigeration Technology Institute
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ASME	American Society of Mechanical Engineers
BWR	boiling-water reactor
CCW	component cooling water
CFC	chlorofluorocarbon
ECW	emergency cooling water
EPA	U.S. Environmental Protection Agency
ESF	engineered safety feature
FSAR	final safety analysis report
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HP	high pressure
HVAC	heating, ventilating, and air conditioning
HX	heat exchanger
IRT	infrared thermography
LCO	limiting condition for operation
LER	Licensee Event Report (database)
LOCA	loss-of-coolant accident
LOP	loss of offsite power
LP	low pressure
LWR	light-water reactor
MP	medium pressure
NPAR	Nuclear Plant Aging Research
NPE	Nuclear Power Experience (database)
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
NUDOCS	Nuclear Documentation System (database)
O&M	operation and maintenance
PNL	Pacific Northwest Laboratory
PWR	pressurized-water reactor
R&D	research and development
RIDS	Regulatory Information Distribution System (database)
SCSS	Sequence Coding and Search Systems (database)
SRP	Standard Review Plan

Definitions

age-related failure

failure that results primarily from normal aging degradation caused by wear, corrosion, vibration, etc. The aging can be accelerated by errors.

chiller

packaged refrigeration machine used to chill water that is pumped to the HVAC room cooler to cool room air - the absorbed heat is returned to the chiller, which transfers the heat to a plant cooling system.

essential chiller

a chiller used to cool rooms that contain safety-related equipment essential to plant safety - Nearly all NPPs use essential chillers to cool control rooms.

failure

inability or interruption of ability of a system, structure, or component to function within acceptance criteria.

high pressure (HP) refrigerant

same as medium pressure except refrigerant (HP) operates at higher pressures - R-22 is a high pressure refrigerant.

limiting conditions for operation (LCO)

"Limiting conditions for operation are the lowest functional capability or performance levels of equipment required for safe operation of the facility. When a limiting condition for operation of a nuclear reactor is not met, the licensee shall shut down the reactor or follow any remedial action permitted by the technical specifications until the condition can be met."

low pressure (LP) refrigerant

a refrigerant that operates below or near atmospheric pressure (zero pounds per square inch gage, 0 psig) and may allow air and moisture to be introduced into the refrigerant during operation or standby - R-11/R-123 are low pressure refrigerants.

medium pressure (MP) refrigerant

a refrigerant that operates above atmospheric pressure and is unlikely to allow air or moisture to be introduced during operation or standby. R-12/R-134a are medium pressure refrigerants.

monitoring

includes both routine process parameter monitoring by operations and a preventative maintenance monitoring program; both aspects are very important to chiller reliability and performance.

partially age-related failure

failure that is a combination of age- and non-age-related factors - often the failure is accelerated when factors are combined (e.g., seal made of wrong material fails prematurely, human error, manufacturing error, etc.).

safety-related items

defined by 10 CFR 50, Appendix A, as "Those structures, systems, and components that provide reasonable assurance that the facility can be operated without undue risk to the health and safety of the public" - for details, see 10 CFR 50.49.

ton, cooling rate

standard ton of refrigeration that is equivalent to an air conditioning capacity of 12,000 BTU/hr.

ton, storage

storage equivalent to the heat of fusion of 2000 lb of ice (2000 lb x 144 BTU/lb = 288,000 BTU to melt a ton of ice).

1 Introduction

The essential chillers provide chilled water to cool the control room and other rooms containing safety-related equipment and personnel at nuclear power plants (NPPs). Essential chiller operability is mandated by Title 10, Part 50 of the Code of Federal Regulations and other regulations that govern habitability of the control room and operation of the safety-related rooms. The essential chilled water systems must be available at all times, have redundancy, and function during and after simultaneous or individual events, such as a safe shutdown earthquake, loss-of-coolant accident (LOCA), or loss of offsite power (LOP).

Because the ventilation systems these chillers serve are safety-related, the chillers are also safety-related. They must be designed, manufactured, and installed in accordance with Seismic Category I, and the American Society of Mechanical Engineers (ASME) Code, Section III, Class 3 requirements. The system must be powered from Seismic Category 1E buses.

With the above requirements in mind, work was initiated on a Nuclear Plant Aging Research (NPAR) Phase I aging study of NPP chillers. The Phase I study was completed and summarized in the Volume 1 report (Blahnik and Klein 1993). Based on the Phase I recommendations the Phase II study focused on chiller condition monitoring, improving maintenance practices, and converting chillers to the newly mandated refrigerants. A concern about the high number of entered Limiting Condition for Operations (LCOs) found during the Phase I study prompted an expanded review of Licensee Event Reports (LERs) during the Phase II study.

A summary of the Phase II aging study is provided in this Volume 2 report. The discussion below summarizes the background and objectives for the study.

1.1 Background

Chillers were first formally identified as a candidate for an NPAR study in a U.S. Nuclear Regulatory Commission (NRC) prioritization study (Levy et al. 1988). In January 1991, work was initiated on a Pre-Phase I study to determine if a full Phase I study was justified. The Pre-Phase I study was completed and summarized in a letter report.

The study recommended that a full Phase I study proceed, and the NRC concurred. The Phase I study was completed and summarized in a report (Blahnik and Klein 1993). The report included the following essential chiller-related information:

- chiller machine descriptions and study boundary description
- description and uses of essential chiller heating, ventilating, and air conditioning (HVAC) systems in nuclear plants
- regulatory, code, and standards requirements for essential chillers
- reference centrifugal chiller detailed design description and materials of construction
- a general evaluation of chiller operating experience for nuclear plants and the HVAC industry.

The results of the Phase I study indicated that chillers age and fail if they are not cared for properly. This study determined that the principal cause of failures is lack of condition monitoring and lack of effective maintenance practices. A major future concern is the need for a careful transition from the current chlorofluorocarbon (CFC) refrigerants used in essential chillers to environmentally acceptable refrigerants.

The Phase I study indicated that the essential (safety-related) chillers are important to cool the control room and other safety-related equipment rooms. The cooling is needed to prevent degradation and failure of safety-related equipment, to protect personnel, and to prevent or mitigate events and accidents. Control of temperature and humidity in these rooms is very important.

High temperatures and humidities in control rooms affect both personnel and equipment. High temperatures can cause operators to become uncomfortable and more susceptible to losing alertness and making errors in judgment. High control room temperatures also cause concern for premature degradation and failure of electrical and electronic components, which are often housed in cabinets with higher than ambient room temperatures. The newer digital control systems are more susceptible to high temperature failure than the older analog systems. Failure of control components and spurious alarms make the operators' jobs more difficult and could become the principal cause of operating error. The situation can be particularly difficult during a Technical Specification LCO Action requirement to shut down the plant after failure of both redundant chillers. Operators may become more tense due to warmer control room temperatures and time limitations to prepare for a plant shutdown. Shutting the plant down after a Technical Specification LCO action requirement cannot be met stresses the entire facility and unnecessarily accelerates aging in many of the plant systems and components.

Essential chillers play an important role in nuclear plant safety and warrant more in-depth studies.

1.2 Objective

The NRC approved a Phase II study to focus on improving chiller condition monitoring, improving maintenance practices, and developing guidelines for the transition to the new refrigerants. Also the LERs were to be reviewed in more depth to see how they could be reduced in the future. The objective of the Phase II chiller study was to make an aging assessment of chillers. The following standard research elements were performed in accordance with the NPAR Program strategy (USNRC 1991):

- Review and analyze available information from chiller designs, specifications, operational parameters, and ongoing research.
- Evaluate chiller operating experience from available databases.
- Utilize industry practices and the knowledge from experts on chillers.
- Characterize aging in chillers.
- Interact with key NRC staff.
- Interact with chiller vendors and manufacturers.
- Interact with codes and standards groups.
- Conduct detailed analyses and evaluations.
- Develop recommendations for inspection, surveillance, maintenance, and monitoring.
- Apply results of the research to
    - developing guidelines for ISMM and service life predictions
    - disseminating the technical research
    - helping the advanced Light Water Reactor (LWR) program.

In the following sections of the report the centrifugal chillers and the boundaries of the chiller study are described. The use of chillers in LWRs is discussed. Failure data evaluation results and information on chiller aging degradation are discussed. Service life monitoring and maintenance, two important ingredients in effective chiller aging management, are also discussed. The upcoming CFC replacement and aging considerations for the new refrigerants are addressed. The end of the report provides the conclusions from the chiller aging studies.

2 Essential Chillers Description and Equipment Boundary Selection

About 90% of the chillers found in the NPP Final Safety Analysis Reports (FSARs) were centrifugal chillers, and most of them were driven by hermetic electric motors. Therefore, this study has focused on the hermetic centrifugal chiller as the reference design. A photo of a typical centrifugal chiller is shown in Figure 2.1. Other types of chillers used in nuclear plant HVAC include the rotary, reciprocating, and screw compressor designs. Because these types were used in the smaller and older plants, not much information was available on them or their related systems.

A cross-sectional schematic view of a centrifugal chiller is shown in Figure 2.2. It shows the major components and the direction of flow of condenser and chiller water and the refrigerant in its various phases. A centrifugal chiller piping and wiring illustration is provided in Figure 2.3 to show how the chiller interfaces with the plant facilities.

A simplified diagram of the major components of a centrifugal chiller and the interfacing systems is shown in Figure 2.4. The research boundary selected for the chiller aging study is indicated by the dashed line. The major components of the chiller are typically a motor-driven centrifugal compressor, a condenser heat exchanger (HX), an expansion device, and the evaporator-cooler HX. The refrigerant used as heat transfer media is usually CFC-11 (R-11) or CFC-12 (R-12) refrigerant. The chiller waste heat is removed by the plant service water system or an emergency cooling water (ECW) system (especially in an accident or LOP situation). The chilled water from the evaporator is used to cool rooms that house personnel and safety-related equipment. The limited FSAR design information indicated the rooms were not cooled directly by refrigerants. More detailed design information would be needed on all of the plants, particularly the older plants.

The rooms cooled by chillers are plant-specific, but the control rooms were included in nearly all of the plants reviewed. The chiller and its interfacing systems (the cooling water system, chilled water system, and electric motor control center) can have a large effect on the performance of one another. Other major systems such as the Emergency Diesel Generator System; the Control Room HVAC System; and other safety equipment rooms are interrelated and can have an impact on the operation of each other. There are many safety interlocks, so design simplification is important. The Phase I report (Blahnik and Klein 1993) included a more detailed discussion of the centrifugal chiller design, its functional description, and a discussion on alternative types; therefore, it won't be repeated in this report.

In reality, a chiller is much more complex than shown in Figure 2.4. A chiller has hundreds of components and is interrelated with many remote safety system-controlled components.

The typical auxiliary components of a chiller include

- compressor guide vane
- control panels and indicators
- wires and terminals
- purge-dehydrator unit(a)
- piping and tubing
- seals and gaskets
- base, package support structure, and vibration dampeners
- lubrication oil system(a)
- sensors, controls, and alarms
- switchgear, starter, and relays
- flash economizer(a)
- relief valves
- transmission gearbox and couplings.(a)

(a) These components have numerous sub-components.

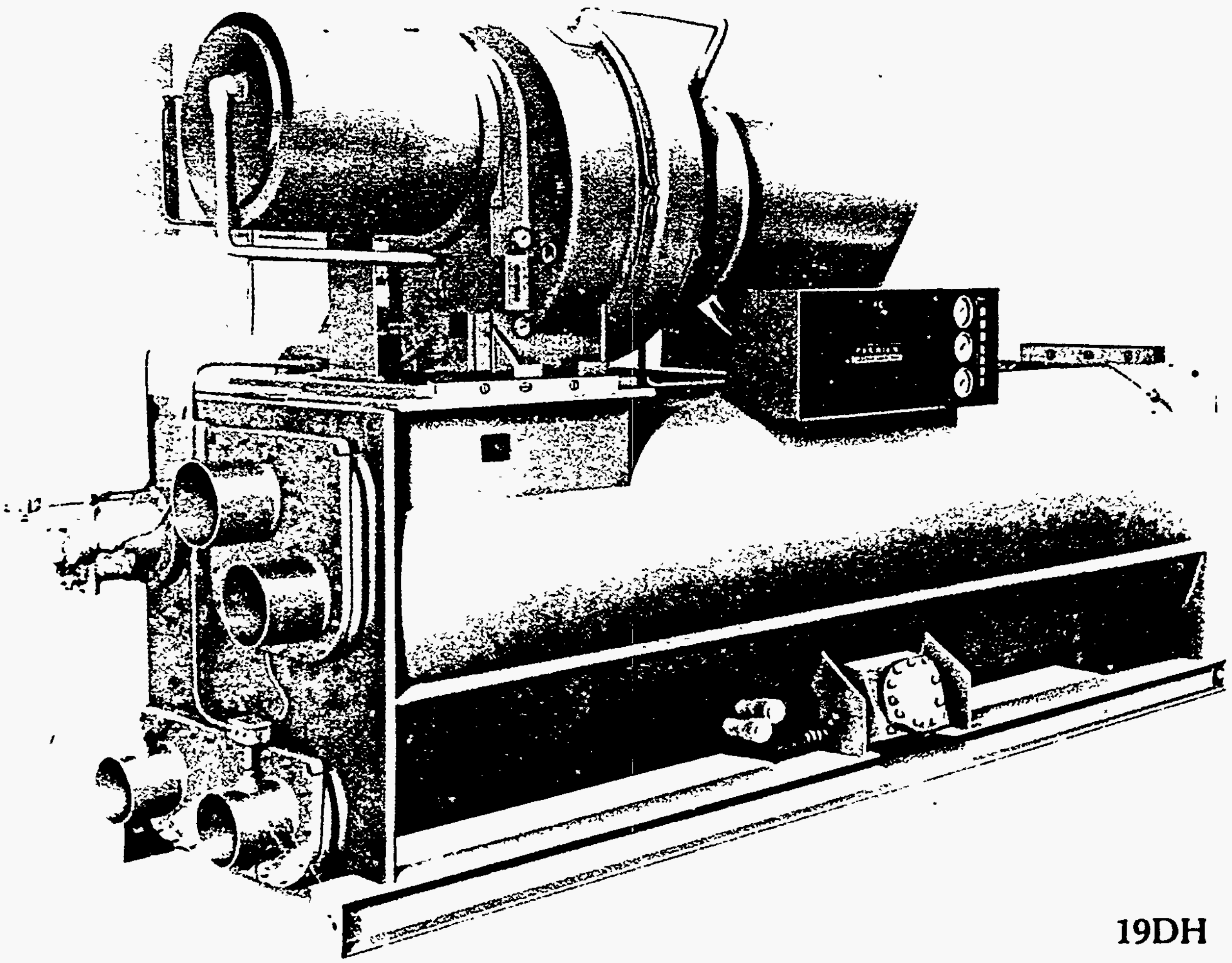


Figure 2.1 **Recent Model of Liquid Hermetic Centrifugal Chiller Manufactured by the Carrier Corporation - Reference Design (Permission to use this copyrighted material is granted by the Carrier Corporation.)**

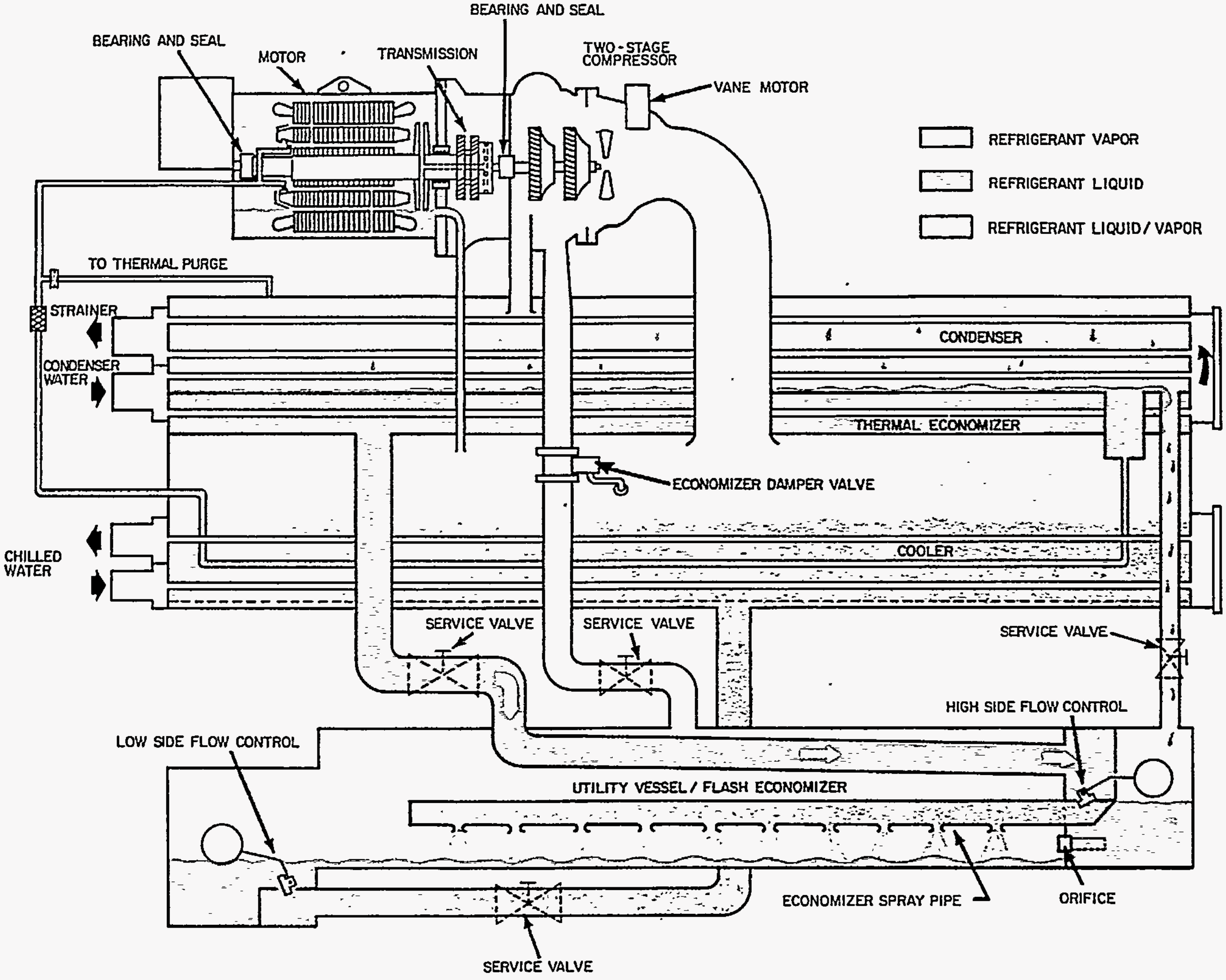
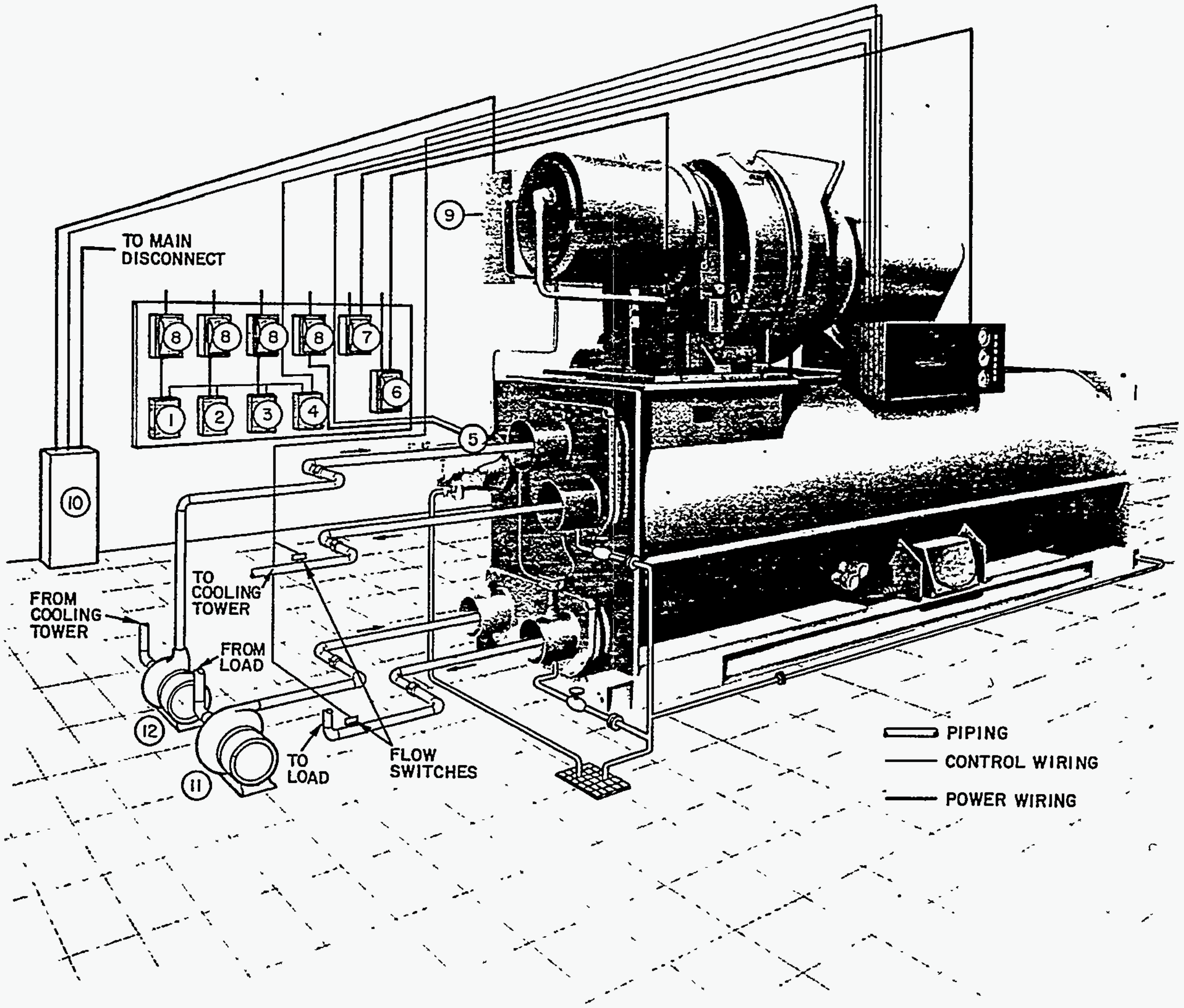


Figure 2.2 Reference Centrifugal Chiller Cross-Sectional View Showing Refrigerant Flow Path and Internal Components (Permission to use this copyrighted material is granted by the Carrier Corporation.)



LEGEND

1 — Cooling Tower Fan Starter
2 — Condenser Water Pump Starter
3 — Cooler Water Pump Starter
4 — Pilot Relay
5 — Oil Pump Starter
6 — Fused Disconnect for Oil Heater and Thermostat
7 — Fused Disconnect for Purge System
8 — Fused Disconnect
9 — Compressor Motor Terminal Box
10 — Compressor Motor Starter
11 — Cooler Water Pump
12 — Condenser Water Pump

NOTES:

1. Wiring and piping shown are for general point-of-connection only and are not intended to show details for a specific installation. Certified field wiring and dimensional diagrams for specific 19 Series machines are available on request.
2. All wiring must comply with applicable codes.
3. Refer to Carrier System Design Manual for details regarding piping techniques.
4. A separate 115-volt fused power source for controls is required unless compressor motor control is furnished with a transformer.
5. Provide a separate fused 115-volt power source for oil heater and thermostat.

Figure 2.3 Reference Centrifugal Chiller Piping and Wiring Illustration **(Permission to use this copyrighted material is granted by the Carrier Corporation.)**

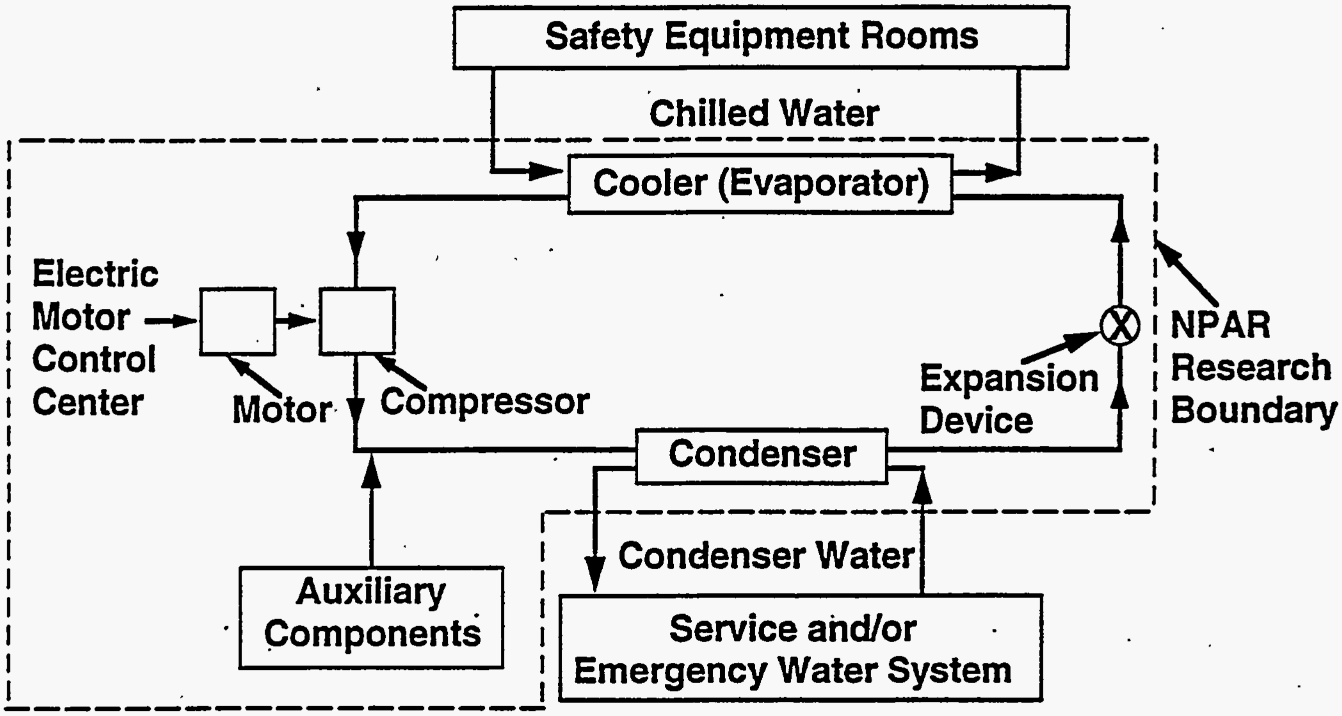


Figure 2.4 Diagram of Major Chiller Components and Study Research Boundary

3 Essential Chillers Use in LWRs

Most of the plants listed in the Phase I LER review (Blahnik and Klein 1993) had at least two essential chillers that served safety systems in the control rooms and various equipment rooms. One chiller serves as a backup and provides the safety redundancy required. Each chiller serves an independent HVAC-chilled water train.

Alternative chiller arrangements include the South Texas plants that have two chillers serving each of three 50% capacity safety-related HVAC trains (total of six). The Perry 1 plant and Surry plant have three chillers serving two safety-related trains; the third chiller is used as a standby unit. The McGuire plants have three chillers that are shared by two plants.

Centrifugal chillers were the predominant type of chiller reported in the LERs that were reviewed. Most centrifugal chillers were hermetic drive (electric drive motor is sealed inside the refrigerant boundary). Some were open drive (sealed outside the refrigerant boundary and exposed to the chiller room environment). Others were screw, rotary, and reciprocating chillers. These latter types tended to be used in older and smaller plants. The NPP chillers that were reviewed all used water to cool the condenser.

The essential chillers were sized in the 50- to 750-ton refrigeration capacity range. Non-essential chillers were in the 200- to 1500-ton range. Based on what was learned from the FSARs, it was decided to focus on centrifugal hermetic chillers during the aging study. The review of the FSARs in Appendix A of the Phase I report (Blahnik and Klein 1993) also provided the following information:

- In some cases essential chillers and their chilled water system are normally on standby for emergency situations (e.g., LOCA, LOP, etc.). During normal operations, non-essential (non-safety) chillers serve the control room and other safety-related rooms. In many cases the essential chillers are used for both normal operations and emergency situations to cool just safety-related rooms. Sometimes the essential chillers serve both safety and non-safety-related rooms, and they reduce their capacity in an emergency to serve just the safety-related rooms.
- Essential chiller condenser cooling water is supplied by systems and arrangements such as the following:
    - Service Water System (both normal and emergency)
    - Service Water System during normal operation and Emergency Service Water System during emergencies
    - Component Cooling Water System (both normal and emergency)
    - Nuclear Closed Cooling System (normal) and Emergency Closed Cooling System (emergency)
    - Emergency Nuclear Service Cooling Water System during emergencies
    - Essential Cooling Water System during emergencies
    - Plant Service Water System during normal operations and Shutdown Service Water System during emergencies.

During an emergency, the particular systems served by essential chillers varies from plant to plant. The control room was served by an essential HVAC system in all of the plants listed. However, the other rooms served by the essential HVAC system varied from plant to plant.

Examples of the rooms and equipment served by essential chillers in various plants include the following:

- Containment Fan Coolers
- Electrical Equipment Room
- Battery Room
- Auxiliary Building Electrical Switchgear Room
- Engineered Safety Feature (ESF) Switchgear Room
- Electrical Penetration Room

- ESF Equipment Room
- Emergency Cooling Water (ECW) Pump Rooms
- Auxiliary Feedwater Pump Rooms
- Reactor Makeup Water and Boric Acid Transfer Pump Cubicles
- Relay Room
- Cable Spreading Room
- Computer Room[a]
- Control Room HVAC Equipment Room
- Remote Shutdown Room
- Component Cooling Water (CCW), Charging, Safety Injection, and Residual Heat Removal Pump Room fan/coil coolers
- Essential Equipment Rooms
- Standby Gas Treatment System Compartment and Area
- Spent Fuel Pool HX and Pump Rooms
- Auxiliary Building ESF Equipment, Switchgear, and Electrical Equipment Protection Room
- Safety-Related Panel Room
- Emergency Motor Control Center.

Based on the results of the FSAR review, it was determined that generic plant designs do not exist. Even multiple plant units at a site may have substantial design differences. A study to determine which design options work the most reliably might be justified.

In addition to the chiller systems that serve HVAC applications, there are other chillers that serve safety systems in non-HVAC applications. Examples are chillers used to recover condensible off-gas from the primary water system in Boiling-Water Reactor (BWR) plants, to make and maintain ice for containment safety ice condensers in eight of the Westinghouse Light-Water Reactors (LWRs), and to follow shim control in the Boron Thermal Regeneration System in some Westinghouse Pressurized-Water Reactor (PWR) plants. The review and aging assessment of those chillers was beyond the scope of this study.

In addition to chiller cooling of essential safety-related rooms, some plants have the option to use water directly from the Service Water System or other intermediate system in lieu of chiller-cooled water. In one plant, service water is cool enough the year around to keep the control room below 29°C (85°F).

(a) In some plants the Computer Room is not considered safety-related.

4 Evaluation of NPP Essential Chiller Aging Failure Data

The initial plan for the Phase II study included visits to a sample quantity of NPPs to gather failure data for a database and to meet with the plant engineering and maintenance staff to obtain insight for the database. These visits were not conducted and, therefore, a more general approach was used to focus on confirming results of the Phase I study and providing a closer evaluation of the numerous Technical Specification LCO entries caused by chillers. It was decided to make a more comprehensive LER search and a more thorough evaluation of the LERs to meet those objectives.

4.1 LER Database

A Summary of the chiller LERs is given in Appendix A. The table in Appendix A provides the LER identification number, plant identification, event date, failure description, failure cause, failure area, and identification of failures attributed to aging. The summary period covers 1981 through 1993. The LERs were compiled from the Sequence Coding and Search Systems (SCSS), the Nuclear Documentation System (NUDOCS/AD), the Regulatory Information Distribution System (RIDS), the ZyINDEX for Windows (RECALL), and the Nuclear Power Experience (NPE) databases. A total of 151 LERs were found; these contained 174 failures because some represented multiple chiller failure areas. The results of the evaluation of chiller-related failures are summarized in Figure 4.1.

Most of the failures (22) were in the condenser/evaporator heat exchanger area. Nearly all of those failures were condenser related. Also related directly to the condensers were 15 failures due to clogged inlet valves and strainers. Most of those occurred at the Surry plants. The other high failure areas included related systems, refrigerant (mostly leaks), and electrical/mechanical control components.

Mechanical and electrical control component failures (46) represented about 26% of the total failures. Electrical component-related failures (31) occurred about twice as often as those believed to be mechanical component-related (16). Many LERs that reported chiller trips were not included because the events were caused by failures in the important condenser cooling water system (e.g., filter, strainer, pump, and valve failures; plugging, air injection, undersize, etc., of cooling water piping), which is outside the study review boundary (Figure 2.4). Also, numerous chiller trips occurred as a result of failures in the emergency diesel generator system, chilled water system, essential cooling water system, and related HVAC train systems. Twenty chiller failures were due to failures in interfacing systems. These failures resulted in chiller trips that caused LCOs charged to the chillers and affected control room cooling in particular.

4.2 Chiller Failure Assessment

The table in Appendix A provides brief descriptions and causes of the failure(s) for each LER. The accuracy of these assessments is limited by the brief text of the LER. It is important to note that in the case of 53 (35%) of the LERs identified by Note 3 in the Appendix A table, failures occurred that caused secondary stresses, which accelerated aging in some or all of the components exposed to the refrigerant atmosphere in the chillers.

As an example of secondary accelerated aging, a "high refrigerant pressure" failure causes shutdown of a chiller due to excessive heat generation. The heat can't be rejected from the chiller fast enough. The causes of "high refrigerant pressure" failures are

- tube fouling from algae, scale, dirt, and microorganisms
- plugged inlet strainers (low flow)
- failed pump in cooling water system (condenser related)
- incorrect valving (waterside)
- division plate gasket slippage, leaking, or missing seal
- vacuum side air leaks (low pressure refrigerant)
- oxides on tube outer diameters

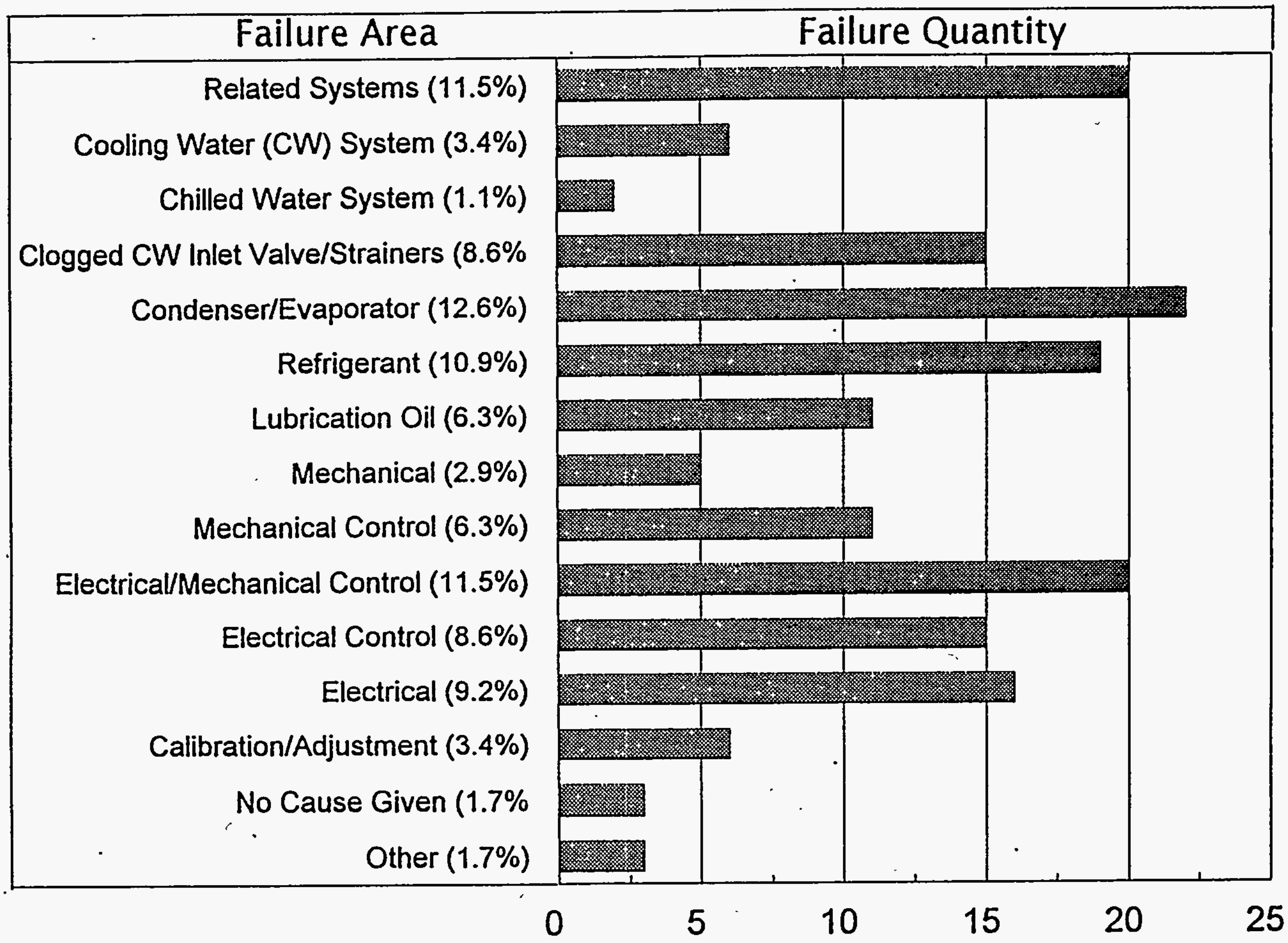


Figure 4.1 Summary of Chiller Failure Evaluation (LER Databases)

- failed tower fan
- improper temperature settings
- failure or improper operation of service water automatic by-pass valve.

