Study on life cycle management system for chillers in nuclear power plant

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Abstract. Daya Bay Nuclear Power Plant has been running for above 20 years. Most of chiller units have begun to run during the commissioning phase before the official commercial operation, combined with demonstration of the operation license extended to 60 years, so it is imminent to carry out the life cycle management of chillers. A life cycle management system for chillers in nuclear power plant is established in this paper, which is applied to management practices of Daya Bay Nuclear Power Plant.

1. Introduction
Daya Bay Nuclear Power Plant has been running for more than 20 years [1]. It is imminent to carry out the management of the life period of major equipment, considering the actual operation state of chillers and research work of nuclear operation license extension to 60 years. Life cycle management is a process of managing equipment in nuclear power plant actively to make power plant achieve the optimal overall performance (security, reliability, and economy), which will maximize the value of the enterprise.

Chillers provide chilled water to various safety-related and non-safety-related heating, ventilating, and air conditioning systems, so whether it is safe and reliable has important influence on the safe and economic operation of nuclear power plant. The purpose of the life cycle management for chillers including carrying out the classification management of chillers thus screening out the main concerns of life cycle management, making detailed analysis of concerns and then working out medium and long term life cycle management plan to provide input for long-term asset management process (medium and long term overhaul plan, retrofit plan, capital plan and so on), ensuring the long-term safe and reliable operation of chillers in nuclear power plant.

2. Research status at home and abroad
Some countries like USA, Canada, Korea, Japan and France have already formed relatively complete equipment life cycle management system, which have been effectively applied. Among them, nuclear power plants in United States are the first to carry out the asset management work taking the advantages of research of EPRI, INPO and NEI and other institutions [2, 3]. The asset management work in USA is the most extensive and the most widely used, which has been applied to the planning and implementation of medium and long term plans and investment plans for power plants. Its
accumulated experience and technology provide an important benchmark for other countries' nuclear power plant asset management work.

Chinese nuclear power plants have not systematically carried out the analysis and research on life cycle management of major equipment before 2010. Daya Bay nuclear power plant as the oldest nuclear power plant in China, has begun to study life cycle management of major equipment after 2010, which is based on the reliability of major equipment and equipment risk analysis, aging management, reliability assessment and life assessment, obsolete product management are systematically used to create a demonstration power plant major equipment life cycle management process and method. The life cycle management of major equipment will be extended to other nuclear power plants within CGN (China General Nuclear Power Corporation) after it is applied in Daya Bay nuclear power plant successfully[4].

3. Overview of the life cycle management system for chillers
The lifecycle management method used in this paper is based on INPO's AP-913 and EPRI's LCM guidelines [5, 6], referring to the good practice of the advanced nuclear power operation unit (Exelon) and combining with the reality of Daya Bay nuclear power plant. The life cycle management process of chillers in nuclear power plant established in this paper is shown in figure 1, which includes life cycle management boundary determination, concerned components screening, collection and screening equipment concerned problems, technical analysis of concerned problems, risk analysis of concerned problems, components and equipment life evaluation, formulation of life cycle management options, comparison and analysis of alternatives, making the optimal life cycle management.

4. Life cycle management evaluation of chillers in nuclear power plant
The life cycle management evaluation of chillers in Daya Bay nuclear power plant was carried out based on the life cycle management system for chillers in nuclear power plant established in this paper.

4.1. Life cycle management boundary determination
The boundary of the life cycle management defines the research object and the scope of the life cycle management for chillers in nuclear power plant. Chillers in Daya Bay nuclear plant are mainly distributed in DEL, DEG, DWE, SAP, DWN, DWL, DVQ, SLT, DWR, DWA system. According to the heat transfer form of condensers in the above-mentioned chillers, chillers in Daya Bay nuclear power plant can be divided into water-cooled chillers, water-cooled chillers with cooling towers and air-cooled chillers. The life cycle management boundary for chillers includes the mechanical boundary and the controlled boundary.

