1 - INTRODUCTION

Nuclear Power Plant (NPP) lifetime has a direct bearing on the cost of the electricity generated from it. The annual unit cost of electricity is dependent upon the operational time, and also annual costs and the capital cost assumptions function of Euros/kw. If the actual NPP lifetime has been underestimated then an economic penalty could be incurred.

But the ageing degradation, of nuclear power plants is an important aspect that requires to be addressed to ensure that necessary safety margins are maintained throughout service life: the adequate reliability and therefore the economic viability of older plants is maintained; that unforeseen an uncontrolled degradation of critical plant components does not foreshorten the plant lifetime. Accommodating the inevitable obsolescence of some components has also to be addressed during plant life. Plant lifetime management requires the identification and life assessment of those components which not only limit the lifetime of the plant but also those which cannot be reasonably replaced. The planned replacement of major or “key” components needs to be considered—where economic considerations will largely dictate replacement or the alternative strategy of power plant decommissioning. The necessary but timely planning for maintenance and replacements is a necessary consideration so that functions and reliability are maintained.

The reasons for the current increasing attention in the area of plant life management are diverse and range from the fact that many of the older plants are approaching for the oldest plants more than 30 years in operation, and for important number of NPPs between 20 and 30 years.

The impact of plant life management on the economics of generating electricity is the subject of ongoing studies and it can readily be seen that there can be both savings and additional
costs associated with these activities. Not all degradation processes will be of significance in eroding safety margins and there is a need to address all threats to plant lifetime in the analyses for guidance on maintenance and component replacement strategies. However the need to ensure that safety related equipment will continue to function in the event of a major fault or transient, requires that equipment has to be qualified for operation during and after such incidents. While there is the need to exchange information in these areas there is also the need to establish methodologies for unqualified equipment.

There is therefore a growing need to exchange information and data in areas of plant life management. The sharing of information can be of mutual national benefit and the role of the International Organisation such as the IAEA and the OECD to act as a focus for these activities is of particular long term importance.

2 - NUCLEAR POWER PLANT LIFETIME

In the plant life management different aspects and definition are to be considered.

The operational lifetime period is the period when the nuclear power plant is in operation and generates electricity. From the start of the plan and the final shutdown the utilities have to be considered the ageing mechanism in relation with:

- the maintain time in good operation of all of components and material,
- the identify of degradation mechanisms,
- the safety an/or performance criteria,
- the financial cost/benefit aspect and economical aspect,
- the licence duration or periodic reassessment.

The diagram of ageing mechanism and the management of ageing is developed in the Fig.1.

2.1 - Plant Life Management Process

2.1.1 - Data

Data availability is a key aspect in life management and the quality and availability of relevant information is directly related to the quality of the decisions on service life and the reliability of nuclear power plants. While most utilities keep data on key components, the data requirements have not necessarily been specified with regard to plant life evaluation. The data needs for this purpose needs to be established at an early stage. In addition there will be the requirement to include data on component repair and replacement, associated hardware etc. There does appear to be the need for a common international approach to identify specific needs and to standardise the methodology and formatting of appropriate date. The aim of the work should be to enable lifetime of components to be evaluated and should encompass the
following groups of data to allow the identification of the ageing component and ageing behaviour:

* component specification data (baseline):
  - materials,
  - initial properties,
  - design loading,
  - anticipated ageing data (ageing sensitivity),
* ageing or failure tracking data:
  - operational history,
  - in-service inspection,
  - in-service monitoring,
* stress or root cause data:

* failure or degradation mechanism data:

* test and maintenance data:

* measures to improve design and operations:

* relevant generic/other plant/R&D information.

Data sets required for plant life management can therefore be categorised as follows:

* a baseline (including design and basic design from construction),
* operating history,
* current plant state (including ISI),
* maintenance,
* technology developments,
* material properties (including results from surveillance testing),
* relevant generic data.

This list can be developed further. For example, material properties required for plant life management includes: initial properties; degraded properties; quantified impact of mitigating actions. Such information is not only specific plant, but it can also of generic value for those plants where there is insufficient data. Recent reviews have shown that existing
records of baseline, operation and maintenance of reactor components are not sufficiently comprehensive or readily retrievable to allow for trend analysis and prediction of component performance, identification and evaluation of the extent of ageing.

2.1.2 - Categorisation of components

Each nuclear power plant has thousands of components. To evaluate the importance of each of these components in terms of its life would be a daunting task. Therefore, it is desirable to categorise or “rank” these components in terms of their importance in order to prioritise the work and to maximise the effective use of resources. This exercise will also assist in the consideration of the technical and economic aspects of life management.

