# CANDU Plant Life Management - An Integrated Approach

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## Abstract

Commercial versions of CANDU® reactors were put into service starting more than 25 years ago. The first unit of Ontario Hydro's Pickering A station was put into service in 1971, and Bruce A in 1977. Most CANDU reactors, however, are only now approaching their mid-life of 15 to 20 years of operation. In particular, the first series of CANDU 6 plants which entered service in the early 1980's were designed for a 30 year life and are now approaching mid life. The current CANDU 6 design is based on a 40 year life as a result of advancement in design and materials through research and development.

In order to assure safe and economic operation of these reactors, a comprehensive CANDU Plant Life Management (PLIM) program is being developed from the knowledge gained during the operation of Ontario Hydro's Pickering, Bruce, and Darlington stations, worldwide information from CANDU 6 stations, CANDU research and development programs, and other national and international sources. This integration began its first phase in 1994, with the identification of most of the critical systems structures and components in these stations, and a preliminary assessment of degradation mechanisms that could affect their fitness for service for their planned life. Most of these preliminary assessments are now complete, together with the production of the first iteration of Life Management Plans for several of the systems and components.

The Generic CANDU 6 PLIM program is now reaching its maturity, with formal processes to systematically identify and evaluate the major CSSCs in the station, and a plan to ensure that the plant surveillance, operation, and maintenance programs monitor and control component degradation well within the original design specifications essential for the plant life attainment. A Technology Watch program is being established to ensure that degradation mechanisms which could impact on plant life are promptly investigated and mitigating programs established. The objective of these programs is to assure safe, economic operation of the CANDU 6 units stations for the remaining portion of their design life, and to preserve the option for plant life extension to about double their original life. Work on comprehensive PLIM programs building on this generic work has started with 2 CANDU utilities. Results of the program are being fed back into the new CANDU 6 and 9 products, to provide customers with the improved assurance of safe and economic operation, with the opportunity for plant life extension.

This paper describes the status of the programs undertaken by both the utilities and AECL to safeguard the investment they have made in CANDU stations and technology.

## 1.0 INTRODUCTION

Commercial versions of CANDU reactors were put into service starting more than 25 years ago. These first stations performed exceptionally well for ten to fifteen years, and most CANDU stations are now approaching their mid-life maturity of 15 to 20 years of operation (Table 1).

| Name | Location | In-Service date | Age (years) |
|---|---|---|---|
| Pickering 1 | Canada | 1971 | 27 |
| Pickering 2 | Canada | 1971 | 27 |
| Pickering 3 | Canada | 1972 | 26 |
| Pickering 4 | Canada | 1973 | 24 |
| Bruce 1 | Canada | 1977 | 21 |
| Bruce 2 | Canada | 1977 | 21 |
| Bruce 3 | Canada | 1978 | 20 |
| Bruce 4 | Canada | 1979 | 19 |
| **Point Lepreau** | Canada | 1983 | 15 |
| **Gentilly-2** | Canada | 1983 | 15 |
| **Wolsong 1** | Korea | 1983 | 15 |
| **Embalse** | Argentina | 1984 | 14 |
| Pickering 5 | Canada | 1983 | 15 |
| Pickering 6 | Canada | 1984 | 14 |
| Pickering 7 | Canada | 1984 | 14 |
| Pickering 8 | Canada | 1986 | 12 |
| Bruce 5 | Canada | 1985 | 13 |
| Bruce 6 | Canada | 1984 | 14 |
| Bruce 7 | Canada | 1984 | 14 |
| Bruce 8 | Canada | 1987 | 11 |
| Darlington 1 | Canada | 1990 | 8 |
| Darlington 2 | Canada | 1989 | 8 |
| Darlington 3 | Canada | 1991 | 7 |
| Darlington 4 | Canada | 1992 | 6 |
| **Cernavoda 1** | Romania | 1996 | 2 |
| **Wolsong 2** | Korea | 1997 | 1 |
| **Wolsong 3** | Korea | 1998 | - |
| **Wolsong 4** | Korea | 1999 | - |
| **Qinshan1&2** | China | 2003 | - |

*CANDU 6 Units shown in bold type

**Table 1** Age Distribution of CANDU Reactors

During the design of these stations, potential mechanisms for aging of the plant were considered, and inspection and maintenance programs were provided. These programs, however, were based on the best, but limited information available from the nuclear power industry at the time. Now that many of the stations are at or approaching middle age, a comprehensive CANDU Plant Life Management (PLIM) program is being developed to assure the future safe and economic operation of these reactors. This program will use the knowledge gained during the operation of Ontario Hydro's Pickering, Bruce, and Darlington stations, worldwide information from CANDU 6 stations, CANDU research and development programs, and other national and international sources. Ontario Hydro is developing it's own Nuclear Asset Optimization program, however much of the industry knowledge is being shared, and most of the program elements are common.