Figure 1. The life cycle management process of chillers in nuclear power plant.
4.2. Concerned components screening

Concerned components screening of life cycle management for chillers is based on the key function of chillers. All the important parts within the boundary range of chillers are classified according to failure consequence and failure probability, which is shown in Table 1. Components ranking level 1-6 in Table 1 are selected as concerned components of life cycle management for chillers.

| Table 1. Component screening grading table. |
|--------------------------------------------|
| Component grade | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-----------------|---|---|---|---|---|---|---|---|---|
| Failure consequence |
| High            | X | X | X |   |   |   |   |   |   |
| Medium          |   | X | X | X |   |   |   |   |   |
| Low             | X |   |   |   | X | X |   |   |   |
| Failure probability |
| High            | X | X | X |   |   |   |   |   |   |
| Medium          |   | X | X | X |   |   |   |   |   |
| Low             | X | X |   |   | X |   |   |   |   |

According to the principle of concerned components screening, the concerned components of chillers in Daya Bay nuclear power plant comprises 17 parts, which includes mechanical components (such as compressor, evaporator, condenser, etc.), electrical components (such as contactors, relays, etc.), instrument control components (pressure switches, temperature switches, flow switches, etc.).

4.3. Collection and screening equipment concerned problems

The collection of life cycle problems is to set up a list of life cycle problems for chillers in nuclear power plant. The life cycle issues include power plant internal operation experiences and performance data, operation problems and elimination problems. After establishing the list of life cycle problems for chillers, screening these problems according to the impact degree and resources needed to carry out the solutions. Problems meeting to one of the following criteria are selected as life cycle management concerned problems.

| Table 2. Life cycle management concerned problems for chillers |
|--------------------------------------------------------------|
| Item No. | Concerned component | Problem description | Problem type | The capital investment that is expected to be needed to solve this problem | Whether concerned problem | Remarks |
|----------|---------------------|---------------------|--------------|-------------------------------------------------|--------------------------|---------|
| GF-2     | evaporator          | Leakage and heat transfer failure of heat exchange copper tube caused by vibration and wear | Potential problem | ≥ 800,000 | YES | Whole unit replacement |
| GF-3     | Condenser (air cooled) | Leakage and heat transfer failure of heat exchange copper tube caused by vibration and wear | Potential problem | ≥ 800,000 | YES | Whole unit replacement |
|          |                     | copper ribs oxidation due to Long exposure to air | Aging problem | ≥ 800,000 | YES | Whole unit replacement |
| GF-4     | Condenser (water cooled) | Leakage and heat transfer failure of heat exchange copper tube caused by vibration and wear | Potential problem | ≥ 800,000 | YES | Whole unit replacement |
|          |                     | Erosion of tube sheet and head | Aging problem | ≥ 800,000 | YES | Whole unit replacement |
|          |                     | Water side fouling | Aging problem | ≥ 800,000 | YES | Whole unit replacement |
Screening criteria is as below:
1) Known equipment problems that the existing preventive maintenance cannot effectively solve or whose consequences are unacceptable;
2) Problems that solving may extend outage duration.
3) Problems that solving is expected to require capital investment of more than 800 thousand RMB.

Life cycle management concerned problems for chillers are shown as table 2.

4.4. Technical analysis and risk assessment of concerned problems
Identify the current status of the equipment, including the existing problems and potential risks, clarify the existing problems and potential risks, and screen the mature processing methods in the industry, so as to prepare for the formulation of life cycle management plan. The following aspects can be referred in the technical evaluation: Identify the current equipment problems, and make judgments based on the importance, severity and urgency of the consequences; a preliminary analysis of the causes of the current problems, Utilization of horizontal research results.

For the concerned problems of life cycle management, evaluate the failure consequence and failure probability of equipment components involved in problems, and determine the problem risk level referring to the risk assessment method of Exelon. Results of risk assessment for concerned problems of chillers are shown as table 3.