The categorisation outlined below is based primarily on the economic consequences of a need for component replacement or repair but the first three categories usually include most of the safety related components. The categorisation given below is not unique, there are variants. There are also many categorisation factors such as: cost to replace refurbish; impact on plant availability; loss of revenue; radiation dose; regulatory importance; modifications required; replacement precedent; generic applicability, mode of failure; consequences of failure on plant safety, and, consequences on plant safety.

CATEGORY 1: COMPONENTS are those which are generally considered “not replaceable”. Examples would include the reactor pressure vessel and also the containment structure. (With regard to replaceability, it can be argued that even the reactor vessel and the containment structure could be replaced – but at great cost. Also with regard to irradiation embrittlement of the reactor pressure vessel in an older NPP it is noted that some fifteen WWEP RPVs have been annealed and that consideration is being given to the practicality of annealing the larger US PWR pressure vessels, thus eliminating a possible plant operational life limiting degradation).

CATEGORY 2: COMPONENTS are those which are replaceable, but are costly in terms of capital expenditure and outage time requirements and needed anticipation to order new components. An example here would be steam generators – which have been replaced on many plants.

CATEGORY 3: COMPONENTS are those which are “key” in terms of plant safety and reliability and are susceptible to ageing, but which are replaceable on a routine basis.

CATEGORY 4: COMPONENTS (all other components) not included in the above category and are not related to “life” considerations.
It has already been mentioned that each NPP is unique. It follows that the categorisation of components is also unique and there may be site/national features which will produce particular peculiarities in these lists. For example, the role of climatic and seismic factors may be also be enhanced for specific sites. However a comparison of such listings may have common factors which could allow the development of strategies in the area of planned maintenance. National lists would possibly reflect that Utility’s experience, operation and maintenance practice, designs and applications, strategies for refurbishment and replacement, priorities and needs to extend the operational life.

2.1.3 - Examples of description of components for Plant Life Management

There are a large number of examples of these listings for several countries of key components in Plant Life Management Program. In USA it is called “big ticket” items. It must be re-stressed that each nuclear power plant is unique so there could be differences between some countries.

A – Example of “modules of components” – for Spanish PWRs and BWRs

- PWR vessel,
- BWR vessel,
- steam generators,
- pressuriser,
- PWR internals,
- main supports,
- diesel generator,
- alternator,
- pumps,
- turbines,
- piping,
- tanks,
- heat exchangers,
- electrical equipment,
- electrical machines,
- motor operated valves,
- cables,
- instrumentation,
- process instrumentation.
B – Example of fourteen key components for the CANDU NPP

- fuel channels,
- steam generators including internals,
- calandria vessel,
- reactor headers,
- PHT piping, pressuriser,
- general nuclear piping,
- vacuum building,
- calandria vault & end-shield c.system,
- cables (power, control, and inst.),
- reactor building,
- turbines,
- generator,
- CW intake structure,
- spent fuel bay/liner.

C – Example of key components for Russian WWERs

- reactor pressure vessel and head,
- control and safety systems,
- primary piping (over 11 mm diameter),
- primary pumps, valves, (ps of stream generator),
- volume compensator (pressuriser, …),
- safety related electrical circuits,
- RPV internals,
- Secondary side of steam generators,
- primary water preparation system,
- safety valves,
- all main equipment in secondary circuit,
- all main electric circuits.

D – Example of Eleven key components for US PWRs

- reactor pressure vessel,
- RPV internals,
- Reactor coolant circuit components,
- Reactor coolant pressure boundary piping,
- CRDM,
- steam generators
- Pressuriser
- auxiliary pipes and equipment
- drywell metal shell
- suppression chamber and vent system
- reactor vessel support,
concrete structures: RPV pedestal, wall foundation, biological shield, fuel pool slabs and walls, reactor building basement, shield wall, reactor building floor slabs and walls, and turbine pedestal.

**E – Example of French lifetime project – 18 major components**

- reactor pressure vessel
- primary system-large diameter pipes
- other primary system pipes
- steam generators
- primary pump casings
- pressuriser
- auxiliary pipes
- control rod drive mechanisms
- vessel internals
- containment
- reactor pit
- anchorings
- turbine
- generator
- instrumentation and control
- electrical cables
- cooling tower
- polar crane

The EdF “Lifetime project” has identified eighteen components considered major because they are either too costly to replace or because of the eventual need for major repairs.

**3- PLANT LIFE MANAGEMENT – OVERALL REVIEW BETWEEN DIFFERENT COUNTRIES APPROACHES**

The Plant Life Management (PLIM) strategies in different countries are selected in three categories of programmes of actions.

