

Research and practice of accelerated ageing management for important and susceptible components in nuclear power plants

HUANG Li-jun¹, CHEN Shi-jun¹, CHEN Yu¹, and QU Meng¹

1. China Nuclear Power Technology Research Institute, Shenzhen, 518124, China (huanglijun@cgnpc.com.cn)

Abstract: This paper introduces the background for the ongoing research on accelerated ageing management (AAM) technology for important and susceptible components in Daya Bay nuclear power plant (NPP) and Lingao NPP. The technical procedure, the work architecture and the interfaces with existing operation and maintenance system in NPPs are also detailed. Finally, some representative examples of the use of AAM to solve practical operational issues are presented, before concluding on propositions for the future development of this technology.

Keyword: accelerated ageing; accelerated ageing management; important and susceptible components; maintenance strategies

1 Foreword

From the commissioning before commercial operation of NPPs, or even backward to the day of being manufactured or constructed, structures, systems and components (SSCs) encounter ageing problems inevitably. Ageing and lifetime management (ALM) has become one of the most important research fields in international nuclear industries. Its objective is to ensure a required safety level throughout the total lifetime of nuclear power plants (NPPs), including the extended lifetime. For ageing management of major equipments in NPPs, such as containment, reactor pressure vessel, reactor internals, steam generator, transformer and generator, some organizations and research institutes like the International Atomic Energy Agency (IAEA) and many NPPs have succeeded in a large number of endeavours like the foundation of an ageing management program (AMP) and a systematic ageing management architecture, which are worth learning from and referring to^[1-7].

China Guangdong Daya Bay nuclear power base consists of two operational NPPs, Daya Bay NPP (2 units) and Ling'ao NPP (2 units), which started commercial operation in 1994 and 2003 respectively, and are operated by the same company. Referring to the AMP recommended by the IAEA and the experiences of Electricité de France (EDF), the Electrical Power Research Institute (EPRI) and other

organizations, the operator has carried out lots of work on ALM, and has achieved remarkable successes in ageing management for some major and critical components^[8].

In recent years, abnormal events and deficient maintenance of components showed that some notable, aggravated degradation and failures had taken place in some important and susceptible components in Daya Bay NPP and Ling'ao NPP, which seriously influenced the reliability of systems. For instance, during the implementation of the periodic test of the emergency diesel generator (EDG) in Ling'ao NPP, the corrosion of cylinder water jackets resulted in water leakage from the cylinders and a failure to finish the periodic test, whereupon the reduced availability of the EDG. In fact, the corrosion happened much before the expected cycle of replacement of water jackets. Besides that, the failure rate of fire detectors kept high in two plants, lots of embrittlement and cracking occurred in instrument and control (I&C) cables, and flow accelerated corrosion was found in downstream pipelines of hydrotest pump turbine generator set (LLS), and so on. Common characteristics of these events were that periods of ageing degradation were much ahead of the design lifetime or expected replacement cycles, and both the speed and degree were prominent. This differed from general ageing events evidently. Through pilot researches, it was found that the accelerated ageing of components was owed to the effect of a certain accelerating factor or the interaction of several accelerating factors. Due to the stresses inflicted by

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these accelerating factors, it is likely that components are suffering from reduced life during the service time of NPP. All such problems are defined as accelerated ageing issues of important and susceptible components in NPPs.

In order to manage accelerated ageing issues in NPPs effectively, the operator in alliance with some departments founded in 2007 a special research team, the mission of which was to analyze accelerated ageing, and develop corresponding O&M strategies. During the research and practice in the past two years, relevant analysis and applications for twenty-three systems and components have been done, including ventilation systems, fire protection systems, seawater systems, grounding systems, cylinder water jacket of EDG, I&C cables, LEACH relay. Practical experience indicated that the reliability and availability of components had been improved as a result of the implementation of the recommendations of previous relevant investigations. This also contributed in the long-term to safe and reliable operation of the systems. This paper describes the research and application of AAM in Daya Bay nuclear power base, which provides a cross-reference for other NPPs.

2 Basic theories of AAM

2.1 Definition and implication of accelerated ageing and objective of AAM

Referring to international research experiences on ALM and AAM, accelerated ageing of components is defined as component failures owing to the effect of a certain accelerating factor or the interaction of several accelerating factors, and the consequence of which are accelerated degradation speed and notable deteriorations or failures prior to the expected time. The typical characteristics are notability, prematurity and particularity. In contrast, general ageing of components is defined as continuous time-dependent degradation of material and performance during all the service lifetime due to normal service^[3]. Thus, there exists a distinct difference between accelerated ageing and general ageing, and Fig.1 illustrates the comparison relationship between them.