Table 3. Results of risk assessment for concerned problems of chillers.

| Item No. | Component          | Concerned problems                                      | failure consequence (high/medium/low) | failure probability Evaluation time limit | Evaluation results | Problem risk level |
|---------|-------------------|--------------------------------------------------------|--------------------------------------|------------------------------------------|--------------------|-------------------|
| GF-2    | evaporator        | Leakage and heat transfer failure of heat exchange copper tube caused by vibration and wear | Medium                              | Year 0-5 Low                            | Low                | Low               |
|         |                   |                                                        |                                      | Year 6-10 Medium                          | Medium             | Medium            |
|         |                   |                                                        |                                      | Year 11 to the end of life High            | High               | High             |
| GF-3    | Condenser (air cooled) | Leakage and heat transfer failure of heat exchange copper tube caused by vibration and wear | Medium                              | Year 0-5 Low                            | Low                | Low               |
|         |                   |                                                    |                                      | Year 6-10 Medium                          | Medium             | Medium            |
|         |                   |                                                    |                                      | Year 11 to the end of life High            | High               | High             |
|         |                   | copper ribs oxidation due to Long exposure to air  | Medium                              | Year 0-5 Low                            | Low                | Low               |
|         |                   |                                                        |                                      | Year 6-10 Medium                          | Medium             | Medium            |
|         |                   |                                                        |                                      | Year 11 to the end of life High            | High               | High             |
| GF-4    | Condenser (water cooled) | Leakage and heat transfer failure of heat exchange copper tube caused by vibration and wear | Medium                              | Year 0-5 Low                            | Low                | Low               |
|         |                   |                                                        |                                      | Year 6-10 Low                            | Low                | Low               |
|         |                   |                                                        |                                      | Year 11 to the end of life Medium         | Medium             | Medium            |
|         |                   | Erosion of tube sheet and head                        | Medium                              | Year 0-5 Low                            | Low                | Low               |
|         |                   |                                                        |                                      | Year 6-10 Low                            | Low                | Low               |
|         |                   |                                                        |                                      | Year 11 to the end of life Medium         | Medium             | Medium            |
|         |                   | Water side fouling                                    | Low                                 | Year 0-5 Low                            | Low                | Low               |
|         |                   |                                                        |                                      | Year 6-10 Low                            | Low                | Low               |
|         |                   |                                                        |                                      | Year 11 to the end of life Medium         | Medium             | Medium            |

4.5. Components and equipment life evaluation
Component and equipment life evaluation includes failure mode analysis, aging state management, aging life assessment, experience feedback life assessment, and reliability life assessment.
4.5.1. Failure mode analysis. A total of 424 units of experience feedback were collected from 24-hour event lists, COMIS/SAP notification/work ticket, NCR, CAPT and mid-term problems of six units in Daya Bay nuclear power base, and all kinds of event data of chillers were statistically analyzed, as shown in table 4.

From the viewpoint of system, DEG accounts for 47%, DEL accounts for 30%, DWE accounts for 11%, SAP accounts for 7%, and DWL accounts for%, as shown in figure 2. From the viewpoint of breakdown component category, the mechanical components account for 38%, the electrical components account for 28%, and the instrument and control components are 24%, which is shown in figure 3. The failure of the instrument and control components of Daya Bay nuclear power plant is mainly reflected in the failure of various plate parts.

Table 4. Failure data of chillers.

| Fault parts         | DEG | DEL | DWE | SAP | DWL | Total | Proportion |
|---------------------|-----|-----|-----|-----|-----|-------|------------|
| Electrical          | 51  | 44  | 12  | 6   | 4   | 117   | 0.28       |
| Mechanical          | 87  | 38  | 15  | 18  | 2   | 160   | 0.38       |
| Instrument control  | 29  | 45  | 14  | 2   | 13  | 103   | 0.24       |
| Cooling water       | 1   | 0   | 0   | 4   | 0   | 5     | 0.01       |
| Lubrication oil     | 22  | 0   | 2   | 0   | 0   | 24    | 0.06       |
| Cryogen             | 4   | 0   | 1   | 0   | 2   | 7     | 0.02       |
| Function            | 5   | 0   | 1   | 2   | 0   | 8     | 0.02       |
| Total               | 199 | 127 | 45  | 32  | 21  | 424   | 1          |

Figure 2. Pie chart of failure system distribution diagram. Figure 3. Failure parts of chillers in Daya Bay nuclear power plant

4.5.2. Aging state management. Preventive maintenance work plan of chillers in Daya Bay nuclear power plant can be obtained by collection of maintenance program of four systems which are DEL, DEG, DWE, SAP and analysis.