**3.1 - Case of countries needing Licence Renewal**

The first case of Licence Renewal procedures was engaged by American approaches. The US utilities have to prepare and to present to the Safety Authority (US NRC) all of documents required by Licence Renewal rules.

In USA the original lifetime is 40 years and for follow Licence Renewal procedures. Several US utilities were engaged plant by plant Licence Renewal procedures, and were obtained Plant Life Extension until 60 years.

Other countries are in a similar situation, for example: South Africa.
3.2 - Case of countries needing Periodic Safety Review for Plant Life Management

Some countries do not applied Licence Renewal approach, they need Periodic Safety Review Procedures (PRS). It the case for example of France, Spain, other European Countries. In France for example, PSR procedures are applied each 10 years, for 10 years reassessment programme, during the preparation for 10 years outages. There are no limitation of duration of plants, but it is mandatory to obtain the agreement from regulator to maintain plants in operation.

3.3 - Case of countries needing Licence Renewal Procedures after original and basic design lifetime to extend lifetime and needing Periodic Safety Review for Plant Life Extension

Several Countries : Japan, Korea, Russian Federation, Ukraine are in this case. The basic design lifetime is 30 years in general and after obtaining Licence Renewal authorization to extend lifetime it is applied Periodic Safety Review rules.

3.3.1 - Case of Japan - Korea

The original Lifetime is 30 years. Japanese utilities have obtained in general the Life Extension until 60 years, but from 30 years to 60 years they need to obtain PSR agreement each 10 years.

3.3.2 - Case of Russian Federation

The original lifetime is 30 years. Specific procedures are applied for life extension :

→ until 45 years for oldest generation of WWER NPPs,
→ until 60 years for new generation of WWER NPPs.

The PSR procedures are needed each 5 years for oldest WWER generation of plants. For new generation of WWER plants, the PSR is applied each 10 years.
The materials properties change in function of the structure or components and the identification of degradation mode. The matrix shown bellow presents different aspects for ageing management in function of type of degradation.

<table>
<thead>
<tr>
<th>DEGRADATIONS MODE</th>
<th>COMPONENT OR SYSTEM</th>
<th>CURRENT MAINTENANCE</th>
<th>EXCEPTIONAL MAINTENANCE</th>
<th>ANTICIPATION MITIGATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiation Embrittlement (1)</td>
<td>Reactor vessel ISI</td>
<td>30 years = over pressure risk at cold conditions valve protection</td>
<td>Surveillance Program (Regulatory) Fuel loading map</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reactor internals (baffle bolts) ISI</td>
<td>Bolts replacement (at 20 years)</td>
<td>UP Flow conversion End of life data</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electric cables</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>THERMAL AGEING (2)</td>
<td>Cast stainless steel – pipes – valves bodies ISI</td>
<td>Elbows replacement (SGR)</td>
<td>Surveillance program</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low alloy steel ISI</td>
<td>Some pipes replacement</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Austenitic welds Electronic components ISI</td>
<td>Temperature</td>
<td>Data collection Expertises</td>
<td></td>
</tr>
<tr>
<td>Fatigue (3) (mechanical, vibrational, thermal)</td>
<td>Primary circuits and auxiliary circuits ISI</td>
<td>Pipe or component repair, replacement</td>
<td>Service loading decreasing Long term management Design conditions accounting Dedicated devise</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Branch connections - Pumps internals - Generator</td>
<td></td>
<td></td>
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<tr>
<td>Stress corrosion type alloy 600 (4)</td>
<td>RV head ISI</td>
<td>Repair Replacement (SGR) Plugging (SGR) Replacement (pressurizer)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SG tubes Vessel BMI SG channel head repairs pressurizer nozzles pipe welds core support lugs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Austenitic High mechanical properties steels</td>
<td>Internals parts (with(1)) ISI</td>
<td>Repair Replacement</td>
<td>Engineering R and D</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Repair areas</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Anchor bolts ISI</td>
<td>Replacement</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Turbine bolts</td>
<td></td>
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<tr>
<td>Erosion corrosion (5)</td>
<td>Carbon steel pipes ISI</td>
<td>Replacement</td>
<td>Engineering expertise tools</td>
<td></td>
</tr>
<tr>
<td>Concrete : Reinforcing bar - Corrosion - Stress relaxation (6)</td>
<td>Containment ISI</td>
<td>Repairs</td>
<td>Surveillance program Long term challenge</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Others</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Physical and chemical ageing of polymers (7)</td>
<td>Silentbloc supports, cables (with(1)) ISI</td>
<td>Insulations measures Replacement Replacement stator bar, or coil</td>
<td>Laboratories programs condition based maintenance</td>
<td></td>
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<td></td>
<td>Insulation electrical machines</td>
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<tr>
<td>Wear (8)</td>
<td>RCCA ISI</td>
<td>Replacement (hard RCCA) Replacement</td>
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<td>RCCA guides ISI</td>
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<td>CDRM</td>
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5- SURVEY OF AGEING MECHANISMS RELATED TO NUCLEAR POWER PLANTS