The additional heat causes secondary impacts like

- surging
- breaking down refrigerant to fluorides and chlorides which, in the presence of moisture, form acids
- reducing gasket and O-ring life (causing refrigerant leaks)
- overheating the motor winding
- lube oil overheating and acid/moisture contamination
- acids attacking motor windings and bearings
- general refrigerant attacking by acids
- accelerating scaling, algae and microorganism growth, and corrosion in the condenser tubes

A "low charge of refrigerant," for example, causes impacts similar to that of the "high refrigerant pressure" failure. Because there is less refrigerant to boil, fewer tubes are exposed to refrigerant, and the superheat goes higher causing reduced compressor cooling; the equipment has to work harder to achieve the same results. This creates more heat, and with less refrigerant, the heat is harder to remove to the condenser for rejecting to the service cooling water and the atmosphere. An additional secondary impact for a low charge of refrigerant is tube freeze up in the evaporator that causes tube stress due to bulging and/or breakage.

Another example is "low oil pressure" that would mostly affect the refrigerant side of the compressor and oil sump. This creates a vicious circle of degradation because low oil pressure causes

- hotter bearings, which causes
- compressor/motor drag, which causes
- a need for more horsepower to work, which causes
- hotter oil, which causes
- breakdown of oil, which causes
- more acid formation and carbonization, which causes
- larger bearing clearances, which causes a return to
- lower oil pressure.

All three of these failure acceleration examples could likely be caught early and prevent degradation to the entire machine if computerized monitoring, as described in Appendix B, were implemented. Computerized monitoring could catch these problems before chiller failure, loss of safety margin, and damaging heat. It should also be possible to determine the cause of heat buildup in advance of serious degradation and result in proper corrective action to prevent and/or diagnose failures.

These problems could be caught earlier by manual monitoring if accurate manual monitoring equipment were available and intensive monitoring training and procedures were used. More frequent manual monitoring would also help early detection of degradation.

4.3 Chiller Aging Assessment

The previous section describes failures and how conditions associated with failures can cause degradation of nearly the entire chiller. This degradation represents accelerated aging of the equipment. An attempt was made to determine the degree to which the LER failures were age-related. The aging assessments are indicated for each LER in the next to last column in the Appendix A table. A summary of the assessments of aging failures is illustrated in Figure 4.2.

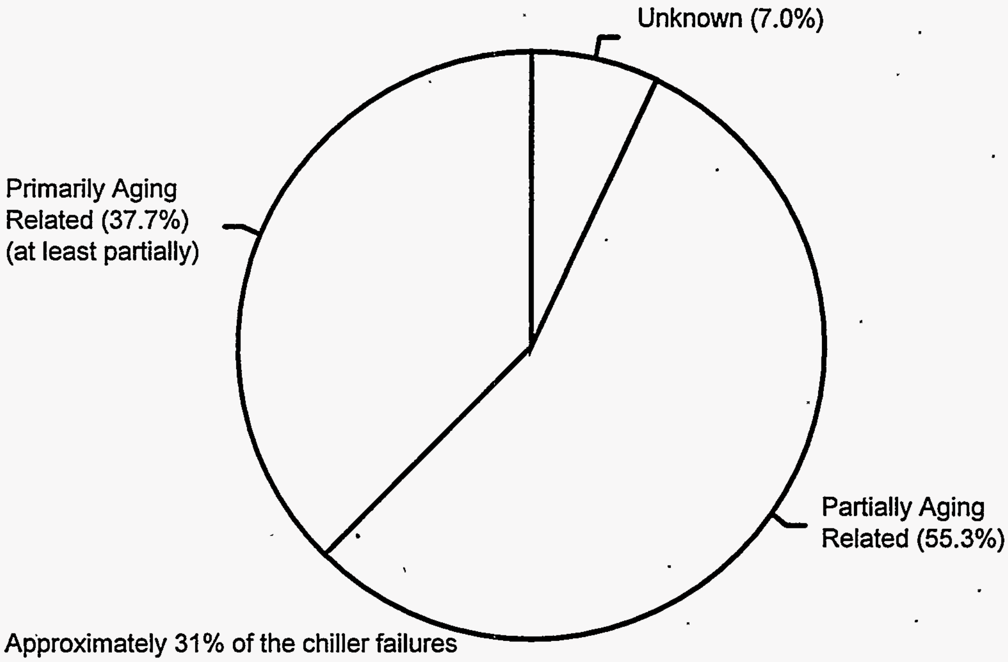
Approximately 38% of the failures were attributed primarily to aging (time-related degradation), 55% were partially aging related, and about 7% of the failure causes were not assignable.

An approximate further breakdown of the failure relationships is presented in Table 4.1.

Approximately 25% of the failures resulted mostly from some kind of error. This is probably due to the complexity of the chiller, the chiller HVAC train, and the related safety and non-safety systems. Nearly all failures occur at least partially due to aging. Multiple factors, like errors, accelerate the aging rate.

4.4 Limiting Conditions for Operation Assessment

Nearly all LERs result from an LCO entry, but it was not always stated in the LER. Some LERs listed incidents such as plant trips, technical specification violations, etc. In nearly all of the LERs, both chiller trains were inoperable for a period of time, resulting in Technical Specification LCO Action requirements not being met. Usually within one to twelve hours after an LCO is entered, if one chiller does not become operable, plant power reduction is initiated. The LER review indicated that power was reduced on 13 occasions at plants, and one of the sites reduced power of both of its plants (McGuire 1&2). On three occasions a plant was completely shut down. The exact number of power reductions or plant shutdowns that resulted from failed or inoperable chillers is unknown because of the limited information available. Some of the utilities are concerned about the LCO situation due to the unreliability and complexity of essential chiller systems (Christie and McDougald 1992).



NOTE: Approximately 31% of the chiller failures (regardless of aging degree) caused secondary stressers which accelerated the aging of all chiller components exposed to the refrigerant system.

Figure 4.2 Aging Assessment of Chiller Failures

Table 4.1 Relationships of Failures to Aging

Failure Relationship Category	Assigned Percentage
Primarily Aging	38%
Partially Aging	30%
Human Error[(a)]	13%
Procedure Error[(a)]	5%
Design Error[(a)]	4%
Other Error[(a)]	3%
Unknown	7%
	100%

(a) Partial aging was accelerated

It is important to avoid chiller failures because the entire plant is affected when the reactor power must be reduced or shutdown.

4.5 Trends in Chiller Failure LERs

The trend in chiller failure LERs has stabilized in the past few years. A graph of the LERs/plant year as a function of years between 1981 and 1993 is provided in Figure 4.3. Rates peaked in 1983 and 1987 due to a particularly large number of LERs at San Onofre 2 and Surry 1&2, respectively. The reason for the reduced rate in 1984 and 1985 might be due to a change in LER filing criteria. Since 1988, the rates have stayed almost constant at about 0.13 LERs per plant year. The mean rate value for the entire 12-year period is 0.12 LERs per plant year.

Factoring in the influence of average plant age (LERs per plant age average) in Figure 4.4 does not significantly change the trend from that shown in the previous figure. This is due to additional plants coming on line compensating for the increase in average age of the other plants. The mean value for the 12-year period was about 1.1 LERs per average plant year age. The influences on rates were about the same as in the previous figure.

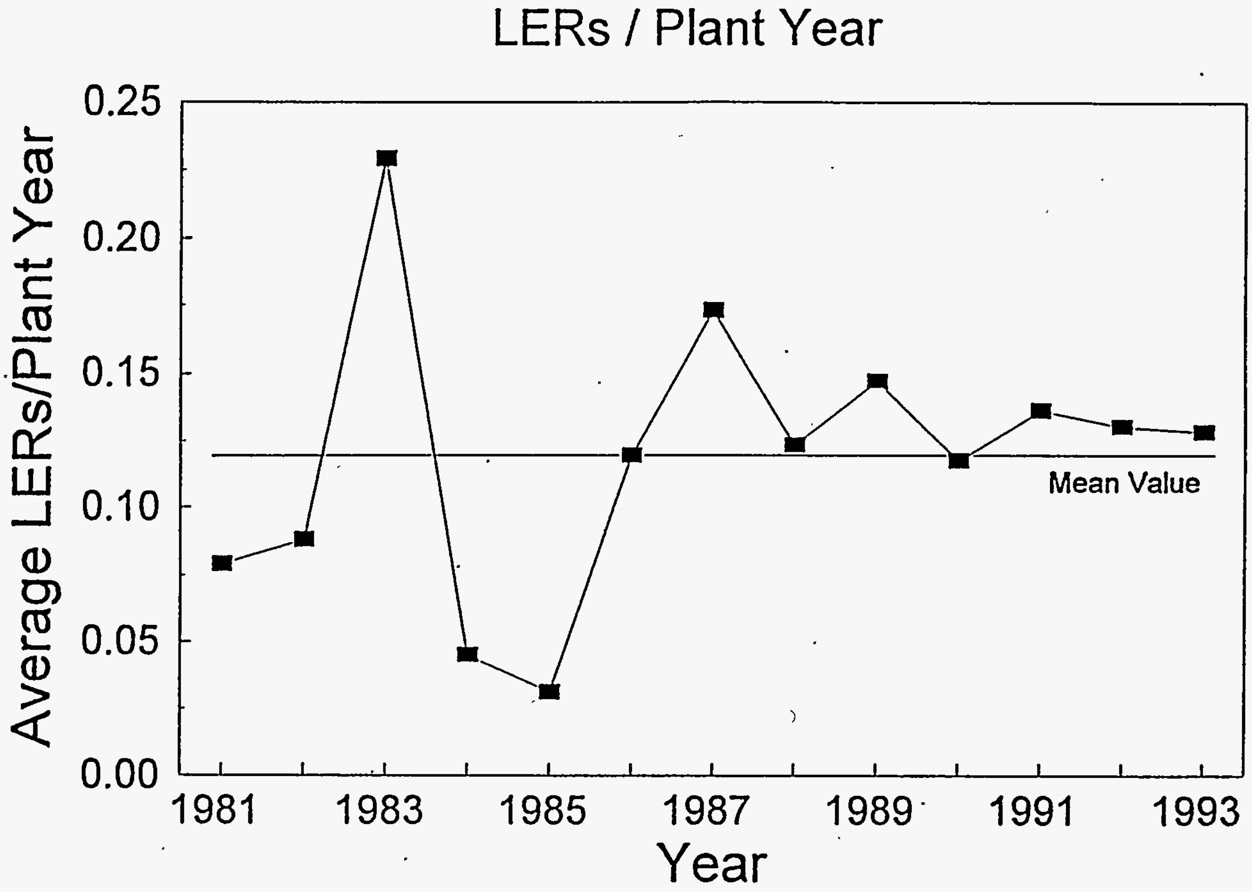


Figure 4.3 Summary of Chiller Failure LERs During Years 1981-1993

4.6 Chiller Failure LERs as a Function of Plant Age

The LERs in the Appendix A table were analyzed to determine how many LERs occurred as a function of plant age. The results are summarized in Figure 4.5. The trend indicated in the figure is that more LERs occur in the early years of a plant and then stabilize for about nine years. The San Onofre 2 plant influenced the increase of LERs shown in the early years. The LERs bottom out in the 9 to 14 year age period and rise again in the plant years between 15 and 21. The Surry 1&2 plant failures had a major influence on the increase of LERs in the later years. If the influence of these three plants were deleted, the trend curve would tend to conform more with a typical "bathtub failure" curve. The calculated mean value was 7.1 LERs per year over the whole age range. The youngest plant was 1-year old and the oldest plant was 25-years old in the base year of 1993, and there were 109 plants in the base year.

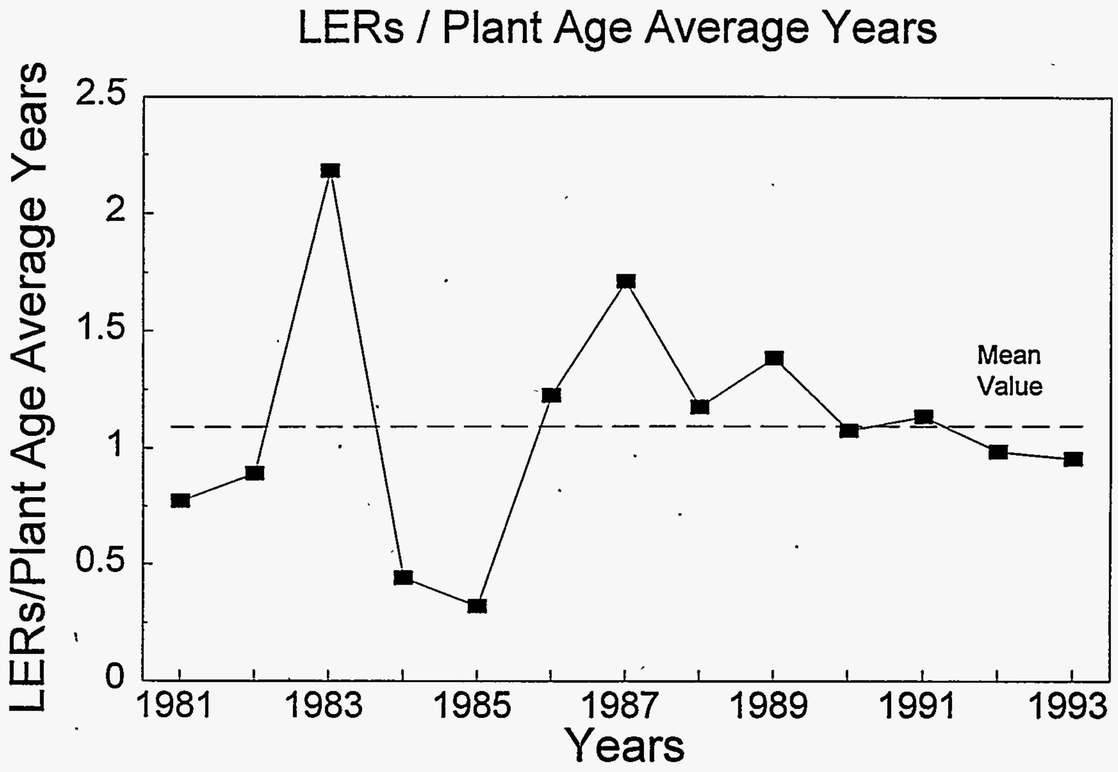


Figure 4.4 Summary of Chiller Failure LERs Per Plant Average Age During Years 1981-1993

4.7 LER Failures Perspective

Chiller failures indicated by LERs represent a small amount of the failures and trips that actually occur with the essential chillers. LERs usually list only the failure of the second chiller, after the first chiller is down, often due to another failure. There are numerous chiller failures that occur to one chiller, and then the second chiller carries the cooling load without need for an LER as long as the first chiller is operable in 3 to 7 days.

Based on the two specific plants evaluated in the Phase I study, there are likely one to two orders of magnitude more failures that cause chillers to be inoperable than the LERs report. In addition there are numerous failures (probably another order of magnitude) of minor chiller components (e.g. indicator lights, etc.) that do not necessarily cause a chiller to shutdown. Therefore, a precise failure analysis requires accurate detailed failure records from a significant number of plants for all their essential chillers.

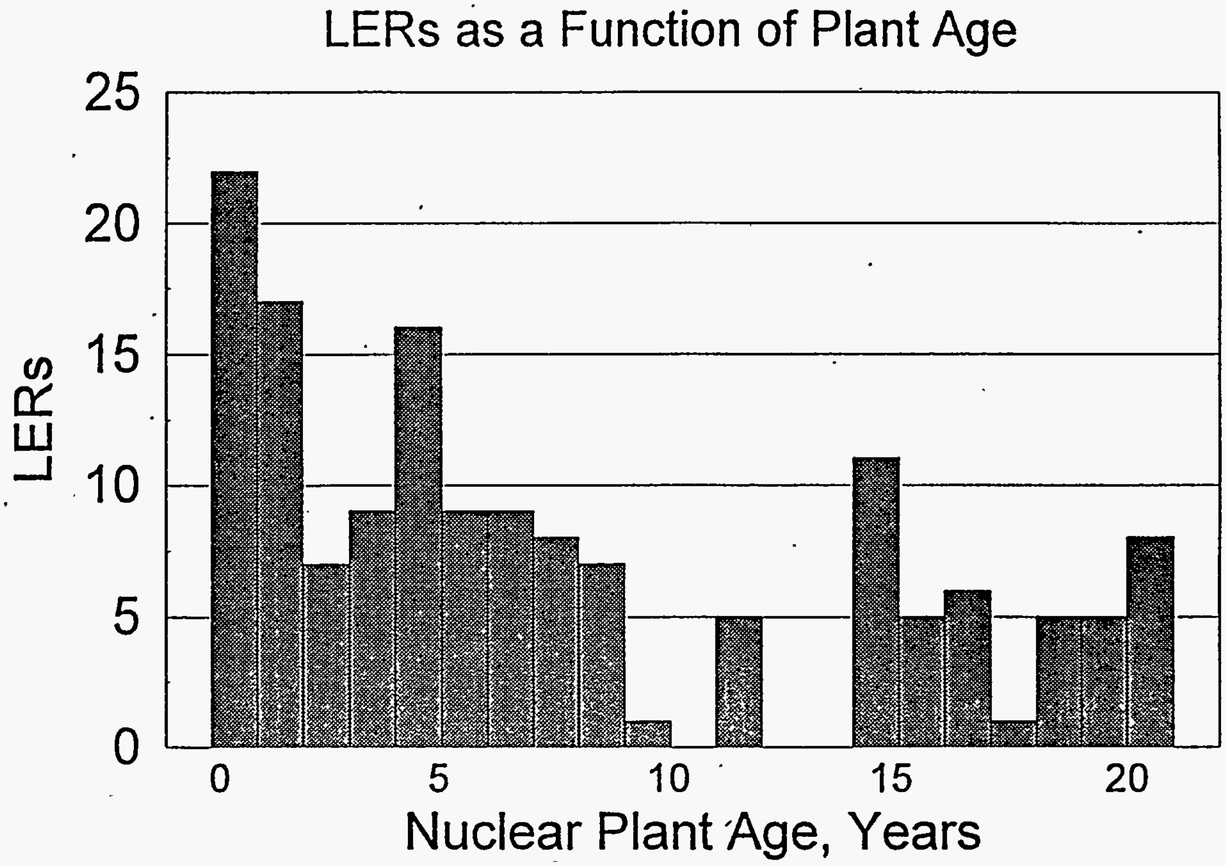


Figure 4.5 Chiller LER Occurrence as Function of Plant Age

5 Review of Chiller Information on Aging Degradation

5.1 Library Literature Review

5.1.1 Experience from Literature Reviews

Examples of age-related failures/causes that occur in chillers were compiled from a literature review. Surprisingly, the information on aging and failures was sparse for such a large industry. There apparently is no database available for the HVAC or nuclear industries to document and compile failure/cause data. Because corrosion was involved at least partially in over 50% of the age-related failures in the Phase II study, a separate report was prepared by Dr. A. B. Johnson, Jr. that focuses on corrosion in chillers. The report is contained in Appendix C of this report. It also contains some information from corrosion research concerning the new refrigerants. The list of major types of failures/causes is outlined below.

5.1.2 Major Age-Related Failures/Causes

Excessive moisture in the refrigerant can cause many problems in the chiller (Traver 1976; ASHRAE 1990). When the moisture exceeds the refrigerant saturation level (only a few ounces in 1000 pounds of refrigerant), the free water reacts with the refrigerant to form hydrochloric and hydrofluoric acid. The acid attacks crevices between the tubes and tube support sheet. Combined with tube vibration, especially from boiling refrigerant in the evaporator, the crevice widens and the tubes ultimately fail, allowing water entry to shut down the chiller and expose the entire system to water. Other degradation as a result of the acid attack includes the following:

- The lubrication oil can become contaminated with acid and attack the bearing surfaces.
- The compressor inlet guide vane assembly can corrode and bind.
- Motor failure can result from insulation breakdown in hermetic units.
- The purge float valve can stick due to pivot corrosion and sludge formation.
- The condenser and economizer float valves can fail, in a mode similar to the purge float valve.
- Shell scaling can cause clogging between tube fins, between tubes, and in the mist eliminators. Subsequently, the scale hardens to restrict heat transfer and refrigerant flow.
- Copper chloride deposits on upper tubes are caused by the wetting/unwetting process. These deposits reduce heat transfer and have hygroscopic properties that make water removal difficult.

Tube fouling and corrosion can cause eventual chiller shutdown due to reduced heat transfer or tube failure (Banta 1974; Leitner 1980; Blake 1977; Alger 1977; Starner 1976). Tube clogging can occur if the condenser water is not filtered, treated, and controlled at the cooling tower or source (Barber 1983).

Non-condensable gases, such as air, get in the refrigerant (especially low-pressure machines) and raise the condenser pressure. This, in turn, raises the compressor's load and requires more power (Barber 1983). In addition, air can accumulate at the top of the condenser and combine with the refrigerant to drastically reduce heat transfer (Webb 1986; ASHRAE 1989).

Vibration can ultimately cause seals, gaskets, pipe joints, and fittings to fail and allow leakage of the refrigerant. Moisture and air can also enter the previously sealed system by the same route (Esslinger 1988; ASHRAE 1991).

The complete American Nuclear Society (ANS) Transactions Summary (Christie and McDougald 1992) of a paper presented in June 1992 is included in the Phase I report (Blahnik and Klein 1993). The plant reliability analysis indicated that safety-related chillers fail three times as often as non-safety-related chillers at the River Bend NPP. The authors felt that the difference in reliability is due to the more stringent controls imposed on the safety-related chillers. The information should be examined more closely.

NRC Notice 85-89 was addressed primarily to the potential loss of solid-state instrumentation following failure of control room cooling. The incident at the McGuire 1 plant resulted in numerous spurious alarms. Previously, the same plant had experienced similar behavior and numerous component failures and degradation due to high temperatures in control cabinets. The licensee had previously reported that their chillers develop oil level problems when operated well below full capacity. The heat load calculated during plant design was too large compared to the actual heat load resulting in oversized chillers.

The question "When does the final chiller failure occur?" is not easy to answer because of the many variables to consider. An extensive survey of building owners and managers was conducted (Akalin 1978). The results indicate that centrifugal chillers usually have a life of 20 to 30 years with a mean value of 23 years. The ASHRAE Handbook estimates the service life of centrifugal chillers at 23 years, but practical use for 30 to 40 years has been realized when the equipment is properly maintained (Calm 1992; 1993). The Landis & Gyr co-author of this report indicated that the major components of a chiller will last well beyond 40 years if they receive proper care and maintenance. Chillers up to 60 years old are in continuous use today. Most chillers fail and are replaced due to a lack of maintenance and monitoring. Other causes for replacing chillers include obsolescence due to

- change of heat load (usually growth)
- energy efficiency improvements
- incompatibility with new refrigerants (see Section 8)
    - efficiency loss
    - design limitations of components
    - aggressive nature of new refrigerants.

Centrifugal chillers have motors that are not designed to be turned on and off frequently. Rapid cycling will lead to motor and starter failure. The main method to limit demand for a centrifugal chiller is by modulating the compressor's pre-rotation vanes, which control the capacity of the chiller. It is critical that it be done gradually. If not, surging of the compressor can occur, resulting in serious damage (Gorzelnik 1977). Prolonged operation in a surging mode is likely to damage the entire chiller, as well as the compressor. Surging loads and unloads the motor about every two seconds so that the motor current varies markedly (Ball 1987). Surging deteriorates performance and heavily stresses the thrust bearings. Surging is most likely to occur at the lower end of the chiller capacity range. Chiller manufacturers claim that their units can unload down to 10% of design loading. However, low load operation is conditional upon having lower condenser temperatures (Harmon 1991).

5.1.3 Voltage Imbalance

One concern about chillers expressed by the NRC was how voltage imbalance affects chillers. Only limited information was found in this area, therefore the Landis & Gyr co-author prepared the following discussion on effects of voltage imbalance on chillers.

Voltage imbalance, under-voltage or over-voltage in an open or hermetic chiller motor, will create excessive heat. Without sufficient cooling, motor winding deterioration will occur over time. In an open motor, eventually electrical failure will occur. In a hermetic motor, refrigerant vapor or liquid cooling will cause capacity reduction and if motor cooling is marginal, or only adequate for normal operation, will allow insulation deterioration and overheating of coolant. In this case refrigerant and insulation will be broken down and motor insulation materials will dissolve and form acids, corrosives, and sludge that will accelerate damage to the winding as well as cause secondary damage to the balance of the machine in the refrigerant atmosphere. Eventually the winding will fail and contaminate the entire machine. If cleanup is not completed in a timely manner, acids, corrosives, and sludge will form and cause secondary damage to the entire machine's refrigerant side.

Phase failure will burn out the motor (open or hermetic) very quickly. If this occurs to a hermetic motor, the entire machine will become contaminated, with possible secondary damage occurring.

Phase reversal can cause mechanical damage. High-speed switching reversal has been known to break shafts due to extremely high torque during reversal. If reversal occurs while the machine is down, low oil pressure failure can occur and lock out the chiller. If lock out does not occur, the ability to achieve proper capacity, as under normal rotation, will allow overheating and possible burn out of a hermetic motor due to insufficient cooling; mechanical damage can occur causing refrigerant breakdown, forming acids and corrosives to contaminate the entire chiller; and the life of the chiller O-rings and gaskets lives will be shortened allowing leaks to occur and causing secondary damage throughout the chiller.

If chillers were not originally ordered with phase monitoring devices, they should be equipped with them to prevent these types of failures.

5.2 Insurance Company Information Review

During the past three years a substantial, yet unsuccessful, effort was made to locate large databases that addressed chiller failures. The manufacturers of chillers maintain data on failures, but they are proprietary. A summary report (Stouppe 1988) from the database of The Hartford Steam Boiler Inspection and Insurance Co. was obtained. The summary was based on insurance claims from 1980 to 1987 concerning failures of motors and compressors used in air conditioning and refrigeration applications.

The average age at failure, and parts that failed for hermetic and non-hermetic motors, are summarized in Table 5.1. The average age at failure, and parts that failed for hermetic and non-hermetic compressors, are summarized in Table 5.2. Knowing the average age of motors and compressors at failure helps in understanding the time period between major overhauls of the chillers. Analyzing the causes of major failure helps establish bases of frequencies of occurrence and severities of loss. Based on these analyses, insurance companies can provide preventive maintenance program recommendations that will minimize the probability of failures.

The predominant failures for motors occurred in the motor stator windings. Usually the windings failed due to degradation of the winding insulation at abnormally high temperatures. Motor manufacturers have a general rule that a temperature of 10°C above design limits will result in approximately a 50% reduction in winding life. Line disturbances such as unbalance voltage and single-phase operation can contribute to excessive winding temperatures. A voltage imbalance of 3% between phases in a three-phase motor can result in about a 25% increase in the winding temperatures. An interruption of the voltage supply to a single phase of the motor also results in winding overheating that breaks down the winding insulation. Short cycling of the motors, not protected by a time delay between starts, causes failures and accelerated

Table 5.1 Summary of Hermetic and Non-Hermetic Motor Failures

Item Description	Hermetic Motors		Non-Hermetic Motors	
Age at Failure (years)				
Air Conditioning	10		11	
Refrigeration	9		12	
Parts that failed	Total	% of Total	Total	% of Total
Motor Stator Windings	5444	84.0	1966	73.8
Rotor Bars	620	9.6	278	10.4
Motor Control Equipment	326	5.0	209	7.8
Bearings	90	1.4	212	8.0
	6480		2665	

Table 5.2 Summary of Hermetic and Non-Hermetic Compressor Failures

Item Description	Hermetic Compressors		Non-Hermetic Compressors	
Age at Failure (years)	15		14	
Parts that Failed	Total	% of Total	Total	% of Total
Bearings	155	55.4	49	69.1
Impeller	69	24.6	13	18.3
Guide Vanes	16	5.7	3	4.2
Shafts	13	4.6	3	4.2
Lubrication System	19	6.8	2	2.8
Keys	8	2.9	1	1.4
	280		71	

degradation of the windings. Contaminating the windings with moisture-laden refrigerant that forms acids is a significant cause of degradation and failures of the windings.

The motor rotor bars, control equipment, and bearings contribute to failures, in that order, for the balance of the motor failures.

Most of the compressor failures were caused by failures of the bearings. The bearings usually failed due to a loss, or lack, of lubrication oil. Refrigerant that dilutes the oil in the crankcase is a principal cause of inadequate lubrication. Service wear is the next highest cause of bearing failure.

Impellers were the next highest failed part in compressors. Degradation and failures of impellers are caused by fatigue, shock loading, surge, and rubbing due to a bad bearing.

The balance of the parts that caused compressor failures were guide vanes, shafts, the lubrication system, and keys. Keyway cracks do not cause frequent failures, but they can cause serious damage to the chiller when they do fail.

6 Service Life Monitoring of Chillers

The Phase I chiller aging study indicated that the number one cause of chiller failures and accelerated aging was a lack of proper service life monitoring. Therefore, information was sought and obtained in this area as one of the primary objectives of the Phase II study. A field assessment of the level of service life monitoring use in NPPs was not performed. This section of the report addresses proper chiller condition monitoring. Essential condition monitoring methods used for chillers include operational data recording, monitoring, and trending analysis (during shutdown, startup and shutdown transients, and operating periods); refrigerant and oil leak detection; refrigerant and oil analysis; vibration analysis; condenser and evaporator tube eddy current testing; and infrared thermal analysis. Computerized monitoring as described in Appendix B is the ultimate method of monitoring.

6.1 Operational Data Recording, Monitoring, and Trending Analysis

One of the areas chiller manufacturers stress is to routinely (on a daily basis) take readings of pressures, temperatures, and flow rates in key areas, and record them in a daily log. Readings should be plotted on a chart so they can be easily monitored and indicate trends. Abrupt and trended changes will then be observed daily so that corrective actions can be taken if negative information develops. In the event of a failure, the root cause analysis can be enhanced by this data. An example of a data recording sheet for the log is included in Appendix D, page D.2.

6.2 Leak Detection for Refrigerants

The need to emphasize leak detection as a monitoring tool is not only to maintain the reliability of the chiller, but also to meet environmental requirements that will soon go into effect (see Section 8). Refrigerant leaks can be detected by using a variety of methods described below.

Massive leaks can be detected in chiller areas by using infrared photo-acoustic technology to sense refrigerant gasses down to levels as low as 1 ppm. Continued use of CFC refrigerants will require this type of control due to more stringent regulations in the future. Units with probes attached can be manually focused in to pinpoint refrigerant leaks from the chiller. Precise laser guide infrared instruments can be used if necessary. The use of infrared thermography (IRT) for chillers is discussed briefly in Appendix E.

Ultrasonic stethoscopes and probes can be used to scan and focus in on refrigerant, air, and vacuum leaks. The pulse sonic technology is well developed to detect problems with bearings, valves, traps, electrical discharge (corona) and others along with leak detection. The use of ultrasonics for chillers is discussed briefly in Appendix E.

The ultraviolet (fluorescent) method uses a high-intensity lamp and specially formulated fluorescent additives to find small and multiple leaks. The additives are placed into the refrigerant and infuse the entire chiller refrigerant system. Leaks can be detected visually wherever lamp access is permitted.

Refrigerants from pressure leaks can be visually detected by using bubble/foam methods.

Accumulation of oil spotting from leaks over a long period of time can be detected visually and, if necessary, detection can be enhanced by chemical solutions.

Sophisticated portable refrigerant leak detectors with an electrochemical sensor and a heating element to ionize the gas can be used. The unit can also be used to continuously monitor an area. Technology is rapidly resulting in other methods as well.

The leaks can show up in various types or combinations of leaks. Leaks can be dependent upon conditions such as pressure, vibration, temperature, standing versus dynamic, combinations, and a cumulative amount of micro-leaks. The method and equipment used has to be evaluated for effectiveness under a variety of conditions.

6.3 Leak Detection for Lubricating Oil

Besides visual inspection, oil leaks can be detected by the ultraviolet fluorescent method. Records of oil gauge levels can be recorded to determine the rate of leaks. The importance of leak monitoring will increase because some of the oils required for use with the new refrigerants are extremely absorbent of air, moisture, and refrigerants and will require more careful oil handling, storing, and monitoring procedures.

6.4 Refrigerant Analysis

The periodic analysis of refrigerants has always been an effective tool for monitoring the condition of the chiller. In the future, close monitoring of the new refrigerants is expected. Because the new refrigerants are incompatible with the old CFCs and machine component materials, it will be important to ensure that residue from previous system materials do not interfere with the operation of the equipment or degrade the equipment. Refrigerant analyses will help ensure that contaminants are compatible with compressor metals, gaskets, seals, or other system components. The analyses will also help in making good maintenance and purchasing decisions. A typical request for a refrigerant analysis form is shown in Appendix D. Important analyses that are a part of the refrigerant analysis to ensure ARI 740-93 requirements are being met include

- moisture, ppm
- particulate/solids, ppm
- acidity, ppm
- oil, % by weight
- air and other non-condensables, % by volume
- boiling point, range, and residue
- other refrigerants and chlorides.

Any recycled refrigerant will require analysis to meet the specifications of ARI 740-91. Strict sampling procedures and instructions should be followed to ensure an accurate assessment of the refrigerant in the machine. Whenever the refrigerant filter/driers start showing signs of residue, a refrigeration analysis should be done immediately. If the equipment performance and operation is good, the refrigerant analyses only need to be done annually or seasonally. Examples of refrigerant analysis reports are provided in Appendix D.

6.5 Lubrication Oil Analysis

The analysis of compressor oil samples has always been an important tool used to prevent chiller failures and high maintenance costs. It provides an indication of the condition of the chiller without requiring equipment teardown and inspection. Routine sampling on a scheduled basis will trend the equipment condition and ensure that the wear pattern is normal. If the wear pattern is above normal, types and quantities of impurities in the oil will indicate what is occurring and will allow corrective action before major equipment problems. The oil analysis is used to augment the periodic equipment teardown and overhaul, not replace it. An example of a refrigeration oil analysis trend report is provided in Appendix D.

The type of oil analysis program followed depends on the type of equipment, application, and operating frequency and duration. O&M history (e.g., past and present O&M problems) are important to know. Knowledge of these factors and the help of a well-qualified chiller expert will determine the frequency of sampling and guidelines for the program. Qualified laboratories should perform the analyses. The oil analysts should be experienced in analysis and be capable of diagnosing problems, if any, and recommending corrective actions. It is important to follow established procedures for the collection, handling, and processing of the samples. It is important to prevent liquid or vapor loss and prevent dust, moisture, or other contaminants from entering the sample. The oil analysis report should include 1) numerical data for the analysis and data from previous analyses, 2) a graph of the data for comparison and trending, and 3) the present and past interpretations on samples from the same chiller.

The report should provide

- the tin content, to indicate babbitt bearing wear and corrosion

- the aluminum content, to indicate impeller rubbing, seals, or rod bearing wear in reciprocating compressors
- the copper content, because high copper might be from corrosion, oil pump bearings, or from condenser or evaporator tubing
- the zinc content, which can identify refrigerant carry-over problems
- the oil acidity; if increasing, it may indicate oil degradation, refrigerant decomposition due to high temperature exposure, and/or excessive moisture. The acid number helps to determine whether the oil is suitable for use and when oil changes are needed; it is needed to ensure that acid corrosion is not present.
- the moisture content, because some oils required for the new refrigerants are extremely hygroscopic and can pick up moisture during storage and the process of filling the machine. It may be necessary to test oil for moisture prior to placing it in the machine where it can cause damage. High moisture can cause sludges to develop that plug filters and affect flow, etc.

Analysis of the chiller lubrication oil provides vital predictive maintenance data to maximize the reliability and availability of the machine for its important safety function.

6.6 Vibration Analysis

Vibration analysis and monitoring is one of the most important tools in assessing the condition of the chiller. It is important to do the analyses with the same equipment, locations, standards, and chiller load levels.

Continuous monitoring is even better because it provides coverage at various load levels and even improves the O&M program for the chiller.

Appendix F was prepared by E. Charles Hart, an expert in the field of equipment vibration monitoring, of Systems Engineering Associates Company (SEACOR), to discuss vibration analysis of chillers as a condition monitoring and predictive maintenance tool.

The report in Appendix E augments the Appendix F report. An expert in condition monitoring of chillers, Gerhard N. Thoen of HEATSCAN, discusses the use of the vibration monitoring method in a complementary condition monitoring approach with IRT and ultrasonic monitoring methods.

6.7 Condenser/Evaporator Eddy Current Testing and Inspection

Another important chiller condition monitoring tool is eddy current testing of the condenser and evaporator tubes. Condenser tubes are subject to corrosion by the cooling water system. Some cooling water systems use untreated or poorly treated water that is very corrosive and erosive to the tubes. Those condensers need periodic eddy current testing to monitor the tubes so they are replaced or plugged when it is necessary. It is especially important to check and monitor the tubes early in the life of the equipment to see which steps in water treatment, tube cleaning, etc., are needed to control corrosion and degradation of the tubes.

Although evaporator tubes usually have a treated and controlled chilled water system, some eddy current monitoring is needed to ensure that vibration and acid crevice corrosion on the shell side do not accelerate the degradation of the tubes.

An expert in the area of chiller tube eddy current testing and inspection, William H. Frazier of Tubular Technologies, has prepared the brief report on his experience in Appendix G.