Preventive maintenance work plan of chillers in Daya Bay nuclear power plant can be obtained by collection of maintenance program of four systems which are DEL, DEG, DWE, SAP, and analysis. Compared with general inspection and maintenance measures in the industry and the guiding management method given by the manufacturer, it can be seen that most of industry recommendation or manufacturer's guidance management methods have been carried out in the recommended period or the period adjusted according to the actual situation in Daya Bay nuclear power plant. Chillers in Daya Bay nuclear power plant is currently running well, the maintenance state is normal and there is no significant failure to be evaluated, so it is considered that the aging mechanism of chillers in Daya Bay plant has been effectively managed by the current strategy and at the same time, the aging effect has been monitored in time in line with the management methods recommended by the industry or by the manufacturer.

In a word, industry experience feedback is of reference to the Daya Bay chillers operating under the current maintenance strategy. In the following paper, the aging life of chillers is evaluated.
according to the plugging rate of heat exchangers and the experience feedback life assessment is made according to the industry experience feedback.

4.5.3. Aging life assessment. The recommended life of chillers is mainly concerned with condensers, evaporators and compressors. The main consideration is corrosion and structural strength, ensuring a certain corrosion allowance under the premise of ensuring the structure strength. At present, condensers and evaporators of DEL/DEG/SAP in Daya Bay nuclear power plant have no plugging tube, and the manufacturer's designed plugging margin is 10%. These chillers that are set redundantly are abundant in plugging while the cooling water is relatively clean, the aging mechanism has been effectively managed by the current strategy and at the same time, the aging effect has been monitored in time in line with the management methods recommended by the industry or by the manufacturer. Therefore, the aging life of DEL/DEG water-cooled chillers can reach 40 (DEL) /25 years. As for the SAP chillers whose cooling water of its condenser comes from the outdoor water tower, on the one hand, the outdoor water tower is prone to corrosion and aging problems such as stainless steel rust, embrittlement of rubber packing, fouling and so on, on the other hand, the impurities and microorganisms in the cooling water from the outdoor water tower whose quality is not as good as that coming from the closed system like DEL/DEG, will aggravate the corrosion of the condenser. Therefore, the life of the SAP chillers can reach 20 years, which is between the water-cooled chillers and air-cooled chillers.

Because the nuclear power plant is at the seaside, the salt content in the air is relatively high. The corrosion of the heat exchange tube and the rib of the outdoor condenser is stronger. At present, the pipe plugging rate of the DWE chiller is about 5%. The aging life of the DWE air-cooled chiller is 15 years according to the aging trend.

4.5.4. Feedback experience life assessment. Based on the industry failure data in the INPO (the Institute of Nuclear Power Operations) and EPIX (Information Exchange System) databases from 1997 to 2006, the overall failure rate of chiller units is as shown in table 5 (per unit per year)[6].

| Year | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | average |
|------|------|------|------|------|------|------|------|------|------|------|---------|
| Failure rate | 0.085 | 0.078 | 0.065 | 0.108 | 0.104 | 0.101 | 0.065 | 0.085 | 0.076 | 0.106 | 0.087 |

When considering the failure caused by the chiller unit itself that happen in the operation stage, it is considered that the failure rate is 0.048 per unit per year, except for human factors, external factors and uncertain factors. The corresponding failure time is about 20 years. After chillers run exceeding the above time, the failure of each component may increase gradually, resulting in the gradual increase of the corrective maintenance cost and meanwhile the gradual decreasing of chiller unit reliability level. In this case, combined with technical elimination, the overall replacement of chiller unit is generally considered during the running time of 25~30 years. Chiller unit replacement information from INPO/WANO is shown as table 6.

As mentioned above, the salt content in the air is relatively high because Chinese nuclear power plant is at the seaside. As for air-cooled chiller units, the corrosion of the heat exchange tube and the rib of the outdoor condenser is stronger. So the overall life of air-cooled chillers is generally 16 years, which is shorter than that of the water-cooled unit. Daya Bay air-cooled chillers replacement time is shown as table 7.
Table 6. Chiller unit replacement information.

