Status of Research Project "Incorporating Ageing Effects into PSA"

Presented at Ageing PSA Workshop, Budapest, 15-16 November 2007

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Objectives

The main objective of this paper is to give an overview of the current status of Ageing PSA research project in the Canadian Nuclear Safety Commission (CNSC) to the Ageing PSA Network participants. We will share preliminary results, methodologies used, lessons learned, and identified issues. In such a way we contribute to the international exchange of information on this complex topic. We believe that this will help to coordinate the Network activities and efficiently use joint resources and experience to obtain at the end useful results for international nuclear community.

Background

PSA is a recognized tool for risk-informed decision making in the nuclear industry. However, it lacks mature methodologies for addressing ageing effects. Implementation of such methodologies promises significant benefits in terms of efficient risk management through a better understanding of risk profile evolution during the plant life and variation of importance measures with the age.

Ageing PSA has several specifics:

1. It is a complex study involving multiple disciplines and extensive operational and experimental data.
2. Presently, many ageing phenomena are not fully understood and described mathematically.
3. New materials and devices are replacing old ones during the plant life and may have different degradation mechanisms, often difficult to predict because of limited operating history.
4. Some new devices introduced at NPPs are more and more complex (e.g., digital control systems), introducing new potential for degradation mechanisms.
5. Operating experience continuously gives a direct feedback to ageing management activities, improving them as soon as new knowledge appears. However, the effect of these modifications in the ageing management practice on the ageing trend is not evident. This creates difficulties with using historical degradation data for prediction of future performance.

All the above aspects drive the major difficulties in implementing the Ageing PSA, such as significant resource intensity and uncertainty in the prediction methodologies. Thus, the cost-benefit is an important factor in this exercise.

It is expected that the major part of resources will be required for development of basic prediction methodologies using reliability physics models. This stage may need extensive experiments and data treatment. Parts of the knowledge are created in different organizations worldwide but there is no integrated vision on the Ageing PSA method. A complicating factor is a lack of consistent data on different degradation mechanisms at the plants due to the fact that reliability data collection was not specifically designed for APSA purposes. In this situation, we believe that a wide cooperation and sharing of information is essential for creating a critical core of APSA methodology.

Canada has currently only one nuclear power technology - CANDU reactors. Although they have some unique design specifics, they share also common features that can be found in other designs. Taking this into account, CNSC concentrates its efforts on CANDU technology to address its current needs, but believes that can contribute to the international efforts in the common areas.

Project Overview

The Ageing PSA research project has been started in CNSC in 2006 to address our concerns with the efficiency of ageing management activities at the plants and efficiency of our regulatory oversight.

The project has been planned for three phases, one year each, with the following high-level objectives:

Phase 1:

- Collect plant ageing data and available to date APSA related methodologies;
- Identify SSCs-candidates for APSA case study;

Phase 2:

- Develop typical time dependent models for selected SSCs taking into consideration effect of ageing management activities;

Phase 3:

- Perform a case study APSA (CANDU generic), evaluate sensitivity and importance effects of different time-dependent models;
- Evaluate cost-benefit and identify needs for additional researches and data;
- Make regulatory decisions.

Taking into account complexity of the subject and a significant number of unknowns, we do not expect to develop by the end of the project final and perfect methodologies, but rather to fill in the major gaps, evaluate a potential impact of ageing and ageing management activities on PSA results, understand associated issues, and identify needs for further researches and/or regulatory actions.

Currently, we are performing Phase 1 of the project. This phase includes the following tasks:

1. Collect and systemize information on similar researches, data, and available methodologies worldwide;
2. Collect ageing related data at Canadian power plants, identify trends of ageing impact on SSCs failure rates;
3. Perform a systematic review of SSCs using the data from previous tasks, plant design documentation, Safety Analysis, PSA, maintenance and ageing management programs, etc., and identify SSCs safety significant from ageing point of view - candidates for APSA.

The work in Phase 1 is performed jointly by Martec Limited, Halifax, NS; and Harve Sills and Associates Inc., Deep River, ON. Also contributing to the study is a panel of subject matter experts (SME) comprising of Prof. Mahesh Pandey of University of Waterloo, ON; Prof. John Luxat of McMaster University, Hamilton, ON; Prof. Rick Holt of Queen's University, Kingston, ON; Dr. Curtis Smith of Idaho National Laboratory, Idaho Falls, ID. CNSC provides funds, documentation, help with access to plant data, general technical guidance and contributes to the work through participation of its specialists in related areas of expertise.

Task 1 - Collect information on similar researches, data, available methodologies

Status

The major work in this phase has been finished with more than 300 sources of information having potential use in APSA being collected. This information passed a preliminary treatment to assess relevance of each item to the subject and prioritize their potential use.

Further in-depth review of selected references has been performed to identify:

- generic degradation mechanisms and their effect on SSCs performance,
- ageing management strategies,
- available ageing reliability models,
- available APSA methods, and
- relevant data and data requirements.

The intention of this exercise is to develop a reference database with a quick access to information sources, methodologies, and data indexed by specific APSA topics. This database will be expanded during following tasks, when new relevant information is obtained, and will be used as a source of methodology and data for this research project and other ageing related CNSC activities. In such a way, we expect to direct our resources on issues not covered yet in the overall APSA approach and obtain maximum value from funds used.

Preliminary Results

The information collection exercise demonstrated that while many reports are available on ageing of NPP Systems, Structures and Components (SSCs), fewer studies have addressed specific APSA methods. Nevertheless, several studies on generic components that should be included in APSA have been performed. This will significantly help in identification of plant specific SSCs. Utilities developed basic principles for prioritizing components for ageing management activities. These principles can be adapted for APSA needs. Finally, several generic methods have been developed for modeling degradation mechanisms in major NPP equipment. There are a few of them that can be directly used in APSA, but most of specific models will require significant additional efforts.