Life management programs have been prepared for some components (for example the fuel channels) on an as needed basis for some time, however the development of a comprehensive CANDU PLIM program began in earnest in 1994, with the identification of most of the critical systems structures and components in these stations, and a preliminary assessment of degradation mechanisms that could affect their fitness for service for their planned life. Most of these preliminary assessments are complete, along with much work to define a CANDU strategy, including several trial assessment of critical systems, structures, and components, and pilot reliability centred maintenance programs. Based on this work [1-5] the CANDU PLIM program is now also reaching maturity, and a three part program is now being follow. The relationships between these three programs and ongoing utility and industry programs is shown in Figure 1

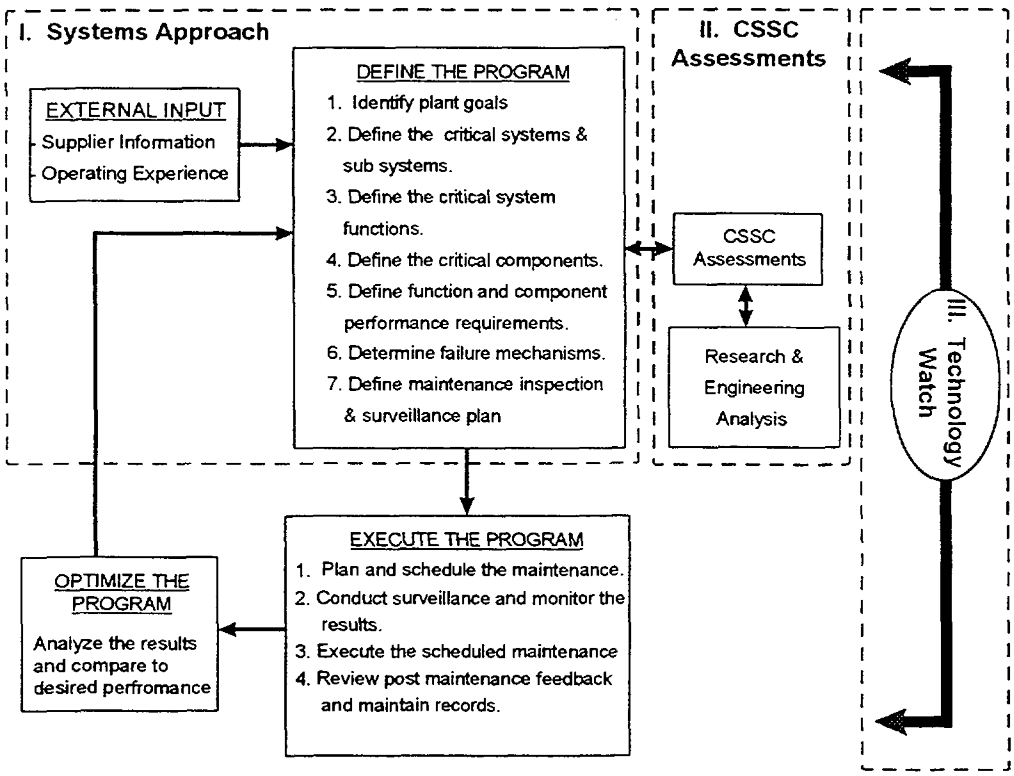



**Figure 1** Plant Life Management Model

I. Systems Approach to Plant Life Management

   A comprehensive assessment of systems is being carried out identifying functions important to plant safety, environment, and reliability, and the failure mechanisms and their impact on plant goals. Components which could cause these failures are being identified. Failure modes and effect analysis for these components are completed resulting in an inspection and maintenance program to assure attainment of the plants goals. For components where the failure modes and effect analysis cannot be completed due to lack of information, components will be added to the list for special aging studies.

II. Assessments of major Critical Systems Structures and Components (CSSCs) to ensure degradation mechanisms are understood and steps taken to mitigate them.

This program identifies the major CSSCs and any potential aging phenomena that might impact on plant safety and availability. The plausibility of aging degradation mechanisms is also addressed and recommendations are made for effective monitoring inspection and/or maintenance required to mitigate these aging effects and ensure reliable performance. These assessments form the basis of a living aging management program. A successful PLIM program provides the plants with the necessary assurances for continued safe, reliable operation.

III. Technology Watch to anticipate new emerging issues as early as possible.

A Technology Watch process is underway to anticipate problems as early as possible which could have major implications for the plants in the longer term. The performance of existing plants has been affected on a number of occasions by unexpected technical or licensing problems. The ability of the industry to respond to these issues is dependent on early detection and identification.