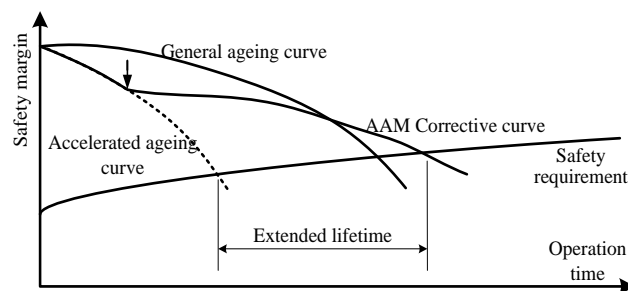


Fig.1 Comparison Relationship between Accelerated Ageing and General Ageing.

For components suffering from accelerated ageing, the degradation speed is much higher than that under general ageing. Therefore, based on Fig. 1, we can say that the actual service lifetime of components, which suffered from accelerated ageing, is much lower than the one observed for components subject to general ageing. It should be noted that, as the uptime grows, safety margin requirements for NPPs from the public increase year by year. This is the reason for the upward slope of the safety requirement curve.

Previous practice showed that the comprehension of ageing mechanisms and the correction of the ageing curve of components could provide a way to manage components' ageing and extend their operational lifetime. As the little arrow shows, after the implementation of effective AAM strategies, the ageing tendency of components "alters orbit" to the corrective curve. In this manner, lifetime extension and safety margin level requirements are obtained.

As with ALM, the objectives of AAM include managing equipment ageing problems effectively, and improving their reliability and availability. What is different with ALM is that it places an heavy emphasis on lifetime extension of major components and total lifetime cycle management, whereas AAM emphasizes the management of components, which are susceptible to ageing and are expected to face accelerated ageing because of the actual condition of specific NPPs. AAM can cover these components, which are not managed by ALM. Combining ALM and AAM, it is possible to fully carry out equipment ageing management and comprehensive lifetime management.

2.2 Research objects of AAM

AAM originated from research on NPP, for which approaches are likely required. Experience Feedback Systems (EFS) record almost all the operation-related abnormal events during both routine operations and overhauls, which is the main source for the screening of AAM research subjects. Besides that, inspection and detection results from operation personnel, maintenance note from maintenance personnel, and so on, should also be taken into account. All the events are screened by the research team periodically. And then, those that are identified as belonging to accelerated ageing-related issues and necessitate in-depth studies are put in the list of AAM research objects. Decisions are then made to assess the impact of these measures on plant safety, expected sensitivity to ageing of components, spares availability, expected obsolescence, and other economic aspects. Some analytic approaches may be used in component selection, including analysis on O&M data, expert judgment approach, and probabilistic analytic technologies, such as probabilistic safety analysis (PSA). It is certain that the process would be influenced to some extent by the attitude of the management team of plants.

In addition to follow-up researches on tracking internal experience feedback, investigations on external experience feedback on ageing management also provide an important source for AAM research objects. It is a useful way to realize “predictive management” on AAM by collection, classification, analysis and application of external experience. Information was gathered from external organizations including IAEA, EDF, EPRI, Nuclear Regulatory Commission of U.S.A (NRC), WANO, INPO, and NPPs all over the world, among which some conventional power plants contained the same or similar equipments. On the one hand, external experience provides direct references for AAM; on the other hand, external experience provides a way to find out potential and undiscovered accelerated ageing problems in NPPs in time, and make proactive management in NPPs. In 2008, while an emergency shutdown of a reactor occurred in Daya Bay unit #2, two R control rods failed to fall into the bottom of reactor as a result of radiation induced swelling; this was classified as internal operation event (IOE). In

fact, events of the same kind took place in EDF NPPs two years before and some corresponding management strategies were developed. In other words, because of the lack of research on external experience, a serious event which could have reasonably been avoided actually happened. This example shows how external experience feedback plays an important role in AAM.