6.8 Infrared Thermal Analysis

Use of IRT was discussed earlier as a tool to detect refrigerant leaks. It was also discussed as a complementary method with vibration monitoring and ultrasonic monitoring methods for chillers in Appendix E. In addition to refrigerant leak detection, this method is good for determining hot and cold spots elsewhere in the chiller boundary. It can help detect potential problems in the electrical switchgear, controls, circuits, etc.

6.9 Computerized Monitoring

The use of computerized condition monitoring of chillers is an excellent method and it is easy to justify when additional facilities in a plant need computerized monitoring as well. Discussion of this monitoring method is contained in Appendix B of this report. Thomas W. Camp of Landis & Gyr Powers, Inc., the chiller expert for this PNL chiller aging study, prepared this discussion.

7 Maintenance of Chillers

The proper O&M operation of chillers is important to provide satisfactory performance of the essential HVAC system(s). In the manufacturing manuals and literature reviewed, the two functions were usually discussed together. The O&M manuals will be discussed first, followed by more specific maintenance items.

7.1 Start-up, Operation, and Maintenance Instruction Manuals

Eight O&M instruction manuals were reviewed. They represented three centrifugal chiller manufacturers, three nuclear plants, and various chiller models. All of the manuals were well prepared and adequate to guide the integrated functions of chiller O&M. The manuals are prepared to

- describe the equipment component layout
- describe the equipment and component functions
- provide packaging and rigging instructions
- provide installation procedures
- provide pre-start-up and start-up instructions
- provide operating instructions
- provide maintenance instructions

Some of the instruction packages contained detailed drawings and parts lists. Maintenance requirements for the major components (e.g., compressor motor) were covered in detail. Plant staff should be involved in all phases, from installation to O&M, of the chillers.

It is not the purpose of this report to promote predictive maintenance for the chillers or the plants. However, it has been established that, properly used, the preventive maintenance programs are justified because of fewer machine failures, less repair downtime, longer machine life, improved safety, reduced costs, verification of repairs, predicted eminent failures, and they help in determining the root cause of failures that do occur.

7.1.1 Description of Chiller Layout and Functions

This part of the manual provides pictures, graphics, and discussion to provide general background information that will assist operators and maintenance staff in understanding the more detailed instructions. The Phase I report (Blahnik and Klein 1993) described these portions of the instruction manuals.

7.1.2 Packaging and Rigging Instructions

These instructions provide guidance on how to safely prepare, ship, and receive the packaged chiller at the installation site and mounting pad. The rigging instructions overlap with the installation procedures described below.

7.1.3 Chiller Installation Procedures

The procedures provide receiving steps such as inspecting the shipment, identification and protection of the chiller, equipment gauge readings, and application of field insulation. The procedures for mounting, piping, and wiring to install the equipment and hook up with plant facilities are detailed.

7.1.4 Start-up Instructions

These instructions cover the initial preparations for chiller start-up. They include items such as machine tightness, vacuum and pressure tests, pump-out procedures, inspection of field piping and wiring systems, charging of oil and refrigerant, and checkout of the starter, operating, and safety controls.

After setting, fine tuning, and calibrating the controls, the final machine adjustments (e.g., oil and refrigerant levels) and operating checks are completed with plant operations and maintenance staff in attendance.

7.1.5 O&M Instructions

These instructions provide detailed guidance and illustrations for the O&M staff to use in operating the chiller. The operator duties are outlined. Machine start-up, shutdown, and steady-state operation are addressed. Automatic and manual operation is covered. Monitoring and recordkeeping are usually included.

Weekly maintenance (e.g., lubrication and scheduled maintenance) is described. Scheduled maintenance includes inspections, checks, tests, changing of oil and oil filters, checking the dampers and float valves, etc. General maintenance involves such items as adjusting refrigerant and oil charge, leak testing, guide vane linkage testing, etc.

Every manual contained a comprehensive trouble-shooting guide. It covered compressor problems, chilled and cooling water temperature variations, oil reservoir temperature variations, and other important chiller operating parameters. An example of the trouble-shooting guide is provided in Appendix D.

General data on the chiller and comprehensive guidance on the refrigeration, motor cooling, and lubrication cycle are included. Comprehensive guidance addresses the controls, operating sequences, and control options.

7.1.6 O&M Warnings, Cautions, and Important Notes

Throughout all the manuals are warnings, cautions, safety concerns and dangers, and important notes to heed during O&M of the chillers. Ignoring these notes can cause severe equipment degradation or facility damage and impact personnel safety. Loss of the essential chillers during an emergency is a major concern.

A sudden release of the refrigerant inventory by vaporization would be a major safety concern to a nuclear plant. As the chillers get larger, so do their refrigerant inventories. Occasionally, in an accident, the entire inventory is released in minutes. An example of a recent refrigerant release accident (1600 pounds of refrigerant in 60 minutes) in a U.S. Department of Energy facility is discussed in a referenced report (Department of Energy 1994).

Refrigerant vapor displaces air and can asphyxiate personnel. Furthermore, decomposition of refrigerant material by exposure to open flames or hot electrical element surfaces, for example, forms hydrochloric and hydrofluoric acids and possibly carbonyl halides. Leaks and accidental release of refrigerants should be prevented. Exposure to liquid refrigerant can rapidly freeze eyes, skin, or other organs.

It is important for the equipment operators to understand that the chiller cannot start until the oil heater has been on for at least 12 hours. The temperature of the oil must be about 60°C (140°F) for the chiller to operate properly. The oil pump should run for about one minute before the chiller is started. A time delay of up to 30 minutes occurs if the chiller trips for any reason (e.g., interrelated safety systems switching times can cause such delays). Special provisions are needed in the design of the chiller and nuclear plant systems to accommodate or circumvent these operating factors.

Examples of "warnings" in the manuals are as follows:

Warning: Always block springs of spring-isolated machines when transferring large quantities of refrigerant.

Warning: Do not start compressor or oil pump even for a rotation check, nor apply test voltage of any kind while machine is under dehydration vacuum. Motor insulation breakdown and serious damage may result.

Warning: Charging refrigerant as a liquid when vessel pressure is below value listed in Table 2, or with water pumps not operating, may cause cooler tube freeze-up and serious damage.

Warning: If the oil level is too high, the oil will have a greater tendency to foam, and the compressor may lose some oil under starting conditions or conditions of a rapidly changing load. The High Compressor Oil Level light will light. If the oil level is too low, the oil pump may cavitate and cause a lower oil supply pressure.

When the oil pressure falls below the lower setting of the oil pressure switch, a unit shutdown will occur.

Examples of "cautions" are:

- After closing valves X and Y, bleed some refrigerant through the packing gland to form a gas pocket in the valve body. Trapped liquid refrigerant can expand to damage the valve and cause refrigerant loss.
- Do not permit water warmer than 38°C (100°F) to flow through the cooler. Refrigerant over-pressure may actuate relief valves and result in loss of refrigerant charge.
- If corrosion or foreign material is found, do not attempt repair or reconditioning. Replace the valve.
- Before using the pumpout unit, read the section entitled, Isolation Valve Operation, page 3. Improper closing of isolation valve can cause valve damage and refrigerant loss.

Examples of "important notes" are:

- The following instructions assume all valves to and from the transfer unit are closed. Valves should be checked prior to transfer operations.
- Manual re-set is necessary to re-start. This condition will occur during initial pull down from high system standby pressure, requiring compressor suction line throttling to avoid excessive motor starts.

7.2 Predictive Maintenance

The value of predictive maintenance principles in the overall maintenance program for a nuclear plant has been demonstrated. The condition monitoring tools discussed in Section 6.0 are an important part of predictive maintenance. The use of vibration monitoring as part of a predictive maintenance program is addressed in Appendix E.

Predictive maintenance is not intended as a substitute for the more traditional maintenance methods (Mobley 1990). Rather, it is a valuable addition to a comprehensive total chiller and plant maintenance management program. The more traditional maintenance programs depend on routine servicing, fast response to unexpected failures, and scheduled overhauls. Predictive maintenance schedules specific maintenance tasks as they are required. It tends to avoid unnecessary maintenance that might increase the equipment failure rate. It cannot replace the traditional run-to-failure and preventive programs, but predictive maintenance can reduce the number of unexpected failures and provide a more reliable scheduling tool for routine preventive and overhaul maintenance tasks.

It is not the purpose of this report to promote predictive maintenance for the chillers or the plants. However, it has been established that properly used predictive maintenance programs are justified by fewer machine failures, less repair downtime, longer machine life, improved safety, reduced costs, verification of repairs, predicted imminent failures, and contributions to determination of the root cause of the failures that do occur.

7.3 Routine Maintenance

The routine preventive maintenance and servicing requirements are well established by the equipment manufacturers. The maintenance manuals from all the major centrifugal chiller companies were reviewed and found to be excellent. A chiller is a complex piece of equipment and needs proper maintenance to keep operation stable and reliable. The plant should use these maintenance procedures and integrate them into the related plant and safety system maintenance procedures. The technicians and craftpersons involved in doing maintenance should be well trained and familiar with the appropriate maintenance manuals and procedures.

7.4 Repair Maintenance

Optimum repair maintenance of chillers mandates that repair personnel be well trained and experienced. Repair personnel and their management should maintain a close relationship with the chiller manufacturer and their overhaul service company.

7.5 Overhaul Maintenance

Overhaul maintenance, where the chiller is disassembled, should be performed by well qualified service companies that routinely perform overhauls. The plant chiller maintenance personnel should work with the overhaul company personnel to maintain a good understanding of the process and any improvements that might prevent future maintenance problems. Use of a good predictive maintenance program is likely to reduce the frequency of overhaul. Human errors and parts replacement errors made during chiller overhauls can result in premature failure or re-start problems.

7.6 Maintenance Tips for Centrifugal Chillers

There probably is no single list of maintenance tips that covers all aspects of chiller O&M (Kozak 1989). The ten tips presented below are a synthesis of reviewed material. An outline of similar tips for centrifugal chiller maintenance is in Appendix D (Stebbins 1991). A checklist for key items to maintain high efficiency of centrifugal chillers is also in Appendix D (Barber 1983).

Performing the following ten activities should reduce chiller problems.

1. *Maintain Equipment Logs.* An analysis of daily log entries can reveal many potential problems and allow maintenance needs to be detected early.

2. *Eliminate Excess Air.* Excess air increases the pressure head and forces the compressor to work harder to maintain required cooling. The purge unit may be malfunctioning or a major leak may need to be stopped. Removing excess air not only allows the chiller to operate more efficiently, but it will also limit corrosion and extend the life of the chiller.

3. *Sample and Analyze Oil.* Checking the condition of the compressor oil and oil filter is crucial. Oil samples should be taken and filters inspected or replaced. An oil sample provides clear evidence of the chiller's condition. The chemical analyses will indicate if acids are present and if metal content indications show abnormal wear.

4. *Test Heat Exchanger Tubes.* Tube failure in a heat exchanger causes the most costly chiller repair. Eddy current testing is the best way to prevent tube failure. Such tests should be performed every 3 to 5 years (sooner if the cooling water is particularly aggressive).

5. *Control Rust in the Refrigerant.* If moisture and air leak into the chiller, rust can be a problem. Rust shortens the chiller's life and inhibits heat transfer capacity. Using a purge system and refrigerant clean-up kit will help prevent rust.

6. *Eliminate Scale in Condenser Tubes.* Scale buildup in the condenser tubes prevents efficient heat transfer and causes excessive head pressure. The tubes should be cleaned periodically by mechanical brushing. In some cases, chemical cleaning may also be needed. The clean tubes should be maintained by a water chemical treatment program and by periodic water bleed-off.

7. *Maintain Condenser Water Flow.* The first step for maintaining flow is given in item 6. Other common problems that affect flow are partially closed valves, clogged cooling tower nozzles, dirty water strainers, and air in the water piping. The cause of reduced flow should be found and corrected.

8. *Verify Proper Refrigerant Charge.* Too little or too much refrigerant also limits heat transfer capacity, increases head pressure, decreases evaporator temperature, and increases energy demand. The system should be charged with refrigerant according to manufacturer's instructions.

9. *Maintain Motor Efficiency.* If the operator's log shows an increasing amount of current draw with no comparable drop in voltage, the motor is probably not being cooled adequately. Many causes can restrict motor cooling, and they should be found and corrected before serious damage occurs.

10. *Follow Proper Procedures.* All operation and maintenance procedures should be strictly followed. Even shutdown procedures are very important. Especially important is proper operation of the motor starter and control center. Safety control switches should be tested and recalibrated to prevent major chiller failure. No deviations from procedures should be allowed without approval of the chiller manufacturer.

8 CFC Refrigerant Replacement and Aging Considerations for NPPs

8.1 CFC Replacement Background Information

Addressed in this section is what might be a future difficult problem in many of the nuclear plants. CFC refrigerants used in NPPs will no longer be manufactured after 1995 and it will be necessary to make some decisions on how to cope with the situation. It was determined during the NPAR aging study that chillers do age and degrade, but the process can be controlled with good O&M practices. Good experience and major chiller improvements have resulted from using the same CFC refrigerants for over 50 years (decades before the introduction of NPPs). It is important to take what was learned about chillers in the past and carefully make the necessary chiller changes that minimize problems with using the replacement refrigerants.

The CFC refrigerants, which most of the nuclear plants use in their chillers, are considered by many organizations to be a major contributor to the depletion of the ozone layer and global warming (Niess 1992). The nations of the world (Montreal Protocol and its amendments) have established rules to phase out CFC production and use. Because of these concerns, the EPA has issued rules pursuant to the Clean Air Act Amendments of 1990 that terminate production of CFC compounds on December 31, 1995. Reaction to the environmental regulations is already reducing the availability and increasing the costs of the CFCs.

The environmental regulations that are being emplaced will affect NPPs unless some kind of exemption is established. Currently, NPPs do not fall into any of the categories that are eligible for exemptions. Checks with manufacturers of chillers indicate that NPPs are not moving very fast on converting or replacing existing chillers to accommodate the new hydrochlorofluorocarbon (HCFC) and hydrofluorocarbon (HFC) refrigerants. None of the major centrifugal chiller manufacturers has their "N-Stamp" or quality assurance programs available anymore to manufacture replacement chillers. The manufacturers of centrifugal chillers have limited capacity to handle the expected rush to convert or replace existing chillers throughout the country, and orders for new NPP chillers would probably require a lot of time and money to complete. The impact from non-centrifugal chiller manufacturers was not assessed.

8.2 Options Available for Existing, Converted, and Replacement Chillers

The demand for the shrinking supply of CFCs and reaction to new refrigerant regulations will mean that NPPs will have three options for continuing essential chiller operation:

- Use the existing chillers and make them leak tight.
- Convert the existing chillers to the new refrigerants by using retrofit conversion kits made available by chiller manufacturers and suppliers.
- Replace the existing chillers with new chillers that use the new refrigerants.

These options all have problems in NPPs and deserve careful and thorough evaluation by the NPP owners and the NRC. Some of the considerations to be evaluated are discussed below. In some plants careful study may be needed even for the non-essential chillers because of new safety and facility installation criteria. Because virtually every NPP has design differences, each plant will need to perform a comparison of the three options from the safety, cost, schedule, and risk standpoints.

8.2.1 Maintain Existing Essential Chillers Using CFC Refrigerants

Use of the existing chillers with the old CFCs will necessitate, as a minimum, making the chillers leak tight well beyond the original manufacturing design standard requirements. It will also compel strict compliance with regulations and standards for the purchase, storage, handling, and use of the CFC refrigerants. Reactor operators will need to cope with the decreasing availability and increasing cost of CFC refrigerants. More restrictions, regulations, guidelines, etc., for CFCs are likely to be developed because this area is continually developing and changing.

8.2.2 Convert Existing Essential Chillers to New Refrigerants

Design requirements, NRC guidelines, etc., for converting existing NPP chillers to the new refrigerants were not found. There apparently have never been guidelines or a Standard Review Plan (SRP) for chilled water systems in NPPs. How conversion will be regulated, handled, and approved in NPPs is uncertain.

The actual physical conversion of existing essential centrifugal chillers with kits should be no problem where the manufacturers and suppliers are still available. The conversion of non-centrifugal chillers has not been assessed and may provide some difficulties as far as conversion kits and expertise are concerned. NPP owners who designed special chillers may have no choice but to replace their chillers.

To consider conversion as an option, it is important to have a good understanding from the manufacturers and suppliers of what should be done to make the proper conversion. The replacement parts should be properly designed and manufactured. All the literature indicated that it is important to have well-qualified personnel involved in all aspects of the conversion (design, manufacture, plant facility, safety, etc.)

Conversions of centrifugal chillers that were done properly are working well at this time. How well they work and for how long will require time and experience to determine. Manufacturers feel confident that the conversion kits will meet the future requirements satisfactorily. Most of the kits involve changing out all the seals, gaskets, and other non-metal parts to materials that are compatible with the specific new refrigerant. If hermetic motors are used, the winding insulation will also have to be replaced with new compatible material.

In some chillers a new impeller would be needed to handle the compression characteristics of the new refrigerant and to help maintain the capacity of the chiller. Use of some refrigerants will require new lubricating oils, which will need special handling, storage, and provisions for use.

Some facility changes would also be needed (e.g., fresh air ventilation openings, restrictions on storage tanks, availability of safety breathing equipment for personnel, etc.). The requirements for facility modifications based upon regulations at the time of the conversion should be factored into the evaluation of which option to use. Some of the new refrigerants are slightly more toxic and have more severe safety concerns than the old refrigerants; therefore, a new safety evaluation should be made.

8.2.3 Replace Existing Chiller with New Chiller Using New Refrigerants

Many of the concerns discussed above for the conversion option due to the impact of new refrigerants apply to the replacement option as well (EPA regulations, standards, plant facility modifications, etc.). Guidelines and criteria need to be developed and applied for specific NPP problems and specific plant safety.

Many of the NPPs may not be able to use the replacement option due to limited egress and ingress for replacing a chiller, especially in the case of large packaged chillers. The one plant visited during the Phase I study had difficult access. Costs and plant downtime to provide access appeared to be high. The replacement chiller would have to be smaller or one that could be assembled manually in the control building. Chiller manufacturers are developing new designs to help cope with the access problem because it applies just about everywhere. The NPP owner should consider access, facility modifications, and the type of replacement chiller when evaluating options.

Manufacturers of new chillers have demonstrated that the new chillers are very efficient and seem to be working very well for their owners. They feel that the chiller modifications are excellent and that more research and development (R&D) was performed on the new refrigerant chillers than on the previous generation of chillers. The manufacturers of the new refrigerants and lubricating oils seem to feel the same way. They all stressed that the manufacturers' O&M procedures should be strictly followed along with the appropriate regulations and standards that are in effect.

8.3 Effect of New Refrigerants on Chiller Aging

It will probably take another 5 to 10 years before the aging impact on chillers using the new refrigerants can be fully evaluated. Chiller conversion and chiller replacement experience to date has not indicated any major age accelerations. As mentioned earlier, manufacturers of chillers, refrigerants, and lubrication oils do not anticipate any aging problems as this point in time. Current literature, trade journals, HVAC magazines, etc., have been reviewed and there has been no negative feedback from owners of converted chillers or new replacement chillers.

Due to the major impact of the CFC issue on the HVAC industry, a tremendous amount of R&D has been performed to develop replacement refrigerants and apply them to use. A comprehensive database (ARTI Refrigerant Database) that summarizes work in this area has been established by the Air-Conditioning and Refrigeration Technology Institute (ARTI) (Calm 1992; 1993).

While some of the manufacturer's development data remain proprietary, the bulk of the salient information needed has been released to help meet the schedule to handle the CFC issue in a timely manner. ASHRAE, ARI, ARTI, and many of the other HVAC industry organizations have sponsored and published much of the materials and articles germane to the issue.

NPPs that do convert or replace their chillers for the new refrigerants should be vigilant and maintain good O&M procedures. If there are any areas of accelerated aging or degradation they should be shared with the rest of the nuclear power industry. To minimize chiller aging problems the NPPs should

- continue to follow manufacturer's recommendations on O&M
- employ predictive maintenance and effective condition monitoring programs
- use qualified chiller service companies to perform all overhaul maintenance and machine teardowns
- use well trained and qualified plant technicians to maintain the chillers.

9 Conclusions

Essential chillers cool the control room and other rooms to provide personnel comfortable working conditions, to prevent degradation and failure of safety-related equipment, and to prevent or mitigate events and accidents. Control of temperature and humidity in these rooms is very important because they are the nerve centers of the plant.

Chillers used in NPPs are essentially the same as those used in other commercial and industrial applications. Chillers are a relatively complex piece of equipment because of all the thermal and flow balances that need to be maintained. The essential safety-related chillers have more stringent standards and codes to meet. The basic equipment must meet seismic requirements that require some minor modifications to the components, structure, support base, and anchoring. The essential chillers use 1E electrical components and have interfacing safety and non-safety systems, often with complex interlocking controls. The analysis of chiller interfacing systems cannot be made generically because the systems vary from plant to plant. Chillers need to be closely monitored and carefully operated and maintained. The essential chillers need to be afforded special care so they can be reliable and fulfill their safety role.

The review of operating experience indicated that chillers experience aging degradation and failures. The primary aging factors of concern for chillers include vibration, excessive temperatures and pressures, thermal cycling, chemical attack, and poor quality cooling water. Aging is accelerated by moisture, non-condensable gases (e.g., air), and other contamination within the refrigerant containment system. Excessive start/stop cycling and under-loading of chillers can promote rapid aging. Aging is also accelerated by corrosion and fouling of the condenser and evaporator tubes. The principal reason for chiller failures is lack of monitoring. It is important to record and trend the operating temperatures and pressure on a daily basis, and to routinely analyze the lubricant oil and refrigerant chemistry. Human errors and omission of scheduled maintenance also contribute to the failures. Failures due to design and manufacturing discrepancies usually occur during the original start-up, shakedown, or first year of operation for a particular new chiller model.

In the NPP data that were reviewed during Phase I, the largest number of failures was related to electrical control component failures. Both electrical and mechanical control component failures represented almost half of the total failures. The lubrication oil system also had a relatively high failure rate. Many of the failures were at least partially age-related. Many failures were the result of human error. Lack of monitoring is suspected to be the greatest contributor to both age- and non-age-related failures. The failures reviewed in the Phase II study followed a similar failure distribution pattern. The data available for evaluation were insufficient in detail to perform failure root cause analyses.

The Phase II evaluation of LERs indicated that about 38% of the failures were primarily related to aging, 55% were partially aging related, and 7% of the failures were unassignable. About 25% of the failures were caused by human, design, procedure, and other errors. The large number of errors is probably directly related to the complexity of chillers and their interfacing systems. Nearly all of the LERs were the result of entering plant LCOs. LCOs are the lowest functional capabilities or performance levels of equipment required for safe operation of the plant. When an LCO is exceeded remedial actions, such as plant shutdown procedures, are required to be taken within a specified period of time. In nine cases power reduction was started, and in three cases the plant was completely shut down. There likely were more such cases that were not listed in the brief LER summaries that were reviewed. In one case two adjacent plants had to start shutdown procedures because they shared common essential chillers that had failures.

The trend for LERs has stabilized and does not seem to be affected whether the plant ages are factored in or not. The plants have experienced about 0.13 chiller-related LERs per plant year since 1988. If the influence of a few plants is neglected, it appears that the chiller LERs as a function of plant age tend to follow the "bath tub" failure curve (Figure 4.5).

Based on the two plants that provided detailed chiller failure data in the Phase I study, there are probably one to two orders of magnitude more failures that caused a chiller to trip than indicated in the LERs. There may be an additional order of magnitude more failures that are minor and do not cause a chiller to trip. LERs indicate the situation where both redundant chillers are inoperable at the same time.

Chiller motor and compressor failure data obtained from a Hartford Steam Boiler Inspection and Insurance Company database indicated that motor failures occurred in the 9- to 12-year age range and compressor failures occurred in the 14- to 15-year age range. About 80% of the motor failures are due to motor stator winding failures. About 62% of the compressor failures occur due to bearing failures, and 22% occur due to impeller failures.

To minimize and eliminate most of the failures, chiller operators need to carefully follow vendor procedures and monitoring schedules. Equipment performance should be recorded and trended. The routine maintenance staff should be trained well. Major overhauls and maintenance that require entering the refrigerant containment region should be performed carefully by well-trained, experienced technicians. It may be preferable to use service company technicians who routinely tear down and overhaul chillers. A small amount of contamination or a damaged or misaligned part can cause major problems during operation of a chiller. It is crucial at all times to keep equipment internals very clean and prevent the leakage of water, air, and other contaminants into the sealed refrigerant containment system.

Periodic operation for a few hours on a weekly or monthly basis is useful to remove moisture and non-condensable gases that gradually build up inside the chiller. A few hours of operation will help to provide the stable operation needed to evaluate the operating parameter performance, especially if the chiller is required to operate as an emergency standby unit. If multiple chillers are available, they should be alternated and their hours of use should be balanced. Chiller pressurization kits are available that will help minimize the amount of moisture and air ingress to chillers during standby periods. These kits are especially beneficial for low-pressure chillers (those that use R-11/R-123 refrigerant) that operate or are on standby at below or near atmospheric pressure.

Chillers should be operated as close to 100% capacity as practical to minimize aging. Usually chillers are replaced due to lack of good monitoring and maintenance. Other causes for replacement of chillers include obsolescence due to 1) change of heat load (usually growth), 2) energy efficiency improvements, and currently, 3) incompatibility with the new refrigerants required by new environmental regulations. In many cases the chillers can be upgraded by installing adaptor equipment packages provided by the manufacturer or chiller vendors.

The assessment of service life condition monitoring of chillers indicated there are many simple to sophisticated methods available that can help in chiller surveillance and monitoring. These methods will help prevent accelerated degradation and failures in chillers. The most effective chiller monitoring methods are refrigerant/lubrication oil leak detectors, periodic refrigerant/lubricant chemical analysis, vibration analysis, tube eddy current testing, and IRT analysis. The ultimate method is a computerized monitoring system that will continually monitor the chillers and their interfacing systems.

Review of numerous maintenance manuals provided by the centrifugal chiller manufacturers indicated that the maintenance requirements for chillers are well prepared and thorough. The operation manuals provided by the manufacturers are also excellent, and they provide warnings and guidelines that, if followed, will prevent accelerated aging and degradation of the chillers. They will also help prevent unnecessary chiller shutdown trips and aid in startups. Some of the older plants use O&M manuals prepared by plant engineers because their chillers were made by designing and assembling components onsite. None of those manuals were reviewed.

A predictive maintenance program with effective service life condition monitoring can be helpful in reducing the number of Technical Specification LCO entries and LERs and possibly eliminate them altogether. This study indicated that such programs and equipment are available and should be used with chillers and other NPP equipment. Literature reviewed indicated that some plants have successfully implemented similar programs. These programs enhance trouble-shooting, root cause analysis, and corrective action.

The number of LERs has continued at about the same level for the past 6 years. On an average of once a month, an NPP invokes a Technical Specification LCO requirement and initiates Technical Specification Actions because both chillers are inoperable. This problem could be reduced substantially, or eliminated entirely, if the NPP used a chiller program that employs condition monitoring and/or predictive maintenance as described previously.

Use of the manufacturer's O&M requirements with a simple augmented condition monitoring program should be adequate if maintenance is scheduled properly. Use of manufacturer's chiller upgrade components will also help.

Changes in environmental regulations are anticipated to impact the choice and use of refrigerants in chillers. Changes in refrigerants may impact the performance and aging of chillers. Three options for accommodation include:

- Improve the existing chillers for CFC refrigerants.
- Convert the existing chillers to use non-CFC refrigerants.
- Replace the existing chillers with new chillers using non-CFC refrigerants.

The option selected should depend on the results of a careful safety, facility, cost, schedule, and risk study. Many plants have access problems for chiller replacement, and the facility ventilation systems may be impacted. New refrigerant handling and storing procedures and guidelines should be accommodated.

Discussions with representatives of chiller, refrigerant, and lubrication oil manufacturers have indicated that the HVAC industry has resolved most of the problems associated with the new refrigerants. New chillers and retrofit kits are well designed and are working satisfactorily. O&M requirements have changed slightly. Time will tell if there are any accelerated degradation problems, but none are currently expected.

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APPENDIX A

LWR Plant Licensee Event Report (LER) Review Summary

APPENDIX A

LWR Plant Licensee Event Report (LER) Review Summary

This appendix contains a summary of LERs that were compiled using the Sequence Coding and Search Systems (SCSS), NUDOCS/AD, RECALL, NPE, and other NRC databases.

Appendix A

Chiller Licensee Event Report LER Review Summary

LER	Plant	Event Date	Failure Description	Failure Cause	Failure Areas(1)	Aging(2) Degree
92-016	Arnold	10-22-92	One chiller down for maintenance and other chiller tripped.	Erroneous low chilled water flow trip possibly caused by air bubble.	15 and 4	Unknown
92-019	Arnold	11-19-92	One chiller down for maintenance and other chiller tripped.	Low oil level and pressure.	15 and 6	A2(3)
93-011	Arnold	11-11-93	Chiller B was down for preplanned maintenance and Chiller A tripped. Neither chiller could be restarted.	Cause of both chiller failures was poor chiller setpoint and freon charge balancing during low load conditions due to cold weather operation.	Both 9,5,15	Both A2(3)
81-040	Arkansas 2	11-06-81	Low freon charge caused chiller failure.	Leaking valve fitting.	5	A1
83-006	Arkansas 2	02-02-83	High condenser pressure made chiller trip.	Power supply for the pressure indicating controller was defective.	11	A1(3)
90-010	Braidwood 1	07-11-90	Chiller main breaker would not allow chiller to trip.	Main breaker failed.	9	A2
90-008	Byron 1	06-27-90	Chiller malfunction. Plant Shutdown.(4)	Evaporator tube leak.	4	A1(3)
83-039	Calvert Cliffs 1	07-22-83	Chiller tripped due to high discharge pressure from the condenser.	Fan drive belts vibrated loose due to loose set screw to shaft.	7	A1(3)
83-040	Calvert Cliffs 1	07-27-83	Condenser fan drive failed.	Fan drive belts vibrated loose due to loose set screw to shaft. Second time in 5 days.	7	A2(3)
93-001	Calvert Cliffs 1	02-02-93	One chiller down for maintenance and other chiller failed due to insufficient refrigerant inventory.	Insufficient refrigerant inventory and possible leak.	15 and 5	Unknown(3)
86-003	Catawba 1	01-16-86	Chiller failed to start. LCO invoked and plant power level was reduced.(4)	Chiller compressor motor temperature sensing module had failed.	9	A1
86-005	Catawba 1	01-17-86	Chiller tripped on low chilled water flow and later on high motor bearing temperature. Other chiller was down for maintenance on related system.	Chiller failure trip causes not explained.	9 and 15	Unknown(3)
88-023	Catawba 1	10-25-88	One chiller down for maintenance and the other chiller tripped due to bearing high lube oil temperature.	High lube oil temperature caused by low cooling water flow in the lube oil cooler.	15 and 6,2	A1(3)
90-019	Catawba 1	03-23-90	One chiller down for maintenance and the other chiller tripped.	Personnel inadvertently pulled a supply power lead for the chiller while it was operating.	15 and 11	A2
90-030	Catawba 1	10-23-90	One chiller down for maintenance on related system and other chiller tripped.	Failed hydromotor and out-of-calibration oil pressure switch.	15 and 7,12	A2
91-005	Catawba 1	02-12-91	Low refrigerant temperature cut out switch set point reached on Train A. Train B also tripped.	Chiller A, refrigerant seal leak at compressor power terminal box. Chiller B, condenser water auto control valve failed open.	5 and 9	A2 and A1(3)

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Chiller Licensee Event Report LER Review Summary

LER	Plant	Event Date	Failure Description	Failure Cause	Failure Areas(1)	Aging(2) Degree
91-023	Catawba 1	11-17-91	One chiller down for maintenance on related system and other chiller shutdown due to damper failure on related system.	Maintenance and failure of hydromotor in related systems.	1 and 1	A1
91-024	Catawba 1	10-09-91	Both essential chillers failed. LCO declared.	Corroded low temperature switch contacts on one and loose guide vane linkage on the other.	10 and 8	Both A2
92-013	Catawba 1	12-03-92	One chiller down for maintenance and the other chiller failed due to guide vane actuator motor trip.	Component failure in guide vane control motor.	15 and 10	A2 and A1
93-009	Catawba 1	09-23-93	Chiller B was down for planned preventive maintenance and Chiller A failed due to an inadvertent internal conductor removal.	Wrong chiller internal conductor was removed and there was a lack of self-checking/independent verification.	15 and 11	Human and procedure errors
89-041	Clinton 1	11-22-89	Low refrigerant pressure in condenser caused a chiller to trip.	Refrigerant leakage, no location reported.	5	A2(3)
91-018	Comanche Peak 1	05-28-91	Safety chiller inoperable for extended period.	A faulty oil sump lever switch due to manufacturing defect.	9	Manufacturing defect(3)
92-012	Comanche Peak 1	06-03-92	One chiller down for maintenance on related system and other chiller failed due to oil system problem. Reactor shutdown started.(4)	Excessive refrigerant in oil and oil return valve was excessively open.	15 and 6	Human error(3)
89-010	Davis-Besse 1	06-12-89	One chiller was down for maintenance and the other chiller tripped on high pressure during a test.	Chiller failed due to high pressure condition caused by a manual valve being in a wrong position.	15 and 4,2	Human error and faulty procedure(3)
83-096	Farley 1	12-30-83	Chiller tripped due to low refrigerant.	Refrigerant high pressure valve was leaking.	5	A2(3)
87-012	Hatch 2	09-16-87	Chiller tripped due to high condenser pressure condition.	Water chiller condenser tubes fouled by calcium deposits.	4	A1(3)
86-025	Hope Creek 1	05-30-86	Chiller tripped on low cooling water flow indication.	Chiller trip caused by maintenance action on a related system.	1	Human error(3)
86-029	Hope Creek 1	06-11-86	Control area chiller tripped on low refrigerant pressure.	Ball float valve that controls refrigerant flow malfunctioned.	8	A1(3)
88-015	Hope Creek 1	05-26-88	Excess oil in one chiller and the other chiller tripped. Reactor shutdown started.(4)	Lack of understanding of seasonal oil migration in first chiller and defective high side float ball in economizer of second chiller.	6 and 8	A2 and A1(3)
89-007	Hope Creek 1	04-06-89	Train B filtration unit became inoperable and Train A became inoperable when Chiller A failed.	A seal failed in chiller A.	1 and 5	A1
90-017	Hope Creek 1	09-12-90	One chiller down for maintenance and the other chiller tripped due to surging.	Differential pressure switch setpoint drifted.	15 and 12	A2

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Chiller Licensee Event Report LER Review Summary

LER	Plant	Event Date	Failure Description	Failure Cause	Failure Areas(1)	Aging(2) Degree
91-011	Hope Creek 1	05-22-91	Both chillers failed.	Chiller A failed due to broken terminal on compressor impeller shaft displacement trip circuit and Chiller B due to spurious trip signal.	11 and 10	A1 and Unknown
92-002	Hope Creek 1	01-28-92	Both chillers failed due to low evaporator pressure trips. Possible leaks.	Insufficient freon charged and pressure switch setpoint drift.	5 and 5	A1. Procedures inadequate(3)
93-010	Hope Creek 1	11-09-93	Chiller B tripped due to a high motor winding temperature signal. Chiller A started, but soon failed because the compressor inlet guide vane linkage was broken.	Chiller B failure was attributed to a loose connector in the control cabinet. Chiller A failure was due to a design deficiency in the guide vane swivel.	11 and 7	A1 and A2, design deficiency
93-044	Indian Point 3	10-18-93	Chillers could not adequately meet as-built central control room heat loads.	Insufficient chiller capacities.	13	Design change errors
91-021	Limerick 1	08-29-91	High toxic gas alarm caused by freon release during maintenance on a chiller.	Freon leaked during a transfer by maintenance personnel. Alarm should have been on standby.	5	Inadequate procedure
81-044	McGuire 1	04-10-81	Chiller failed to start.	Chilled water thermostat set too low.	4	Human error
82-072	McGuire 1	09-27-82	Chiller tripped due to high bearing temperature.	Excessive oil in chiller.	6	Procedure deficiency(3)
83-048	McGuire 1	06-24-83	Chiller tripped due to refrigerant low temperature cutout switch trip.	Condenser tube cleaning resulted in better heat transfer which caused increased backpressure. LER may be caused by refrigerant leak instead.	4	A1(3)
83-056	McGuire 1	07-14-83	Low refrigerant temperature tripped chiller.	Loose flange on suction side of compressor caused refrigerant leak.	5	A2(3)
84-018	McGuire 1	06-04-84	One chiller was down for maintenance and other chiller tripped. Plant power level was reduced(4) and high control room temperatures caused printed circuit cards to fail.	Low oil in chiller and low chiller load caused failure.	15 and 6,1	A2(3)
85-031	McGuire 1	10-17-85	One chiller was down for maintenance and the other chiller tripped on low chilled water flow.	Pressure switch was faulty and tubes needed cleaning.	15 and 9,4	Both A1(3)
86-012	McGuire 1	07-30-86	Chiller B tripped on low oil level. Chiller A was started, but tripped on low chilled water flow and would not restart.	Insufficient oil level on Chiller B and design/management deficiency on Chiller A.	6 and 4	A2 and design/mgt. deficiency(3)
87-001	McGuire 1	01-07-87	Loss of refrigerant made Chiller A inoperable and Chiller B tripped on refrigerant low temperature. Power reduction was initiated at both plants.(4)	A leaking threaded fitting on oil cooler caused the refrigerant loss on Chiller A and the Chiller B chilled water exit thermostat was adjusted to provide warmer water.	5,6 and 10,12	Both A2(3)