This paper describes the status of these programs undertaken by both the utilities and AECL to safeguard the investment, and AECL's program to incorporate the gains made into its latest CANDU 6 and CANDU 9 products

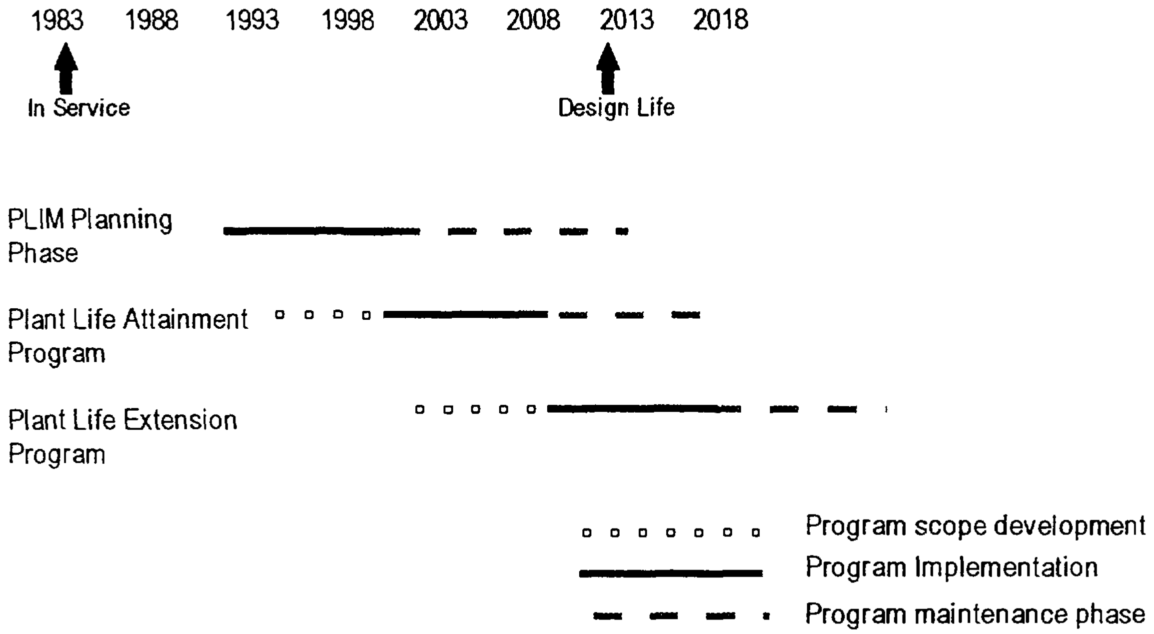
## 2.0 PROGRAM OBJECTIVES

The overall objectives of the PLIM program are to ensure continuing safe, reliable and cost effective operation of existing CANDU stations, and to apply the information to new CANDU 6 and CANDU 9 products in accordance with the following goals:

- The risk to the public from operation is well within the regulatory requirements throughout the design life.
- Plant availability is greater than 85% (90% for new CANDU products) and contributes to providing electricity at a competitive cost during the design life.
- Major unexpected problems are avoided through identification of potential aging issues before their occurrence. Means for monitoring and mitigation to ensure reliable component performance are implemented in a timely fashion.
- The option for life extension to about twice the nominal design life is preserved.

## 3.0 OVERALL APPROACH & METHODOLOGY

The approach has been designed to integrate these programs to meet the needs of utilities for a phased work plan in support of PLIM. Utilities must be in a position to assess the economic viability of the various elements of the programs in a timely manner. For the first generation of CANDU 6 plants the execution of the program elements have been grouped into three major phases illustrated in Figure 2.




| *Phase* | *Scope* |
|---|---|
| PLIM Planning Phase | • Identification of major CSSCs.<br>• Aging assessment studies & R&D of critical components<br>• Technology Watch planning<br>• Advanced technology development |
| Plant Life Attainment Program | • CANDU 6 plant specific detailed inspection and residual life assessment of key components<br>• Implementation plant monitoring and surveillance life management programs<br>• Enhancement of plant inspection and maintenance<br>• Technology Watch implementation |
| Plant Life Extension Program | • Replacement component strategies and planning<br>• Assessment of regulatory and safety related design changes for life extension<br>• Rehabilitation/Replacement programs for components identified in CSSC studies or from inspection in plant life attainment program |

**Figure 2** The CANDU 6 PLIM Phased Approach

## 4.0 SYSTEMS APPROACH TO PLANT LIFE MANAGEMENT

A comprehensive systems assessment will be carried out using a process that allows for importance ranking as well as risk ranking thereby providing an overall criticality ranking. The methodology, illustrated in Figure 3, consists of the following steps:

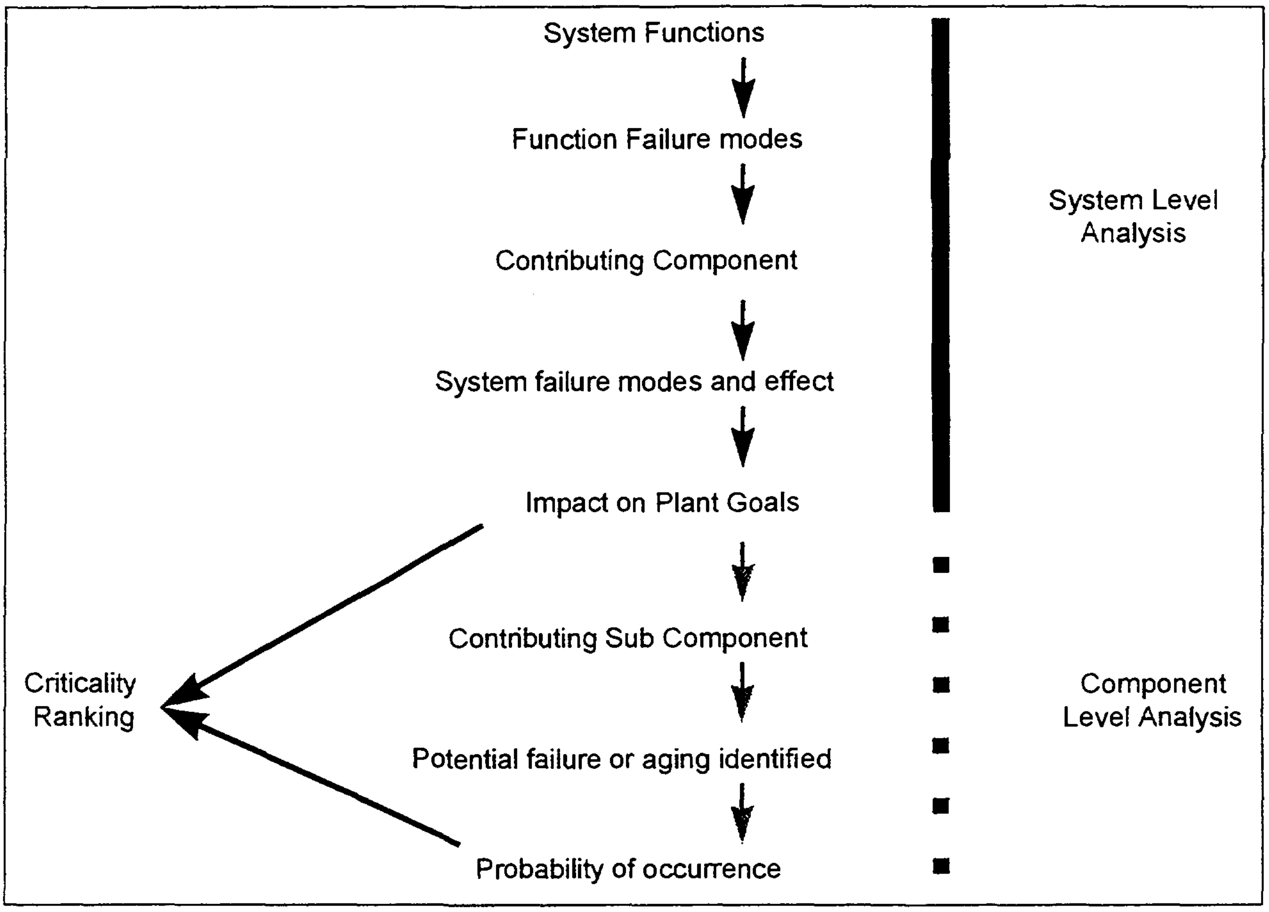



**Figure 3** PLIM Systems Approach

- For each system, functions important to plant safety, environment and reliability are being identified.
- For each function, the failure mechanisms and their impact on plant goals are being identified. In particular, the requirements established in the plant safety analysis and probabilistic safety analysis will be reviewed in detail to ensure that any degradation mechanisms which could impact on the analysis assumptions are identified.
- Components which could cause these failures are being identified. Both active and passive components will be included.
- Failure modes and effect analysis for these components are then completed. For components where the failure modes and effect analysis cannot be completed due to lack of information, then these components are added to the list for special aging studies.