3 Methodology of AAM

3.1 Technical routine of AAM

The general process of AAM consists in the following steps. First, a screening of both internal and external ageing management experience feedbacks is done. Afterwards, important and susceptible components are selected and comprehensive data is gathered. Consequently, failure mode, effects, and criticality analysis (FMECA) and ageing tendency analysis are carried out to identify accelerating factors. Accelerated ageing mechanisms are then analyzed and the status of related components is evaluated to finally develop AAM strategies. In order to ensure the efficiency of the corrective activities, it is necessary to follow the application on the field, and in return produce feedback to upgrade the AAM strategies. Figure 2 shows the technical routine of AAM in Daya Bay nuclear power base.

Main procedures of AAM will be introduced as follows:

3.1.1 Acquisition of relevant data

Relevant data about components used in AAM includes field data, basic data, and O&M procedure data. All the data should be integrated in the researches on the management of accelerated ageing issues.

(1) Acquisition of field data

- a) Service environment parameter should be collected, such as temperature, humidity, atmosphere, vibration and irradiation;
- b) Service conditions should be collected, such as state and quality of fluid in pipelines, actual usage rate, and number and alteration frequencies of reluctant series;

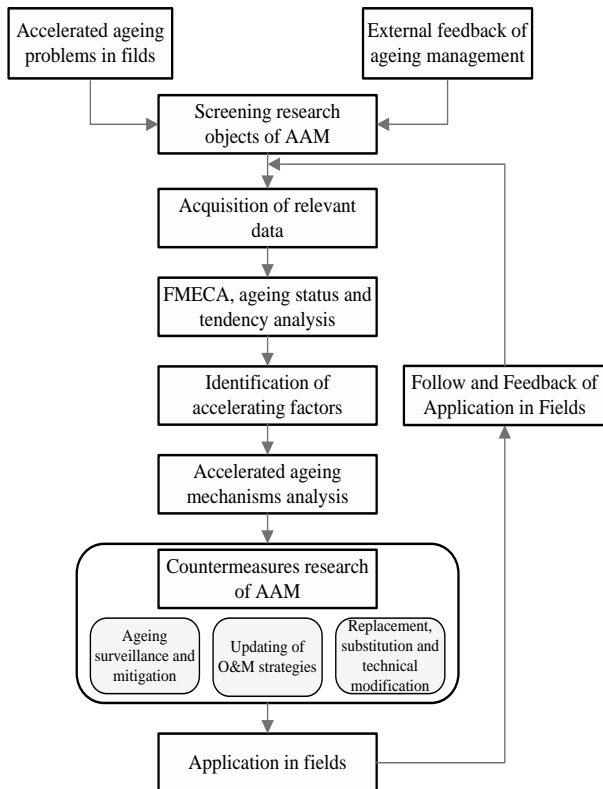


Fig.2 Technical Routine of AAM.

c) Data about ageing-related phenomena in fields, such as images, written records, samples of components failures should be collected. If possible, the causes and processes of events should be recorded, and preliminary analysis and corrective actions should be performed;

d) Historical O&M data should be collected, such as historical failure records, maintenance records, condition monitoring records, deviation and constant.

(2) Acquisition of basic data

Basic information about components mainly come from equipment operation and maintenance manuals (EOMM), which are provided by vendors of equipments, and system design manual (SDM). The useful information include material, manufacturing process and accuracy grade, design service environment parameters, service condition, design lifetime, function and functional failures of system and components, *etc.*

(3) O&M procedures data

Operation standards, maintenance program, maintenance procedures and relevant technical documents are the objects of optimization after AAM

analysis; therefore, all those should be collected and studied.

3.1.2 FMECA, equipment ageing status & tendency analysis

Failure Mode, Effect and Criticality Analysis (FMECA) can be used in correspondence with accelerated ageing-related failure modes, including research on the effects of ageing degradation on systems and plants, and serve to determine the criticality of each component and sub-system by considering the severity and probability of failure modes. FMECA helps to find out the dominant accelerated ageing failure modes, and results of this analysis assist in formulating the subsequent propositions of management strategies. In parallel, the achievements of relevant researches or work, for example, Reliability-centered Maintenance (RCM), Critical Component Management (CCM) and Probabilistic Safety Analysis (PSA)^[9] could support FMECA.

The objective of equipment ageing status and tendency analysis is to get general knowledge on the current ageing status of components, and predict the development trends in future. Ageing related events are statistically analyzed, and the accelerated ageing tendency curve is drawn by curve fitting.