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Chiller Licensee Event Report LER Review Summary

LER	Plant	Event Date	Failure Description	Failure Cause	Failure Areas(1)	Aging(2) Degree
87-006	McGuire 1	03-10-87	Chiller A was down for maintenance when Chiller B tripped due to a low condenser water flow signal.	Low water flow was caused by personnel that closed the cooling water header valve by mistake.	15 and 4	A2
87-023	McGuire 1	10-01-87	Loss of essential control power in Chiller A and control room air handling unit suction damper not open causing Train B to be inoperable. Power reduction started in unit 2.(4)	Blown fuse in Chiller A due to design deficiency of fuse rating being insufficient.	10 and 15	Design deficiency
88-034	McGuire 1	10-23-88	One chiller was down for maintenance and another chiller was inadvertently shutdown for cleaning HX in component cooling water system.	Personnel error to start maintenance on related system when one chiller was already down for maintenance.	1 and 15	Both A2
89-007	McGuire 1	03-10-89	Non-safety components found installed between safety related air supply solenoids and valve operators.	Unapproved materials used in components due to design and construction/installation errors.	9	Design deficiency
89-018	McGuire 1	08-29-89	Both chillers tripped due to failures.	One chiller tripped due to low refrigerant. Backup chiller failed due to low service water flow to the condenser caused by mis-positioned valve due to inadequate procedure.	5 and 4,2	A2 and operator -procedure error(3)
93-004	McGuire 1	05-13-93	One chiller down for testing and the other chiller tripped due to high bearing temperature alarm.	Faulty temperature sensor contact on alarm.	15 and 10	Both A2
86-015	McGuire 2	08-09-86	Chiller A tripped when fuse was overloaded and failed to restart due to an inoperable electro-mechanical timer. Chiller B was down due to maintenance on related system.	Blown fuse was caused by incorrect wiring design and chiller start timer was not properly set.	10,9 and 1	Design error, human error
91-003	Millstone 2	02-12-91	Chillers can not receive start signal due to loss of instrument air.	Design inadequacy would cause loss of vital DC Switchgear Room cooling.	9	Design Error
90-001	Nine Mile Point 2	01-03-90	Electrical interference caused by chiller breaker.	Power breaker on chiller failed.	11	A2
81-025	North Anna 1	04-28-81	Improperly operating steam chiller and mechanical chiller.	Lack of adequate low temperature cooling water from the cooling tower.	2	A2
83-032	North Anna 1	05-21-83	Chiller malfunctioned.	No cause given.	Unknown	Unknown
83-056	North Anna 2	07-11-83	Chiller tripped on low compressor oil pressure.	No cause given.	6	Unknown

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Chiller Licensee Event Report LER Review Summary

LER	Plant	Event Date	Failure Description	Failure Cause	Failure Areas(1)	Aging(2) Degree
81-003	Oconee 2	03-02-81	High temperature on reactor building chiller unit.	Bearing high temperature caused by grease starvation.	6	A1
92-008	Palisades	02-06-92	One chiller was out of service and the other chiller failed due to a leak in the hot bypass line.	Copper bypass pipe was in contact with floor plate and eroded away due to vibration. Installation error.	15 and 4,5	Installation error(3)
85-063	Palo Verde 1	09-12-85	Chiller failed due to loss of refrigerant. Plant trip(4).	Refrigerant leak.	5	A1
86-014	Palo Verde 1	04-11-86	Chiller failed to start.	Designed cross trip failed in related system.	1	A2
87-018	Palo Verde 2	10-04-87	Essential chiller tripped due to high bearing temperature after starting.	Excessive oil level was in the sump.	6	A2(3)
88-017	Palo Verde 1	05-28-88	Root isolation valves for flow transmitter were closed for 9 days shutting down both emergency chillers.	Closed valves on both chillers violated administrative controls. Human errors were involved.	8 and 8	Both A2
88-019	Perry 1	05-15-88	Both Chillers failed.	Mechanical failure of a compressor guide vane linkage connector in one chiller and an intermittent fault in the motor starter circuit of the supply fan caused a blown fuse in the other chiller.	8 and 11,1	A1 and A2(3)
88-040	Perry 1	10-07-88	One chiller down for planned maintenance and other chiller failed due to electrical fault in chiller control power.	Degradation of wire insulation due vibration rubbing results in grounding of control power supply.	15 and 11	A1
90-012	Perry 1	06-07-90	One chiller failed due to guide vane linkage problem and other chiller inoperable due to ineffective corrective actions.	Poor guide vane linkage design and human error.	8 and 13	Both A2
91-008	Perry 1	03-05-91	One chiller down for maintenance and the other tripped for low refrigerant temperature.	Refrigerant leaked through solenoid valve on the thermal purge unit.	15 and 5	A2 and A1(3)
85-011	Prairie Island 1	08-01-85	Chiller tripped due to power interruption.	Inadvertent closure of breaker by construction crew shutdown the chiller motor control center.	11	Human Error
92-017	Quad Cities 1&2	08-04-92	Chiller failed because the refrigeration condensing unit was cycling on and off on low compressor suction pressure.	Failure caused by excessive discharge pressure that caused carbon to build up and plug the compressor liquid discharge line.	4,5	Vendor manual unclear(3)
90-002	River Bend 1	02-02-90	One chiller shutdown for maintenance and other chiller had inadequate service water flow. Plant shutdown started.(4)	Procedures were incomplete and cooling water flow was out of balance to the chillers.	15 and 2	A2

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Chiller Licensee Event Report LER Review Summary

LER	Plant	Event Date	Failure Description	Failure Cause	Failure Areas(1)	Aging(2) Degree
90-013	River Bend 1	04-05-90	One emergency chiller down for extended maintenance and backup chiller had motor current limit set substantially to low. Both chillers inadequate for over 7 day limit.	Motor current limiter was incorrectly set at 56 versus 100 percent needed.	15 and 10	Inadequate job plan
92-024	River Bend 1	10-18-92	Two chillers failed.	Pneumatic control valve failure in panel.	Both 9	A2
92-025	River Bend 1	11-10-92	One chiller down for maintenance and the other tripped for motor over-current condition.	Faulty connection on motor over-current trip breaker.	15 and 11	A2
90-013	Robinson 2	09-11-90	Freon leak due to inadvertent line cut released toxic gas into area. An unusual event was declared and the area was evacuated.	A freon line was cut by a contract worker due to human error and lack of training.	5	A2
82-039	San Onofre 2	07-16-82	Emergency chiller refrigerant compressor failed to start.	Defective impeller displacement switch was cause of failure. Later LER indicated failure may be under voltage caused by wrong smaller capacity fuse.	9	A1
82-040	San Onofre 2	07-19-82	High bearing temperature indication tripped chiller.	Faulty high temperature bearing alarm module was the cause of failure. Later LER indicated failure may be under voltage caused by wrong smaller capacity fuse.	9	A2
82-059	San Onofre 2	04-07-82	A faulty flow control switch was found during maintenance of a chiller.	The flow control switch was out of calibration. Later LER indicated this may have been a actual flow problem.	12	A2
82-060	San Onofre 2	04-16-82	Emergency chiller tripped on low flow.	Erratic flow control switch caused failure.	9	A1
82-065	San Onofre 2	07-11-82	Both chillers failed to start.	Chiller B tripped due to a faulty compressor motor bearing high temperature alarm module and Chiller A failed due to a cover that prevented a trip relay from operating properly. Later LER indicated failure may be under voltage caused by wrong smaller capacity fuse in Chiller B.	10 and 11	A1 and A2
82-173	San Onofre 2	12-28-82	Chiller failed to start.	Loose wire on the low lube oil pressure switch.	11	A2
83-012	San Onofre 2	01-08-83	Chiller failed to start.	Faulty program timer.	9	A1
83-042	San Onofre 2	04-22-83	Chiller failed due to low compressor suction pressure trip.	Valve was closed on surge line.	8	Human error
83-049	San Onofre 2	04-29-83	Chiller failed to start following a TGIS.	Power supply breaker was misaligned.	10	A2

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LER	Plant	Event Date	Failure Description	Failure Cause	Failure Areas(1)	Aging(2) Degree
83-066	San Onofre 2	07-01-83	Chiller failed to start during test.	Power supply breaker malfunctioned. Later LER indicated another power problem may have existed.	9	A1
83-110	San Onofre 2	08-21-83	Chiller failed to start.	Incorrect fuse and it failed due to thermal fatigue. This fuse likely caused previous LER failures.	11	A1
83-130	San Onofre 2	10-21-83	Emergency chiller trip indicated by low CCW flow.	Spurious trip from control circuit. May have been existing flow problem indicated in another LER.	10	A2
84-029	San Onofre 2	06-14-84	Emergency chiller tripped.	Personnel error in tripping the wrong breaker.	9	Human error
84-046	San Onofre 2	08-15-84	Emergency chiller inoperable due to lack of condenser cooling water.	Fault indication reading was on improper channel. Plant shutdown was initiated.	10	Human error
88-010	San Onofre 2	05-06-88	Two chillers were inoperable due to low freon. Plant power reduction was initiated.(4)	Two chillers were low on freon due to inadequate operating procedure on freon level requirements and a slow leak.	5	A2(3)
89-009	San Onofre 2	09-07-89	Chiller removed from service.	Caused by personnel error. Another LER indicates a power problem may have also existed.	Unknown	Human error
83-043	San Onofre 3	07-08-83	Chiller failed to start.	Either a malfunction of chiller control circuitry or mechanical malfunction in the power supply breaker.	9	A1
83-048	San Onofre 3	08-21-83	Chiller failed to start.	Incorrect fuse failed thermally.	11, Human error	A1
90-001	San Onofre 3	01-30-90	High motor/bearing temperature trip indication.	Intermittent failure of a trip relay.	10	A1
93-021	Seabrook	11-17-93	One chiller was down due to failure in related system and the other chiller tripped during operation.	Chiller tripped due to failure of the oil pump.	15,1 and 9,6	A1(3)
87-007	Shearon Harris 1	02-10-87	Chiller A was inoperable for maintenance purposes. Chiller B tripped and was restarted several times but wouldn't run. Plant power reduction was initiated.(4)	Chiller failed due to low compressor lube oil pressure.	15 and 6	A1(3)
90-017	Shearon Harris 1	06-20-90	Chiller could not be started and indicated low pressure.	Mis-positioned root isolation valve for the refrigerant low pressure switch on the chiller. Error by maintenance personnel.	8	Human Error
91-004	Shearon Harris 1	03-14-91	One train down for maintenance and other chiller tripped.	Chiller tripped due to check valve closure problem.	15 and 8	Unknown

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Chiller Licensee Event Report LER Review Summary

LER	Plant	Event Date	Failure Description	Failure Cause	Failure Areas[1]	Aging[2] Degree
93-002	Shearon Harris 1	03-30-93	One chiller down for maintenance and other chiller tripped due to fan bearing failure in ventilation system. Time was required to take chiller off maintenance and restart.	Failure of fan bearing in related train system and backup chiller unavailable.	15 and 1	A1
87-015	South Texas 1	11-21-87	Oil heater switches on two chillers were de-energized and failed to start because they must be on 12 hours prior to start-up.	Administrative error of leaving chillers on standby when they needed to be operable.	Both 1	Human Error
88-039	South Texas 1	06-16-88	While one chiller was down for inspection the other chiller failed due to a lube pump oil seal failure.	Failure of lube oil pump shaft bearing caused the seal failure.	15 and 6	A1
89-014	South Texas 1	06-20-89	Diesel generator failure due to lack of adequate chiller maintenance procedure.	EDG untied from ESF bus. Inadequate procedure due to lack of management planning.	1	Admin. Error
89-023	South Texas 1	12-16-89	Essential chiller tripped.	Contact oxidation and low contact pressure on an auxiliary relay of chiller.	9	A1
92-001	South Texas 1	01-30-92	One chiller train was down for maintenance and the other tripped.	Low oil level.	15 and 6	Procedure needs change
89-024	South Texas 2	05-28-89	Essential chiller removed from service for maintenance and maintenance on a related system for over 72 hours violating technical specifications.	Related system and chiller were down in a time exceeding technical specifications due to communication error.	1 and 15	A2
83-019	Summer 1	03-17-83	One chiller was down and the other chiller failed.	Failure associated with starting circuitry of chiller.	15 and 10	A1
83-038	Surry 1	08-29-83	One chiller down for maintenance and second chiller failed due to clogged condenser supply strainer.	Strainer clogged with materials from service water.	15 and 4	A2[3]
83-041	Surry 1	09-09-83	One chiller down for maintenance and second chiller failed due to control panel fire.	Control panel failure and fire caused by water from a blown condenser zinc plug which shorted motor starter contacts.	15 and 4,11	A2
86-024	Surry 1	08-13-86	Loss of two control room and relay room A.C. chillers.	Clogging of chillers due to unfiltered river water flowing through tubes.	Both 4	A2[3]
86-027	Surry 1	10-09-86	Two of three control room A.C. chillers inoperable. One down for maintenance and the other failed.	Chiller failed due to relay failure.	15 and 10	A2
86-030	Surry 1	10-29-86	Two of three control room A.C. chillers inoperable. One down for maintenance and the other failed.	Chiller failed due to a high condenser discharge pressure caused by marine growth.	15 and 4	A2[3]

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Chiller Licensee Event Report LER Review Summary

LER	Plant	Event Date	Failure Description	Failure Cause	Failure Areas(1)	Aging(2) Degree
86-032	Surry 1	11-04-86	Chiller failed due to loss of cooling water flow.	Flow was lost after air was introduced by inadequate venting of an alternate cooling water supply line due to procedural deficiency.	2	A2. Procedural Deficiency(3)
86-034	Surry 1	11-17-86	Two of three chillers inoperable. One down for maintenance and other failed.	Chiller failed due to a clogged inlet strainer at the condenser.	15 and 4	A2(3)
87-002	Surry 1	01-04-87	Two of three chillers inoperable. One down for maintenance and other failed.	Chiller failed due to a clogged manual isolation valve for the service water at the condenser inlet.	15 and 4	A2(3)
87-003	Surry 1	02-13-87	Chiller inoperable because of lack of service water and another because compressor relief valve lifted, discharging refrigerant.	Clogged suction strainer and excessive throttling of compressor service water outlet valve.	4 and 8	A2
87-005	Surry 1	02-21-87	One chiller was down for maintenance and the other two chillers tripped due to insufficient service water flow.	Marine growth accumulated inside of rotating strainers in both chillers.	15 and 4 and 4	A2(3)
87-006	Surry 1	03-10-87	Service water pump for B control/ relay room chiller tripped. Chiller A was down for maintenance.	Suspect thermal overload device at the motor control center activated, tripping the pump.	10 and 15	A2(3)
87-007	Surry 1	03-23-87	Two of three chillers tripped due to low service water flow which caused a high condenser discharge pressure.	Service water discharge valve was restrictive on both units. Flow reduction due to condenser debris was probably contributor.	4 and 4	A2(3)
87-008	Surry 1	03-26-87	Three chillers down. One for related system, one for clogged condenser strainer, and one for high condenser discharge pressure.	Clogged strainer caused by biological growth debris and other failure was due to operator closing manual service water discharge valve inadvertently.	15 and 4 and 4	A2 and human error(3)
87-018	Surry 1	07-29-87	Two of three chillers tripped due to low cooling water flow through the condensers.	Low cooling water flow caused high condenser discharge pressure which tripped chillers. Buildup of seaweed in strainers caused low water flow.	4 and 4	A2(3)
87-021	Surry 1	08-18-87	All three chillers were inoperable due to debris accumulated in service water inlet strainers.	Debris from biological growth made up debris that blocked water flow.	4 and 4 and 4	A2(3)
88-007	Surry 1	02-24-88	Insufficient service water flow.	Bad pressure control valve.	4,2	Yes
88-025	Surry 1	08-15-88	Three chillers failed due to condensers being too warm and required delay in starting.	Starting procedure inadequate for starting/ stopping chillers. Need to avoid residual heat in condensers.	Inadequate procedure	A2(3)
88-034	Surry 1	12-03-88	Two chillers tripped due to insufficient condenser water flow.	Pressure control valves were out of calibration.	Both 12	Human error(3)

Appendix A

Chiller Licensee Event Report LER Review Summary

LER	Plant	Event Date	Failure Description	Failure Cause	Failure Areas(1)	Aging(2) Degree
88-039	Surry 1	10-11-88	Control/relay room chiller tripped on high condenser discharge pressure. Another chiller was down for maintenance.	A small refrigerant leak in combination with insufficient service water flow.	5 and 15	A2 and Yes(3)
89-021	Surry 1	06-03-89	One chiller down for maintenance and other Chiller trips due to lack of service water flow to the condenser.	Tripped on high condenser discharge pressure due to lack of sufficient service water flow caused by design error.	15 and 1	Design error(3)
89-023	Surry 1	06-13-89	One chiller down for maintenance and other chiller trips due to low refrigerant charge.	Service water flow valve improperly set due to human error.	15 and 1	A1. Human error(3)
89-024	Surry 1	06/24/89	Two chillers tripped due to insufficient flow to the condensers.	Insufficient water flow resulted from insufficient supply water capacity due to design error.	Both 2	Design error(3)
89-031	Surry 1	07-23-89	Two chillers tripped due to high condenser pressure.	The high condenser refrigerant pressure was caused by air accumulated on tube surfaces from the service water system.	Both 4	A2(3)
91-008	Surry 1	04-25-91	Two chillers inoperable due to relay failure and inoperable emergency power source. Power was decreased.(4)	Failed oil pressure/overload reset relay. Other chiller declared inoperable due to inoperable EDG.	10 and 1	A1 and A2(3)
91-015	Surry 1	08-08-91	Two chillers inoperable due to thermostat failure and inoperable emergency power source.	Failed thermostat on one chiller. Other chiller declared inoperable due to inoperable EDG.	9 and 1	A1 and A2
91-016	Surry 1	08-11-91	One chiller inoperable due to lack of condenser water flow. Other chiller down for previous thermostat failure in LER 91-015.	Chiller condenser water flow insufficient due to service water pump failure.	1 and 15	A2
91-018	Surry 1	04-25-91	Control/emergency switch gear room chillers inoperable. Power reduction.(4)	Failed oil pressure/overload reset relay.	15 and 9,6	A1
92-009	Surry 1	07-12-92	Two of three chillers were shutdown due to low water flow in condensers.	Y-type service water strainers at condenser inlets became fouled.	4 and 4	A2
93-005	Surry 1	03-25-93	Two of three chillers were failed due to freon over-pressure in the condenser.	Lack of service water flow due to mis-positioning of inlet strainer valves.	4 and 4	Human Error(3)
93-006	Surry 1	05-13-93	Service water strainer backwash line leak.	Line leakage.	2	A2
81-021	Surry 2	03-21-81	Insufficient water flow to condenser caused chiller to trip.	Chiller condenser inlet strainer clogged with debris.	4	A2
81-060	Surry 2	09-15-81	Insufficient service water flow caused chiller trip.	Not known	4,2	Unknown

Appendix A

Chiller Licensee Event Report LER Review Summary

LER	Plant	Event Date	Failure Description	Failure Cause	Failure Areas(1)	Aging(2) Degree
88-011	Surry 2	04-23-88	Control/relay room chiller removed from service to perform minor maintenance. Another chiller was already down for major overhaul.	Refrigerant filter/dryer was becoming clogged on a chiller.	5 and 15	A2 and A1
92-003	Surry 2	03-25-92	One chiller train down for maintenance and another chiller tripped due to high service water pressure.	High pressure was caused by condenser sedimentation buildup.	15 and 4	A2 and A2(3)
92-004	Surry 2	03-26-92	One chiller was down for maintenance and another chiller failed to start.	Chiller failed to start due to the hand operated rocker switch being in "off" position.	15 and 11	A2 and Procedure error
87-022	Susquehanna 1	06-19-87	Chiller experiencing spurious trips while backup chiller down for maintenance.	Problems with cycle timer and low refrigerant trip switch caused the trips.	15 and 9,9	Both A1
84-014	Susquehanna 2	07-23-84	High temperature in filter demineralizer room due to chiller failure.	No chiller failure cause given.	14	Unknown
87-049	Vogtle 1	07-22-87	While one chiller was down for maintenance on a related system the other chiller failed.	A temperature switch failed on chiller.	15 and 9	A1
89-003	Vogtle 1	01-19-89	One chiller down for maintenance on a related system and other chiller was inadvertently shutdown for routine calibration work.	Technician started calibration work on the wrong chiller. Confusing paperwork.	15 and 12	Human and procedure errors
91-006	Vogtle 1	07-19-91	Inadvertent shutdown of both chillers by operator. Delay time to restart caused LCO.	Circuit board failure on radio-gas monitor.	Both 1	A2
93-005	Vogtle 2	08-09-93	Chiller A was in stop position. Chiller B was started for monthly test, but tripped shortly after started on high condenser pressure.	High pressure was caused by non-condensible gases which accumulated due to a clogged purge system solenoid valve.	15 and 9,5	A2
87-022	Waterford 3	08-14-87	Chiller B tripped due to a trip of a control power breaker.	The trips were triggered by a related system where a control circuit board failed and caused excessive cycling of a relay which overheated and shorted to ground.	9	A2
89-004	Waterford 3	03-03-89	Low pressure valve ball float developed crack allowing float to fill with freon, sink, and close valve.	Inter-granular stress corrosion cracking of float.	7	A1
90-008	Waterford 3	07-03-90	Compressor motor high temperature trip on one chiller. Backup chiller tripped on low chilled water temperature.	No causes given.	4 and 4	Unknown(3)

LER	Plant	Event Date	Failure Description	Failure Cause	Failure Areas(1)	Aging(2) Degree
91-023	Waterford 3	12-20-91	When shutting down Chiller B and starting Chiller A it was discovered that the valves were cross-connected at the chiller cooling water inlets.	Chiller valves were mis-positioned and position indicators were inadequate.	Both 3	Human error and valve mis-identification
92-016	Waterford 3	12-01-92	ACCW valve could make Chiller A inoperable in certain accident conditions.	Maintenance procedure inadequate.	1	A2
89-011	Wolf Creek	06-23-89	Both chillers were inoperable.	Caused by loose wire on pump-down switch.	Both 11	Human error

Notes: (1) Failure Areas

1. Related Systems (Emergency Diesel Generator, IE Systems, Emergency Cooling Water System, Control Room Systems, Etc.)
2. Cooling Water System
3. Chilled Water System
4. Condenser/Evaporator
5. Refrigerant
6. Lubrication Oil
7. Mechanical
8. Mechanical Control
9. Electrical/Mechanical Control
10. Electrical Control
11. Electrical
12. Calibration/Adjustment
13. Other
14. No Cause Given
15. Chiller Down for Maintenance, Testing, Etc.

(2) Degree of Aging to cause failure:

A1 - Mostly Aging
A2 - Partially Aging
Others - Mostly Nonaging as described or unknown

(3) This LER caused accelerated aging stress to all components exposed to the refrigerant side in the chiller (e.g., compressor, condenser, evaporator, motor, etc.)

(4) This note applies to the LERs where the reactor power had to be reduced or shutdown and it was mentioned in the LER. It is unknown how many other LERs resulted in plant power reduction.

APPENDIX B

Computerized Service Life Condition Monitoring of Chillers

APPENDIX B

Computerized Service Life Condition Monitoring of Chillers

In order to achieve optimum performance, efficiency, and reliability, a computer system that is active (continuously collecting data) can advise of future potential problems and provide probable cause for failures. Continuously monitoring the points, as shown in the example diagram 631MC 1325-1, and the appropriate software program can provide all of the information needed to address the condition and specific needs of the HVAC "Train" system. This information can allow timely trendable information and instruction to make corrections before failure and secondary damage occurs. By using a computer system, all information would be standardized, consistent, and without human error. It will be able to spot individual problems in specific facilities that need attention and would provide corrective action recommendations. The information would accompany every LER to eliminate erroneous assumptions and provide rapid accurate probable/root causes of a chiller failure. In fact, had such a system been used in plants, many of the events for which chiller-related LERs were written, would never have occurred. This type of computerization will help optimize reliability and eliminate erroneous information.

The example diagram indicates selected locations which would have appropriate sensors needed to make the computer chiller train system perform continuous condition monitoring. The pressure and temperature sensor readings are integrated so they all interrelate with each other in the computer program (e.g., pressure drop across pump converts into pump performance curves and flow). The computer will automatically convert the pressure and temperature values into the appropriate monitoring and technology relationships with each other. The software would be programmed for each specific plant system to provide warnings, pinpoint problem areas, provide effective preventive maintenance, and provide probable/root causes of failures on the computer screen. Chiller debilitating failures would be minimized or eliminated.

Plants which use their essential chillers for emergencies only, would get more accurate assessments of the entire chiller train's condition when periodic tests are performed. Even when the chiller trains are in the standby operational status, useful information and diagnostics are continuing (e.g, can indicate leaks that are allowing air and moisture to enter the system and/or refrigerant to leak out). Systems like this can be retrofitted to existing systems as well as installed in new systems. Since the basic software requires some modifications for each plant, a pilot program might be run in one or two plants which have had problems with their chiller trains in the past. The information could be shared with all of the nuclear plants, so use performance and justification for systems may be evaluated on a plant-by-plant basis. The advanced LWRs should strongly consider monitoring systems like this to operate with optimum reliability and safety; and at the lowest cost.

LANDIS & GYR

Landis & Gyr Powers, Inc.

JOB
COMPUTERIZED MONITORING
LOC.
EXAMPLE ONLY
SYSTEM
CHILLER TRAIN CONDITION MONITORING

JOB# 631-MC -1325-25		DWG 1
DATE 09/08/93	DRAWING FILE CHILLER	CHKR
REV 0	DESCRIPTION SIDE VIEW	CHKD BY DRFTR

☒ = BEARING LOCATION

A = VERTICAL VIBERATION SENSOR

B = HORIZONAL VIBERATION SENSOR

C = AXIAL(THRUST) VIBERATION SENSOR

ALL A,B,C POINTS RELATE TO BEARING CONDITION AND BALANCE.

ALL P & T POINTS MARKED '1' RELATE TO CHILLER OPERATION BASED ON LOAD % OR AMP DRAW.

ALL P POINTS MARKED '2' RELATE TO PUMP GPM (PERFORMANCE).

ALL T POINTS MARKED '3' RELATE TO COIL AND FAN PERFORMANCE.

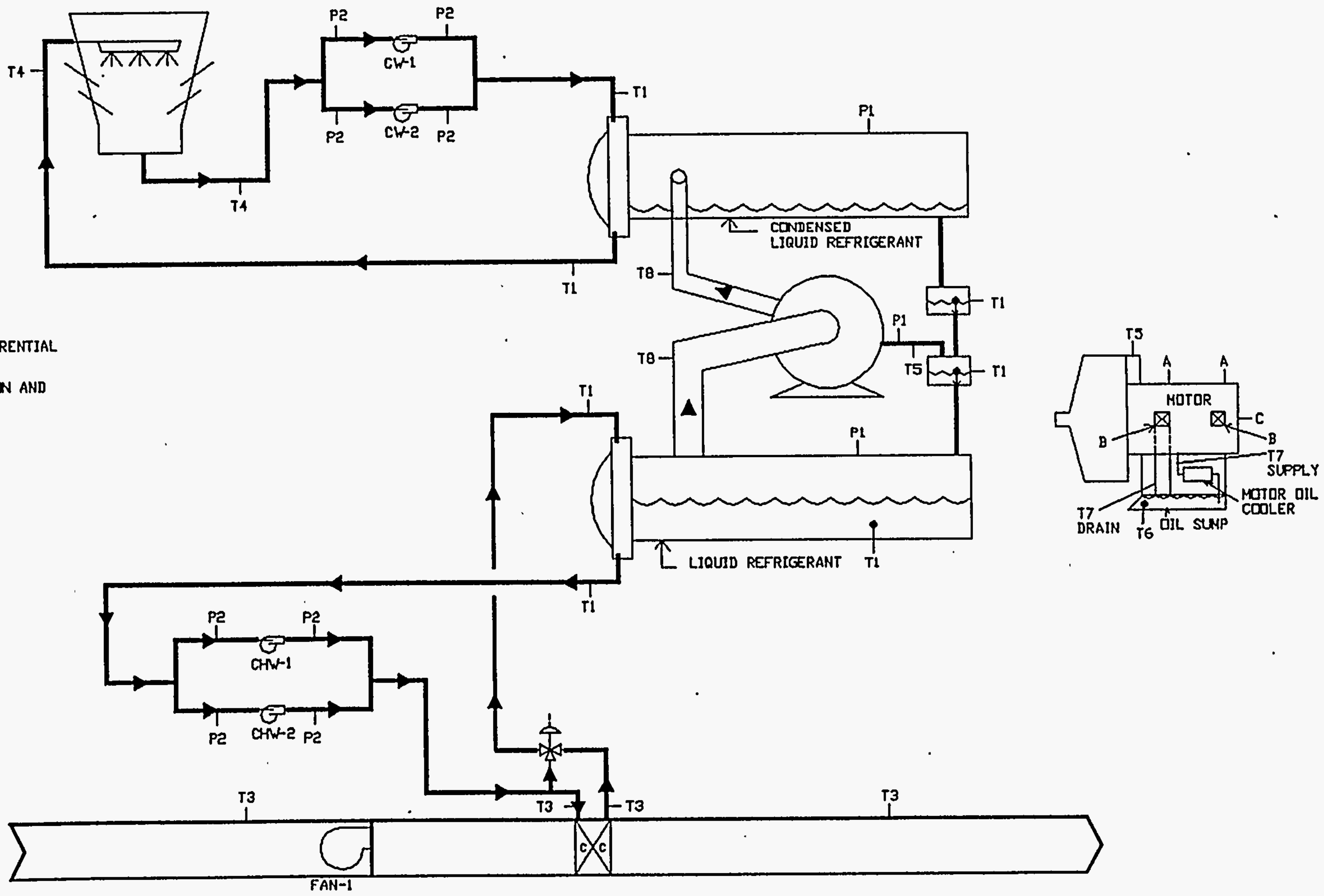
ALL T POINTS MARKED '4' RELATE TO COOLING TOWER PERFORMANCE.

ALL T POINTS MARKED '5' RELATE TO MOTOR TEMPERATURE AND DIFFERENTIAL (FLOW)

THE T POINT MARKED '6' RELATES TO OIL RESERVOIR TEMPERATURE.

THE T POINT MARKED '7' RELATES TO OIL SUPPLY AND RETURN TEMPERATURE DIFFERENTIAL (FLOW) AND BEARING TEMPERATURE.

ALL T POINTS MARKED '8' RELATE TO SUCTION AND DISCHARGE DIFFERENTIAL TEMPERATURE



APPENDIX C

Corrosion in NPP Chiller Equipment

APPENDIX C

Corrosion in NPP Chiller Equipment

Dr. A. B. Johnson, Jr. - Pacific Northwest Laboratory

Corrosion is an important element of chiller aging. This Appendix summarizes corrosion-induced degradation of chiller equipment, including information from Appendix G on corrosion and tube defects. To understand the potential range of corrosion impacts it is useful to recognize the components, materials, and environments (Table C.1).

Materials Compatibility with Refrigerants

The CFC compounds are designated by the E.I. DuPont de Nemours & Company trade name Freon. The chemical formulas for Class I refrigerants, CFC R-11 and CFC R-12, are shown in Table C.1 and below. The significance to this assessment is that the CFCs are being phased out by 1996. The leading replacement refrigerants are the Class II HCFC compound R-123 and Class III HFC compound R-134a.

Materials compatibility of CFC refrigerants continues to be relevant to aging considerations until they are phased out. However, the advent of Class II and Class III refrigerants is approaching and, therefore, they are included in this assessment.

Refrigeration equipment has operated with minimal degradation for more than 60 years, subject to replacement of tubes, bearings, etc., as required. Equipment subject to extreme conditions has seriously degraded in approximately five years. Characteristics of leading CFC, HCFC, and HFC compounds are provided below.

A. R11 - CCl_3F - operates at low pressures (vapor pressure, 1 atm at 25°C); adequate compatibility with materials specified for CFC service if moisture level is controlled.

B. R12 - CCl_2F_2 - operates at medium pressure (vapor pressure, 6.4 atm at 25°C); adequate compatibility with materials specified for CFC service if moisture level is controlled.

C. R123 - $CHCl_2CF_3$ - operates at low pressures (vapor pressure, 0.9 atm at 25°C); a more active solvent than CFC-11; can degrade seals, gaskets, motor windings, bushings, diaphragms not specifically designed for R-123 compatibility. This compound will replace R11.

D. R134a - CF_3CH_2F - operates with a positive pressure in evaporator and condenser (vapor pressure, 6.5 atm at 25°C); no need for purge unit to expel non-condensibles; good compatibility with standard materials; does not react with elastomers, polymers, seals, gaskets, motor windings. This compound will replace R12.

As a general observation, effective control of moisture has been the key factor in corrosion control in equipment that operates with CFC refrigerants. "Dry" refrigerant generally has moisture levels below saturation; "wet" refrigerant denotes free water that reacts with CFCs to form HF and HCl. The acidified free water floats on the refrigerant. It wets and attacks component surfaces and is drawn into crevices (Traver 1976).

Effective moisture control measures seem likely to assure compatibility of the HCFC and HFC refrigerants with materials similar to those currently in service. Need for changes in gasket, O-ring, and winding materials has been recognized as a need to facilitate implementation of the newer refrigerants; the details of those considerations are emerging (Calm 1992) but are beyond the scope of this assessment. For example, a test of R-123 and distilled water with several metals common to refrigeration equipment was conducted (Calm 1992, p.14). Results indicated that R-123 is suitable for service with all metals under dry conditions but was only suitable with stainless steel after a 100-d wet exposure. Also, nitrile swelled 400 - 600% more in R-123 than in R-11 (Calm 1992, p.14).

A compressor was inspected after operation for 8.7 y with R-134a and a polyalkalene glycol lubricant (Calm 1992, p.23). The refrigerator was operating normally when shut down for the inspection. The R-134a had very little effect on the metal parts in the compressor. Particles carried by the oil produced slight scars on the metal contact surfaces. The molecular sieve driers contained 5% residual water compared to ~25% at saturation. Use of a different oil may be suggested. Other studies of compatibility of newer refrigerants with non-metals and lubricants are referenced in Calm (1992).

TUBE BUNDLE CORROSION

Pitting

ID pitting and/or corrosion is most frequent; pits can propagate by erosion.

OD pitting is most often caused by moisture in the refrigerant, resulting in HF and HCl that attack tubes, supports, and shell; HF and HCL also attack impellers, motor windings, etc.; this pitting is difficult to arrest.

Condensers tend to have a higher incidence of tube ID pitting; evaporators tend to have higher incidence of support-related defects.

Crevice Attack

The HF and HCl attack crevices between tubes and support tubesheets.

Support/Baffle Wear and Corrosion

Vibration, caused by mechanical motion or water flow, is the stressor causing support wear. Once started, the wear process can be accelerated. If the environment is aggressive, corrosion can exacerbate degradation by corrosion of freshly exposed metal (fretting corrosion); continuously-finned tubes are more vulnerable to support wear; most reciprocating chillers tend to vibrate more than centrifugal chillers. Thinner walled tubes and internally enhanced tubes may have shorter service lives.

Obstructed Tubes

Age-related phenomena (scale buildup or biological deposits) can result in reduced or fully obstructed flow. Erosion can result from partially-obstructed flows. Proper and timely tube cleaning can eliminate fouling or scale. However, hard deposits can be difficult to remove.

Incorrect Roll-Joining

Tube rolling (mechanical displacement) is used to seal tubes into a heat exchanger. When too much tube is rolled or expanded, high stress locations can result; also the tube may not be expanded at the support. Over-rolling or off-target rolling can compromise the tube. Grooves left by rolling may promote erosive attack by the flowing fluid; stresses left by rolling may contribute to stress corrosion cracking (SCC).

Effects of Surface Imperfections from Manufacturing

Scarring and mechanical metal loss may go undetected in initial inspections, but can cause degradation by erosive attack. Small metal discontinuities on the gas or refrigerant side often present less tendency to initiate erosive attack and therefore may be acceptable.

Metallic Deposits

Most metallic deposits originate from piping or the shell, but can also be introduced during manufacturing, e.g., weld slag. They generate signals in eddy current scans that may be misinterpreted. Dissimilar metals can promote galvanic attack or they may cause flow disturbances that result in erosive attack. If the deposit is loose, it can be removed by brushing.

Freeze Damage

While not directly age-related, freeze damage may cause tube distortion that results in high stresses. Also, tube rupture can introduce water to the refrigerant that will promote serious corrosion attack, as indicated previously.

Stress Corrosion Cracking

Three main factors contribute to stress corrosion cracking: stress level, metallurgical state, and aggressiveness of the environment. In copper tubes, ammonia provides an aggressive species. Chlorides are aggressive to stainless steel. Stress corrosion cracking failures occur more frequently in absorption units than in centrifugal units. Also, SCC occurs more frequently in evaporator tubes, but can also occur in condenser tubes. Units with active SCC sometimes require complete retubing.

Erosion

Erosion of tubes can result from flowing liquids. Particulates, dissolved oxygen, water velocity, turbulence, deposits (flow disturbances), and dimensional changes can contribute to erosive attack. Sites where corrosion is active may be further attacked by erosion. Erosion eventually affects every heat exchanger.

Fatigue

Cyclic processes acting on a metal contribute to fatigue phenomena that may result in cracks through the metal.

OD (Refrigerant-Side) Corrosion

OD corrosion is common on condensers of centrifugal chillers. Excess moisture, leading to HF and HCl in the refrigerant, is the principal cause.