This approach will provide a comprehensive Life Management program that goes far beyond the list of economically ruining major CSSC's and ensure that the plant surveillance, inspection and maintenance program are enhanced to cater to aging mechanisms before they impact on plant safety or performance.

To put this in perspective, the maintenance practices at the Canadian CANDU 6 stations are currently a combination of corrective and preventive maintenance practices. A significant fraction of the maintenance activities fall into the corrective maintenance category. As plants age and a shift in their goals to achieve excellence in safety and operation occurs, it is predicted that the maintenance strategy will move from a predominantly corrective maintenance program (70:30 corrective:preventive) to a predominantly preventive maintenance (30:70 corrective:preventive) one. A sample application of this systems approach is described below:

### 4.1 CANDU Auxiliary Feedwater System

A pilot project was undertaken for one of the CANDU plants to demonstrate the methodology used to identify the CSSCs and optimize plant surveillance, inspection and maintenance programs. The pilot project was performed on the auxiliary portion of the Boiler Feedwater System (BFS). The Auxiliary Boiler Feedwater System (ABFS) supplies feedwater to the boilers when the main feedwater pumps are unavailable or when the demand for feedwater is low during unit shut downs.

The operating experience with the ABFS has been good. The system contribution to plant incapability has been low. The system performance has been meeting the availability requirements for a safety related system. Maintenance can be carried out on redundant component with the unit operating. A large percentage of the components did not have any preventive maintenance specified.

The assessment consisted of identifying system functions and the components essential to carrying out the functions. Possible component failure mechanisms were analyzed to determine which components could have an impact on plant reliability and economic performance.

This process uncovered potential failure mechanisms which could impair the system and remain undetected for an extended period of time. In particular:

- Testing of the auto start logic was found to be fortuitous through another test carried out annually. The regular biweekly test bypasses the auto start logic since the pumps are started using the test portion of the pump control logic. An alternate surveillance test was recommended.

- The non return valves downstream of the main boiler feed pumps of the BFS must prevent backflow in order to ensure that the design flow required in the safety analysis is met. The analysis concluded that a periodic test and condition assessment should be carried out on these components. External experience with similar components suggests that failures are probable with aging and therefore periodic testing and inspection was justified.

- The electric auxiliary pump is equipped with reverse rotation protection which closes the motorized discharge valve in the event of a check valve failure or excessive passing. This circuit is important from two perspectives; it warns the operator of a reverse rotation and protects the pump. Failure of this circuit to function could result in the pump becoming unavailable due to reverse rotation and possible damage during the next scheduled test start. A functional check of the protection feature and calibration of the associated equipment was recommended.

- For some of the more critical motorized valves, a condition based maintenance program using valve diagnostics was recommended. While a corrective maintenance strategy has been acceptable to date, experience has shown that these components in time will require refurbishment and condition based maintenance is the most effective strategy.

From this analysis work, we concluded that the methodology was sound. The recommended changes will ensure that the system performance does not deteriorate as the plant enters the second half of it's design life. Redundant equipment down time for maintenance will also be minimized.

## 5.0 CSSC EVALUATIONS

This part of the program started in 1994 as part of Phase 1. It consisted of the identification of 14 major CSSC's These components included:

- Fuel Channels
- Steam Generators (including internals)
- Reactor Headers, Reactor Coolant Piping
- Reactor Assembly/Calandria Supports
- Conventional Piping
- Large Pressure Vessels
- Cables
- Large Pumps
- Airlocks
- Turbine Generator
- Cooling Water Intake
- Containment Structures
- Instrumentation and Control
- Major Civil Structures

These CSSC's were classified as critical for plant life based on the economic impact to the utility on the operation of the plant.

In advance of the formulation of the integrated approach described in this paper, a number of aging studies were launched on obviously critical components including: Fuel channels, containment civil structures, and reactor assembly/calandria supports. The methodology used for these studies is illustrated in Figure 4. Preliminary results from these studies are discussed below.