Overall, a valuable reference database including APSA-related methods and data has been assembled.

Task 2 - Collect ageing related data at Canadian NPPs, identify ageing trends

Status

The data collection task has been performed at Bruce Power, New Brunswick Power, and Ontario Power Generation sites covering in total experience from 21 reactors.

The collected data include:

- reliability data and reliability reports,
- ageing and life-cycle management programs,
- plant condition assessments,
- SSC health reports,
- environmental qualification reports, etc.

Since plant operators do not collect reliability data in the format readily applicable for APSA purposes, maintenance records have been reviewed for a limited number of components to assess quality of the information available for APSA purposes, and resources required to present the data in a format that can be easily used in APSA.

Preliminary Results

The project found multiple useful data and studies collected and developed by plant operators for their ageing management programs. These data and studies do not perfectly fit to the project purposes, but in many cases they provide a good approximation for a case study. Currently, we are identifying potential deficiencies of data used, and leave them for later consideration if they do not affect significantly our expectations. This is driven by limited resources of the project and the fact that we don't know now where the best benefit from the work can be obtained. For instance, it may be proved that detailed modeling of some of ageing issues is not cost effective and it is better to continue the current ageing management practice. If results of the project demonstrate a need to improve some parts of the input used in the project, we will do it later having already a good understanding where improvements are required.

Below, we present some of power plant studies, data, and practices that were assessed for their applicability and eventually used in the project.

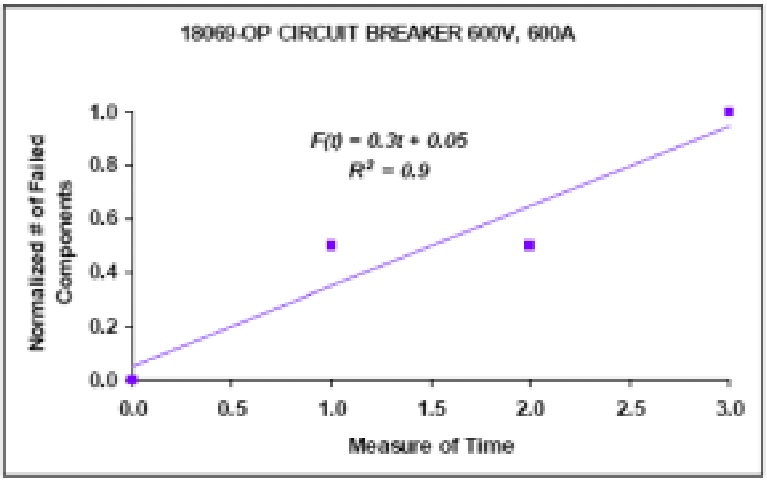
Trending of Ageing Effects at NPPs

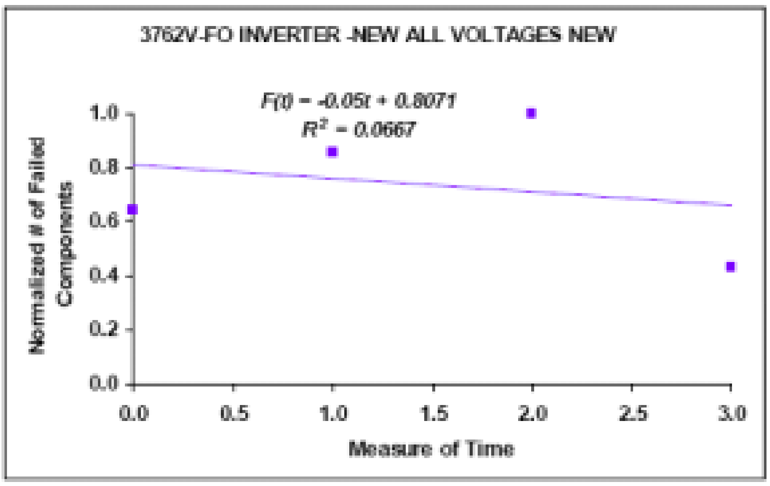
Plant operators in Canada survey performance of systems and components both as response to requirements of CNSC standard S-98 "Reliability Programs for Nuclear Power Plants" and as their own initiative for ensuring plant safety and economic performance. However, the reliability trending is usually designed to answer emerging issues and, therefore, is limited in time. For instance a typical trending for active components degradation may use a last four years moving average for observed component groups. For decision making, data points are normalized by maximum number of failed components to obtain numbers between 0 and 1, and linear trends are fitted into plots.

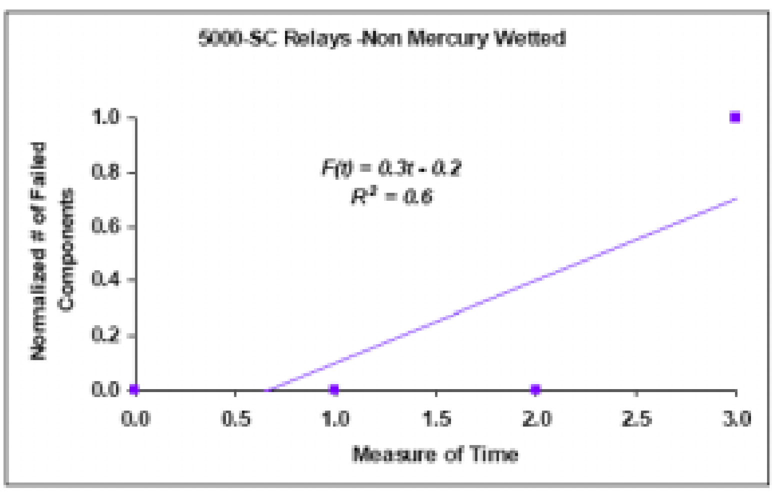
As a result, the trending reliability data may take the form as presented in Table below.