3.1.3 Identification of accelerating factors

Accelerating ageing factors represent stresses that impact on components and result in their accelerated ageing. The identification of the dominant accelerating factors is needed to design corresponding measures for controlling and eliminating these stresses. Based on relevant studies, the major types of accelerating ageing factors were identified as the following ones:

(1) Design factors: ill-conceived design may happen at the design stage, such as a poor choice of material or connecting structure type, unreasonable design of install location. These deficiencies may cause accelerated ageing during operation;

(2) Environmental factors: if actual service environmental parameters such as temperature,

humidity, corrosion, or radiation go beyond the scope of what was allowed in the design files, accelerated ageing usually takes place in components. Based on relevant research experiences, the environment and conditions of service are the major causes of accelerated ageing problems, and environmental factors affect the lifetime distribution of components very much. Distinctive areal characteristics of different NPPs could be distinguished by their influence on the ageing or accelerated ageing of components;

(3) Manufacturing process and quality assurance (QA): this includes substandard machining precision or QA gradation and wrong choosing of face processing methods, and so on;

(4) O&M factors: imperfection in the operation standards, the maintenance program, or the maintenance procedures may result in a lack of effective surveillance and control for accelerated ageing. Human errors in O&M activities are also one of the causes of accelerated ageing problems.

3.1.4 Accelerated ageing mechanisms analysis

Based on international experiences, in order to understand the failure laws and ageing mechanisms of accelerated ageing issues in-depth, numerical simulation analysis and experimental investigations should be combined to make clear how the accelerating factors affect components and to find out the breakthrough points for AAM. For revealing the essential laws underlying accelerated ageing phenomena, support from experts and research organizations on material and ageing would be needed on some occasions.

3.1.5 Countermeasures research of AAM

The ultimate goal of AAM is to establish some effective countermeasures, which are defined as management strategies, to control the ageing of systems and components under an acceptable level and meet the requirements in term of safety margin level in NPPs. AAM strategies include three aspects as described below:

(1) Application of ageing surveillance technology: based on condition monitoring, in-service inspection and periodical test, *etc.*, potential ageing development trends of components are sought, and timely preventive activities to control and mitigate the speed of ageing are taken;

(2) Updating of O&M strategies: through an update of the operation standards, the maintenance program and the maintenance procedures, the inspection and maintenance methods of important and susceptible components are enhanced, and eventually accelerated ageing issue in O&M process can be managed effectively.

(3) Replacement, substitution and technical modification: on some occasions, giving comprehensive consideration to some aspects, it may be necessary to perform replacements, substitutions and technical modifications. Besides that, it should be noted that improvement on the environment and conditions of service is also necessary.

3.1.6 Follow and feedback of application in fields

Application processes and effects of AAM strategies should be followed and feedback should be given in time, to allow dynamic adjustments to the accelerated ageing analysis process, and adapt AAM to get the best effect.

3.2 Interfaces with existing O&M systems

Figure 3 indicates interfaces between AAM work architecture and existing O&M systems. It shows that, besides of internal and external experience feedback, relevant work architectures and achievements also provide considerable supports for AAM, such as ALM, RCM, PSA, CCM, root cause analysis (RCA) and EFS. Supports of knowledge and technicians include AAM special team, O&M personnel in NPPs, and supports from experts and research organizations on material and ageing, and reliability methods. Besides that, on some occasions, suggestions from nuclear safety authorities and vendors of equipments should be taken into account too.

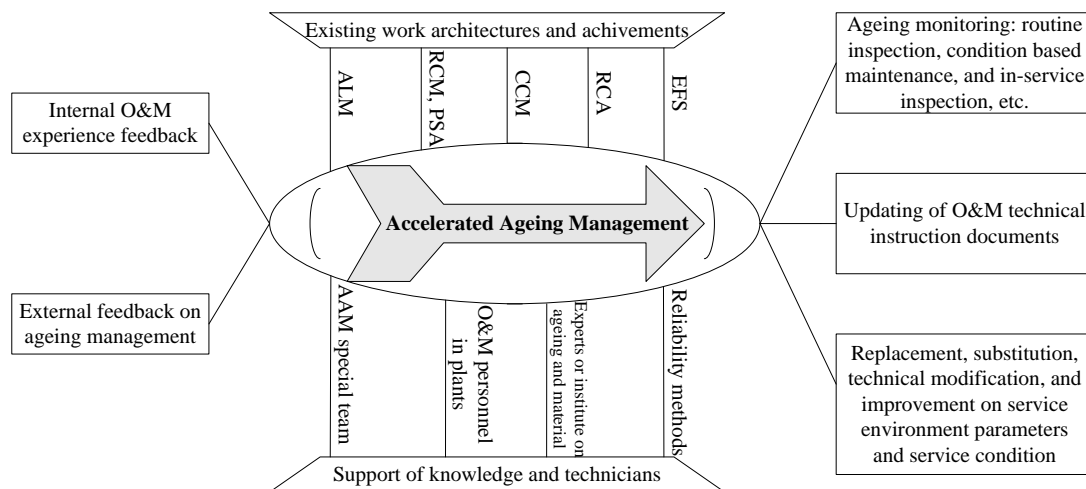


Fig.3 Interfaces between AAM work architecture and existing O&M systems.