| Power Station            | Commercial time/start time (year) | Replacement object | Replacement time (year) | Service life (year) | Information resources                                      |
|--------------------------|----------------------------------|--------------------|-------------------------|---------------------|------------------------------------------------------------|
| Kewaunee (America)       | 1974.3                           | chiller            | 2000                    | ~26                 | INPO Kewaunee Unit 1-12_20_1999                             |
| Cliffs Unit 1 (America)  | 1974.10                          | two chillers       | 2001.2                  | ~26                 | INPO OE12196 - Preliminary Notification - Mobile Crane      |
|                          |                                  |                    |                         |                     | Potentially Fatal Near Miss 010- measures_use_of_oc_in_kar |
|                          |                                  |                    |                         |                     | achi_npp_to_improve_stati                                    |
|                          |                                  |                    |                         |                     | on_performance-jawed_iqbal                                  |
| KANUPP                   | 1972.1                           | old main chillers  | 2003                    | 31                  | WANO                                                       |
| KANUPP                   | 1972.1                           | old main chillers  | 2006                    | 34                  | WANO                                                       |
| Darlington, Unit 0       | 1990.1                           | Overall replacement| 2015                    | 25                  | WANO MER ATL 10-259                                        |
| V. C. Summer Unit 1      | 1984.2                           | Overall replacement| 2009                    | 25                  | WANO MER ATL 11-307                                        |

Table 7. Daya Bay air-cooled chillers replacement time list.

| Power Station            | Chiller unit          | Business running time | Replacement time (year) | Service life (year) | Replacement object | Information resources |
|--------------------------|-----------------------|-----------------------|-------------------------|---------------------|--------------------|-----------------------|
| Daya Bay nuclear power   | D0DVQ-101-GF          | 1994                  | 2010                    | 16                  | Overall replacement| MRTEN070057           |
|                          | D1SLT-001-GF          |                       |                         |                     |                    |                       |
|                          | D2SLT-001-GF          |                       |                         |                     |                    |                       |
|                          | D0DWR-300-GF          |                       |                         |                     |                    |                       |
|                          | D0DWR-350-GF          |                       |                         |                     |                    |                       |
|                          | D0DWA-001-GF          |                       |                         |                     |                    |                       |

5. Conclusions
Considering the equipment's aging and degradation, condition assessment, failure risk assessment, feedback experience, design life and so on, the life of chiller unit is evaluated, which is shown in table 8.

Table 8. Life assessment of chillers

| Condenser Type               | System | Design Life (year) | Aging life(year) | Feedback experience life (year) | Comprehensive life(year) |
|------------------------------|--------|--------------------|------------------|---------------------------------|--------------------------|
| Water-cooled                 | DEL/DEG| 40/25              | 40/25            | 25                              | 25                       |
| Water-cooled (with outdoor water tower) | SAP    | 25                | 20               | NA                              | 20                       |
| Air-cooled                   | DWE    | 20                | 15               | 16                              | 15                       |
The chiller unit is a non-standard product. There is no condition and special equipment for the on-site verification of the device function after replacing the heat exchanger separately. Thus the chiller unit is generally replaced by the whole unit. The life cycle management of chiller unit is as following.

1) As for water-cooled chiller unit, the comprehensive life is 25 years. After 15 years' operation, the specific time of unit replacement is determined considering factors such as equipment status, maintenance cost, retrofit cost and implementation window.

2) As for water-cooled chiller unit with outdoor water tower, the comprehensive life is 20 years. After 17 years' operation, the specific time of unit replacement is determined considering factors such as equipment status, maintenance cost, retrofit cost and implementation window.

3) As for air-cooled chiller unit, the comprehensive life is 15 years. After 10 years' operation, the specific time of unit replacement is determined considering factors such as equipment status, maintenance cost, retrofit cost and implementation window.

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List of Abbreviations

EPRI Electric Power Research Institute
INPO Institute of Nuclear Power Operations
NEI Nuclear Energy Institute
CGN China General Nuclear Power Corporation
LCM Life Cycle Management
DEL Electrical Building Chilled Water
DEG Nuclear Island Chilled Water
DWE Main Switchyard Ventilation
SAP Compressed Air Production
DWN Site Laboratory Ventilation
DWL Hot Laundry Ventilation
DVQ Waste Auxiliary Building Ventilation
SLT Transit Changing Room Ventilation
DWR Security Building Ventilation
DWA Hot Workshop and Warehouse Ventilation
EPIX Information Exchange System
WANO the World Association of Nuclear Operators