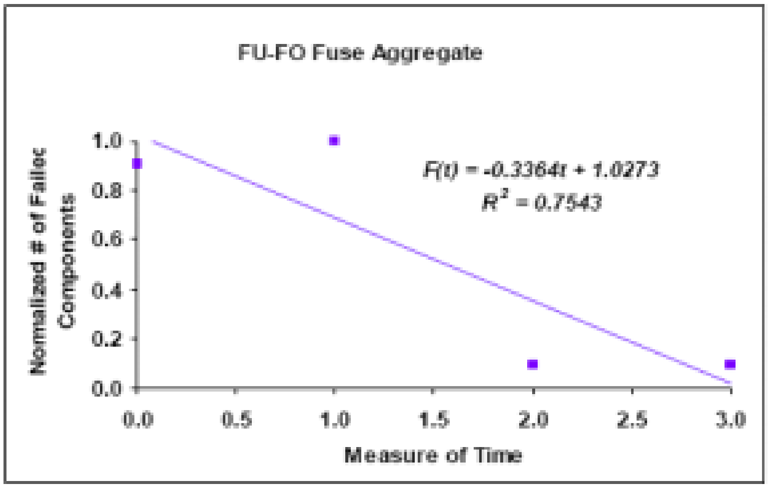
Group	Description	Year				Number of components
		1	2	3	4	
18058-SO	Circuit Breaker - 4.16 KV, 3000A	1	1	1	2	22
18069-OP	Circuit Breaker - 600 V, 600A	0	1	1	2	89
3762V-FO	Inverter - New - All Voltages	9	12	14	6	8
5000-SC	Relays - Non Mercury Wetted	0	0	0	2	198
5100-SC	Contacts - Relay - Composite - Non-MWR	1	3	2	2	2253
6899-EP	BOP Valves - Manual <= 2"	0	1	3	3	244
8020-LP	Controllers - Electronic	2	2	0	1	52
8330-SC	PROC Switches - Level	0	1	2	3	48
8360-SC	PROC Switches - Pressure	0	2	4	4	72
99SG-SF	Standby Generator - 7 MW	19	32	33	22	6
99THS-SO	Process Switches - Thermostat - Composite	0	0	1	2	11
B4311PA-SF	BOP Pump - PA Centrif. Horiz.	0	0	0	2	20
B6802AH-CP	Valves-BOP - Butterfly >=12"<=24"	3	3	3	0	24
B6804BA-OP	BOP Valves - Gate Motorized <=2"	0	0	4	5	56
EPG-SF	Combustion Turbine - Emergency Power Generator	5	8	8	10	2
FU-FO	Fuse - Aggregate	10	11	1	1	1946
FU-VP	Fuse - Aggregate	1	1	1	4	501
GR137-SO	Relay - Time Delay - ECI D2O Injection Valves	2	5	4	3	56
GR13-LP	Amplifier - SDS1 ROP	5	6	3	2	136
GR14-LP	Amplifier - SDS2 Ion Chamber	0	1	2	2	12
GR14-VP	Amplifier - SDS2 Ion Chamber	3	4	3	3	12
GR167-SO	Damper - NPC Box-up (8,20,24 inch)	0	1	2	4	52

Resulting plots may look as follows.









These plots provide a simple tool for monitoring short life active components having a sufficient number of testing data during a year. They allow to quickly identifying unpredictable degradation trends and timely initiate corrective actions. However as it is seen from the plots provided above, the linear approximation does not always fit well into data points and the simple direction of the line to the increase or decrease of component reliability may not be convincing. Therefore, some additional interpretation is required. This is related, for instance, to the fact that during the same year there may be components in the same group with different age and slightly different maintenance history and operating stressors. Also, the testing and maintenance practice may change from year to year depending on new operating experience and this may impact the behavior of data points.

The approach may not be wrong for trending at the system level, because performance of the whole system is defined by performance of all, often highly redundant, components and their different age and maintenance history partially eliminates the common cause effect. However, this restricts the use of such trending for APSA screening or modeling purposes.

The limited number of data points does not give a full variation of component reliability over plant life. Furthermore, it does not give the trend over the component life and does not discriminate failures due to different degradation mechanisms and impact of testing and maintenance. Thus, it does not provide a tool to identifying degradation trends. Therefore, we used this data in the project only as an additional plant specific weighting factor for selection of APSA case study SSCs, but with the prevalent reliance on other plant data, generic data, and expert opinion.

One important point to consider is that this trending practice with an immediate feedback to surveillance activities:

1. Covers unknown degradation mechanisms;
2. Impacts the accuracy of prediction if a model has been developed with predefined surveillance activities (the feedback may change the modeling assumption);

3. May maintain the component reliability virtually constant over the plant life with some yearly fluctuation around the basis level.

The last consideration may be an important factor for screening components out for APSA purposes, because uncertainties of prediction models may be comparable with the range of the reliability fluctuation and, therefore, the significant additional efforts for modeling may not be justified.

Plant Condition Assessments

Plant condition assessments have been developed by some Canadian utilities as part of Integrated Ageing Management (IAM) Program required by CNSC. Usually, they are also closely linked to the life extension projects and associated Integrated Safety Review, which explicitly requires a report on actual condition of the plant. Plant condition assessments typically include System Condition Assessments (SCA) and Component Condition Assessments (CCA) and evaluate ageing management criticality for plant systems and components.

System Condition Assessments we used in the project were developed for approximately 60 systems per plant. They typically identify:

- existing testing, surveillance, and maintenance practices;
- ageing concerns;
- mitigating measures;
- practices required to reach current plant end of life and for life extension;
- replacement and refurbishments required.

These are extremely useful sources of information and references to more detailed data for the project purposes. However, they do not contain any probabilistic prediction of system reliability trend over the plant life. The basic approach used is "Fit-for-service".

Component Condition Assessments provide similar information on the component level. They consider components by commodity groups including same component type with same environment/operating conditions and same AM practice. About 400 commodity groups may exist per plant covering passive and active, long life, medium life, and short living components.