ID (Water-Side) Corrosion

Several mechanisms contribute to corrosion in water systems (Johnson, Jarrell, and Burns 1992) including pitting, uniform attack, galvanic attack, microbial-influenced corrosion (MIC), erosion-corrosion, and crevice corrosion. Differentiating similar mechanisms is important, e.g., determining whether pitting attack is due to chemical corrosion or to MIC, so that effective counter measures can be applied. Shut-down conditions need to be considered for systems that are susceptible to corrosion in quiescent waters. Systematic attention to keeping the system clean is more cost-effective than recovering from serious system degradation. A basis for effective management of a water system has been published (Johnson, Jarrell, and Burns 1992).

Other Corrosion Phenomena in Refrigeration Systems

Corrosion that can result from acid attack and other mechanisms on the refrigerant side includes:

- Acid contamination of the lubrication oil that causes attack of the bearing surfaces.
- The compressor inlet guide vane assembly can corrode and bind.
- Motor failure can result from insulation breakdown in hermetic units.
- The purge float valve can stick due to bearing and pivot corrosion; also due to sludge scavenged from the rest of the machine.
- The condenser and economizer float valves can similarly fail.
- Shell scaling can cause clogging between tube fins, between tubes, and in the mist eliminators. Subsequently, the scale hardens to restrict heat transfer and flow of the refrigerant.

- Copper chloride deposits on upper tubes are caused by the wetting/unwetting process. These deposits reduce heat transfer and have hygroscopic properties that make removal of water difficult.

Tube fouling and corrosion can cause eventual chiller shutdown due to reduced heat transfer or tube failure (Banta 1974; Leitner 1980; Blake 1977; Alger 1977; Starner 1976).

Vibration can ultimately cause seals, gaskets, pipe joints, and fittings to fail and allow leakage of the refrigerant. Moisture and air can also enter the previously sealed system by the same route (Esslinger 1988; ASHRAE 1991).

Water-side corrosion and fouling problems were addressed previously and are discussed in more detail in Johnson, Jarrell, and Burns (1992).

<u>Corrosion Control</u>

To summarize corrosion control measures for systems utilizing Class I and Class II refrigerants and interfaces with an aqueous system:

- Clean metal surfaces after fabrication, e.g., remove slag from steel components; also clean copper tubes after extrusion.

- Limit H_2O concentrations in refrigerants, including specification of initial moisture levels and utilization of desiccants (molecular sieves and activated alumina); moisture that exceeds the refrigerant saturation level (a few 10's of grams in ~500 kg of refrigerant) reacts with refrigerant to form acids.

- Use charcoal to remove acids (HF and HCl)

- Purge system to remove free water

- Keep flow rates in acceptable range (2 to 3 m/s for Cu for aqueous systems)

- Monitor for evidence of water-side degradation and apply effective and timely mitigation (Johnson, Jarrell, and Burns 1992).

There may be many plants that are on the brink of massive tube failure with only a small amount of run time (the plants where chillers are for emergency use only). Those chillers should be run several hours once per month if using R-12 refrigerant and once per week if using R-11 refrigerant. This will verify the chiller's operatibility and remove the air and moisture that may have accumulated.

Plants that use essential chillers for both normal and emergency operation need to alternate chiller operation to meet the same objectives and balance use of the chillers.

Corrosion Surveillance

Effective and timely surveillance measures provide the basis for control of corrosion and other aging mechanisms. The following surveillance methods are applied in refrigeration systems:

- Routinely analyze refrigerant to assure correct chemistry based on results of lubrication oil analysis.
- Conduct nondestructive eddy current testing of the tubes to monitor degradation.
- Periodically examine tubes; clean if necessary on a schedule.
- Periodically perform vibration analysis using same equipment locations.
- Heat-scan the electrical components with infrared temperature sensing instruments to detect areas overheating due to poor contact.
- Visually inspect and record gauge readings on a daily basis.
- Record daily readings on trending charts. Analyze the trend and take immediate corrective action if the trend becomes adverse.
- Perform all routine maintenance and service per manufacturer instructions.
- Annually service and test components to determine/assure reliability. Field strip motor control and starter contacts, change oil and filters, service purge/dehydrator unit, change drier, run operation and safety control tests, inspect HX tubes for fouling and corrosion, etc.
- Periodically (3 to 10 years) overhaul and inspect all wearing parts (using an interval based on the shortest life of the materials) within the chiller (typically the O rings, gaskets, and carbon seals).
- In all cases, cleanliness and care are most important.

Corrosion generally develops slowly and can be detected by monitoring during plant maintenance outages. Tube cleaning, inspection, and eddy current testing are important elements in effective management of corrosion in chiller tube bundles.

Age-Related Operational Impacts in Chillers at Nuclear Plants

Review of LERs related to chiller operation (Appendix A) indicates that many problems are caused by the age-related impacts of corrosion, vibration-induced degradation, deposition, and fouling.

Small tube leaks can be plugged in 7 days or less. Retubing, caused by a high incidence of leaks, will require removing the chiller from service for 7 to 21 days.

A case of chiller degradation at a nuclear plant (Blahnik and Klein 1993) provided insights to maintenance of a degraded chiller, eventually leading to partial retubing.

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Environments				
CCl$_3$F) Low P	R123 (CHCl$_2$CF$_3$) Low P$^{(c)}$	R12(CCl$_2$F$_2$) Med P	R134a (CF$_3$CH$_2$F) Med P	Water
-Down -V ning - V–L/V–L r may be ed by L ral oil added	Shut-Down -V Running - V–L/V–L Motor may be cooled by L mineral oil added	Shut-Down -V Running - V–L/V–L Motor may be cooled by L mineral oil added	Shut-Down -V Running - V–L/V–L Motor may be cooled by L New oil added that scavenges H_2O and debris, e.g., solden fluxes, brass oxides, dirt	Not applicable
t-Down - $V^{*(g)}$ ning - V–L/V–L possible under ormal conditions	Shut-Down - $V^{*(g)}$ Running - V–L/V–L * L possible under abnormal conditions	Shut-Down - $V^{*(g)}$ Running - V–L/V–L * L possible under abnormal conditions	Shut-Down - $V^{*(g)}$ Running - V–L/V–L * L possible under abnormal conditions	Open loop: T: 18 - 38°C Flow rate: 400-5000 l/min 2 m/s typical 3.6 to 4.5 m/s unusual
t-Down - L + V ning - L–V	Shut-Down - L + V Running - L–V	Shut-Down - L + V Running - L–V	Shut-Down - L + V Running - L–V	Closed loop: T: 4 - 15°C Flow rate - slightly lower than open loop rates
t-Down - $V^{(g)}$ ning - L + V	Shut-Down - $V^{(g)}$ Running - L + V	Shut-Down - $V^{(g)}$ Running - L + V	Shut-Down - $V^{(g)}$ Running - L + V	Not applicable
$V^{(f)}$	$L + V^{(f)}$	$L + V^{(f)}$	$L + V^{(f)}$	
	Air	Air	Air	Air

= Liquid
= liter
/ = vapor
C = Centrigrade [C = 5/9 (F-32)]
n/s = meters/second
1 m/s = 3.3 f/s
/m = liters/min; 3.8 l/min = 1 gallon/min
T = Room Temperature

TABLE 1. Centrifugal Chiller: Summary of Components, Materials, and Operating Conditions

Component	Service Conditions[a]			Sub-Component	Materials[b]
A. Compressor	Shut-Down -	Normal	20 - 25°C (RT)	Motor shaft:	Carbon steel
		Unusual	4 - 40°C	Drive shaft:	Heat-treated alloy steel (high speed)
	Running -	Suction	2°C	Demisters:	SS or nylon
		Discharge	40°C	Impellor:	High-strength Al casting
				Casing:	Cast Fe
				Labrynth seals:	Al alloys, brass
				Bearings:	Al alloy, bronze or babbitt (brass or steel body
				Pre-rotation vanes:	Mn bronze, Al steel
				Shaft seal:	Carbon ring with elastomer O-ring
B. Condenser	Shut-Down -	Normal	20 - 25°C (RT)	Same as evaporator	For parallel components, Except for No Eliminators
	Running -		21 - 41°C		
		Water-side	10 - 20 atm[d]		
			flow - 4.3 m/s		
C. Evaporator	Shut-Down -	Normal	20 - 25°C (RT)	Eliminators:	Bronze, Zn-coated steel
	Running -		10 - 0°C	Shell:	Carbon steel
				Waterbox:	Carbon steel
				Division plates:	Carbon steel
				Tubes:	Seamless Cu or Cu 90/Ni10[e]
				Tubes sheets:	Carbon steel, sometimes Cu/Ni-Clad on epoxy
				Tube supports:	Carbon steel
D. Economizer	Shut-Down -	Normal	20 - 25°C (RT)	Vessel:	Carbon steel
	Running -		12 - 30°C	Wiers:	Carbon steel
				Orifice plates:	Stainless Steel
				Mini-eliminator:	Bronze, Zn-coated steel
E. Oil Sump	Shut-Down -	Normal	57 - 63°C	Oil pump:	Steel
	Running -		60 - 71°C	Oil cooler	Zn-Lead-dipped Cu, Cu90/Ni10
				Motor:	Steel housing
F. Room Conditions (Air-side)		Normal	18 - 27°C	Shells:	Carbon steel
		Extreme	4 - 40°C	Gasket & O-Ring edges:	See footnote (b)
	Space to be kept clean and ventilated			Shaft seal:	Carbon ring with elastomer O-ring
				Piping:	Carbon steel, copper

(a) Conditions equalize on shutdown, Components A through E
(b) Components A-F have O-rings (viton, nitrile, neoprene) and gaskets (asbestos, cork, neoprene)
(c) Aggressive to motor windings
(d) Depends on building height; 45 atm for 100 story building
(e) Recent use of titanium
(f) Liquid is oil, vapor is refrigerant; sump is at same pressure as evaporator
(g) L where liquid traps occur and where physical positioning of components allow equilization of pressure or gravity allows reverse flow of refrigerant

APPENDIX D

Examples of Forms, Analysis Reports, and Guideline Outlines

APPENDIX D

Examples of Forms, Analysis Reports, and Guideline Outlines

This appendix includes a variety of forms, analysis reports, and guideline outlines that are used in chiller condition monitoring procedures, tests, and analyses. They are referenced in the text of this report.

Centrifugal Chiller Efficiency Checklist

The following checklist is taken from and Energy User News article written by Jeff Barber. He interviewed users and manufacturers of chillers as a basis for the checklist. By following certain procedures the operators of centrifugal chillers can extend the life of their equipment and maintain peak cooling efficiency by following a preventive maintenance schedule as outlined in the checklist.

Reference

Jeff Barber, 1988. "How to Improve Efficiency in Centrifugal Chillers", Energy User News, March 7, 1988, a Fairchild Business Newspaper.

Centrifugal Chiller Efficiency Checklist

PERSONNEL MANAGEMENT

Training:	OK	Needs Action
1. Training and education seminars conducted by manufacturer.		
2. Outside consultants.		
3. Service and maintenance agreement contracted to outside firm.		

PERFORMANCE RECORDS

Daily log report:	OK	Needs Action
1. Check and record oil pressures and temperatures.		
2. Check and record refrigerant pressure and temperature in condenser and chiller.		
3. Check and record cooling water inlet and outlet temperatures.		
4. Note and record any unusual sounds during chiller operation.		
5. Record all oil and filter changes.		
6. Check and record chilled water exit and inlet temperatures.		

PURGE SYSTEM

Periodic Maintenance:	OK	Needs Action
1. Clean all filters.		
2. Clean and examine valves and motors.		

CONDENSING SYSTEM

Maintenance:	OK	Needs Action
1. Check condenser seals periodically to make sure there are no air leaks.		
2. Remove condenser head annually and brush clean tubes.		

OVERALL MAINTENANCE

Oil System:	OK	Needs Action
1. Regularly examine and test system oil for metal flakes, sludge formation, and acid buildup.		
2. Regularly replace filters.		

Miscellaneous maintenance:	OK	Needs Action
1. Regularly check overall tightness of chiller seals.		
2. Periodically check refrigerant level.		
3. Check and clean chiller coils.		

Tips for Maintaining Centrifugal Chillers

The following tips for effective maintenance of centrifugal chillers are from a conference paper prepared by Wayne L. Stebbins. The outlined tips were developed based upon an effort to reduce energy consumption and obtain the best possible level of chiller systems performance. The paper also addressed compressed air and boiler systems.

Reference

Wayne L. Stebbins, 1991. "Implementing an Effective Utility Testing Process: A Keystone for Successful Energy Management", 1991 Annual Textile, Fiber, and Film Industry Technical Conference, Institute of Electrical and Electronic Engineers, Greenville, SC.

Outline of Tips for Maintaining Centrifugal Chillers

1) Maintain Good Equipment Logs

   a) Documents all day-to-day changes
   b) Reveals potential problems
   c) Allows early detection of maintenance needs

2) Eliminate Excess Air in the Refrigerant

   a) Use pressure data from log readings
   b) Convert pressure to temperature and compare to table
   c) A difference of 2 degrees F or greater indicates excess air
   d) Every 2 degree F difference requires 3% increase in full load power

3) Sample and Analyze the Oil

   a) Filters inspected and cleaned, and oil samples taken annually
   b) Analysis shows presence of destructive acids from oil breakdown
   c) Analysis shows presence of metal deposits from abnormal parts wear
   d) Analysis done during period of low cooling demand, so that necessary repairs can be made at that time

4) Test Heat Exchanger Tubes

   a) Prevent tube failure by eddy current test every 3 to 5 years
   b Water and refrigerant mix to form hydrochloric and hydrofluoric acid which attacks metal parts, and motor insulation on hermetic chillers
   c) Eddy current tests last 1 to 2 days and cost $1,500 to S2,000 per chiller
   d) Eddy current tests identify internal pitting, freeze damage, support wear, erosion and metal deposits, and corrosion
   e) Defective tubes can then be plugged or replaced

5) Control Rust in the Refrigerant

   a) Moisture and air leaking into the steel condenser and evaporator shells form rust, which shortens the useful life of the equipment and inhibits the heat-transfer capacity
   b) Rust can be reduced by installing a refrigerant clean-up kit consisting of a large-capacity filter/dryer as a retrofit
   c) The kit continuously draws a mixture of refrigerant, sludge, oil, and rust from the evaporator, removes the impurities, and returns clean, dry refrigerant to the system

6) Eliminate Scale in the Condenser Tubes

   a) Scale buildup hinders heat-transfer process and causes excessive head pressure, resulting in the compressor working harder for a given cooling demand
   b) The tubes should be cleaned with mechanical brushes and maintained clean with a proper chemical water treatment program

7) Maintain Proper Condenser Temperature and Water Flow

   a) Every 5 degree F decrease in leaving condenser water temperature yields a 1-1/2% increase in tonnage capacity for a given power input, or a 1-1/2% decrease in power required for a given tonnage output
   b) A 20% reduction in flow rate of condenser water will increase full load energy consumption by 3%
   d) In addition to scale buildup, other common causes of reduced flow include: partially closed valves, dirty water strainers, clogged cooling tower nozzles, and air in the water piping

8) Ensure Proper Refrigerant Charge and Temperature

   a) Too little or too much refrigerant limits the heat transfer capacity of the chiller, and increases head pressure and power consumption
   b) Improper levels can decrease evaporator temperature
   c) Every 1 degree F the evaporator temperature can be raised saves 1-1/2% of the full load energy or provides 1-1/2% more tonnage for the same power input
   d) Refrigerant level can be monitored through the sight glass in the evaporator shall, and if necessary, the system can then be charged according to the manufacturer's instructions

Carrier ® Air Conditioning Company
A DIVISION OF CARRIER CORPORATION

DATE ____________________

REFRIGERATION LOG
CARRIER 19D HERMETIC CENTRIFUGAL REFRIGERATION MACHINE

PLANT ____________________ MACHINE SERIAL NO. ____________________ MACHINE SIZE ____________________

	COOLER					CONDENSER				COMPRESSOR						PURGE				
	GPM ____					GPM ____					OIL									
				Water Temperature				Water Temperature												
Time	Vacuum	Refrigerant Temperature	Refrigerant Level	IN	OUT	Vacuum or Pressure	Condensing Temperature	IN	OUT	Bearing and Transmission Temperature	Level	Temperature	Pressure	Reservoir Pressure	Motor Amps or Vane Position	Refrigerant Level	Condenser Pressure	Frequency of Pump Operation	Refrigerant Pump On or Off	Operator's Initials
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21

REMARKS: Indicate shut-downs on safety controls, repairs made, oil or refrigerant added or removed, and water drained from purge. Include amounts.

E-56A (6-68)

APPENDIX E

Condition Monitoring of Chillers Using Infrared Thermography, Ultrasonics and Vibrations Methods in a Complementary Approach

APPENDIX E

Condition Monitoring of Chillers Using Infrared Thermography, Ultrasonics and Vibration Methods in a Complementary Approach

The material in this appendix was prepared by Gerhard N. Thoen of HEATSCAN. It provides information that expands upon the vibration condition monitoring in Appendix F and includes the use of infrared thermography and ultrasonics in a complementary approach. The report includes a discussion of background, equipment, procedures, examples, program set-up, charts and data.

Condition Monitoring of Chillers Using Infrared Thermography, Ultrasonics and Vibration Methods in a Complementary Approach

For

Battelle, Inc.
Pacific Northwest Laboratories
P.O. 189624

G. N. Thoen
September 1993

HEATSCAN
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Kelso, WA 98626
206 423-7167

Abstract

Rotating equipment operating at various RPM generate levels of vibration coincident to component conditions. These levels or frequencies can be measured by non-destructive testing using displacement(low), velocity(medium), acceleration(high) and ultrasonic(very high) transducers. At each frequency range there are indications of specific problems and the amplitudes show the severity of those problems. By trending, or making several measurements over time, predictions can be made about possible failure times. Coupling infrared thermographic analysis to vibration data can also determine overheating at gears, bearings, and the electrical components and controls of the equipment. Costly downtime can be avoided by monitoring the machines with these relatively new non-destructive strategies.

Key Words: Chiller, Infrared Thermography, Ultrasonics, Vibration

Table of Contents

I Background

II Equipment

III Procedures

IV Examples

V Program Set-up

VI Charts and Datas

I Background

The advent of non-destructive testing has opened the door to testing of machines such as centrifugal chillers in an unprecedented way. This science is called Predictive Maintenance and seeks to determine time of failure for machine components without shutdown and disassemblage.

All energy using equipment generates some energy in the form of heat and vibration. This is not the useful work of the machine but a side effect. In the case of heat in the infrared spectrum of 3-5 and 8-15 microns, real time infrared thermographic scanners can detect this heat. With energy dissipated in the 600 to 600K CPM range vibration detecting analyzers can detect and measure the frequency and amplitude being generated.

Rotating equipment generates typical thermal patterns and frequencies of vibration commensurate with components responding to energy input. For most machines these levels of side effect losses are benign and indicate normal wear and operation.

Monitoring these outputs can be useful to detect subtle changes indicating excessive heat loss and vibration levels trending towards breakdown. Wear, imbalance or misalignment, cracked impellers, broken or missing gear teeth and electrical motor problems can usually be detected before serious damage is done.

ISO 2372 deals with "Good to Not Acceptable" levels of vibration in rotating equipment and the International Electrical Commission has established levels of temperature ranges for wiring, switch gear and other electrical equipment needed to operate chillers.

II Equipment

Infrared thermographic scanners can be of two types, 3-5 microns and 8-15 microns. Either type will allow a visual image of the equipment taken from these ranges of infrared. Good instruments will allow video taping for later examination and documentation. Some of the less expensive instruments will also need to have an infrared non-contact thermometer available for temperature recording. The more expensive instruments incorporate this feature.

There are many vibration analyzers on the market and for the most part they are all quite suitable for this type project. They range from the very basic to the most sophisticated FFT(Fast Fouier Transforms) equipment. Most of our studies have been carried out on an IRD Model 820 which gives a strip chart over 600 to 600K CPM with a "Spike Energy" range in the ultrasonic spectrum used for roller bearing measurements. Transducer pick-ups are used for displacement and velocity/acceleration. These can be hand held using a wand or stinger or can be mounted with a magnet to the machine at the various testing points. Drawing 1.

III Procedures

The machines in this discussion will be limited to centrifugal chillers.

The first step in testing is to obtain drawings and specifications of the machine. From this test points can be chosen that will give the best information about the various components. These test points become very important for future data collection and must be precisely marked for each test.

Most chiller motors use sleeve bearings, however some roller elements can also be used. It is very important to know which are being tested because they both have different vibration characteristics. Sleeve bearings will show looseness, eccentric journals, metal to metal contact and side to side movement while roller bearings will show imbalance, misalignment, pitting/spauling among other problems.

Gears and impellers can also be tested by vibration analysis. Here the number of teeth or blades can be determined by knowing the RPM of the shaft and counting multiples to find them. Damage or wear to the teeth or blades can be detected by the spread of frequency around the determined frequency and measuring the amplitudes.

Electric motors will also give vibration information showing excessive air gaps, broken rotor bars, axial float of the rotor as well as imbalance or misalignment of the shaft. The electrical problems can be detected and separated from the mechanical problems by testing as the current is shut off. Frequencies at line current levels of 60 to 120 Hz will disappear when this is done.

Infrared thermographic analysis consists of opening the electrical cabinets and scanning the switch gear, fuses, controllers and wiring for temperatures in excess of the IEC standards. Electrical imbalance in phases can also be checked. Cooling towers, pumps and motors can be scanned and temperatures taken and anomalies recorded. Heated water and chilled water can be tracked to find excessive energy losses through missing insulation or leaking valves and seals. Heat exchangers can be scanned to find plugging or short circuiting of fluids and gases. Leaking valves can be confirmed by taking ultrasonic readings on both sides, up and down stream.

Another important aspect of predictive maintenance of chillers is to take oil samples for spectrochemical analysis. If there is excessive wear or damage to the compressor components it will show up in metal contamination in the oil. This information adds to the accuracy of the predictive analysis.

After the field data is taken it is analyzed by using various chart(Fig 1-2) standards. These analyses now provide the present chiller condition overall and of the particular components. A report is then prepared with an eye toward immediate interpretation and as a data baseline for future monitoring or trending.

IV Examples

No. 1. Moss Heat pump(Trane Centravac)(Fig 3 & 3A)

Vibration readings taken over a 11 month period show an increase of 195% on bearing No. 4. This bearing was repaired several months before the readings were taken. A chart of these readings show the trend of wear. Figure 3A

No. 2. Medical Center(McQuay Chiller)(Fig 4)

Infrared thermographic scan found that a 480 V bus had a loose bolt that was generating a temperature of 167°F and was found to be 4 turns out. If this had shorted the entire cabinet would probably have been destroyed with possible damage to the chiller as well.

No. 3. Hospital(2 Trane Centravacs)(Fig 5 & 6)

Chiller comparisons No.1 and No.2. Both chillers were tested at the same time and same load. No.1 chiller had just been overhauled. Before this oil samples were taken and showed definite bearing deterioration with silicon(dirt)iron, aluminum, copper, lead and tin(from babbit) present in high amounts. After overhaul these metals drop but magnesium, zinc and phosphorus are still present. Phosphorus is probably from cleaning agents used in overhaul.

Vibration testing shows the D bearing(outboard-2nd stage) on No.1 chiller is over 1.5 acceleration G-Pk while No.2 chiller D bearing is 0.5. In this case No.1 D bearing is definitely in trouble and will fall under "Not acceptable", "Short life " and "ASAP" on the charts.

Velocity readings on No.1 D bearing also show mechanical looseness at 2 times RPM along with bearing roughness at 10 times RPM(this is also the effect of the second stage impeller with 10 blades which might be rubbing).

V Program Set-up

Failure of a chiller or compressor can cause serious load changes as well as substantial cost in downtime and unscheduled repairs. By monitoring the condition of machines over time and making full use of the data trends, time to failure can be predicted long before breakdowns occur. What then are the advantages of developing a predictive maintenance program and what costs can be expected?

Costs of Program	Savings Available
Initial investigation/research	Increase of time between overhaul
Training of staff	Elimination of unplanned shutdowns
Selection/purchase of equipment	Elimination of secondary damage
Selecting monitoring points	Elimination of component waste
Building data base	Reduction of spare parts inventory
Developing experience	Assessment of wear-out time

Measurements should be taken at set time periods and, more importantly, at the same precise locations. These reading should be entered onto data sheets for comparison over time as well ratings with ISO standards.

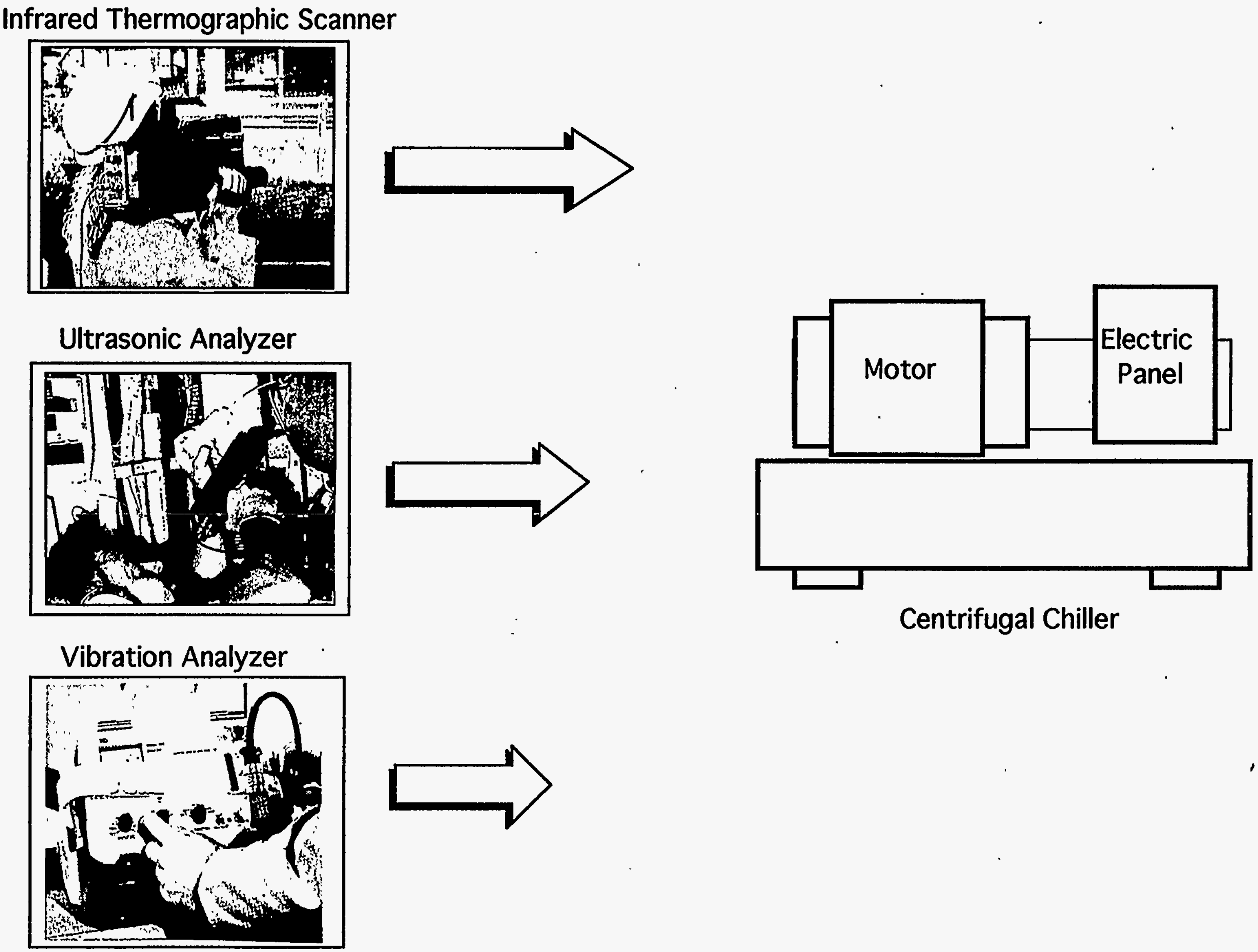
Attributes of a good program should consist of the following:

- Training of personnel
- Identification and location of critical machines to be tested.
- Selection of oil sampling times and analysis.
- Determine acceptable levels of machine vibration and temperatures.
- Select the best test points and mark them.
- Determine interval for periodic testing.
- Set up and keep accurate records including repairs.

Portable instruments are best to start a program. Many new analyzers consist of field data gathering and then down loading to a computer with software capable of performing the analyses and recording the data for future comparisons. The training of personnel should also be considered even more important than the hardware. A well trained technician can offset the lack of "bells and whistles" in basic instruments.

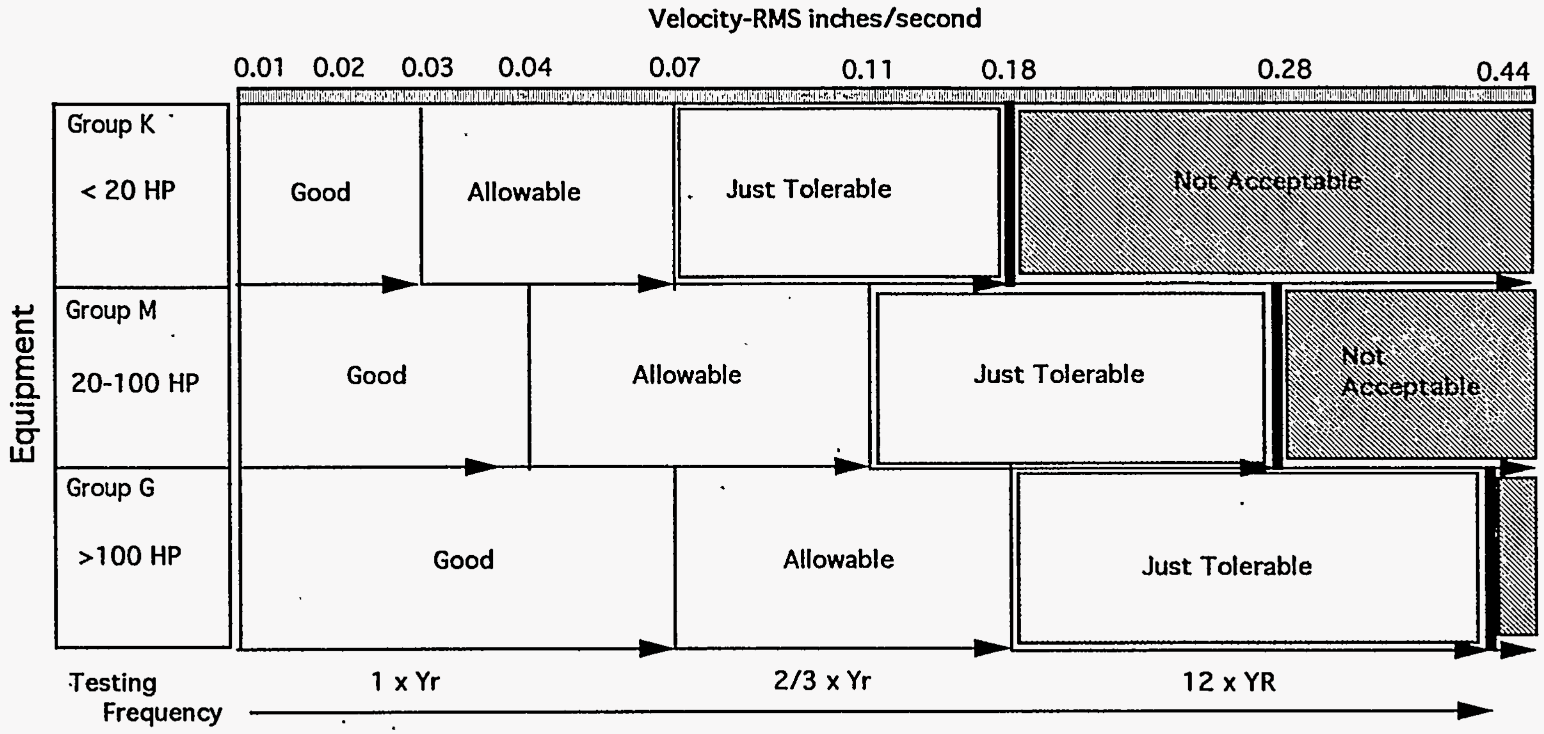
Equipment costs can range from $27,000 to over $100,000 depending on the program sophistication required. These costs include infrared thermographic real time scanners and basic strip chart to computer driven vibration analyzers.

Another important consideration is to have the work done by outside contractors who are knowledgeable in these disciplines and can speed up the whole program at less cost.



Instrumentation for Chiller Conditioning Monitoring

Drawing 1



Velocity readings taken from strip charts as amplitudes. Maximums averaged and compared to above table.

Several analysis should be made with time to see how the readings progress, however one time readings can be compared to the chart for use in analysis frequency.

Project: VIBRATION SEVERITY CHART
ISO 2372, VDI 2056, BS 4675

Date: 8/92

Client:

Scale:

Figure 1

Figure 2

Vibration Limits for Maintenance

Taken from Canadian Government Specification CDA/MS/NVSH 107

	New machines		Worn machines		
Machine Type	Long Life *	Short Life **	Service [1]	ASAP [2]	
	in/sec	in/sec	in/sec	in/sec	
Compressors					
Free piston	0.39	1.26	1.26	2.56	
HP & AC	0.18	0.39	0.39	0.71	
Refrig.	0.02	0.22	0.39	0.71	
Diesel Generators	0.06	0.39	0.71	1.26	
Gear Boxes					
over 10000 HP	0.04	0.39	0.71	1.26	
10-10000 HP	0.02	0.22	0.71	1.26	
up to 10HP	0.01	0.13	0.39	0.71	
Pumps					
over 5 HP	0.06	0.22	0.39	0.71	
up to 5 HP	0.03	0.13	0.22	0.39	
Fans					
below 1800 rpm	0.04	0.13	0.22	0.39	
above 1800 rpm	0.02	0.13	0.22	0.39	
Motors					
over 5 HP	0.01	0.07	0.13	0.22	
under 5 HP	0.01	0.07	0.13	0.22	
Transformers					
over 1 KVA	0.01		0.02	0.04	
1 KVA or less	0.004		0.013	0.02	

* Long life- 1000 to 10000 hours operating time.

** Short life-100 to 1000 hours operating time.

1 Service-recondition before failure & reanalyze more frequently.

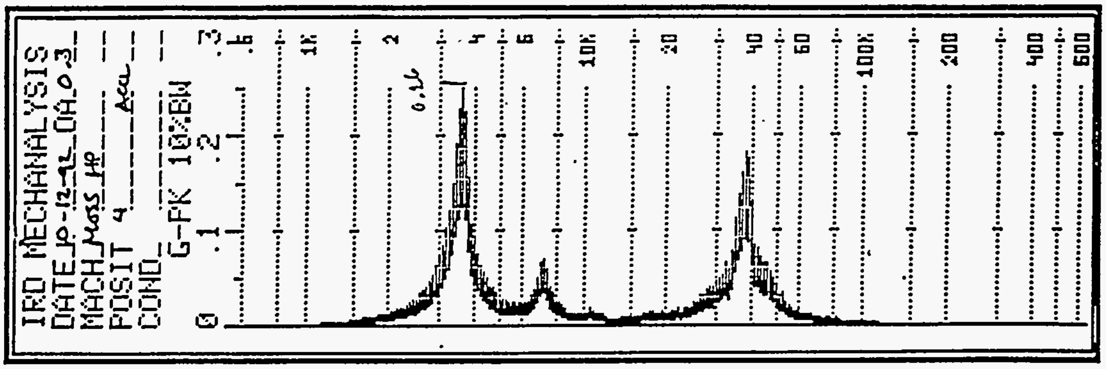
2 ASAP-repair or recondition immediately.