Examples of relevant O&M systems to be integrated into the AAM include:

- Preventive maintenance program;
- In-service inspection, surveillance, testing and monitoring programs;
- Data collection and record management programs;
- Equipment qualification program;
- Chemistry program;
- Operation procedures;
- Feedback of operation experience, analysis of significant events and research programs;
- Spare-parts program.

4 Examples of application of AAM in Daya Bay Nuclear Power Base

4.1 Ventilation system

The function of the ventilation system is to provide an appropriate environmental condition for the safe work of personnel and the normal operation of components, as well as to restrict the discharge of polluted gas. Failures of equipments in the ventilation system may result in serious effects such as the damage of electrical equipments or the release of radioactive substance. Many events arise in turbine hall ventilation system (DVM), electrical building main ventilation (DVL) and auxiliary nuclear building ventilation (DVN) in Daya Bay nuclear power base. Using statistical analysis on the number of ageing related events in the ventilation system of Daya Bay NPP, we found out that the number has almost been increasing year by year as shown in Fig. 4. On the field, some ventilation fans, doors and plates, pipelines and cooling coils have

suffered from serious corrosion and even perforation in some local parts, which reduced the efficiency of ventilation system. In fact, the lifetime of the major components of the ventilation system is 40 years; that is to say, ventilation systems in both plants are suffering from accelerated ageing, and the situation is getting worse with time.

Daya Bay nuclear power base is located on the subtropical coast. Taking this into account, we can deduce that some characteristics of the environment in which the ventilation is used include high humidity, high temperature, and corrosive atmosphere. Field data shows that there exists condensing water around the flange of cooling coils, as well as humidity and white corrosion products in local parts of pipelines and doors. From the composition analysis of condensing water around some cooler, we could learn that the content of Cl^- was 1189 ppb, SO_4^{2-} was 6328ppb, and F^- was 111ppb, meaning that the contents of Cl^- and SO_4^{2-} were too high. The composition analysis of the corrosion product found inside of the ventilation pipelines indicated the presence of Cl and some metal elements, such as Na, Mg, Al, *etc.* (i.e. metal salts) (Fig. 5). This demonstrates that, in Daya Bay, a corrosive saline-alkaline wind exists, which is the dominant factor of accelerated ageing of ventilation systems. Furthermore, condensing water and corrosion products promote the deterioration and degradation of components.

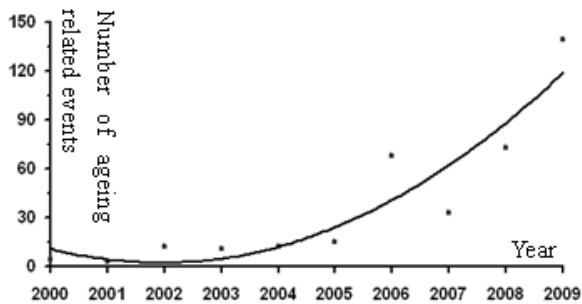
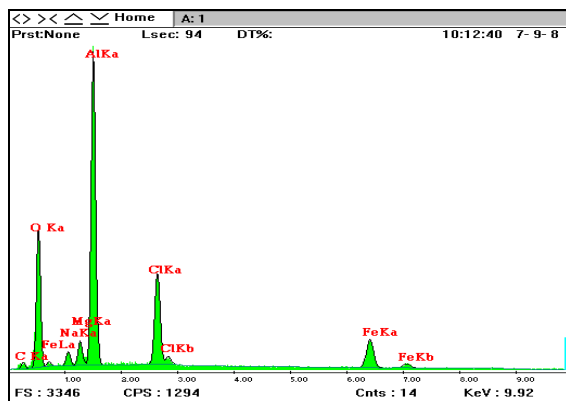


Fig.4 The number of ageing related events in the ventilation system of Daya Bay NPP increases from year to year.