A typical Component Condition Assessments includes:

- Component type and class;
- Physical description, purpose and function;
- Component ageing management criticality and consequences of failure;
- Ageing damage and degradation mechanisms;
- Component stressors;
- Effects of ageing damage;
- Current component conditions;

- Current ageing management practices;
- Adequacy of current ageing management practices for component end of life and life extension;
- Obsolescence issues;
- Cost and schedules.

Typical summary information extracted from a Component Condition Assessment may be as presented in the following table.

Component Class/ Associated System and Remarks	Component	Ageing Damage Mechanisms	Stressors	Possible Ageing Effects	Ageing Maintenance Practice
Power and Control Boiler Steam and Water Systems - Cables 4.16kV, 600V, 125V, 250V, 120V Passive Component No time ageing analysis to predict performance or failure of component Cables given same critically value as load or system they support Dec 2006 practice Expected life of 30years	Cables	Fatigue Mechanical fatigue cable insulation breakdown Thermal ageing	High and low temperature Electrical - high resistance bolted connections in loose circuits	Decreasing dielectric and physical properties of the cable, insulation and jacket materials Localized heat due to faulty termination Cable loss could result in associated equipment being out of commission for a long time	Current AM practice is to monitor and test cables (NIR and qualification) to determine condition of insulating materials for various cables. For this system very little has been done. Component is not expected to reach end of life with no AM. Current AM practice is not considered sufficient. Additional AM practice suggested: One time Inspection at termination of motor boxes, panels and cable splices. NIR testing should be performed for samples of cables not just EQ or Safety related ones. No current industrial practice to predict when cable will fail and it is suggested that a cable-test database be maintained. Practices Suggested for 25 years life extension: Replacement of certain safety system cables may be required based on testing and inspection (Total replacement not considered economical).

This information was considered as well to be extremely useful for the project purposes, but again no reliability based prediction models have been found.

Ageing Management Criticality Assessment

One of important inputs we used in our project was the SSCs ageing management criticality assessment. This assessment has been performed by some plants as part of plant condition assessment and integrated ageing management. It typically takes into account reactor safety, economic performance, and conventional safety. We considered in our project only SSCs identified within the reactor safety list of the overall criticality coding. This list was generated using several inputs, such as:

- Probabilistic Risk Assessment;
- Fire Safe Shutdown Assessment;
- Code Classification List for Nuclear Safety Components;
- Seismic Margin Assessment;

- Operational Safety Requirements;
- Environmental Qualification.

Both probabilistic (e.g., FV and RAW) and deterministic criteria have been used for this process.

The ageing management criticality evaluation considered current condition of the component, duty cycle, environment, efficiency of current ageing management practice and a need for additional ageing management activities.

Although the criticality assessment has several deficiencies with respect to APSA application (e.g., consideration if initiating events), it is a good approximation for use in a case study.

Life Cycle Management (LCM) Reports

These reports have been developed by plant operators within the framework of Integrated Ageing Management programs as response to CNSC requirements and for economic operational needs. Usually, LCM reports are provided for major components such as steam generators, fuel channels, feeders, etc. A typical LCM report contains:

- CANDU specific degradation mechanisms;
- Material properties;
- Modeling of degradation (mostly deterministic);
- Ageing management plans, strategies and activities.

These reports may be very useful in subsequent phases of the work, because they include a significant amount of information, which can be used for modeling purpose. At this stage all components having LCM have been included into APSA scope based on their importance for safety and plant life-limiting status. Another important consideration is that for all these components, LCM is extremely costly. Therefore, there is a good chance for obtaining a substantial benefit from APSA results through optimization of the LCM activities.

Environmental Qualification Reports

The components requiring environmental qualification have specific EQ programs to qualify the components and to maintain their qualification during the plant life. Usually, the EQ reports include a significant amount of information on degradation mechanisms, experimental and analytical work related to modeling of ageing progression, accelerated ageing experiments, evaluation of component life, etc. The modeling and conclusions are deterministic by nature, but the supporting information may be extremely useful for probabilistic modeling purposes.

System and Component Health Reports

System and component health reports are prepared quarterly at Canadian NPPs and provide information regarding the health of the various systems and components using plant specific performance indicators. These reports contain information on performance evolution of systems and components, major issues impacting the system and component reliability, and proposed solutions for improving the performance. This information can assist in screening SSCs for APSA purposes.

Reliability Data Bases

Plant reliability data bases have been reviewed to understand their applicability to the APSA purposes. The preliminary conclusion is that the available statistical data do not contain information required for sound degradation modeling or extraction of such information may be difficult. For instance:

- The failure data is usually averaged for a component type in plant year. This does not take into account the component specific age, maintenance, and operating stressors. Thus, a correlation of the failure rate with age-dependent degradation trends may be irrelevant.
- It may be difficult to associate a particular failure with a specific degradation mechanism. Although the failure causes are recorded, they are not consistently presented in the database for automatic search and treatment purposes.
- Ageing management activities and operating stressors have a determinative impact on degradation trends. However, it is difficult to extract all necessary information to model such impact, because appropriate records are not incorporated in the reliability database and are kept separately, for example as maintenance programs and records. Tracking maintenance and operating history to each specific component may require significant data processing efforts. Without such treatment, the statistical modeling may not be accurate.
- Reliability data bases provide actual failures and not cases of degradation, which are more relevant for APSA. As a result, the data do not represent the degradation trend, but the trend of combination 'degradation plus ageing management activities'. In this situation, optimization of the ageing management is questionable using such data.