Project: ______________________________

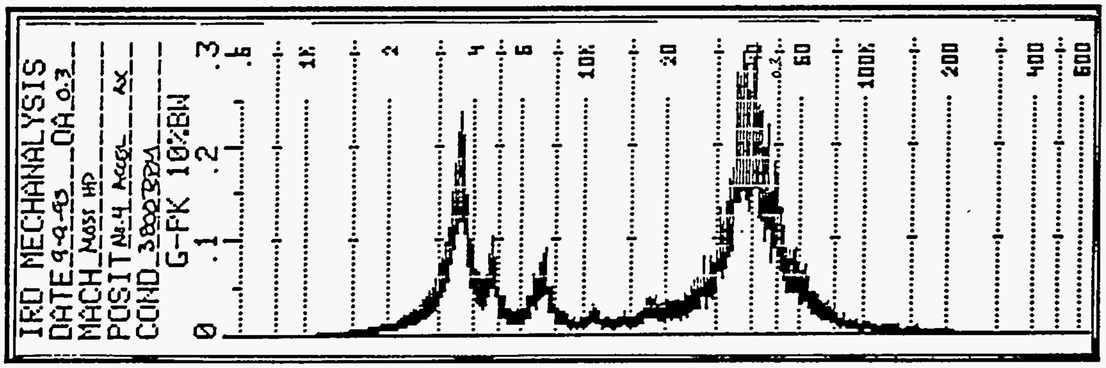
______________________________ Date: __________

Client: ______________________________ Scale: __________

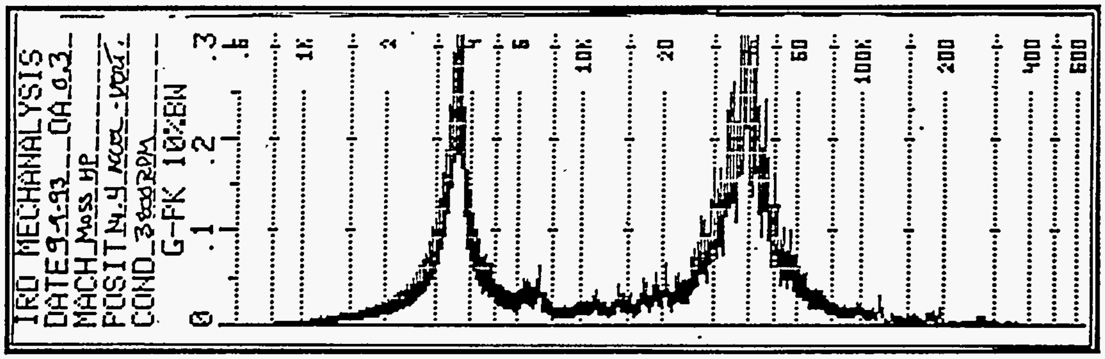
Centifugal Chiller-No. 4 Sleeve Bearing-Vibration readings/Acceleration Transducer Figure 3



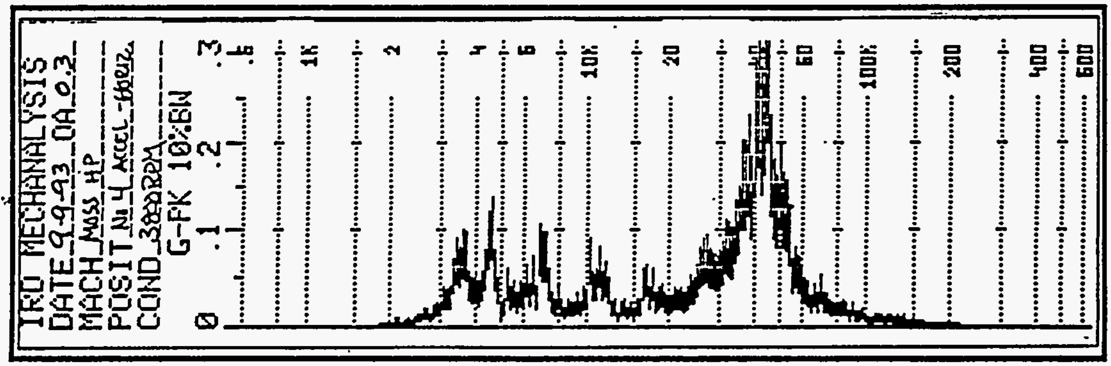
Sleeve bearing No.4 strip chart after repair/replacement by contractor.
RPM at 3800 CPM with 38000 CPM at 0.18 G-Pk amplitude. These are allowable readings for long life from charts.



Strip chart showing amplitude after 11 months at 0.35 G-Pk.(increase of 195%).
Now it is just tolerable/not acceptable and close to short life on charts.



Reading taken in the vertical position showing unbalance and looseness with movement up and down and axially.



Strip chart taken horizontally showing bearing looseness but little movement end to end.

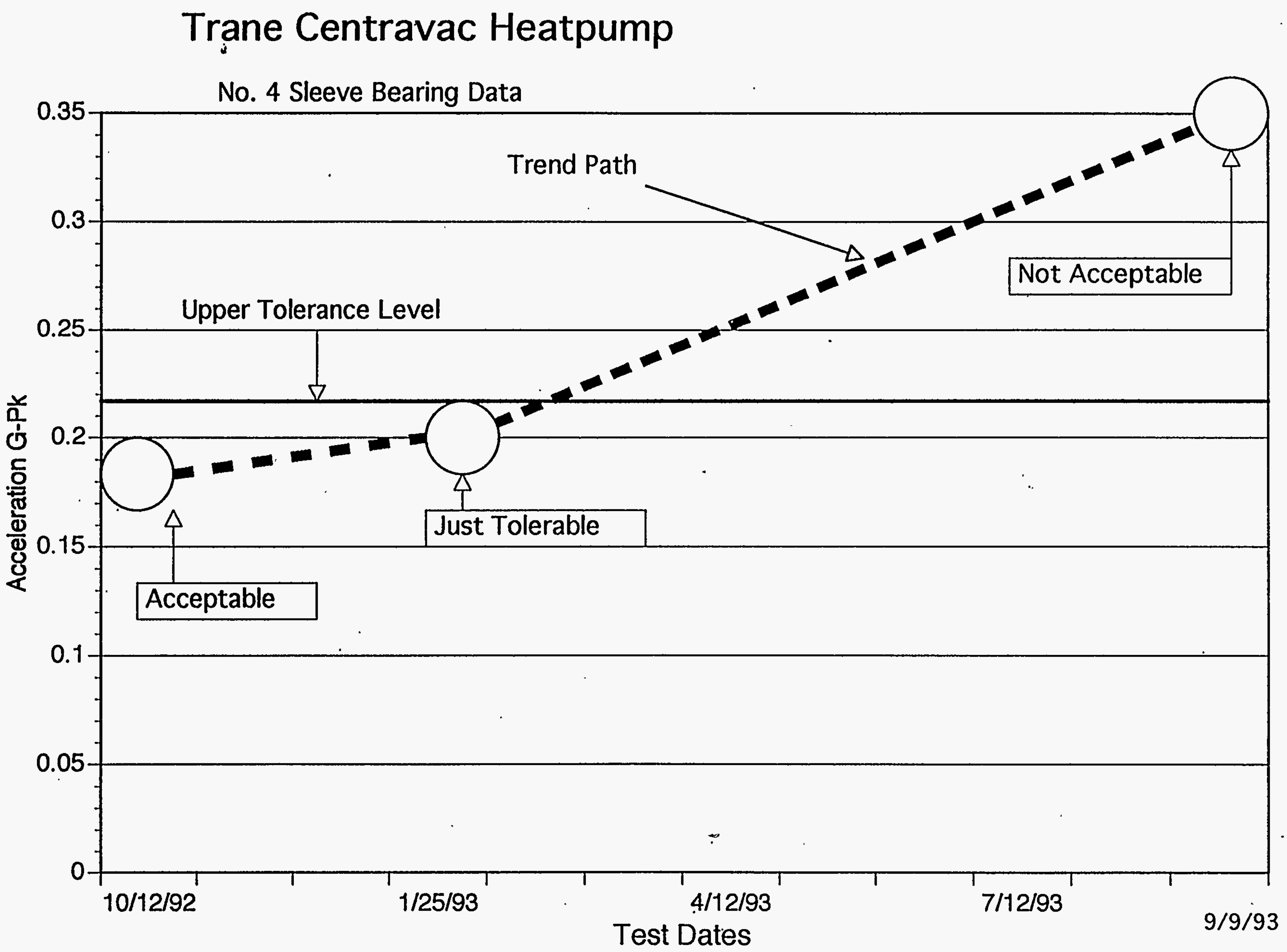
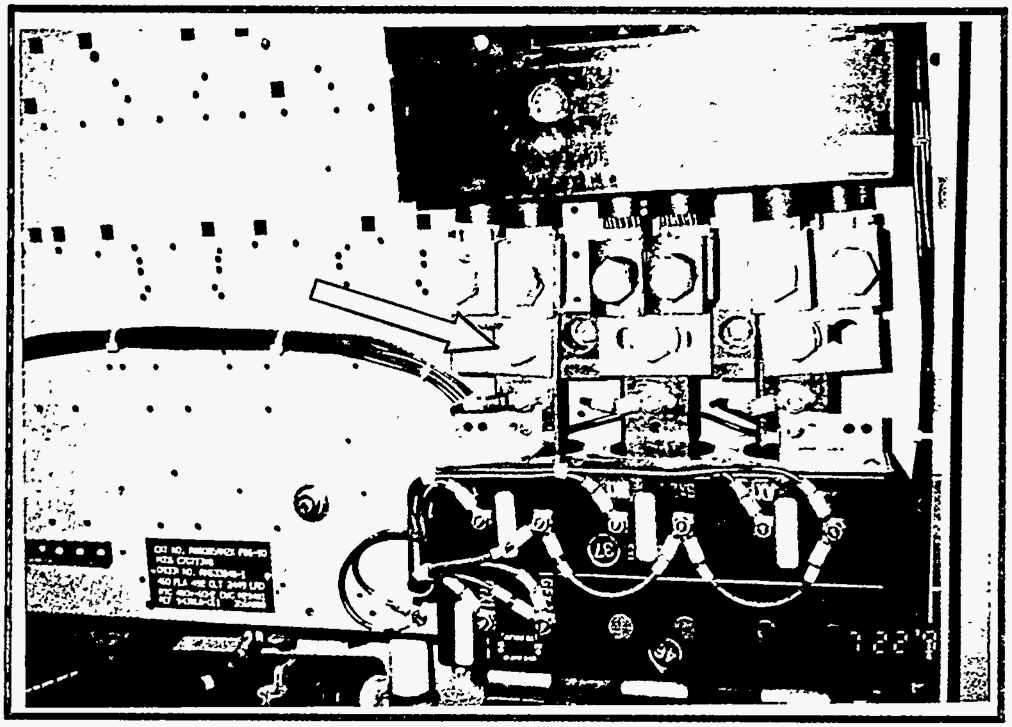

Trane Centravac Heatpump
No. 4 Sleeve Bearing Data
Acceleration G-Pk
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Trend Path
Not Acceptable
Upper Tolerance Level
Just Tolerable
Acceptable
10/12/92
1/25/93
4/12/93
7/12/93
9/9/93
Test Dates

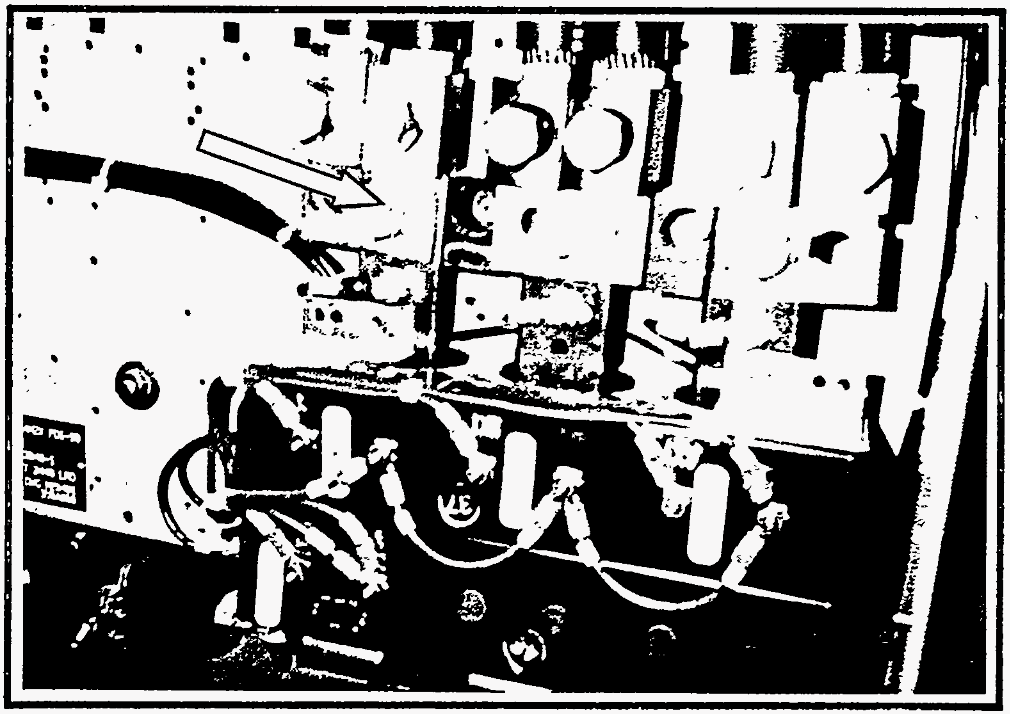
Figure 3A

Figure 4

Client:
Date: August 4, 1992
Project: IR-Electrical-



Above: Chiller No. 1
Left bolt on copper bus
is at167°F.



Above: Chiller No. 1-
Left bolt on copper bus appears to be loose.
Plastic wrap on red wire has turned brown.
Bolt was found to be 4 turns out.

Analysis Conditions
Infra red Thermography
Hughes Probeye 650
Argon cooled

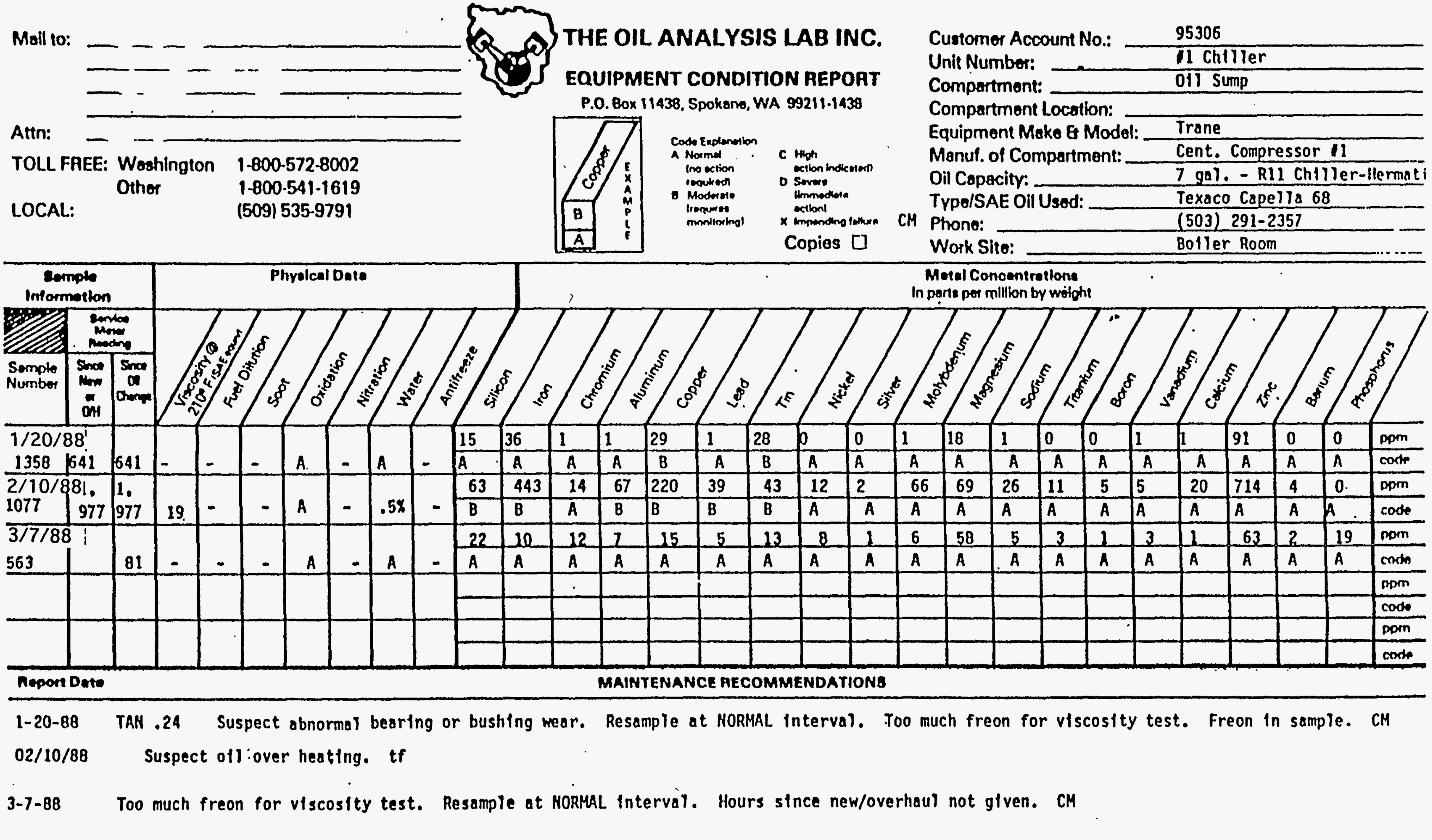
Interior ☒ Exterior ☐

Systems on ☒ off ☐

New ☒ Old ☐

Previous scan Y N
Date 7/22/92

ELECTRICAL SYSTEMS ANALYSIS



Mail to:

Attn:

TOLL FREE: Washington 1-800-572-8002
Other 1-800-541-1619
LOCAL: (509) 535-9791

THE OIL ANALYSIS LAB INC.
EQUIPMENT CONDITION REPORT
P.O. Box 11438, Spokane, WA 99211-1438

Code Explanation
A Normal (no action required)
B Moderate (requires monitoring)
C High (action indicated)
D Severe (immediate action)
X Impending failure

CM

Copies ☐

Customer Account No.: 95306
Unit Number: #1 Chiller
Compartment: Oil Sump
Compartment Location:
Equipment Make & Model: Trane
Manuf. of Compartment: Cent. Compressor #1
Oil Capacity: 7 gal. - R11 Chiller-Hermati
Type/SAE Oil Used: Texaco Capella 68
Phone: (503) 291-2357
Work Site: Boiler Room

Sample Information			Physical Data							Metal Concentrations In parts per million by weight																			
Sample Number	Service Meter Reading Since New or O/H	Since Oil Change	Viscosity @ 210° F/SAE equiv	Fuel Dilution	Soot	Oxidation	Nitration	Water	Antifreeze	Silicon	Iron	Chromium	Aluminum	Copper	Lead	Tin	Nickel	Silver	Molybdenum	Magnesium	Sodium	Titanium	Boron	Vanadium	Calcium	Zinc	Barium	Phosphorus	
1/20/88										15	36	1	1	29	1	28	0	0	1	18	1	0	0	1	1	91	0	0	ppm
1358	641	641	-	-	-	A	-	A	-	A	A	A	A	B	A	B	A	A	A	A	A	A	A	A	A	A	A	A	code
2/10/88	1,	1,								63	443	14	67	220	39	43	12	2	66	69	26	11	5	5	20	714	4	0	ppm
1077	977	977	19	-	-	A	-	.5%	-	B	B	A	B	B	B	B	A	A	A	A	A	A	A	A	A	A	A	A	code
3/7/88										22	10	12	7	15	5	13	8	1	6	58	5	3	1	3	1	63	2	19	ppm
563		81	-	-	-	A	-	A	-	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	code
																													ppm
																													code
																													ppm
																													code

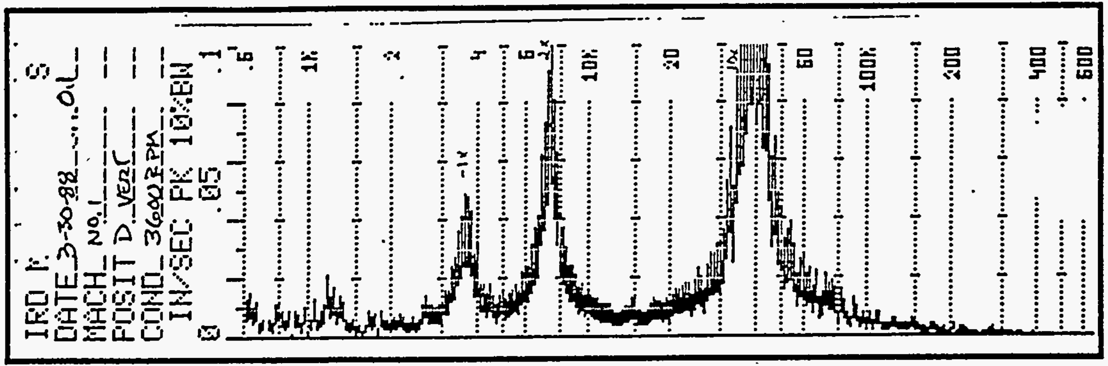
Report Date	MAINTENANCE RECOMMENDATIONS
1-20-88	TAN .24 Suspect abnormal bearing or bushing wear. Resample at NORMAL interval. Too much freon for viscosity test. Freon in sample. CM
02/10/88	Suspect oil over heating. tf
3-7-88	Too much freon for viscosity test. Resample at NORMAL interval. Hours since new/overhaul not given. CM

Oil analysis of chiller No.1 showing bearing deterioration before overhaul. After overhaul magnesium and zinc show up along with phosphorus. Freon in the oil is not uncommon in centrifugal chillers but the vibration charts show oil whirl and possible leakage past worn seals. Impeller rubbing is also a possiblity at 10 times RPM.

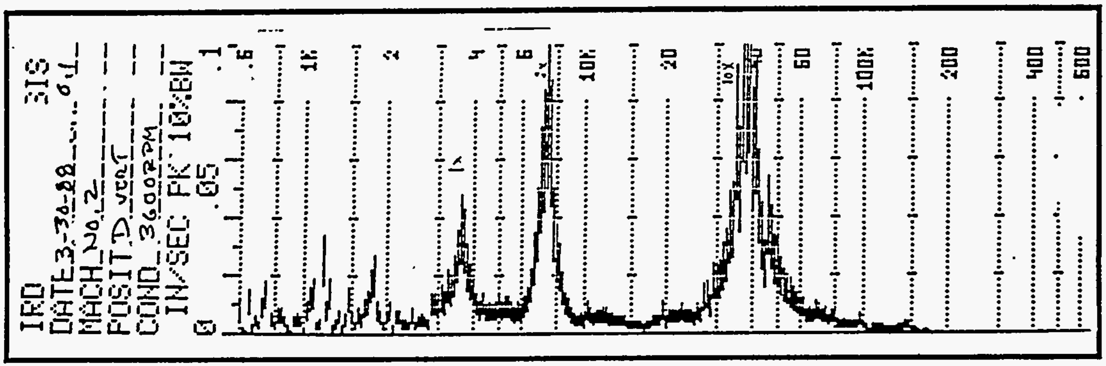
Figure 5

Centifugal Chillers-D Sleeve Bearings-Vibration readings/Acceleration Transducer

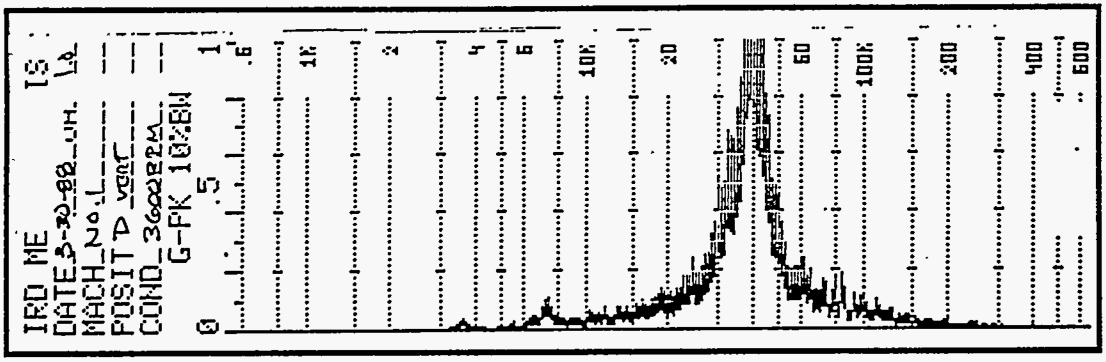
Figure 6



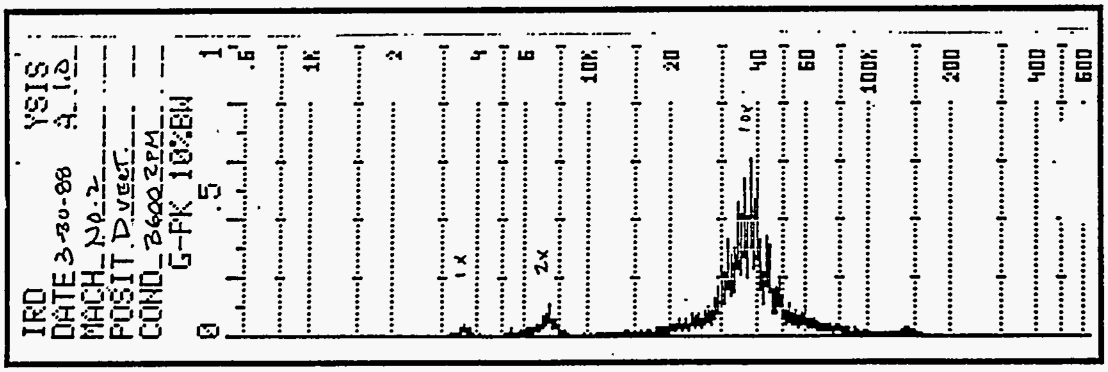
No.1 chiller D bearing-<u>velocity</u> showing mechanical looseness at 2 times RPM. and bearing roughness at 10 times RPM(10 blades on impeller).



No 2 chiller D bearing-<u>velocity</u> showing slight looseness but much less bearing roughness at 10 times RPM.



No.1 chiller D bearing-<u>acceleration</u> showing 1.5 G-Pk at 10 times RPM. This is a real problem and should be taken care of before damage occurs to secondary equipment.



No.2 chiller D bearing-<u>acceleration</u> showing 0.5 G-Pk at 10 times RPM. This machine has not been repaired and no oil analysis was available. It is probably starting to show wear due to age.

APPENDIX F

A Predictive Maintenance Vibration Monitoring Program for Chillers

APPENDIX F

A Predictive Maintenance Vibration Monitoring Program for Chillers

Material in this appendix was prepared by E. Charles Hart of the Systems Engineering Associates Company (SEACOR). It provides vibration condition monitoring information about chillers in the following areas:

- Background
  - Discussion
  - Predictive Maintenance (PDM)
  - Supplemental PDM Program Requirements

- Methods, Equipment, and Procedures
  - Methods
  - Equipment
  - Procedures

- Case Histories
  - Imbalanced Chiller
  - Suspected Chiller Problem and Vibration Trending

- Sample Program
  - Planning
  - Selection
  - Training
  - Preparation

- Costs, Advantages, and Disadvantages
  - Costs
  - Advantages
  - Disadvantages

- Summary of Past Experiences

A PREDICTIVE MAINTENANCE VIBRATION MONITORING PROGRAM FOR CHILLERS.

FINAL DRAFT REPORT

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SEPTEMBER 27, 1993

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Prepared for Battelle, Inc. PNL
under Purchase Order No. 18963AII

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A PREDICTIVE MAINTENANCE VIBRATION MONITORING PROGRAM FOR CHILLERS

ABSTRACT

A condition–based maintenance program, based on periodic vibration measurements, can be a cost–effective method for improving equipment reliability and preventing unscheduled breakdown. This report describes different maintenance concepts, addresses the planning requirements, hadware and software considerations, and program structure to support a vibration monitoring program for chillers. Case histories are used to illlustrate maintenance advantages.

BACKGROUND

DISCUSSION

Most equipment maintenance programs have common goals. These goals usually include reductions in equipment downtime, open-and-inspect evolutions, employee overtime, and interruptions in plant production. The benefits of these programs include optimized use of repair and maintenance funds, increased plant production, and increased equipment reliability. Maintenance programs have evolved through several iterations, some of which are described below.

- *Run-to-Fail* — Where a machine is permitted to run itself to death and then repaired. This course of action usually requires a major overhaul. The failure frequently occurs at the worst possible time and interrupts, or worse yet, halts plant operation and production. On occasion, a catastrophic failure occurs that results in an unrepairable machine that must be replaced; a very expensive form of maintenance.

- *Time Based Open-and-Inspect* — Here, a perfectly good machine is partly dismantled to find out why it's running so well. Unfortunately, it may never be the same again. There always seems to be enough time to open the machine, but the reassembly is rushed because something else, somewhere else, must be repaired.

- *Calendar Overhaul* — Where a machine is overhauled regardless of whether it needs it or not, no care about the cost. Of course, some other machine may need the repairs more desperately. This is wasteful of precious maintenance funds and can lead to the Run-to-Fail problem.

- *Condition Based* — Where some methodology helps determine machinery condition and failure potential, ie. Predictive Maintenance. Usually, the dynamic performance characteristics are measured. Current technology lends itself well to monitoring the condition of machinery with a wide variety of instruments and methodologies.

PREDICTIVE MAINTENANCE

The Predictive Maintenance (PdM) concept is based on the idea of conducting non-intrusive tests to gather data that can be evaluated to assess the material condition of a machine, thereby supporting repair definition before in-service failure can occur.

Another way to say this is that some sort of condition monitoring or measurement methodology is employed to determine which machinery is most likely to fail, and when it may be approaching failure.

The monitoring method must be simple to execute and have little or no impact on plant production or the operation of the machinery. Continuous (on-line, real time) monitoring may be conducted or portable instruments can be used.

While no single PdM technology can address all the parameters that can, or should be tested, the single technology that measures the overall mechanical condition of equipment best is vibration monitoring and analysis. Even vibration monitoring has its limitations, such as measuring of efficiency in a pump system. The applications of a vibration-based PdM program include rotating and reciprocating machinery, process systems, and even assembly lines. Examples of some common causes of excessive vibration are listed in Table 1.

Probable Cause of Excessive Vibration	Frequency of Excessive Vibration
Oil Whip	Lower than RPM
Imbalance	1 x RPM
Misalignment	2 x RPM
Bent Shaft	1x or 2x RPM

Rolling Element Bearing	15x to 50x RPM
Worn Gears	No. of teeth x RPM

TABLE 1. Causes and identification of excessive vibration frequencies.

The equipment faults that can be identified by vibration analysis are not limited to the basic examples in Table 1. Examples include determination that a coupling is misaligned, but not the shafts; the identification of a faulty turbine stage in a multi-stage compressor; identification of loose components; and the identification of faulty motor stator laminations.

Vibration analysis can even help prevent unnecessary work. An example is when an motor, previously identified as imbalanced, has been inspected and found to be in need of a thorough cleaning. After cleaning, the motor should be retested because frequently the imbalance characteristic becomes acceptable, indicating that the reason for the imbalance was a buildup of dirt. This also suggests that the preventive maintenance program may have overlooked scheduled cleaning of this motor.

SUPPLEMENTAL PdM PROGRAM REQUIREMENTS

If on-line monitoring, using permanently installed sensors, is not conducted, the portable test instruments should be simple to operate and maintain. They should also be sturdy and appropriate for the plant or facility's operating environment. Intrinsically safe test equipment may be required.

Test instruments should automatically collect and store data in non-volatile memory until entered into a database.

Minimum manpower to collect the data. One person preferred, and not more than two.

Analysis of the data should be accomplished by skilled people who have been appropriately educated or trained. If a computer system is involved, "smart or expert" software may augment this skill requirement. Expert software is expensive, however, and can be a costly approach.

A regular test equipment calibration program should be established. This may require manufacturer or outside laboratory calibration.

Feedback to verify the effectiveness of PdM and demonstrate this to management.

- Broadband Monitoring.

  - General information.

    The term broadband merely means that the indicating or metering system delivers a "lump sum" number indicating the vibration amplitude.

    The only frequency involved is the frequency range over which the system gathers data for the indication. That is to say, the meter system measures a wide band of frequencies, about 30Hz -5kHz, thus the name broadband. The meter conditions the vibration signal, and indicates the result a gross vibration amplitude.

    The meter indication can be in terms of vibration Displacement[1], Velocity[2], or Acceleration[3] units. There may be a selector switch that can set which vibration quantity to indicate.

  - Applications.

    The broadband measurements are used for trending overall vibration amplitudes to learn if vibration severity is increasing. This trended information can help determine when to inspect the machine for faults.

    Specific faults, such as misalignment, bad bearings, etc. can not be detected because these faults are associated with specific (discrete) frequencies which the broadband meter cannot indicate.

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[1] Displacement is the actual physical movement of a vibrating surface or machine, usually considered to be about its normal rest point; measured in Mils (0.001").

[2] Velocity is the speed of the vibration — the rate of change of displacement over a period of time; usually measured in inches/second (ips).

[3] Acceleration is the rate of change of velocity — the forces exerted on the object as it changes velocity relative to time; measured in g units (386"/sec/sec).

If many measurements are taken at several points on a rotating machine, it may be possible to identify misalignment or a soft foot[4].

- Bearing Monitoring (Shock Pulse–Spike Energy–High Frequency Detection [HFD]).

  - General Information.

    Different from the broadband meter because it measures a narrow frequency band around the resonant frequency of the accelerometer.

    When the accelerometer "rings" or goes into mechanical resonance, it is a result of rolling elements impacting with faults in bearing races. The impact energy excites the resonant frequency.

    The meter will indicate whichever units of measurement the manufacturer has selected. Generally, the higher the number, the greater the chance the bearing is failing.

  - Applications

    The applications are similar to the trending of broadband vibration. This can be the first indication of bearing wear in most systems.

    As bearing wear increases, this measurement may decrease. Usually, by that time, the acceleration and velocity measurements have begun to increase.

    High frequency detection measurements can give erroneous readings when gears, vee-belts, compressors, etc. are involved. They are not applicable to anti-friction, sleeve-type bearings.

- Narrowband

  - General Information.

    A narrowband instrument performs a Fast Fourier Transform (FFT) on the vibration time signal. This converts the signal from the time to the frequency domain. The complex time signal becomes a display of discrete frequency vs. amplitude.

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[4] A mounting foot is not as firmly bolted or secure as the remaining feet on the base of a machine.

The resolution of the spectrum will vary with the number of electronic amplitude components or "bins" that make up the spectrum for any frequency range.

A 400 line (bin) spectrum has 1 Hz resolution if the displayed frequency range is 0-400 Hz. A 400 bin spectrum has 2.5 Hz resolution if the displayed frequency range is 0-1kHz.

The minimum resolution for effective analysis is considered to be 400 lines. State-of-the-Art systems go up to 6400 lines. It will not be long before 800–line resolution becomes the minimum acceptable standard.

Narrowband systems usually provide for conversion of signals to display the amplitude of displacement, velocity, or acceleration units.

- Test Equipment Variations

Realtime Spectrum Analyzer (RTA) — This is usually a large, luggable instrument that is carried to the test location. It can weigh from 20 - 60 pounds. There is a monitor screen for viewing the vibration spectra. Some units have LCD displays, similar to a laptop computer. The RTA has a wide range of capabilities for manipulating the vibration measurements to support engineering studies. An RTA can serve double duty in the laboratory. Tape recorded vibration measurements can be analyzed and vibration spectra can be plotted. The data can be entered into a computer database for storage and review. Some RTAs have a non-volatile memory, but most are part of an instrument system that tape records vibration measurements on-site for laboratory analysis. In the field, the RTA is used to verify the quality of the recorded signal and for field analysis of the machinery. The system includes vibration sensors, signal conditioning devices, and perhaps an XY plotter. The cost of a RTA instrument suite could be $75k–$90k. The system may weigh in the 75–100 lb. range.

Vibration Data Collector — This is a lightweight (5-8 pounds), battery powered, non-volatile[5] memory instrument. A data collector is usually programmed by a computer with software designed to communicate with the data collector, although many functions can also be performed manually by the operator. In its purest form, the data collector indicates to the operator which machine to test and the test point, performs the measurements on command of the operator, stores the data in a preselected format, and then sets up for the next machine or test point. Some recently manufactured data collectors can also perform many functions of the RTA. Figure 1 illustrates a data collector in operation. The instrument usually has a harness that

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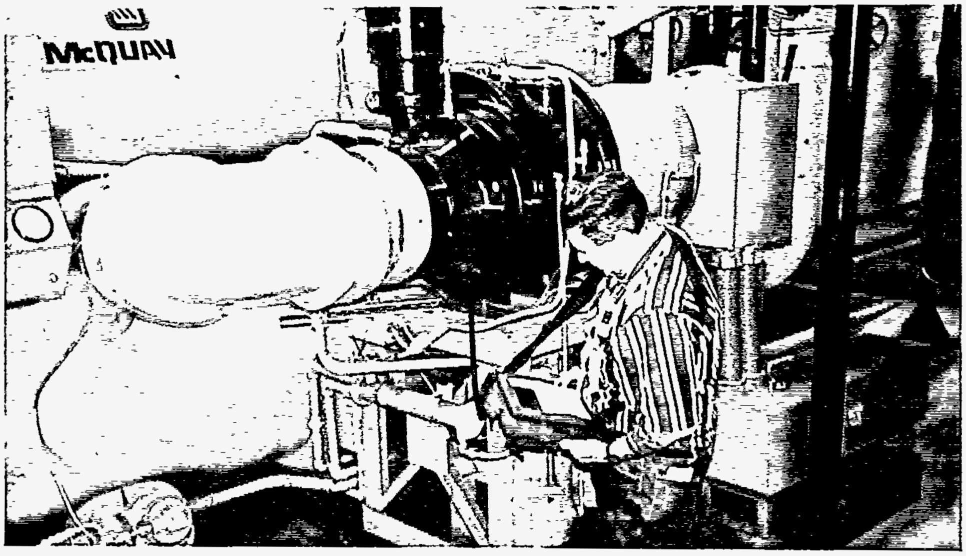
[5] Retains all stored data in memory when the power is off.

allows the operator to "wear" the collector as he/she moves from machine to machine. The harness can be adjusted for maximum visibility and convenient manipulation of controls.

Figure 1. Vibration Data Collector



- Applications

RTA - Generally the more versatile of the two instruments because it can display vibration data in a wide variety of formats and scales. The RTA is now most often used for studies that require extensive control of measurements over a wide variety of ranges and scales.

The RTA is more expensive and may not have the memory capacity of vibration data collectors. This limits its usefulness for the collection of vibration measurements in the field.

Data Collector - Versatility is limited to the pre-programmed measurements that are contained in its memory. Once the measurements are collected the host computer can perform some data manipulation, but not very much.

The Data Collector acts in response to the instructions of the host computer and software. If it is programmed to collect velocity over the frequency range of 0-200 Hz, that's just what it will do, then it will store the data in memory. One cannot expect to review data in the 0-500 Hz range unless it is collected that way. The collector will auto-range for the most appropriate full-scale amplitude. Data collectors can also collect random, on-the-spot measurements.