Standardless			
PEI User Set : 2, Elements			
Element	K Ratio	Weight %	Atomic %
C K	0.0151	1.506	2.790
O K	0.4172	41.719	58.033
NaK	0.0127	1.265	1.225
MgK	0.0216	2.162	1.980
AlK	0.2776	27.765	22.901
SiK	0.1255	12.553	7.880
FeK	0.1303	13.030	5.192
Total		100.000	100.000

Fig.5 Results of the material composition test of the corrosion products found inside the ventilation pipelines.

In order to deal with the accelerated ageing of the ventilation system, countermeasures recommend enhancing visual inspections of the ventilation pipelines, cleaning the corrosion products and condensed water in time, placing emphasis on internal inspections of pipelines, and carrying out ageing surveillance and mitigation. Referring to management experiences on ventilation systems in American NPPs, it is suggested to add anticorrosion coating to wind pipelines and doors for improving the resistance to corrosion.

4.2 Cylinder Water Jacket of the Emergency Diesel Generator^[10]

The emergency diesel generator is an important standby power supply in NPPs. It supplies power

during losses of offsite power supply as well as emergency safety shutdowns of the reactor, and it protects key equipments from damage. The cylinder water jacket is installed between the cylinder head and cylinder block to form a cooling water channel. If an ageing failure occurs in the water jacket, the cooling water will leak. This results in an insufficient cooling ability, and reduces the reliability and safety performance of EDG. In recent years, several events in Daya Bay NPP and Ling'ao NPP show that ageing related issues have taken place as common mode failure in the form of cooling water leakage in EDGs.

The material of the water jacket is fluoros rubber (pvdf-hfp copolymer), which is a kind of ageing-resistant polymer with stable performance. The water jacket is supplied by the same vendor of EDG from France, and the design lifetime is 8~10 years. However, the actual replacement cycles at Daya Bay nuclear power base are much less than the design lifetime given by the vendor. From statistical analysis, the calculated actual service lifetime is only 2.78 years. This indicates that accelerated ageing has occurred on the water jackets of the EDGs in Daya Bay base.

Through detailed analysis, it was found that the weak miscibility between fluoros rubber and promoter in French water jackets is the root cause. As a result of the weak miscibility, the internal balance and stability of the fluoros rubber is destroyed under stresses of temperature and pressure during storage and operation, and then stiffen, bubble, chap, delaminating in short service time, and the loss of sealing performance at the last. Degradation of water jackets would reveal under higher temperature and vibration in periodic tests, and take the form of leakage of cooling water. The dominant accelerating factor of the events is the wrong usage of additive in the manufacturing process of water jacket.

Corresponding management strategies include the alteration of the replacement cycle of the water jackets, which should be adjusted for Daya Bay NPP and Ling'ao NPP from respectively 4.5 years and 6 years to 3 years, the implementation of research on the localization and substitution of water jackets,

which is to be done through cooperation with famous domestic research and manufacture organizations to develop new substitutes, including the improvement of the manufacturing process and the optimization of material composition. Test results of a comparative study between domestic and French water jackets indicate that the performance of domestic water jackets is evidently better than the original. The estimated lifetime of domestic water jackets is more than 8 years against 2 years for the original. Considering this test results, further trial operations for domestic water jackets in the field was launched to demonstrate their applicability for EDGs, and provide support to determine whether to implement a total replacement of water jackets. The research provided a solid base for thoroughly solving the issue of the accelerated ageing of the cylinder water jacket. At the same time, collection and feedback of relevant information would help for the continuous improvement of the reliability of EDGs in Daya Bay nuclear power base.

5 Development prospect of AAM

As the AAM of important and susceptible components is still under development, the scope of AAM in Daya Bay nuclear power base will be enlarged as more and more accelerated ageing problems are to be investigated and managed. At the same time, we seek to facilitate and enhance the combination of AAM with O&M, ALM, *etc.*, to prevent any type of accelerated ageing of important and susceptible components in advance and control them.

As a management technology, there exists great space for improvement for AAM, for example:

- a) Enhancing the application of reliability methods, and strengthening quantitative study support for AAM;
- b) Developing ageing detection technologies, ageing mechanism analysis methods and residual lifetime evaluation models;
- c) Accumulating AAM experience data, developing data acquisition platforms and databases;

- d) Developing computerized analysis systems.

AAM for important and susceptible components will play a more important role in the reasonable, effective and continuous improvement of equipment management, and contribute more and more to the safe, reliable and economical operation of NPPs in the future.

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