Taking into account the above issues regarding the actual configuration of reliability databases, there may be the following preliminary thoughts on database requirements for APSA:

- The database shall store:
  - surveillance, testing, operating stressors, and maintenance history for each component,
  - failure and degradation history fore each component,
  - measurable parameters of observed degradations.
- The database shall have sufficient resolution to capture specific degradation mechanisms and the degradation mechanisms shall be documented in a consistent searchable form;
- The database shall be able to produce reliability parameters:
  - by plant age,
  - by component age,

  - by degradation mechanism.
- The database shall provide analytical tools to correlate surveillance, testing, operating stressors, and maintenance history to observed degradation mechanisms.

We believe that if such databases are created and maintained at power plants, they may provide a significant benefit for reliability trending and optimization of ageing management activities.

Maintenance Records

Since it was found that the reliability databases do not provide information ready for APSA parameters evaluation, it was decided to perform a limited search of maintenance records for several selected components. Potentially, maintenance records should contain all necessary data, but it was found that the records are not sufficiently well documented for this purpose. For instance, there is no predefined list of degradation mechanisms to perform a simple extraction of necessary records, degradations discovered are described in a free form incompatible with automatic data treatment, the degree of the degradation is not evaluated, etc. This means that a significant amount of data processing including interviews with personnel and interpretation is required to obtain the required data format. This is not practical in the framework of this project.

Preliminary Conclusions

The data collection exercise demonstrated that there is little information that can be directly used for APSA purposes without significant additional treatment. The major reason for this is that current reliability data collected for standard PSA and other data used at plants, for instance, for ageing management activities, are not intended for time-dependant reliability prediction. APSA needs specifically collected and configured data to account for degradation progression (not only failure rate) as a function of component life, operational stressors, and surveillance activities. Power plants do not usually store all this data in easily retrievable format. As a result, the exercise of APSA data collection is very resource intensive and the output is not always what was desired. Additional data collection, researches, experiments may be required for developing a credible APSA.

Task 3 - Identify SSCs - candidates for APSA

Status

This task is now in progress. The status of detailed activities within the task by the date when this paper was prepared was as follows:

- A generic CANDU hierarchical list of safety related SSCs has been developed;
- A generic list of degradation mechanisms has been developed;
- Survey documents for subject matter experts (SMEs) have been prepared and reviewed;

- Phenomena Identification and Ranking Tables (PIRT) and ranking criteria have been developed;
- Expert elicitation workshop with participation of SMEs and CNSC staff has been held on October 2007;
- Final ranking of SSCs is under way.

Methodology

This task is still progressing and the approach used is improving on the road using the new data collected and lessons learned. Therefore, the methodology described below reflects the most recent modifications and some thinking not implemented in the process yet. The finalized methodology may be different of the one presented here.

Since the project is oriented on a generic CANDU power plant to identify CANDU generic APSA insights, a hierarchical list of typical CANDU safety related SSCs has been developed. For these SSCs, a generic list of applicable degradation mechanisms has been produced.

The project benefited from a large amount of work done by plant operators for their ageing management and other operational activities. Although practically none of the results can be applied directly to a full scope APSA, many of the results can be used for the case study to test available methodologies, fill gaps, identify major issues, and improve the methods used at later stages when the most efficient areas of APSA application are identified and better understood.

At this stage such sources of information were used as plant specific PRAs, Safety analyses, design documentation, reliability programs, ageing management programs, plant condition assessment, other research project in CNSC, generic international sources, etc.

Gradual Screening Approach

Taking into account a large amount of components at a typical nuclear power plant, the fact that all of them are ageing, the different safety importance of different components, and the significant efforts required for ageing reliability modeling, a gradual screening of SSCs is necessary to optimize the work.

Overall we anticipate four levels of screening in this project:

1. <u>Preliminary qualitative screening</u>. This screening will identify components which may require age-dependent reliability modeling to evaluate their importance for APSA results. It is this phase of the project and it is based on:
    - Importance of SSCs in existing PSAs;
    - Known degradation mechanisms/reliability trends;
    - Expert opinion (SSCs not important now can become important to safety due to ageing, most likely SSCs which may lead to wide spread common cause damages);

- Ageing management efficiency considering:
  - component life;
  - efficiency of surveillance activities to identify negative trends before actual failures;
  - cost of surveillance, testing, replacement;
  - ability to maintain the failure rate constant.

2. System level quantitative screening. This screening will identify what components shall be included in the plant APSA model. It will be based on the impact of the component ageing on system reliability. We will develop screening criteria at later stages of the work. We anticipate that some SSCs may not need detailed time-dependent models at this stage. An effort will be made to perform a simplified conservative evaluation of the component reliability at the end of their life and screen them out if the risk contribution due to ageing effects is negligible.

3. Plant level quantitative screening. This screening will identify what components may require a more detailed modelling, data collection and research activities. It will be based on the impact of component ageing on APSA results.

4. Cost-benefit analysis.

PIRT Process

Phenomena Identification and Ranking Table (PIRT) process has been selected for identification of SSCs candidates for the case study APSA in this phase of the project. This selection was based on the following considerations:

- PIRT is a structured process integrating multiple inputs with extensive use of expert judgment;
- it was tested by US NRC for similar projects in the framework of NPAR program;
- it brings into focus the phenomena that dominate;
- it identifies all plausible effects to demonstrate completeness;
- it ranks all inputs;
- it defines structured prioritized decision criteria.

This method has been adapted for the project purposes as described further in the text.

A crucial step in the process is the identification of the Figure of Merit (FOM), which is the criterion against which the relative importance of all plausible ageing deterioration phenomena is judged. FOM for this study is the impact of different ageing phenomena on PSA.

For the purpose of this project, the Figure of Merit had two major contributors:

- Safety Importance of a SSC, and
- Ageing Management Effectiveness for this SSC.

SSCs with Safety Importance rank of High (H) or Medium (M) and AM Effectiveness score less than 2 are selected for further APSA study.