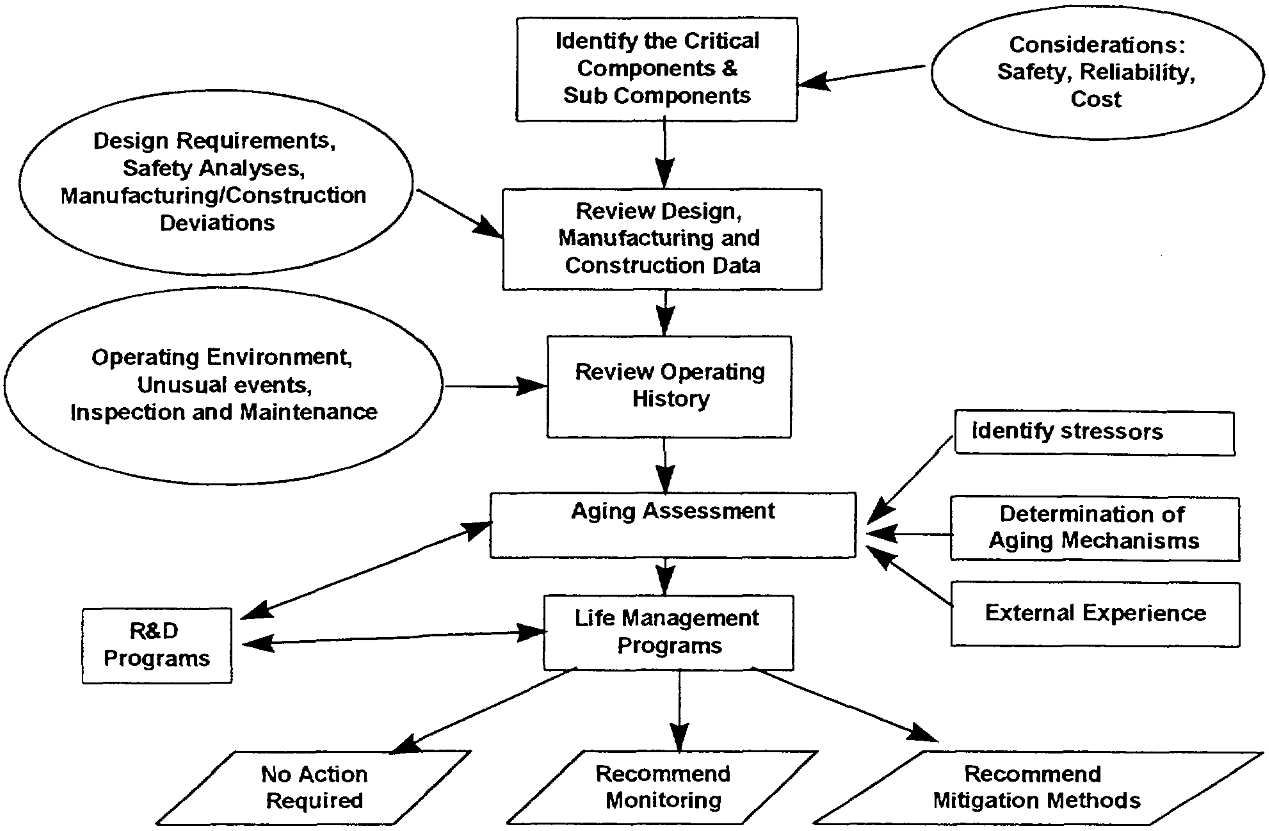



**Figure 4** Critical SSC Studies - Key Elements

## 5.1 Fuel Channels

To date, pressure tube aging degradation mechanisms have been fully characterized through extensive R&D and inspection of current reactors. These resulted in the development and application of fitness for service guidelines (FFSG) and methods for mitigating aging in current plants. Operating CANDU stations have Life Management programs in place to follow these guidelines. Table 4 provides a summary of key fuel channel aging mechanisms and life management programs. For CANDU units currently under construction or planned, the fuel channel design and material property improvements that have been developed are expected to result in less degradation and significantly reduced inspection and maintenance requirements to achieve the design lifetime of the tubes.

| Mechanism | Units Affected | Life Management Actions |
|---|---|---|
| Irradiation Enhanced Deformation | Pickering (1-4) Bruce (1&2) | Large Scale Fuel Channel Replacement (LSFCR) |
| | All other units | • Monitor deformation of operating tubes using the Channel Inspection and Gauging Apparatus for Reactors (CIGAR)<br>• Testing at fast flux facilities for end of life properties |
| Delayed Hydride Cracking (DHC) due to a hydride blister | Pickering (1-4)<br>Bruce (1-2) | LSFCR<br>LSFCR |
| | Units with 4 potentially displaced spacers | Relocate spacers using the Spacer Location and Relocation (SLAR) tool. |
| | All other units | No special program required |
| DHC due to stress concentration (tube flaw) | Early units | Fuel channel with flaws removed |
| | Later units | Sources of serious tube flaws eliminated. Reference to FFSG. Generally no action needed |