5.1 - Physical ageing phenomena

Under the effect of degradation mode the properties change in materials during the lifetime of a nuclear component occur because of ageing phenomena.

All ageing phenomena derive from the consequence of ageing stress or degradation and the particular ageing mechanisms.

All factors which influence and cause changes to the atomic structure, the binding forces by increasing temperature or by irradiation and also the action of corrodatns, form stress and may result in ageing. As a consequence of these stress or ageing mechanisms can start to act.

Ageing mechanisms do not act on their own in most cases: they operate together with other mechanisms. In many cases it is the interaction of single mechanisms which leads to ageing effects. Every stress and degradation as a consequence, every ageing mechanism, demonstrates a lower limit, below which no remarkable ageing mechanism occurs. The combination of two or more objecting mechanism however, may reduce the threshold value.

Working conditions in nuclear power plants normally cause little ageing effect by fatigue. However, if corrosion is acting simultaneously then corrosion fatigue effects have to be regarded more thoroughly. Creep on the other hand may assist diffusion processes, therefore, irradiation by embrittlement may be reduced if rapid over-ageing of hardening particles takes place.

Design aspects have also to be taken into account: A common of problems may arise when seams are ot welded properly. Weld characteristics, as weld geometries have to be regarded very carefully to exclude problems due to inappropriate properties.

Heat treatment of components may decrease the toughness of austenitic cladding. If the austenitic cladding develops cracking, a corrosion attack of the base metal may result. Therefore, the heat treatment of clad pieces has to be controlled carefully to reduce the formation of the brittle sigma phase.

Initial ‘as built’ properties are also very important particularly with respect to defects. The smaller the initial defect size, the longer the operational will be.

This has been considered in the case of high frequencies of fatigue loading amplitudes: A pressure vessel is subjected to only few large cycles. Conversely, main re-circulating pumps work at a very high number of cycles and in this case, fatigue and corrosion fatigue may be developed. The presence of small initial defects sizes has to be checked very carefully in these components.
Initial values, which are the start of ageing have to be taken into account. Even if creeps does not occur in NPPs because of generally low stress and strain levels. At some highly stressed regions fatigue and corrosion fatigue may develop. Therefore, not only the threshold level has to be taken into account if a single mechanism becomes active, but the combinations which may enhance or reduce the threshold values, have also to be taken into account. Only those ageing mechanisms, which are above the appropriate threshold values, act as stress due to ageing.

This consideration requires that temperature is taken into account. The particular temperatures present have to be considered. Therefore, the temperature aspects of the loading case have always to be considered parallel to the mechanical loading.

5.2 - Manufacturing aspects of ageing

If property changes are considered as a consequence of the particular degradation mechanism then the properties at the end of fabrication and at the start of service have to be considered. For instance in the case of RPV, the initial toughness has great importance, if irradiation damage has to be considered. The transition temperature in core belt regions was in some cases near to 0°C. By improving the fabrication methods, the NDT temperature was shifted to a value below –30°C. The shift of the transition temperature during subsequent service therefore did not do much harm if the transition temperature was low at the start of life.

If the shift due to irradiation is likely to be about 130°C, then the start of life hydro test difficulties in the end of life case when the NDT temperature is near to 0°C, whereas an NDT temperature below –30°C will demonstrate no real difficulties.

The copper content in the submerged arc girth welds contributes strongly to the irradiation embrittlement of the weld. Therefore, a heat treatment to restore toughness of the irradiated material will become necessary earlier in life, with high copper content. The phosphorus content in low-alloyed steels can increase irradiation embrittlement on the one hand, and thermal ageing and temper embrittlement on the other hand. Therefore, a very careful specification, of the chemical composition of materials as well as their purity could play a very important role in the prevention of component ageing.

Surface roughness, in the case of reactor coolant pipes, for instance, may influence corrosion resistance and also fatigue corrosion behaviour. Therefore, it is very important to measure and optimise and specify the surface quality.

Also in case the of fatigue, small cracks and also uneven surface geometry can increase ageing.