SSC Safety Importance Factor

Scale	Definition
High	SSC Important to Safety as per current Canadian industry practice
Medium	All other Safety Related SSC which do not meet criteria "High" or "Low"
Low	Not critical or Run-to-failure SSCs as per OPG ageing management criticality coding

Ageing Management Effectiveness Factor

Scale	Definition
3	Fully effective; failure rate can be maintained virtually constant
2	Partially effective; degradation rate can be attenuated
1	Ineffective; no impact on degradation rate

Practically the selection of SSCs started from lists of safety-related systems and components developed by plant operators. SSCs are considered as safety related in Canadian practice if they have any potential impact on initiation, prevention, detection or mitigation of accident sequences leading to radioactive release from the plant. On one hand, by taking these lists as the starting point we rely on the work done by plant operators to screen out plant components that have no impact on safety. On the other hand, we don't screen out components that are not modeled in the current PSAs due to their supposed low contribution.

Further, lists of plausible degradation mechanisms and current ageing management practices for each SSC are compiled. System and component health reports, condition assessment, life cycle management programs, etc. are used for this task. At this stage, such components are identified that are either non-critical for safety or can be run-to-failure due to specifics of surveillance activities and system configuration (e.g., components with high redundancy, frequent staggered testing, low historical failure rate, low cost of surveillance and replacement). These components are rated with "Low" safety importance rank for APSA purposes.

Finally, lists of Systems Important to Safety are used to identify those components with highest contribution to the plant safety. These SSCs are identified by plant operators as response to the CNSC standard S-98 "Reliability Programs for Nuclear Power Plants". The criteria used for identification of such SSCs use importance measures from current

PRAs, such as Fussel-Vesley and Risk Achievement Worth, and additional deterministic criteria such as defense-in-depth. It is considered that these SSCs have the highest impact on Core Damage Frequency and Large Release Frequency.

At this point, a preliminary list of SSCs with safety importance ranking is obtained.

Ranking of ageing management effectiveness is more subjective and requires consideration of additional weighting factors decreasing the subjectivity. As such, the project use:

- Level of Knowledge of Ageing Phenomena.
  This factor evaluates uncertainties associated with our understanding of ageing effects and identifies needs for additional data, experiments and/or analysis.
- Ageing Phenomena Importance.
  This factor evaluates impact of specific ageing phenomena on evolution of the component and system reliability and, therefore, on potential consequences of the component ageing for PSA results. Generally speaking, it is related to the potential degradation rate and consequences of the degradation. Higher ageing phenomena importance is assigned to higher degradation rates and worst consequences.
- Component Type.
  This factor is described in more details below and helps to evaluate ageing management effectiveness.

Level of Knowledge of Ageing Phenomena

Scale	Definition
4	Fully known; small uncertainty
3	Known; moderate uncertainty
2	Partially known; large uncertainty
1	Very limited knowledge; uncertainty cannot be characterized

Ageing Phenomena Importance

Identifiers	Definition
High (H)	The phenomenon has a controlling impact on the FOM
Medium (M)	The phenomenon has a moderate impact on the FOM
Low (L)	The phenomenon has a minimal impact on the FOM

Three types of components have been defined to help with Ageing Phenomena Importance and Ageing Management Effectiveness ranking:

- (S) - Short living active components (e.g., relays, transmitters, controllers)

- (M) - Medium life active and passive components (e.g., valves, small pumps, small pipes)
- (L) - Long life passive components (e.g., big pipes, vessels, structures, cables)

Short living active components are characterized as follows:

- their service life is much shorter than plant life;
- they are frequently tested, easily repairable and replaceable (may be replaced with a different design);
- they require regularly some form of surveillance;
- up-to-date plant-specific reliability data is usually available;
- identification of unsafe trend is generally simple;
- these components have high redundancy such that consequences of single failures are usually insignificant (AM may be reactive);
- degradation of such components is usually adequately addressed by existing surveillance and maintenance programs.

For such components, statistical modeling strategy may be the most efficient. However, the above specifics of these components make them good candidates for screening out for the APSA purposes. Efforts spent on degradation prediction and associated high uncertainties may not be worth while.

Medium life active and passive components are characterized as follows:

- their service life is usually somewhat shorter than plant life;
- test and inspection frequency for such components is relatively low;
- plant-specific reliability data may not be representative;
- identification of unsafe trend may be difficult;
- components are relatively costly to replace or repair;
- they have a relatively low redundancy, which means that consequences of single failure are not negligible;
- effectiveness of ageing management may be questionable (AM needs to include proactive elements).

Age-dependent reliability models for such components can be based both on statistic methods and reliability physics. These models can be cost-effective, but further investigation is required.

<u>Long life passive components</u> are characterized as follows:

- they are designed to reach the end of plant life with an adequate safety margin still remaining;
- inspection, surveillance, and service conditions might be the only way to obtain ageing data;
- inspections are costly, their frequency is low and may have to be increased as plant ages;
- failure data is practically unavailable; ageing information is in the form of degradation data and condition monitoring;
- it is difficult to detect degradation and identify unsafe trends;
- consequences of single failure are very significant or catastrophic (LCM shall be proactive);
- usually no corrective or preventive maintenance can be done for such components.

Reliability physics models may be the only way for predicting reliability trend. It is expected that time-dependent models can be extremely helpful and beneficial.

This classification of components on different types helped in ranking adequacy of ageing management practice. This ranking is generic for the industry. Plant specifics and typical Canadian practice were accounted by reviewing plant condition assessments, health reports, maintenance programs, etc. It was found that this generic classification of components for ageing management purpose represents plant specifics acceptably well. Since this project is CANDU generic by nature, the approach can be considered as adequate. For plant specific APSA, more attention may be required to component specific ageing management approach. The cost-benefit considerations will be important taking into account a significant number of components at the plant.

The PIRT-style process based on the above information will be:

Step 1: List all the safety-related SSCs in a hierarchal fashion based on plant documentation.

Step 2: Indicate which SSCs are determined to be important to safety. This would include anything the stations rated as important to safety based on Fussel-Vesely, Risk Achievement Worth, or other arguments including expert judgement.