The data collector is usually designed to work with a specific vibration database. Some collectors can store up to 1,000 spectra in memory to be downloaded to the host computer for storage, trending, and analysis. Limited third-party software is available for some data collectors.

EQUIPMENT

- Test Instrument(s)

The test equipment enables the.operators or technicians to take readings of machinery vibration, temperature, pressure, flow, and other conditions that can be used to evaluate the condition of the machinery. The sensors can be portable or permanently installed. Some RTAs can store vibration measurements, but may not be able to store other measured parameters. The data collector stores all vibration and other parameters that is is programmed to collect. Operators can even enter comments regarding equipment conditions observed during a survey. After all points have been tested, the data will be transferred to the computer system.

- Vibration Database Software

The vibration database provides several functions including, equipment lists, test points and setup; route lists; display selections, and report generation functions. The vibration data can be graphically displayed and printed in addition to printed reports. When a data collector is used, the database and collector communicate or "shake hands" and the computer downloads to the data collector the database setup for the equipment to be tested. After the prescribed measurements have been made, the operator commands the data collector to upload the measurements to the computer for storage in the database and analysis. Not all vibration databases can communicate with all data collectors, most are proprietary. Some databases can accept data from several different manufacturers equipment. If an RTA is used, the database and the RTA probably will not be able to communicate.

Vibration database software generally comes in three levels of sophistication, (1) a bare bones type where only broadband measurements for trend graphs are stored; (2) A comprehensive form when both broadband and narrowband data are stored for analysis and can produce a wide variety of graphs and reports; and (3) Expert software that can be programmed to automatically analyze the vibration data, and then prepare reports that detail the analysis of the vibration measurements, identify and diagnose the problem(s), present the rationale for the diagnostics, and list the recommended repairs.

PROCEDURES

Ideally, the procedures to be followed in a PdM program start well before any measurements are taken.

- Key Elements.
  - Planning — Identifying the equipment to monitor, gathering data that identifies current maintenance costs and problems, preparing the justification for establishing a PdM program. Also necessary is a review of the O&M manuals for engineering data. This may require contacting the local manufactures representative or the manufacturer.
  - Preparation — developing a preliminary company program directive; assembling the engineering data to be inserted into the database.
  - Selection — selecting the test equipment and software, guidance here is provided by the vibration specifications addressed by the chiller manufacturer.
  - Setup — preparing the equipment for vibration testing; setting up the vibration database, including alarm amplitudes, test points, and other supporting information.
  - Training — training operators to collect data; training operators to use the software database and in the principles of vibration analysis, gain management support.
  - Implementation — collecting baseline measurements; evaluating the baseline data; collecting, trending, and evaluating periodic measurements; and finalizing the company policy directive.
  - Repair, Feedback and Promotion — equipment repair based on the recommendations; verification of the repair recommendations; and informing upper management of program success.
  - Test Equipment Calibration — performed prior to and after the completion of each survey by using a known vibration source; also performed yearly by the manufacturer or a laboratory to certify the accuracy of the system.

These procedures are detailed in the sample program described in following paragraphs.

- The procedures necessary to execute a PdM program after the planning and implementation stages have been completed include
    - Baseline Measurements Survey — The baseline survey is used to establish the initial measurements against which future trending surveys measurements are compared. This survey also helps evaluate the condition of the equipment. The baseline survey frequently identifies equipment faults that were previously unknown. When this occurs, the equipment should be repaired and another baseline survey conducted.
    - Periodic Trending Survey — The trending survey may be conducted weekly, monthly, quarterly, or at any calendar or elapsed time periodicity deemed appropriate. Monthly monitoring is recommended for the first six months to build up the database, train operators, and establish the program in the normal work routine. The minimum recommended periodicity for a new program is quarterly.
    - Repair Actions and Feedback — The greatest contribution in support of a PdM program is action on the repair recommendations and feedback to the operators on the accuracy of the vibration analysis.

CASE HISTORIES

IMBALANCED CHILLER

The chiller is installed in a 15 story office building. The vibration survey was conducted to determine if repairs were required under the service contract. Operating personnel believed the chiller was satisfactory, but complained that the chiller was noisier than the other two chillers. To the touch, the chiller also seemed to vibrate more than the other chillers in the facility.

Figures 2 and 3 illustrate the chiller and the vibration test points. Figures 4 through 6 illustrate the velocity vibration measured at the free end of the motor. The manufacturers maximum allowable vibration, measured at the free end of the drive motor, is 0.25 ips in any direction[6].

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[6] "Any direction" — usually means two radial measurements 90 degrees apart and the axial direction. This is also known as a triaxial measurement.

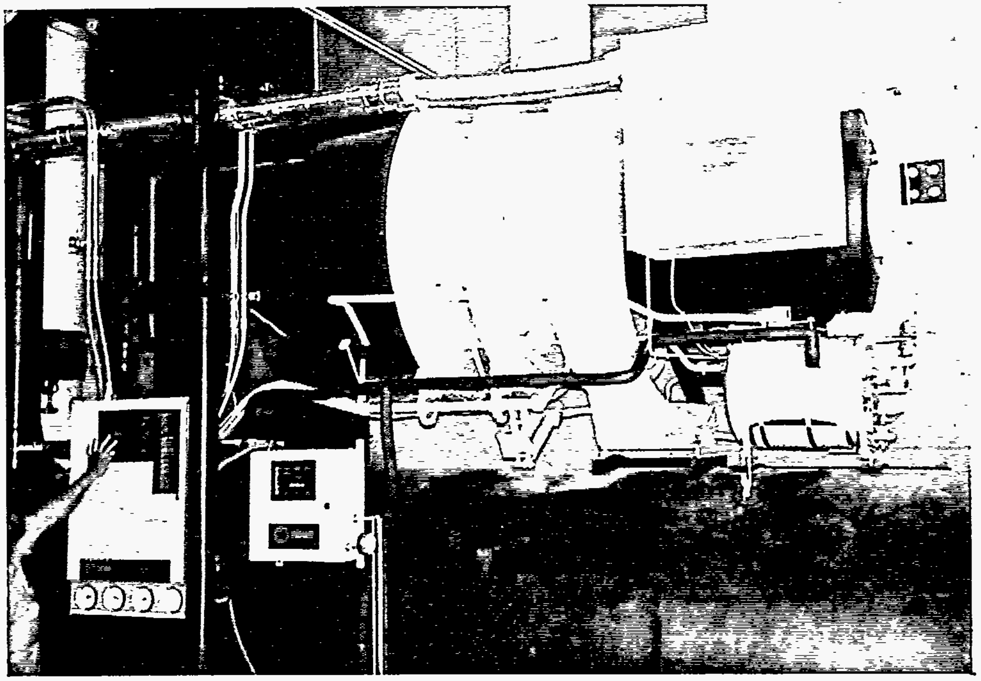

Figure 2 - Centrifugal Chiller

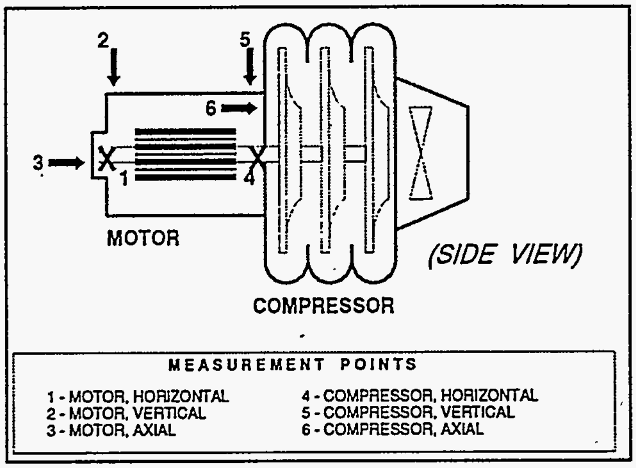

Figure 3 - Vibration Test Points

The velocity at the fundamental frequency (1X) of 59.5 Hz in the horizontal direction, Fig. 4, was about 0.14 ips, the vertical, Fig. 5, was less than 0.045 ips, but the axial direction, Fig. 6, was greater than 0.08 ips (56% of the horizontal radial vibration). The motor was describing a horizontal ellipse. Additionally, there were low amplitude 119 Hz, twice the fundamental (2X), frequencies in all three directions. These factors indicated the system had minor imbalance that could be corrected to improve chiller reliability.

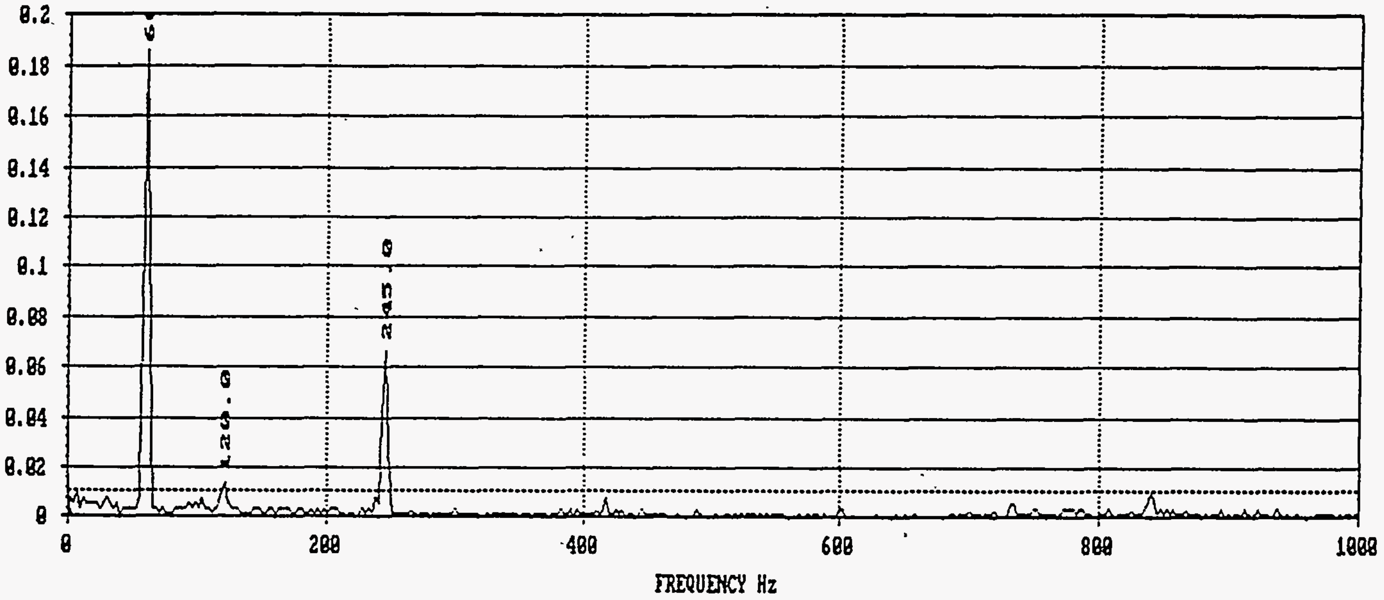

Figure 4 — Horizontal Vibration, Motor Free End.

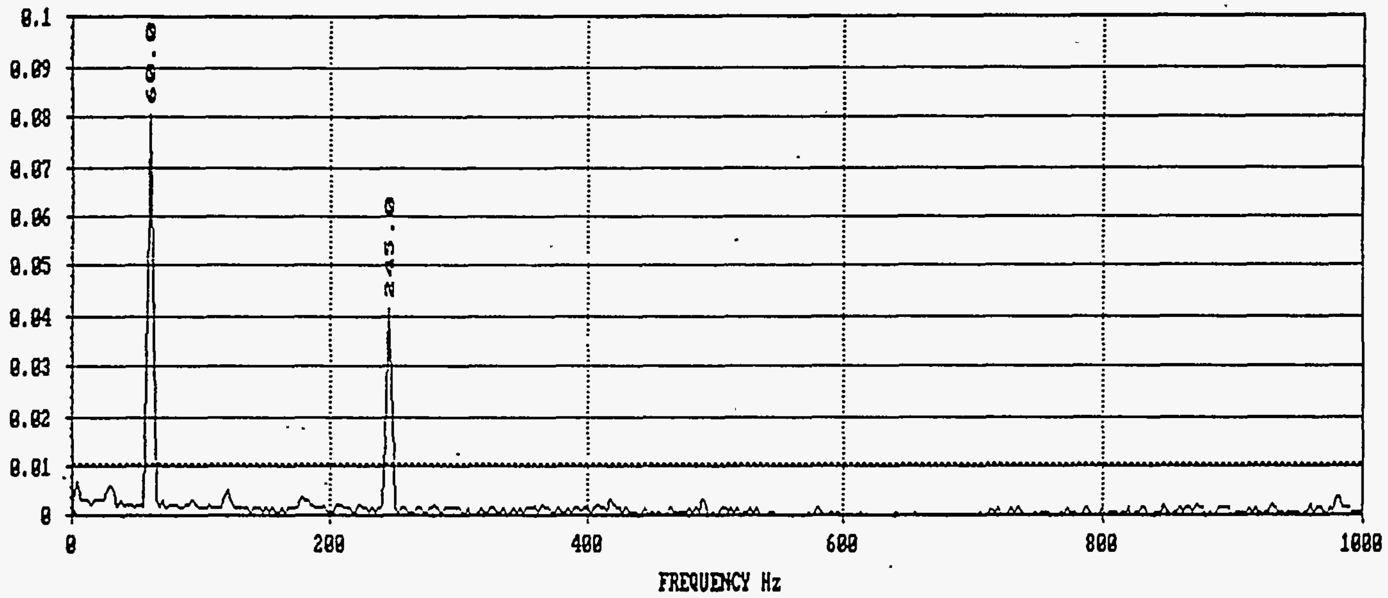

Figure 5 — Vertical Vibration, Motor Free End.

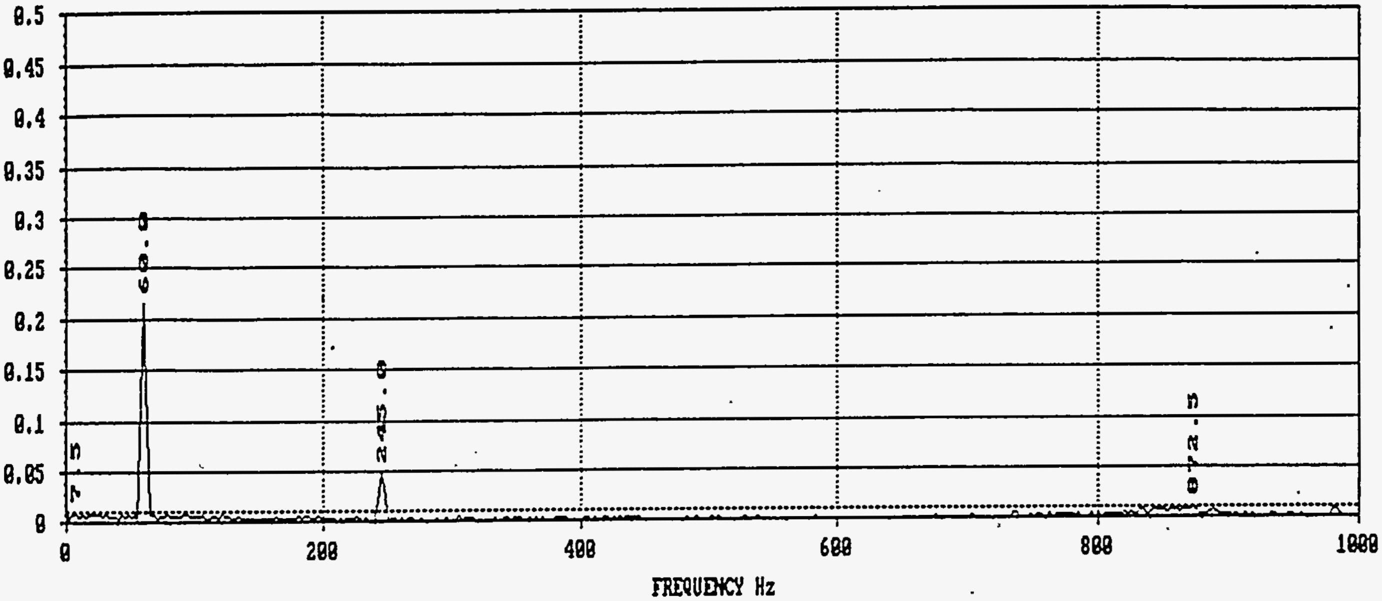

Figure 6 — Axial Vibration, Motor Free End.

The motor was trim balanced in place. Operating personnel noted that the noise was no longer present and that the vibration was hardly notable. Post–repair vibration measurements were not acquired. The chiller is currently performing to specification.

Worthy of note is the fact that other identical chillers had 1X vibration less than 0.08 ips, even less in the axial direction. Also, the 2X component was seldom notable in the vibration spectra of other chillers.

SUSPECTED CHILLER PROBLEM AND VIBRATION TRENDING

- Suspected Problem

The chiller involved is installed in a silicone chip fabricating facility. There is a total of 4 chillers at one location and 2 more at another location. Initially, the No. 2 chiller had a history of frequent repairs and was suspected as vibrating excessively subsequent to the last repair in early 1990. The plan was to shut down the chiller for inspection and repair. It was determined that a vibration analysis survey should be conducted prior to any repair actions.

Figures 7 and 8 illustrate the chiller and the vibration test points. Figures 9 through 11 illustrate the velocity vibration measured at the motor. The manufacturers maximum allowable vibration is 0.14 ips. As shown in figures 7 and 8, the motor and compressor are both overhung, with no bearing support at the free ends. Therefore, couple imbalance[7] is likely unless an in-place trim balance is performed.

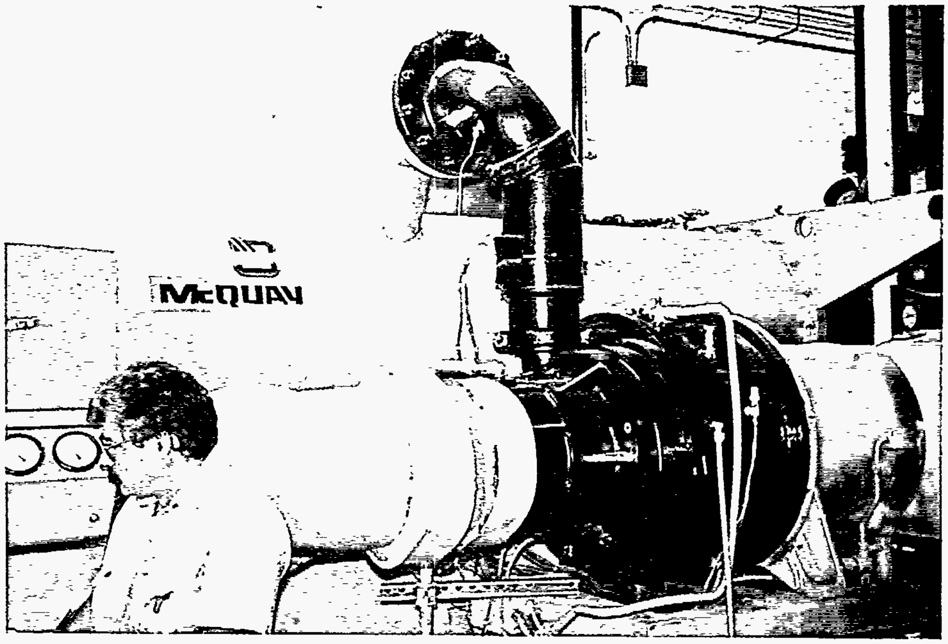

Figure 7 - Centrifugal Chiller

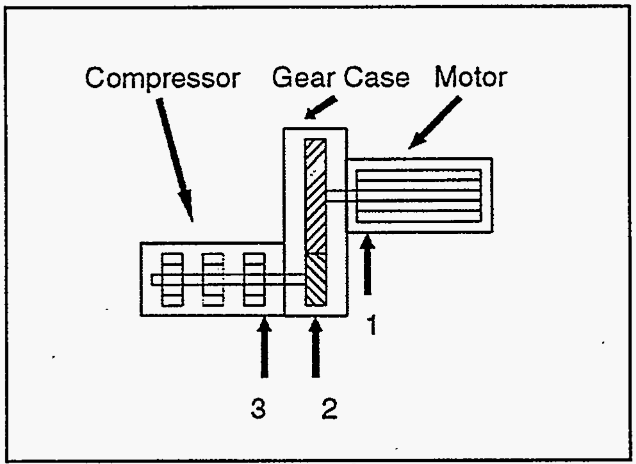

Figure 8 - Vibration Test Points

The motor 1X frequency is 60 Hz (3585 RPM). The rotary compressor, driven through a speed increaser gear box, is 242 Hz (14,520 RPM). The motor vibration was 0.18 ips at the coupled end. The gear case was 0.08 ips, and the compressor was less than 0.05 ips. Although the motor was classified as slightly rough, the decision was to not do any repairs unless the chiller was torn down for other maintenance actions. If this was done, the repair recommendations included a trim balance of the motor rotating element.

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[7] The imbalance force is equal in separate planes, but 180° apart at opposite ends of the rotating element.

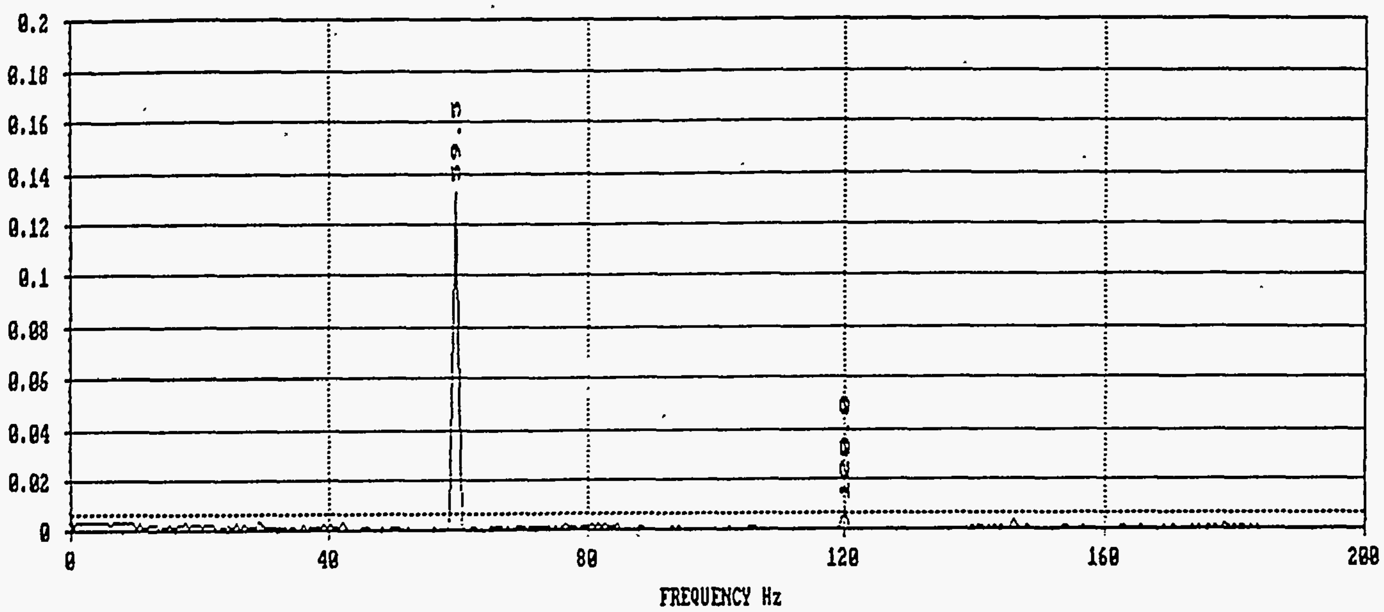

Figure 9 — Horizontal Vibration, Motor Free End.

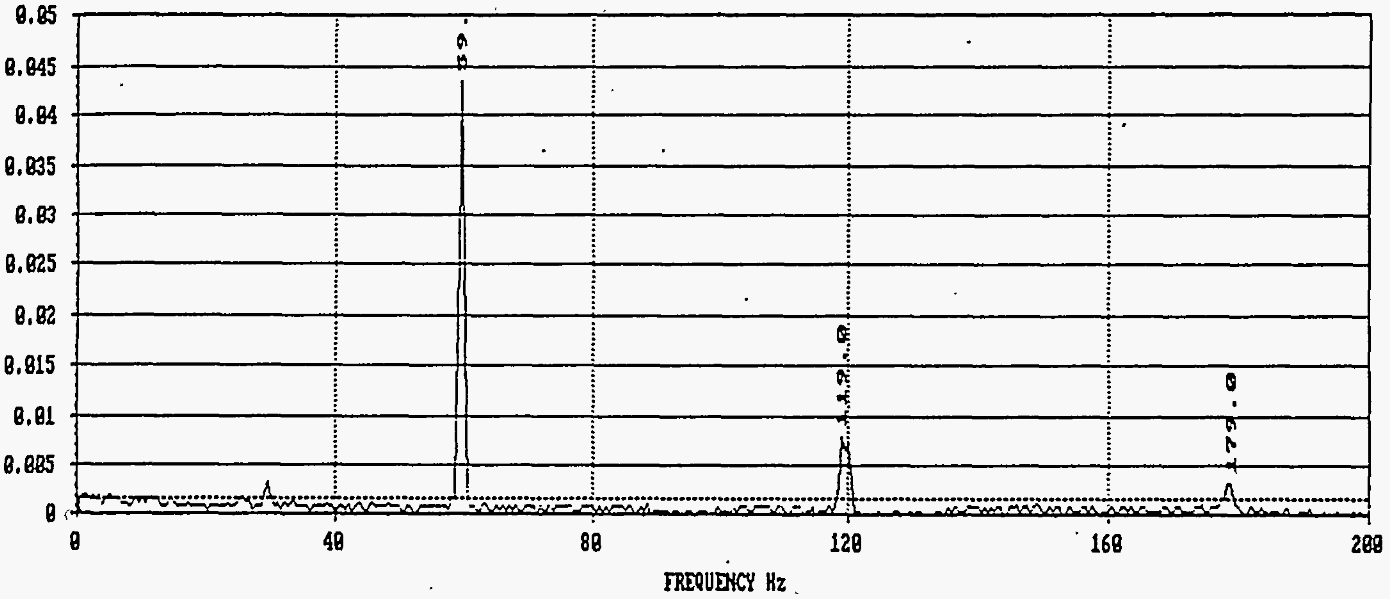

Figure 10 — Horizontal Vibration, Bull Gear.

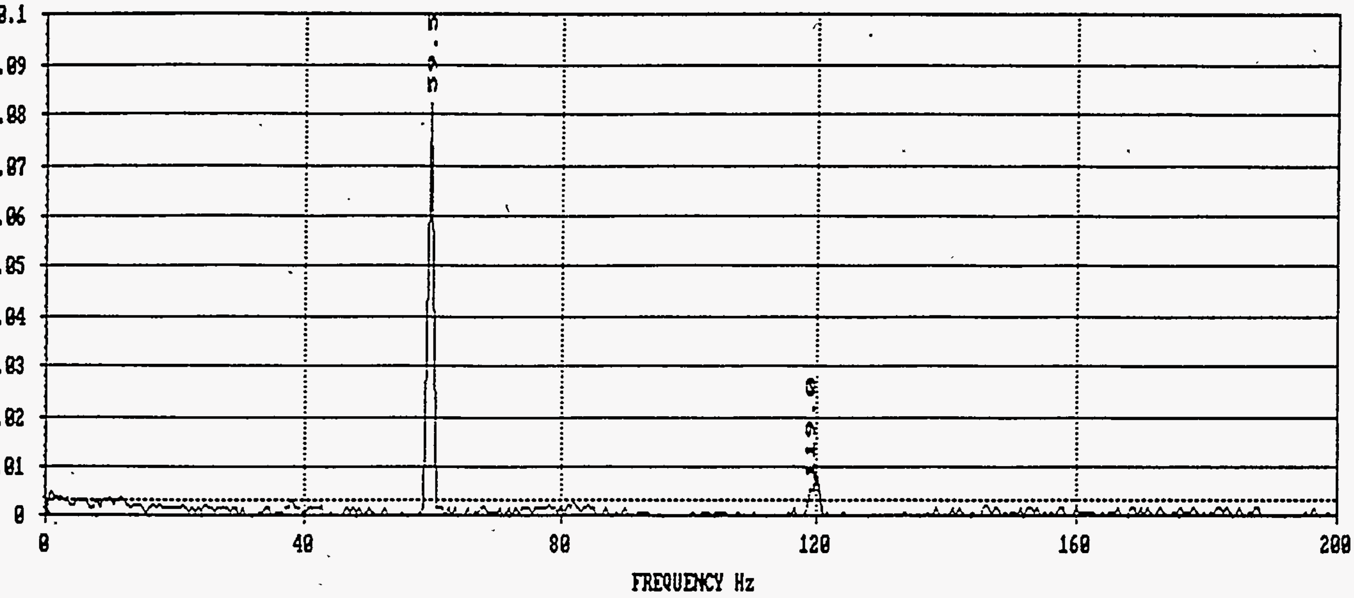

Figure 11 — Horizontal Vibration, Compressor.

The facility decided to not perform the initially planned shutdown and anticipated repairs. Instead, the chiller has received only normal maintenance since September, 1990. It is presently operating normally and there have been no major repairs.

- Vibration Trending

As a result of the previously described chiller case history, in October 1990, the silicone fab facility implemented a twice yearly routine of PdM on approximately 100 machines. Six of these machines are the chillers.

The chillers are monitored twice yearly, in May and October. The chillers are tested while on line, under normal load.

Figure 12 illustrates the broadband vibration trend for the #2 chiller. Any trends in vibration amplitude are easily discernable. Figure 13 illustrates a vibration signature and an alarm envelope[8] that is based on the original baseline signature. Significant frequencies that exceed the envelope are identified and help to evaluate the mechanical condition of the chiller. In this case, although the 975 Hz frequency pierces the envelope and is the 4X of the compressor rotational speed, there is no problem.

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[8] An envelope is an amplitude limit drawn above the vibration spectrum. It is calculated and inserted by the database.

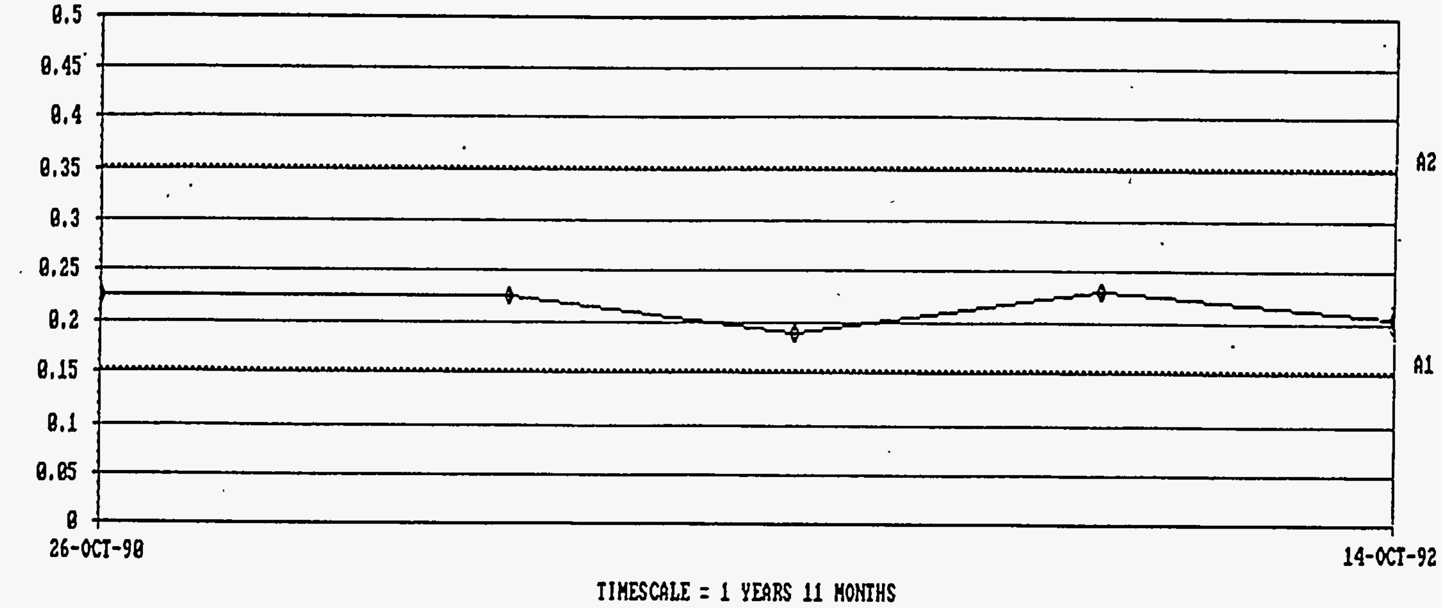

Figure 12 — Trended Broadband Vibration.

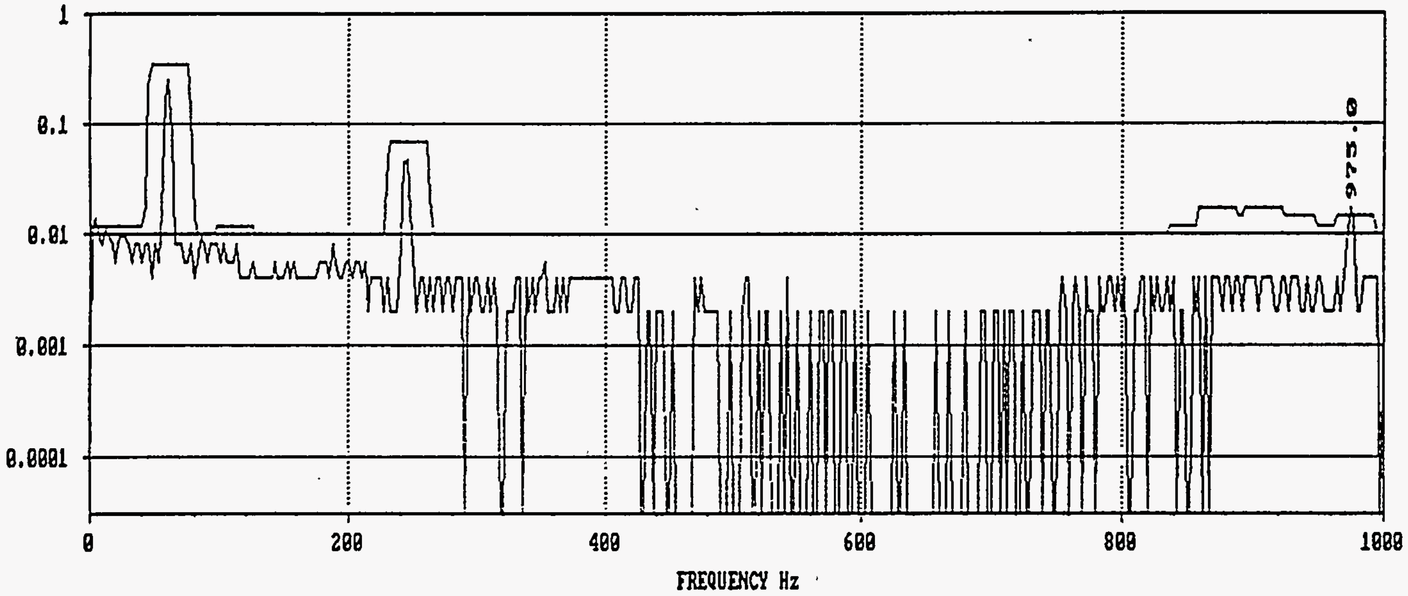

Figure 13 — Vibration Signature vs. Envelope.

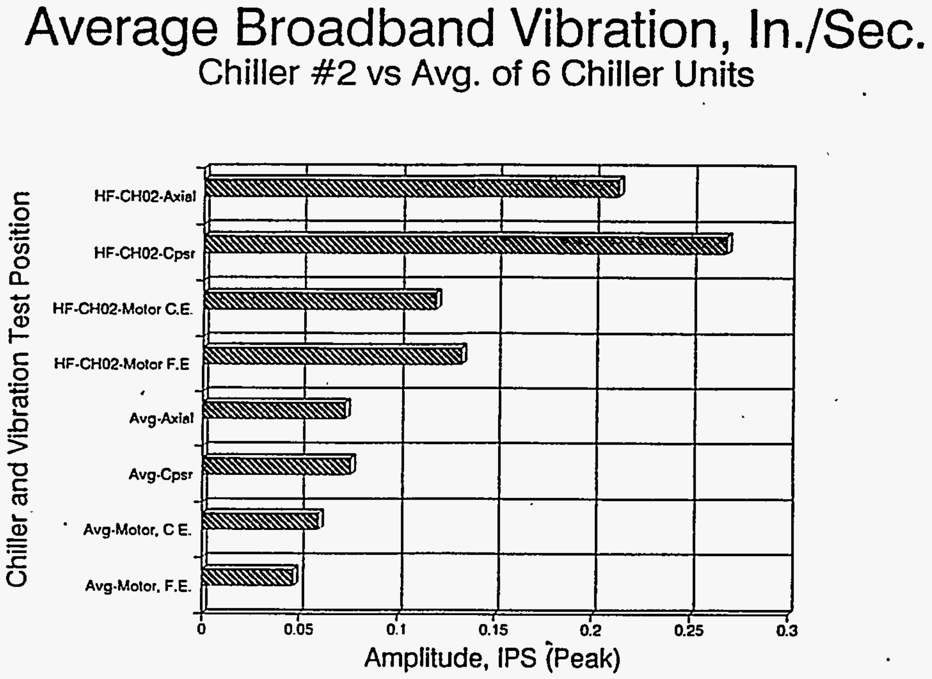

Figure 14 — Chiller #2 vs. Other Chillers.