**Table 2** Summary of Key Aging Mechanisms of CANDU P/T Life Management Actions

### 5.2 Steam Generators

Steam generators (S/Gs) in CANDU plants have performed well compared to PWR plants. However they have contributed to the incapability of operating plants particularly in Bruce A and Pickering. Experience to date with Incoloy 800 tubing on Darlington and CANDU 6 Steam generators has been relatively good. Strict control of operating conditions (especially system chemistry to reduce secondary and primary side deposits) and aggressive remedial actions and careful proactive maintenance activities, backed by significant R&D have led to a decrease in S/G related unavailability of CANDU plants. CANDU utilities have developed programs for remedial actions to combat degradation of performance and strategic plans to ensure good future operation. CANDU specific FFSGs are currently being prepared capturing R&D results, and specify methods for controlling corrosion and mechanical degradation of tube bundles and internals through thermal hydraulics and chemistry control, cleaning and inspection. To implement the FFSGs, recommendations, aging mitigation programs are being implemented including advanced S/G tube primary and secondary side cleaning and regular water lancing of sludge piles. Some of the specific technologies developed include:

- Analysis capability to predict wear and corrosion given specific operating conditions
- Inspection probes
- Chemical cleaning processes for the primary and secondary side
- Tooling for plugging, sleeving or removal of tubes

The combined effects of all proactive measures/ improvements in operating practices and chemistry modifications will ensure S/G design life with minimum impact on capacity factors.

### 5.3 Containment Civil Structure

The first iteration of the containment civil structure study is complete. Potential long term aging mechanisms for the containment structure have been identified, the most important being minor concrete cracking and a slight increase in permeability of containment. The main aging mechanisms that have been identified are freeze/thaw cycles, concrete shrinkage and creep, and stress due to the pressures used during the containment leak rate test. A number of specific recommendations for each station are being considered for the plant life attainment program.

## 6.0 TECHNOLOGY WATCH

Recently, unanticipated problems such as outlet feeder pipe flow assisted corrosion, and reduced reactor overpower trip margin due to changing flow conditions in the heat transport system suggested that a more comprehensive approach for the identification of potential aging mechanisms is required. While these aging phenomena are not life limiting by themselves, the combined impact of these types of problems on plant capacity factors could be a concern. To address this concern, a technology watch program has been developed.

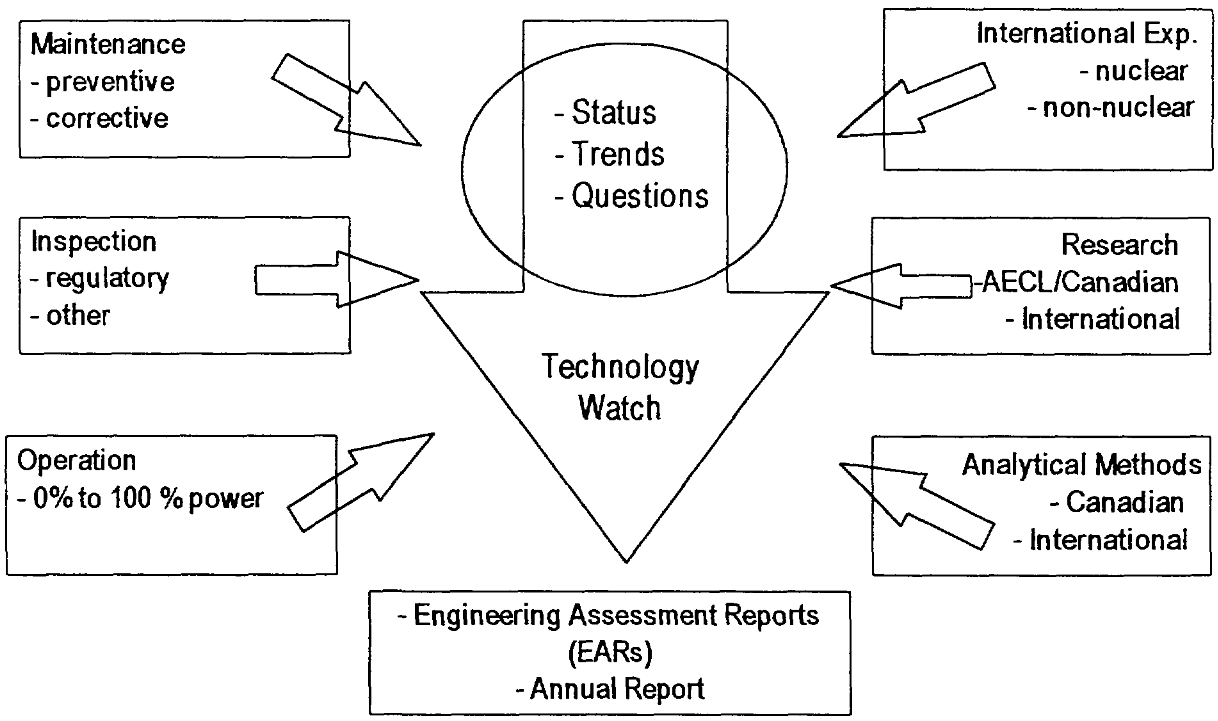



**Figure 5** Technology Watch Methodology

The overall Technology Watch mode of operation is illustrated in Figure 5. The Technology Watch Methodology involves:

- Scrutinizing plant feedback from operation, maintenance and inspection activities. The objective is to seek out the unusual or unexplained phenomenon, which on the basis of external experience, could represent a significant plant life issue. For example, the waterhammer events during certain test or discovery of erosion/corrosion in unexpected locations would warrant specific attention.
- Examining external experience, analytical methods and technology development for potential plant life issues or new technology which could assist in resolving CANDU aging issues. For example, recent concerns regarding motorized valve operation under accident conditions in the US would warrant special attention.
- Bringing together this knowledge and identifying specific issues which need to be investigated on a high priority basis. The Technology Watch process will also *recommend new technologies that are identified that can expand the capability of* , and/or reduce the time and cost of related activities (for example inspection of piping systems).

This process is not a substitute for operation experience feedback but utilizes the process by scrutinizing the collection of events and action items and looking for recurring or common themes and raising the profile of the follow up activities. This process also extends beyond plant events and considers inspection results outside of the norm.

## 7.0 PLANT LIFE EXTENSION PROGRAM

For the older CANDU plants, fuel channels are currently the only known limiting component for life extension beyond 30 years based on an 80% capacity factor. While research activities may lead to strategies which could extend life of these original fuel channels beyond 30 years, utilities had prudently put plans for a retubing outage some time between 25 years of service and 30 years. The retube outage is therefore an opportunity to consider rehabilitation of other CANDU 6 systems or components to ensure a 50 year or greater life is achieved thereby avoiding another major outage after retubing. Up front planning of this rehabilitation is key to maximize its benefit. This PLIM program is intended to undertake the up front assessments, analyses and planning sufficiently early to ensure any major outage rehabilitation work required for a 50 year or greater plant life is identified and planned for execution during the retubing outage. The scope of this program is preliminary at this stage and will depend heavily on the remaining work from the PLIM planning phase, the result of the economic/risk assessments and the result of inspection programs executed as part of the plant life attainment program. Some of the considerations at this stage include:

- Assessment of emerging regulatory and licensing requirements on plant life extension
- Instrumentation and control equipment obsolescence
- Control computer system upgrades

## 8.0 APPLICATION TO NEW CANDU PRODUCTS

AECL is incorporating the results of these CSSC assessments, RCM analyses, and Technology Watch program into the designs of its new products through AECL's Feedback Process. Some important achievements that have already been made are improved pressure tube, calandria tube, and feeder pipe materials, steam generators designed for ease of inspection and cleaning, and incorporation of information systems to assist the operator in inspection and maintenance. The goal is to continually advance the CANDU 6 and CANDU 9 products by improving their availability, reducing operation and maintenance costs, and providing further assurance that the plants will operate safely and economically throughout their lives.

## 9.0 CONCLUSION

AECL's objective is to maintain the CANDU NPP as a safe and reliable means of electricity production in recognition of its role in today's global economy. To achieve this standard, the industry has focused on an effective strategy for PLIM and life extension. For existing CANDU stations, the program must now be executed in co-operation with the utilities to assure continued good performance of the CANDU 6 units and preservation of the life extension option. Feedback from these programs, the optimized plant inspection and maintenance and the technology watch, will result in a continuous improvement process benefiting existing and future CANDU 6 and CANDU 9 plant owners and operators.

## 10.0 REFERENCES

1. Charlebois, P. et al - "CANDU Plant Life Management - Safeguarding the Investment" paper to be presented at the 1998 PNBC Conference (May 3-8, 1998) Banff, Canada

2. Shalaby B.A. - "Key Programs On Lifetime Management Of CANDU NPP" paper presented at the PLIM + PLEX 97 Conference (8-10 Dec. 1997) Prague.

3. Charlebois, P. - "CANDU Plant Maintenance - Recent Developments" paper presented at IAEA, TCM on "Advances in Safety Related Maintenance" 15-19 Sept., 1997 Vienna.

4. Shalaby B.A "CANDU Owners Group Programs in Support of Plant Life Management" paper presented at the PLIM/PLEX 95 Conference 27-30 Nov. 1995, Nice, France

5. M. DeVerno, J. De Grosbois, M. Bosnick, H. Pothier, C. Xian, and G. Gilks, 'Canadian CANDU Plant Historical Data Systems: A Review and Look to the Future', Canadian Nuclear Association/Canadian Nuclear Society Annual Conference, 1996 June, Fredericton, NB