Step 3: Indicate ageing mechanisms, potential ageing effects, level or knowledge of ageing phenomena, component type.

Step 4: Based on expert judgement supported by rationale, for each system / component / phenomenon, assess the impact of increased failure due to ageing on the top event (i.e., APSA rank).

Step 5: Document current ageing management practice, existing concerns, possibilities for improvement.

Step 6: For each system / component / phenomenon, indicate the effectiveness of the AM program. Each assessment requires a rationale.

Step 7: Based on the results from Step 2 and Step 6, identify SSCs-candidates for further APSA consideration.

Simplified examples of PIRT working tables

System	Component	Ageing Mechanisms	Potential Ageing Effects	Knowledge of Ageing Phenomena	Comp. Type (Life)	Ageing Phenomena Importance	Current Ageing Management Practice Summary	AM Effective-ness	Safety Importance	APSA Rank
Annulus Gas System	Alarm-Annunciator	Mechanical Fatigue, Thermal Aging	Electronics, capacitor, mechanical parts, loss of indication/ alarm	3	S	M	Fixed Area CO2 monitoring/ alarm assembly comprise of the Horn, rotating Beacon, panel & tubing. Components are replaced as they fail. Run-to-failure equipment, replacement parts are available.	3	L	3,L
Annulus Gas System	Motor Control Centre (MCC)-600 / 208 V A.C. 125 V D.C.	Mechanical Fatigue, Thermal Fatigue, Thermal Aging, General Corrosion, Self-Loosening	Over long periods of operation certain components associated with MCC starter modules/cells fail due to contact erosion (due to arcing), or protection settings change due to general aging (O/L relays, process relays etc.). Contactor devices may not operate due to failure of the electro-magnetic coils, or weakness of the return springs. Device fails to operate per design Civil: Mechanical loading on MCC housings is sufficiently low to not cause any effects of concern.	3	M	M	Current practice is to repair existing equipment (starter module components) as per existing CMP's together with the information list indicating "Design Approved" substitute parts for obsolete components. This approach will allow the equipment to be maintained up to the current plant end of life. Specific recommendations for programmatic replacement of these MCC's and a civil walk down will be covered in SCA #5 electrical. Civil: Normal routine system / area walkdowns are deemed adequate to detect any deficiencies.	2	M	2,M
Annulus Gas System	Cable - 4.16 kV, 600V, 125V, 250V - Power Cables	Radiation Embrittlement, Galvanic Corrosion, General Corrosion, Self-Loosening	The cables and trays are subject to aging by, cable tray corrosion, loosening of cable tray supports and fasteners, cable insulation aging and loosening of cable terminations or connectors Civil: Loosening of mechanical fasteners on cable tray systems and supports may lead to overloading of adjacent supports and	3	L	M	Current practice has been to test the insulation properties of selected EQ cables using a "Near Infrared Reflectance" (NIR) process. The process allows for the comparison of insitu cable insulation properties to a known quality sample of the same or like material. Results indicated that the tested cables were within insulation tolerances. There are no direct means to determine a cables true life expectancy (before insulation total break down). Civil: No current practices to detect the deficiencies	1	M	1,M

System	Component	Ageing Mechanisms	Potential Ageing Effects	Knowledge of Ageing Phenomena	Comp. Type (Life)	Ageing Phenomena Importance	Current Ageing Management Practice Summary	AM Effective-ness	Safety Importan ce	APSA Rank
			ultimately to failure of the cable tray. Deterioration of cable trays due to corrosion is sufficiently low to not cause any effects of concern.				of cable trays.			
Annulus Gas System	Motors-600 V	Stator winding contamination, High Vibrations, Stator Winding and Cable Thermal and Radiation Ageing	Misalignment or loosening of the coupling between pump and motor - results in excessive bearing wear, and high vibrations. Stator wear, cable thermal and radiation aging cause of wear.	3	M	M	Current practice of Run to Failure is sufficient for these motors. System has redundant motors/compressors and there is also a back up bottle supply.	3	M	3,M
Boiler Feedwater System	Pressure Gauge	Wear, Corrosion	Gauge Failure/Inaccuracy/ Leakage	3	S	L	Run to Failure - easily replaced if failed	3	M	3,M
Boiler Feedwater System	Boiler Level Control Air Operated Valve (AOV)	Wear, Corrosion, Erosion	Failure of CV would be loss of redundancy & potential loss of boiler level control & reactor trip.	3	M	M	PMID for overhaul & diagnostics. Operator round visual inspection.	2	M	2,M
Boiler Feedwater System	Main Boiler Feed Pump Discharge Non-Return Valve (NV)	Erosion, Corrosion	Reverse rotation of Main BFP resulting in pump damage making pump unavailable	3	M	M	Operator rounds & alarm. SST P-058.	2	M	2,M
Boiler Feedwater System	Concrete Pads Outside RB Support	Unanticipated static load, Dynamic load, Cyclic load, Residual stress, Surface cracking, Surface porosity, Excessive load and vibration, General corrosion, Galvanic corrosion, Crevice corrosion, Pitting corrosion, Mechanical fatigue, Concrete or grout cracking, Loss of bond, Loss of strength, Concrete scaling, Concrete spalling	Failure to support equipment	3	L	H	No direct current practice.	1	H	1,H
Boiler	0.5 HP (.37	Wear Mechanisms -	Misalignment or loosening of	2	M	L	Current practice of Run to Failure is sufficient	3	M	3,M