Additional reports can be prepared when there are similar machines. Figure 14 illustrates the average vibration amplitudes of 6 identical chillers versus the No. 2 chiller. If repair funds were to be allocated based on vibration data, the No. 2 chiller would be top priority. However, when the trended vibration are considered, it becomes obvious that No. 2 chiller is stable, even though the amplitudes are considerably higher than the average. The avoidance of unnecessary repairs is a frequently overlooked advantage of a PdM program.

SAMPLE PROGRAM

PLANNING

- The selection of equipment to monitor is based on a number of factors, including how critical it is to facility operations, redundancy, availability of spare parts, difficulty of repairs, and machinery performance/repair history. Although this report addresses chillers, there is support equipment that usually includes chilled water pumps, condenser water pumps, filter pumps, and cooling towers. A comprehensive chiller PdM program would address the chiller system and not just the chiller(s). Figure 15 illustrates a chilled water pump.

Figure 15 - Chilled Water Pump

- The vibration quantity to measure is the next matter that should be decided. Generally, velocity is considered to be the best indicator of machinery "health" in the lower frequency ranges generated by chillers and support equipment.

- Maintenance costs must be determined because they will be used to help justify the program to management and as a measure for evaluating the success of the program.

- The justification of the program should be specific, but not overstated, with regard to the anticipated benefits of the program. It is not unreasonable to estimate that the cost benefit ratio will be approximately 10:1; that is, ten maintenance dollars are saved for each maintenance dollar spent on PdM.

SELECTION

- Test Instrument(s)

The data collector type of test equipment is recommended for general applications. The following discussion will assume that a data collector with appropriate software has or will be selected.

The data collector should have some minimum capabilities, including: 1 meg memory for storage of overall values and spectra; controls that can be adjusted in the field for the collection of vibration measurements than have not been pre-programmed by the database; visual display of the overall and spectral data, both during the measurements and as a review after the measurements; selectable backlighted display for use in low light areas; easily replaceable battery with no loss of data if the battery must be replaced during the conduct of a survey; the capability to perform dynamic, in-place balancing; the capability to accept other input sensors such as infrared, tachometers, etc.; ability to calculate the displacement, velocity, and acceleration modes and also display other sensor quantities; rechargeable batteries; and lightweight, not exceeding 8 pounds.

- Vibration Database Software

First, determine if there are third-party sources for software. That is to say you may find the software written by some other company to be more suited to your needs than the software that the data collector company provides. Third-party software may be more user friendly, offer more capabilities, etc. It may also be more expensive than the software offered by the data collector manufacturer. A demonstration disk is frequently available to evaluate the software. The software manufacturer should also be requested to demonstrate the software on-site. Software and hardware should be demonstarted together, if possible, to show compatability.

The vibration database software should have some minimum capabilities, including; a tutorial to help you learn the basic operation and special features; selectable color schemes; optional expression of frequency in Hz or CPM[9], optional expression of vibration quantities and amplitudes in metric or english systems; simple methods for selecting display, reporting, graphing, and printing functions; "OOPS" capability to recover something that was accidentally deleted; capable of constructing generic machine test point templates and storing them in an accessible directory; ability to select report formats according to data requirements, according to necessary spectral information requirements, and according to necessary broadband requirements; gross printing capability to support printing many spectra without the operator being in attendance; and a reasonably priced software support and upgrade policy.

TRAINING

- Operators
    - Data collector operators should be selected based on their enthusiasm for the program, their reliability, their interest, and their attention to detail.

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[9] Cycles per Minute, more commonly known as revolutions per minute, RPM.

  - Vibration Analysis Engineers/Specialists should have inquiring minds, clarity of thought, and a sound knowledge of the engineering system that supports their facility.

- Formal and/or on-site

  - Data collector operators should receive training in basic vibration theory, instrument nomenclature and operation, selection of vibration test points, preparation of the machinery for measurements, familiarization with the database, terminology, and setup, hands-on training and practice surveys, and on-the-job training assistance with baseline and trending surveys.

  - Analysis specialists are not required to have an engineering degree, but should have an electrical background that includes electrical and electronics theory. The analyst should receive the same training as the data collector operator, plus dedicated training in machinery vibration monitoring and analysis theory[10], detailed database operation. Additional training support includes membership in the Vibration Institute, vibration industry reference books and manuals, and trade magazine subscriptions.

PREPARATION

- Engineering Data

  The O&M manuals should be carefully reviewed to extract data that will support the calculation of forcing frequencies generated by the internal components. Examples include manufacturer and model of bearing(s), number of poles, bars, and slots in the motor, number of blades on the cooling fan of the motor, gear tooth counts and ratios, number of compressor stages and blade counts per stage, etc.

- Manufacturers Vibration Specifications

  Liaison with the manufacturer can identify vibration limits of the chiller. This is usually based on the rotational speed of the compressor rotor and addresses maximum allowable vibration at that speed. Other characteristics of the vibration spectrum are rarely addressed by manufacturers. In fact, many O&M manuals merely state that vibration should not be excessive — when called, the manufacturer often has no answer for maximum allowable vibration questions.

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[10] There are schools and seminars that offer fundamental and advanced training.

There are charts and graphs available in the vibration industry that can help with the identification and evaluation of vibration amplitudes.

- Equipment Preparation

  Based on the O&M manual and significant calculated frequencies, the chiller must be prepared for vibration measurement. The test points must be identified in the manual and then located on the chiller.

  Each test point is permanently marked or tagged to identify for future surveys. This supports repeatability of data collection. Depending on the system selected, test points are marked with Mylar labels, metal tags, steel pads, or paint.

- Company Directive

  About this time in the development of the program, it is appropriate to write a preliminary directive that will institutionalize the PdM program. The goals, objectives, procedures, responsibilities, and program evaluation techniques should be addressed. The accountability of each individual that participates in the PdM program should be clearly stated in the directive. It would be good to establish a vibration or predictive maintenance team where accountability is integrated into this concept.

- Vibration Database

  The initial setup of the database will include the equipment, test points, test parameters, alarm set points, and all other inputs required by the software. The accuracy and thoroughness of this action can set the tone of the program. If extensive errors or data omissions are permitted, the baseline vibration measurements can be invalid. A complete baseline survey re-test may even be necessary.

- Implementation

  - *Baseline Survey* — The baseline measurement survey is conducted to establish several parameters including current equipment condition, identify repair requirements, and set the reference for future trending surveys. Collect more data at the baseline than will be trended. You can never do the baseline again.

    The baseline measurements should be carefully collected, evaluated and preserved. The initial analyses will often identify matters such as misalignemt, imbalance, bearing wear, etc. These items should be corrected and a retest conducted.

In cases where repairs are identified but not performed, the equipment condition should be closely tracked during follow-on trending surveys. Specific faults, especially misalignment and bearing wear, may deteriorate in a non-linear manner.

- *Trending Survey —*

  The trending surveys should be accomplished as scheduled. If not, they tend to be delayed and delayed, and delayed. Eventually, survey #3 and survey #4 are performed too close to each other. Operating personnel may begin to question their leadership and the management of the PdM program. This can result in a lack of confidence and poor performance on the part of the vibration team.

  The trending survey data is reviewed to identify changes and the rate of changes in both overall and narrowband vibration amplitudes. When the previously set alarms are exceeded, the equipment should be identified as requiring repairs.

- PdM Program Directive

After the PdM program has operated for several months, the directive should be reviewed and tailored to the actual conditions under which the program functions. The directive should also address field calibration by the operators before and after each survey, and the procedure for yearly laboratory calibration of the data collector.

- Repair Feedback and Promotion

  - Operators should be informed of the program status. If possible, the operators should be present when the equipment is opened or inspected. This is a valuable learning tool for the program. It also helps confirm the diagnostic analyses.

  - Use whatever internal communications device there is to communicate to other employees just what the PdM program is and what it does. Highlight the success of the program. A company newsletter is a good candidate for this type of promotion.

- Advise Upper Management of Progress

  - Whenever possible, management should be notified of the successes, problems, and failures produced by the program. With the successful episodes, aspects such as maintenance gains and estimated financial savings in labor, material, and production should be addressed. Problems should be noted along with suggestions and recommendations for corrective actions. In the case of the failures, it is usually wise to cite measures that have been implemented to reduce the chance of a recurrence.

- Complete documentation can help develop a program that has the vigorous support of upper management.

COSTS, ADVANTAGES, DISADVANTAGES

COSTS

- Hardware
    - The cost for the data collector ranges between $10,000 and $15,000 depending on features.
    - The computer and printer system will cost approximately $3,000.
- Software
    - The basic software program for use with the data collector is approximately $6,000.
    - Additional software modules for special features can add about $1,500 per module.
    - Expert vibration analysis database systems cost approximately $12,000–$15,000.
- Personnel Training
    - Training requirements will vary based on the skills and experience of facility maintenance personnel. Minimum recommended knowledge levels include working backgrounds in electricity or electronics; mechanical theory; computer literacy. Occasionally, one or two individuals "find" themselves and vibration testing and analysis become a way of life.
    - Training at dedicated classes or seminars is in the $2,000–$4,000 range for specialized vibration analysis courses.

- On-site training can be arranged through the data collector/software vendor for about $600-$800/day plus per diem; provided from vibration consultants for about $500/day; or even self-taught.

  Vendors often offer training classes at their facilities at rates that are lower than on-site. Of course, then the travel and per diem expenses for the employee must be paid.

- An in-house training program can be established after the initial training is accomplished.

ADVANTAGES

- The initial report of baseline survey findings and recommendations will support the short-range maintenance schedule. It will also provide information about potential "bad actor" equipment to help plan the long-range maintenance schedule.

- The potential for in-service equipment failures and the resulting problems, such as unscheduled downtime, will be reduced.

- The potential for overtime labor will be reduced because with advance knowledge of impending failures, maintenance managers can plan corrective maintenance actions at convenient times.

- Improved control of spare parts because PdM can help identify which repair parts to order. This can also help reduce the inventory of bearings, coupling components, spare motors, etc. Also, it helps when there is a requirement to order long lead-time repair parts.

- There will be a reduced potential for catastrophic in-service equipment failure.

- There will be a reduced requirement for open-and-inspect maintenance actions. This has a secondary benefit because it helps reduce the potential for reassembly errors.

- Accurately maintained PdM records will help maintenance managers develop meaningful reports.

- The facility operational commitment will be supported more fully because the reliability of the equipment will be enhanced.

- Continuous or On-line monitoring has the added benefits of 24-hour measurements for realtime condition assessment, automatic alarm and/or shutdown based on vibration amplitudes, and a non-labor intensive monitoring scheme.

DISADVANTAGES

- A $20,000-$40,000 capital investment is necessary if the PdM program is performed in-house. Hardware, software, a computer system, and dedicated office facilities are required. An added expense is the cost of a qualified vibration consultant to assist with program design, implementation, and development.
- Will require additional training for maintenance personnel. May also require 1 or more new maintenance positions. The skilled personnel will likely mean higher paid positions.
- The program will likely grow because the success will result in the addition of more facility equipment. This may require additional personnel and improved scheduling of the surveys.
- False alarms are possible if personnel are poorly trained. This can result in a lack of confidence in the PdM program because unnecessary maintenance actions may be performed. False alarms usually diminish with experience.
- PdM programs often start on shaky ground because personnel, even with schooling, are in unfamiliar territory. This can be alleviated by hiring a consultant experienced in PdM and vibration analysis for the first 6-12 months of the program. As a minimum, the consultant should be on-site for the database setup, equipment preparation, and baseline survey, including data analysis and recommendations. After this, he or she could be used on an as-needed basis.
- Continuous or On-line monitoring has the added disadvantages that 24-hour measurements may result in extreme data base sizes; the chance that alarms and/or machinery shutdown may be false alarms; without frequent human interface, the program may get de-personalized; and the hardware requirements for permanently installed vibration sensors, cabling, multiplexing switches, etc. will add significantly to the initial cost of the program.

SUMMARY OF PAST EXPERIENCES

- PdM has proven to be a cost effective method of monitoring the condition of chillers. If a vibration consultant collects the data, the chillers can be tested during normal working hours, there are no special operating conditions to establish before testing, the measurements don't require more than a few minutes, and the data can be quickly evaluated, and corrective action(s) can be initiated or scheduled for the most convenient time. Usually, the consultant analyzes the measurements, prepares the repair recommendations report, and stores the measurement data.

- These same advantages apply where operating personnel collect their own measurements. However, there are often other demands placed on the operators that can affect the PdM program. These demands can include items such as higher priority work causing the measurements to be postponed — sometimes indefinitely; the trained data collector is on vacation; the workload is too great — vibration measurements are postponed because they don't "fix" anything; or the measurements are improperly collected for any number of reasons just to "get it done" and please the supervisor — the data may be invalid but at least the job is done.

- In the 1970's, the U.S. Navy noted that an 18:1 cost benefit ratio could be achieved when vibration monitoring and analysis is performed. With state-of-the-art test equipment and modern computer software, that estimate is surely greater. The vibration industry usually suggests a 10:1 cost benefit ratio. That is to say, $10 in maintenance funds are saved for every $1 paid out for PdM.

- Keys to successful PdM programs include personnel who are dedicated and interested, support from all levels of management, praise where praise is due, and correction when it is necessary. The current proactive maintenance concept can also benefit from a PdM program because, when personnel see the results and benefits of the program, they are more likely to actively participate.

- There are more advantages to a PdM program. These include sharing of system expenses between multi-facility applications; QA for newly installed or overhauled machinery, with the obvious impact on warranties; and finally; the QA aspect reduces the chance that deficient equipment will be accepted that can cause trouble in the future.

APPENDIX G

Nondestructive Electromagnetic Eddy Current Analysis of Chiller Condenser and Evaporator Tubes

APPENDIX G

Nondestructive Electromagnetic Eddy Current Analysis of Chiller Condenser and Evaporator Tubes

The material in this appendix was prepared by William H. Frazier III of Tubular Technologies. The report discusses eddy current testing as it applies to analysis of chiller condenser and evaporator tubes. The outline for the report is:

- History
- Eddy Current Principle
- Applications
- Why Test???
- When to Test???
- The Test
- Findings/Results
- The Cost
  - Field Service Inspection
  - In-House Testing
- The Analyst
- Discontinuities
  - ID Pitting and/or Corrosion
  - OD Pitting and/or Corrosion
  - Support/Baffle Wear
  - Obstructed Tubes
  - Mechanical Displacement
  - Inherent Metal Loss
  - Missing or Misaligned Skip/Land Areas on Finned Tubes
  - Metallic Deposits.
  - Zipper Cracks
  - Freeze Splits
  - Stress Corrosion Cracking
  - Erosion
  - Fatigue

NONDESTRUCTIVE ELECTROMAGNETIC EDDY CURRENT ANALYSIS OF NONFERROUS HEAT EXCHANGER TUBES
"Simply Put/Laymen's Terms"

by

William H. Frazier III

History

Magnetism was first recognized by a Greek philosopher in 600 B.C. but was understandably somewhat misunderstood. Hundreds of years later Ben Franklin's contributions brought us much closer to modern theory. Since then, several more individuals have contributed to the principles of eddy current testing: Coulomb, Ampere, Faraday, Henry, Arago, Oersted, Kelvin, and Maxwell. Faraday and Henry, without knowing, were both experimenting with electro-magnetic induction at the same time. In 1832 Faraday documented and published his findings and thus received most of the credit. These discoveries led to the present uses of alternating current. It was about a century after their efforts that we learned electromagnetism could be used to detect numerous changes or discontinuities in or related to conductive materials.

Eddy Current Principle

When electricity was first pondered it was believed to be a fluid, and the flow of electricity was referred to as current. The opposing electrical current generated by the primary magnetic field flows very much like an eddy in a river or stream. This descriptive name holds true to the age-old reference to fluid. To further explain, the eddy current principle uses electromagnetic induction. If you pass an AC current or primary current through a test coil, an electro-magnetic field or primary field is produced that is perpendicular to the primary current. If a conductive test object is placed in close proximity or in contact with the primary field, an opposing secondary current or "Eddy Current" is induced in the test object. The Eddy Current then produces its own magnetic field that opposes the primary electromagnetic field. The test instrument then measures impedance changes in the test coil caused by changes in conductivity, dimension, or permeability of the test object.

Applications

The possible uses of the eddy current principle are virtually endless. New uses are developed continuously. This is understandable if you consider that any conductive material in its raw form, as a finished product or at any point in between, may have a practical application. Eddy current technology can also be utilized to monitor many nonconductive materials by creating a measurable relationship between the magnetic field and the material. For example, paper products are often measured using the eddy current method. Another example is the periodical eddy current test that airplane skins are commonly required to undergo to identify anomalies. This may entail determining a paint thickness, which offers an application example of both conductive and nonconductive materials. This paper focuses on eddy current testing on nonferromagnetic heat exchanger tubing primarily as it applies to air conditioning chillers.

Why Test ???

Tube failure is the leading cause of catastrophic heat exchanger loss. So, when you relate preventive maintenance to shell and tube vessels, Eddy Current evaluation is by far the most complete and accurate method for obtaining the condition of a vessel. Many insurance carriers demand that you periodically test your equipment. Hartford Steam Boiler Inspection and Insurance Company, the nation's largest machinery insurer, often requires many vessels of 100 tons in capacity or more, and over five years old, be subjected to an Eddy Current tube analysis. Their company magazine "The Locomotive," is quoted as saying:

- "Eddy Current inspection can detect tube corrosion, pits, and vibrational wear before leaks and resulting unscheduled shutdown can occur."
- "Eddy Current evaluation has successfully been used in air conditioning chillers and condensers, petrochemical process vessels, heat exchanger tubing and utility steam turbine surface condensers," as well as "on submarines for almost 20 years by the nuclear navy."
- "The savings realized in leak avoidance, retubing costs, and avoidance of recurring leaks should far outweigh the cost of the inspection."

Money is the best reason for employing periodical Eddy Current Analysis of your heat exchanger tubes. Most vessels tend to fail when you need them the most. Repairs after tube failure are extremely expensive and can affect much more than the vessel itself. Computer data and or software can be lost or damaged. Just ask the Nuclear, Petrochemical, Aerospace, Semiconductor, Medical, Scientific, and Manufacturing industries about expensive down time. I've heard of figures over one hundred thousand dollars ($100,000) an hour may be attached to unscheduled down time. Removing and replacing chillers is never easy and in some cases a huge undertaking. Sometimes helicopters or cranes are needed to reach a rooftop penthouse. Streets may even be excavated to access below-ground equipment rooms. Such activities are usually difficult to accomplish in any downtown area. Permits, street closings, and some very expensive machinery with well-paid operators may be involved. I could go on and on about the cost, but I think you're getting the idea. I find that many facilities are somewhat fearful of discovering the condition of their tubes. Overall, I condemn a relatively small percentage of the heat exchangers I test. It's much more common to find that only a few tubes need to be plugged. It's not uncommon to find tube bundles with virtually no defect indications. There are those who still believe if one tube is bad they all must be bad. Partial retubing is frequently a less expensive option in larger chillers. Defects can often be documented and then monitored again for advancement in a few years. I have managed even some fairly advanced corrosion or wear in chillers for several years without problems. This is done when there is risk but budgets won't absorb retubing or new equipment.

When to Test ???

Under most circumstances, I recommend that a machine be tested for the first time at about five years of age. Ideally it should be done shortly before the warranty expires. I strongly urge anyone to test by the time a tube bundle is ten years old. If a company has a large budget and can afford such luxuries, inspecting a brand new vessel has some merit, but I rarely suggest doing so. If all goes well during manufacturing and installation, there should be no need to inspect a new vessel. Most chillers come with a five-year warranty that covers any failures caused by defective tubes or workmanship. However, this can entail a lot of metallurgical analysis that usually starts with an Eddy Current test. Time intervals between inspections vary based on the overall condition of each heat exchanger. Normally, I recommend a test every three years. Obviously a chiller without any discontinuities may go longer and vise versa. A test should be performed at the first sign of a problem, and always before deciding to retube a tube bundle. After a few inspections, estimates of failure rates or defect advancement can be made.

The Test

Before the analyst arrives all preparations for the test should be completed. The end bells or heads should be removed, and the tubes should be reasonably free of scale and/or debris but do not have to be dry. If needed, scaffolding should be available. There should also be a standard three pronged outlet in the vicinity.

When the analyst arrives, he/she will then set up his/her equipment and complete a calibration process in accordance with a specification using a tube standard that is identical to the tubes in the heat exchanger. This is a good time to get a demonstration of the Eddy Current principal. The Eddy Current specification that is most widely used in the air conditioning industry is Section V, Article 8, of the ASME Boiler & Pressure Vessel Code.

After the equipment is set up, the test may begin. The entire length of each tube is probed at a rate of speed that conforms to the specification and is comfortable to the analyst. All of the defects and discontinuities should be noted and/or recorded. The results are instantaneous and should be made available to the customer. The calibration procedure may have to be repeated from time to time. Strip chart recordings should be made for all of the defective tubes and sometimes all of the tubes. If applicable, magnetic tape recordings may be made as well. The tubes with defects and/or discontinuities should be marked and mapped for reference and should be contained in the formal report. If plugging or repairs are recommended before the chiller returns to operation, this should be conveyed to the customer to avoid having to tear down the heat exchanger a second time.

The analyst should not rely on alarms or buzzers during the inspection. The analyst should give his/her complete attention to the display mechanism. I highly recommend that the tubes be tested both in the absolute and differential modes. This can be done simultaneous with two or more channel equipment.

The report should contain all of the identifiable information such as model number, serial number, chiller number, etc. Each vessel should have a tube sheet diagram with any or all defective tubes marked or mapped. The report should convey the defect type, location, and degree of severity. The report should include comments and recommendations. The report should include test parameters and a description of the tube type and dimensions. The strip chart recordings should also be included. My reports include pictures of the tube sheets with the defective tubes appropriately marked, but this is not necessary - merely helpful to the customer. Finally, a retest date should be recommended.

Findings/Results

Certain types of defects are much more common than others. It's also very true that you never know what to expect. There are so many variables and exceptions to the rule that it's hard to predict a tube bundles condition without an Eddy Current Inspection. One vessel of a machine may have extensive corrosion and the other has none. All of the tubes are without defects and one tube has a severe indication. Two machines sitting side by side which have the same water treatment, hours of operation and so forth may have extreme differences in the overall condition of the tubes. Condensers, evaporators, open loops, closed loops, vibration, continuously finned tubes, skip finned tubes, surging, endless sources of stress and or variables make each and every tube of each and every vessel a justified concern. I would have to say inside diameter pitting and or corrosion is the defect most frequently found. Support related defects such as vibrational wear, and over rolling probably follow in frequency. Obstructed tubes, outside diameter pitting and or corrosion as well as manufacturing defects are not uncommon. There is no rule or guide to follow which one can apply with great confidence to any given tube bundle. Certainly there are some probable scenario's which can be applied. A heat exchanger with a continuously finned tube is more likely to suffer support wear. Most reciprocating chillers have continuously finned tubes in the condenser sections and also tend to vibrate more than a centrifugal chiller. Thinner walled tubes and or internally enhanced tubes may have a shorter life span. Condensers tend to have higher rate or percentage of tubes with inside diameter pitting and or corrosion as well as erosion. Evaporators tend to have a greater number of support related defects. Geographically differences in the water make up tend to lend themselves to more waterside defects than other parts of the country. Some equipment and or tube manufacturers tend to produce more manufacturing or installation defects than others. The important thing to remember is even with these tendencies and those not mentioned, there are as many or more exceptions. An Eddy Current inspection is the best and really the only way to get a very accurate profile of an entire tube bundle. Even very minute defects can be detected long before they present any problems. The last inch or so at both ends of a tube is not effectively tested because of what's known as "End Effect". Most of the people who take the time to observe and listen to an Eddy Current demonstration seem genuinely impressed with the sensitivity and accuracy of this nondestructive principle.

The Cost

Field Service Inspection

The cost for testing varies from one company to another. Geographically, one company may charge expenses, while they may not apply to another company. Expenses may include air fare, car rental, lodging, and a food allowance, if applicable. Whenever possible, jobs can be scheduled so that expenses may be divided between two or more customers thus making it more cost effective.

Most testing companies charge by the tube or on a per tube basis, which also includes a minimum charge. Normally, the cost per tube ranges from $0.80 to $3.00. In some cases, special probes or tube standards may be required.

The following example shows the cost for a field inspection of a 450-ton centrifugal chiller which averages just under one tube per ton for each vessel:

Condenser 432 tubes + evaporator 402 tubes = Total 834 tubes @ $0.90 per tube = $750.60 plus air fare and one day per diem (if applicable).

In-House Testing

The difficulty of in-house testing is maintaining qualified experienced technicians. Often there is not enough inspections needed or practical applications to maintain a level of expertise; however, a very large company with numerous facilities and/or many different applications may find it cost-effective to conduct in-house analyses. Another problem with in-house testing is the loss of trained personnel due to turnover. In-house testing costs would be approximately as follows:

- Equipment: $30,000 to $65,000 new
- Formal technical training in the eddy current principal: $2,000 for each level
- From time to time other costs may be incurred, such as replacing probes, new tube standards, strip chart paper, equipment calibration, and so forth.

The Analyst

Experience is, in my opinion, the most important factor in picking an eddy current analyst. The American Society for Nondestructive Testing developed Recommended Practice SNT-TC-1A, which is the main set of guidelines used by testing companies to qualify their analysts. It establishes criteria to qualify test personnel to Levels I, II, and III, with modified sub-levels.

The highest level requires additional study and testing in theory and application of the scientific principle. However, this does not always equate to additional experience in actual testing or practical experience. In my opinion, practical experience or hands-on testing is the key to an analysts qualifications. Normally, if I had to choose between a Level I or Level II analyst who is a high school drop out but has good common sense and a half a million tubes of testing experience, or a Level III analyst with a doctorate in physics and only a thousand tubes of testing experience, I would choose the analyst with the half million tubes of testing experience. Obviously we all need to obtain experience somewhere and the above statement should not be taken as a criticism of analysts with less experience.

I discourage hiring a testing company that also performs retubing, because of the conflict of interest. You are best served by an analyst who specializes in field service eddy current testing of tubular products. One should avoid using someone who only dabbles in testing. An analyst should be able to thoroughly explain and demonstrate the eddy current principle. On the spot instantaneous test results or interpretation of data should not be a problem for a qualified analyst. Using one person to probe the tubes and someone else to later interpret the data is not advised. Alarms or buzzers should not be used to make pass or fail decisions.

Knowledge of tube manufacturing and installation processes is also very applicable and quite valuable to an eddy current analyst. Some knowledge of metallurgy and corrosion is beneficial as well. In addition to experience-related qualifications, inductive and deductive reasoning skills coupled with a lot of common sense is vital. Ultimately, one must use their own best judgment when choosing an eddy current analyst.

DISCONTINUITIES

ID Pitting and/or Corrosion

There are several ways ID pitting and/or corrosion can occur by both corrosive and mechanical means. Once the protective film layer is removed or breaks down, the tube wall is subject to attack. Pitting can range anywhere from one localized pit to a very general overall condition. Erosion will then advance any pit, corrosion or not.

OD Pitting and/or Corrosion

Most often, outside diameter pitting is caused by the presence of moisture in the refrigerant. When moisture is introduced to Freon, hydrochloric and/or hydrofluoric acids form, which may attack the tubes, supports, and shell. The acids can also destroy impellers, motor windings, and more, if it goes undetected. Once this process begins, it is almost impossible to completely arrest.

Support/Baffle Wear

Vibration is the principle source of support wear. It's caused by the machines operation and or water flow. Obviously, both can vary greatly in severity. The mechanical vibration wears or cuts the tube where it contacts the support or baffle. Once wear begins, the process can accelerate as the metal loss increases and the space between tube and support grows. Thermal expansion and contraction can add to support wear when tight spacing between tube and support exists. This is a very unpredictable defect.

Obstructed Tubes

A tube in which the probe cannot pass through at any given point is considered obstructed. Unfortunately, you can't always be sure of the cause. Usually proper tube cleaning will eliminate most fouling or scale buildup. However, hard deposits can be quite stubborn. All kinds of debris (e.g., pipe metal or rocks) can become lodged or adhere to a tube. I've even seen a chunk of a soda can come out of a tube. A tube can also be dented during manufacturing or installation. When a tube is obstructed by a foreign object, the flow characteristics change, which is likely to cause erosion in and around the area. If an obstruction can't be removed, and the tube cannot be retested, plugging or replacement should be considered. Caution should be used when working with obstructed tubes.

Mechanical Displacement

Tube rolling is a more popular term for the process I call mechanical displacement. This is the process used to affix the tubes in the heat exchanger which create the hermetic seal. This can also be done at skip areas of a skip-finned tube. Using this process at the interface with the land and support is a sincere effort by the manufacturer to prevent vibrational wear. In many cases this works well, but it also can cause a lot of trouble. Three or five roller expanders are used, which spread out slowly, mechanically displacing the tube wall. Normally, this seems to work well at the end sheet where the drive mechanism and expander are more easily controlled. Most of the problems result from the process of touch rolling or expanding the tube at the internal supports. Sometimes measurements are incorrect, and the tube is not expanded at the support. Instead,they're expanded on either side of the support. Over rolling and/or off-target rolling can seriously compromise the tube. Because rolling is done intentionally, there is some gray area when trying to decide just how much is too much. Normally, any defect or metal loss greater than twenty percent (20%) should be removed from service; however, this is not always practical in this case. Another potential problem with rolling at the supports is the additional mechanical stresses placed on the tube. Grooves that could increase the chance of erosion are left behind after displacement takes place. Skip-finned tubes were developed to help prevent wear at the supports, and rolling was added to further help. The skip-finned tube does quite well by itself. However, the rolling could be more trouble than its worth. This is not to say that expanding the tubes at the support is a wide-spread problem or without merit. It began and remains a sincere effort to prevent vibrational wear.

Inherent Metal Loss

Often during manufacture and installation of tubing, defects occur that are acceptable or escape detection. For instance, handling and installation can produce scarring and mechanical metal loss that, unless severe or actual leaks are found, could go unnoticed. The extrusion and finning processes are very aggressive by nature and can produce anomalies from very minute to very extreme. Many small discontinuities are deemed acceptable if they present little or no risk to reliability that might compromise the vessel in the foreseeable future. Small discontinuities on the gas or Freon side often present less threat from erosion and, therefore, become more acceptable. One well-known manufacturer has a small outside diameter discontinuity at one or more locations along each of the tubes in an entire vessel that is in approximately fifteen percent of their machines. In every case these have presented little or no risk to reliability. However, speculation is always part of the unknown and common sense should prevail.

Missing or Misaligned Skip/Land Areas on Finned Tubes

If a tube bundle is designed to have a land or skip area at every support, it should have one at each support and in every tube throughout the vessel. Once in a while I find a heat exchanger which has one of the following mistakes:

- Tubes that are continuously finned (except for the ends); that lack unfinned land/skip areas at the appropriate inner supports.

- Tubes that have unfinned land/skip areas, but do not correctly line up with the inners supports. Normally, this misalignment is less than two inches. The tube might fit properly if it were turned around. The importance of a missing or misaligned land/skip area is the lack of a built-in defense against vibrational support wear. This is fairly rare (one or two machines out of a hundred). Since a tube without a land/skip area is more likely to suffer vibrational wear, it's good to have this information. Without an Eddy Current Inspection, a missing or misaligned land/skip area would be hard to detect.

Metallic Deposits

A metallic deposit is a metallic source or alloy different than that of the tube. This will generate a signal when the magnetic field is induced, based on a change in conductivity. Most metallic deposits are caused by metal from piping or the shell. These metallic deposits often adhere or fuse themselves to the tube. They can also be trapped in the tube scale or remain free moving. Most metallic deposits can be easily identified, it is the adhering or fused deposits which cause concern. Dissimilar metals can create a corrosive state, or like a rock in a river, possibly set up the potential for erosion. A proper cleaning and/or brushing becomes very important when deposits are present. Zinc deposits are somewhat frustrating. A few products that used zinc in one form or another as a sacrificial metal have produced signals during testing which mimic or duplicate inside-diameter defects. Even if you determine that sacrificial zinc was used, you are not comfortable letting it go at that. Metallic deposits can come in various forms: metal that becomes imbedded in the tube during manufacturing, and metal from the shell or a piece of welding slag on the tube's outside diameter. Tubes made up of more than one alloy such as copper-nickel may have a deposit of copper or nickel in a higher concentration than the rest of the tube. Metallic deposits could be an indication of a serious problem, or be of virtually no concern.

Zipper Cracks

Zipper cracks are not very common because they are the result of a manufacturing defect and are usually detected in production. Tube manufacturers call this defect a fin split. A fin split is a result of drawing a prime or smooth-walled tube through a die that mechanically crushes the fins into the tube. Foreign material or small pieces of the metal die get drawn along with the tube for a distance leaving behind a gouge or split in the fins. The splits vary in depth and length, with some splits less than .005" being acceptable. This inherent split or gouge can later propagate down toward the tube wall, eventually cracking, due to normal operational and/or built-in stresses.

Freeze Splits

When controls fail to prevent the tubes water side from freezing, the extreme pressure or force from the expanding liquid can easily rupture tubes. A skip-finned tube will almost always rupture at the land or skip area on either side of a support because the finned section of the tube is mechanically hardened from the finning process. A continuously finned tube may fail anywhere along its length. Tubes can bulge without bursting but are severely compromised and should not remain in operation. A tube with a freeze bulge or split is extremely hard to remove. Cutting a hole or window in the shell may be necessary. Therefore, whenever possible, plugging is advised. If the water side happens to be on the outside diameter, or shell side, the freezing force will collapse or crush the tube.

Stress Corrosion Cracking

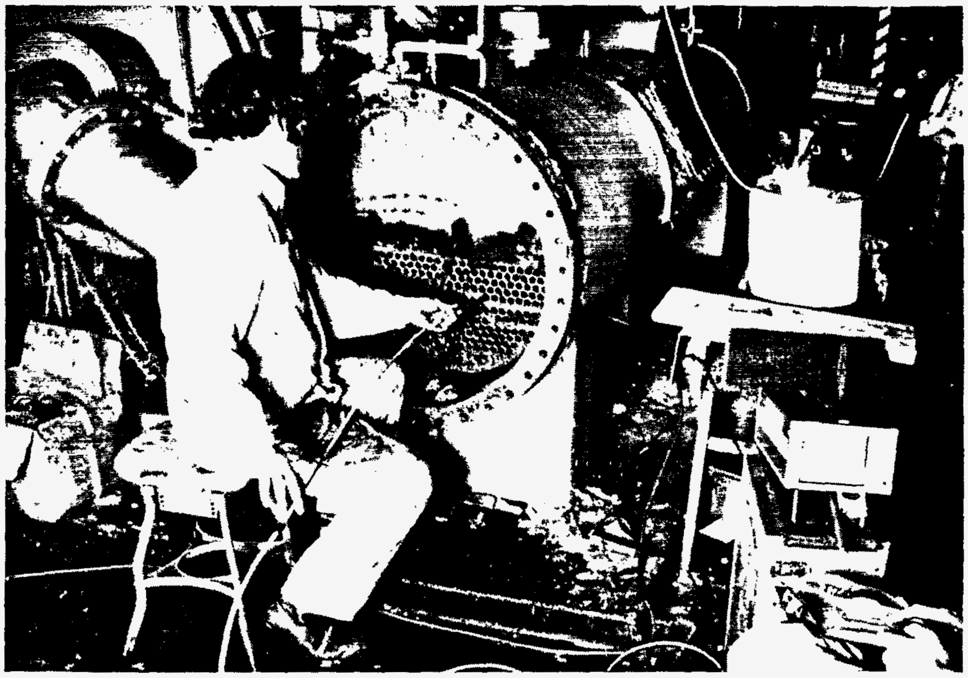
Stress corrosion cracking is somewhat of a phenomenon as to why it occurs but can be partially explained. During manufacturing, a tube goes through one or more processes such as extrusion and finning which create stress areas that remain from then on. Installation adds further stress. In addition, stresses from operation, like thermal cycling and vibration, play a role. Corrosion affects the metallurgical grain boundaries, which define the stress areas themselves. The corrosion eventually attacks these areas until cracks or relief occurs. These cracks range from microscopic to very large crevasses. In copper alloy tubes ammonia is the corrosive element, even in very small quantities. Copper nickel tubes seem to be more resilient to stress corrosion. In stainless steel tubes chloride is the corrosive element. There also seems to be a correlation between an increase in operating temperatures and the rate of failure. I find this type of defect more common in absorption units than in centrifugal chillers. I recommend a complete vessel retubing when stress corrosion cracking has occurred.

Erosion

Water flow in and or around tubes will eventually cause erosion. Particulates/solids, dissolving oxygen, water velocity, turbulation, deposits, and dimensional changes can all contribute to the erosion process. Erosion will often attack the tube ends and tube sheets because of the violent water activity at this location of a vessel. Any metal loss created by corrosion or manufacturing will then be advanced by erosion. Erosion eventually affects every heat exchanger.

Fatigue

Fatigue is basically the effects of any and all stresses placed on the tube from manufacturing and operation. It is the break down of the metallurgical grain and the boundaries of stress. A narrow or particular type of fatigue relates primarily to a state of brittleness caused by thermal cycling and the expansion and contraction that occurs. Stress cracking that is not attributed to specific corrosive elements is sometimes referred to as fatigue cracking. Fatigue can be part of several types of defects or stresses. Fatigue is probably best used as an adjective and not a defect classification.



Tube Analysis in Progress
In conducting a tube analysis, the technician inserts a probe into chiller tubes. Signals from the probe are displayed on the oscilloscope screen.

Figure G.1 Example of Analyst Conducting an Eddy Current Examination on a Chiller

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