System	Component	Ageing Mechanisms	Potential Ageing Effects	Knowledge of Ageing Phenomena	Comp. Type (Life)	Ageing Phenomena Importance	Current Ageing Management Practice Summary	AM Effective-ness	Safety Importan ce	APSA Rank
Feedwater System	kilowatt) 600 V Motor	Wear, Stator winding contamination, Thermal Aging	the coupling between motor and load - results in an excessive bearing wear, and high vibrations				for these compressors, pumps and damper motors. These are generally small 600 volt AC motors; easily replaced			
Boiler Feedwater System	Piping	Residual stress, Stress concentration, Wear, Fretting, Erosion, Vibration, Unanticipated static load (broken hanger)	Pipe failure & loss of feedwater. Large breaks lead to harsh environment and flood in powerhouse with consequential failures of multiple safety equipment.	3	L	H	Hanger inspection program	1	H	1,H
Boiler Steam and Water System	Piping-Piping Components	Flow Assisted Corrosion (Erosion-Corrosion)	Corrosion erosion may result in pipe wall thinning which compromise the integrity of the piping and could result in external leakage. Large breaks lead to harsh environment and flood in powerhouse with consequential failures of multiple safety equipment.	2	L	H	This equipment is periodically inspected under the FAC-Pipe wall thinning program.	2	H	2,H
Boiler Steam and Water System	Cable - 4.16 kV, 600V, 125V, 250V - Power Cables	Thermal Aging, Environmental Degradation	The cables and trays are subject to aging by, cable tray corrosion, loosening of cable tray supports and fasteners, cable insulation aging and loosening of cable terminations or connectors. Failure of SRV control cables may lead to loose of several important safety functions. Civil: Loosening of mechanical fasteners on cable tray systems and supports may lead to overloading of adjacent supports and ultimately to failure of the cable tray.	3	L	M	Current practice has been to test the insulation properties of a selected group of EQ cables using a "Near Infrared Reflectance" (NIR) process. The process allows for the comparison of insitu cable insulation properties to a known quality sample of the same or like material. Results indicated that the tested cables were within insulation tolerances. There are no direct means to determine a cables true life expectancy (before insulation total break down).	2	H	2,H
Digital Control Computer	Computer-Unit DCC Control Computer	Thermal Aging, Wear Mechanisms - Wear	Failure or degradation of DCC leading to loss of multiple safety functions.	3	M	H	The aging DCC hardware is being supported to EOL by obtaining sufficient spares, routine field walkdowns and implementing various upgrade programs. There are potential risks in	2	H	2,H

System	Component	Ageing Mechanisms	Potential Ageing Effects	Knowledge of Ageing Phenomena	Comp. Type (Life)	Ageing Phenomena Importance	Current Ageing Management Practice Summary	AM Effective-ness	Safety Importance	APSA Rank
							software deficiencies in control and non-control programs due to constraints in the aging DCC hardware and system functions must work around this aging hardware. The current practice could not go beyond EOL of the DCC for life extension without potentially incurring significant risks in loss of production.			
Emergen-cy Power Supply	Major Equipment-Emergency Power Generators	General Corrosion, Thermal Fatigue, Mechanical Fatigue, Thermal Aging, Fatigue, Vibration	Fatigue, Vibration potential for degradation of the rotating element and bearings. Mechanical Fatigue potential for cracks in compressor and turbine blades. Civil, No civil aspects.	3	L	H	PMID's in place using minor and major planned outages to maintain turbine and associated equipment as per OEM specifications. This should address AM concerns to EOL. Recommend review of engine status to allow LE.	2	H	2,H

Preliminary Results

The Figure of Merit used for selection of SSCs still includes a lot of subjectivity, because it is impossible to predict at this stage the final effect of degradation mechanisms and related ageing management strategies in different SSCs on PSA results.

Uncertainty in data and methods is a challenge, which may undermine credibility of conclusions. Therefore, the decisions shall be on conservative side to not miss important issues.

As a result, the list of preliminary selected SSCs is still relatively long. Even this stage of the project is quite resource intensive, but the actual time-dependent modeling is expected to require even more resources. Therefore, significant additional work on grouping, ranking and screening will be required in the following stages of the project to make sure that the cost does not outweigh benefits.

Currently, SSCs selected for further consideration are grouped by classes of equipment to develop in Phase 2 generic time-dependent reliability models. The generic models may give additional screening possibilities. For instance, it may be demonstrated that predicted degradation effect on SSC reliability is insignificant and is within uncertainty range of the method. Further in Phase 3, the generic models will be adjusted for specific elements of APSA. This will give the real impact of ageing on PSA results and provide with one more screening level. Finally, the cost-benefit analysis will demonstrate what models can provide a noticeable benefit to optimization of surveillance activities.

The high-level preliminary list of components-candidates to APSA includes:

- Cables
- Batteries
- AC and DC buses
- Breakers
- Transfer switches
- Selected small and large piping
- Pressurized tanks
- Steam Generators
- Pressure tubes
- Feeders
- Turbine
- Standby Generators
- Motor operated valves
- Check valves
- Safety relief valves
- Liquid relief valves
- Air operated valves
- Pumps
- Heat exchangers
- Turbine support
- Containment components

At present, these components are not ranked each to other. This is related to the fact that the list is rather generic and, therefore, cannot be reasonably ranked. When the generic models are developed and the project comes to modeling of specific plant components, the overall ranking may be done using, for instance, a SWIM index, lessons learned from the generic models, and other inputs such as deterministic criteria for components not modeled currently in PRA.

Preliminary Conclusions for this Phase of the Project

Taking into account the amount of work to be done and unclear outcomes, multilayer gradual screening is required to make the job manageable.

Significant additional analytical and experimental researches may be needed to support APSA studies, because the data and level of knowledge of degradation mechanisms available now may not allow sufficiently accurate modeling.

Reliability data collection shall be specifically designed to address APSA needs and include specific APSA data treatment tools.

Identification of components which are not currently modelled in PSA, but may have a significant impact on the PSA due to ageing is not trivial, because no numerical importance measure exists for such components before prediction models are actually developed.

Nevertheless, we expect to produce a good reference database for APSA analysts, practical methodologies and useful results, which can be beneficial to Canadian and international nuclear community.