Heat treatment has to be evaluated very carefully. As residual stresses may increase internal stress, stress relief heat treatments are therefore beneficial for fatigue loading. However, the
degradation of strength and toughness has to be considered and the balance evaluated. At the same time, an improper heat treatment regime can “sensitize” austenitic stainless steels and thus enhance initiation of the inter-crystalline type of corrosion damage.

Additionally, the heat treatments may add to fatigue damage by reducing strength and perhaps decreasing toughness. Therefore, the condition of the component at the start of service has to be considered as a trend-line start condition.

5.3 - Operational (service) conditions of NPPS

Service conditions of NPP components depend mainly on the type of reactor, the design and, to a smaller extent, the national/utility practice.

In principle, the most important parameters from the point of view of component/material ageing, are as follows:

- Pressure of the primary/secondary coolant, which loads mainly to fatigue damage – due to changes in the operational pressure, i.e. in the calculated stresses in the components,

- Temperature of the primary/secondary coolant which affects all ageing processes, mainly thermal ageing and radiation damage,

- Neutron fluence which can change the mechanical properties of the beltline part of the reactor pressure vessel as well as reactor internals materials,

- Water/steam chemistry conditions which can, together with other parameters, result not only in component wall thinning (homogenous corrosion, erosion-corrosion) but also in component cracking (stress corrosion, pitting). Two elements are most important – oxygen and chlorine: while chlorine content is usually held at low values, oxygen concentration PWR (approx. <<10 ppb).

5.4 - Some examples on the importance of databases reactor pressure vessel and steam generator

5.4.1 - Reactor pressure vessel

Several parameters and database are important for ageing evaluation. Concerning the RPV the good knowledge of chemical composition of each vessel (vessel by vessel) and each part of the vessel are major data to evaluate the initial properties and the RTndt (Fig.2).

The collect of different situations in operation and transient is necessary for ageing assessment, mainly for the integrity evaluation in each case of situation (Fig.2).
5.4.2 - Steam generators

5.4.2.1. **Main degradation mechanisms taken into account in the monitoring strategy**

Primary Water Stress Corrosion Cracking (PWSCC) occurs at locations on the inside surfaces of recirculating steam generator tubing with high residual stresses (introduced during fabrication and installation of the tubes). These locations are primarily the roll-transition regions in the tube sheets, the U-bend regions of the tubing in the inner rows (i.e., the tubes with a small bend radius), and any dent locations in tube support plate areas. Tub denting is a deformation (resulting in residual stresses) due to build-up of corrosion products. PWSCC generally occurs on the hot-leg side of the recirculating steam generators; however, cold leg PWSCC has also been observed.

Dents do not themselves result in tube wall penetration or reduction in wall integrity. However, denting at some plants in the past has been sufficiently severe to cause structural damage to the tube supports. Denting is a concern because even small dents can induce tensile stresses above yield strength in the tube wall. As a result, these tubes may be subject to PWSCC or IGSCC on the dents during subsequent operation. In addition, severe denting in tubes with small radius U-bends has accelerated Stress Corrosion Cracking in the U-bends, due to distortion of the tube legs. Furthermore, tubes with dents at the top tube support plate in the U-bend region of the SGs are more susceptible to high-cycle fatigue failure.

5.4.2.2. **In-service inspection and strategy for replacement**

In France, the SG belong to the set of main components on which specific maintenance is performed.

The objectives of SG tubing maintenance are the following:

- To maintain the tube rupture probability at a sufficiently low level,
- To limit the number of forced outages due to primary / secondary leakage.

Therefore, many surveillance technique are required in the corresponding guidelines. They are of three types:

1) Leakage monitoring, involving:
   - activity of condensates and bleeds (continuous monitoring),
   - dosing with nitrogen 16 in the steam,
   - hydrotest and helium testing during ten-year outages.

2) Non destructive examinations, including notably:
   - eddy current testing (standard bob-bin coil and rotating probes),
advanced signal processing,
ultrasonic testing (under development),
television inspections.

3) Destructive examinations of extracted tubes:
- all analyses, including leak and burst tests,
correlation with NDE results.

The surveillance programme of the SG depends on the characteristics of their tub bundles:
- Tube bundle having undergone a stress relieving heat treatment,
- Tube bundle without stress relieving heat treatment,
- Inconel 690 tubes (alternative SG).

The lifetime of the SGs depends on the condition of their tube bundles. When the number of plugged tubes exceeds a certain value, it is no longer possible, on the basis of present knowledge, to operate at full power. Typically, “overplugging” tubes beyond the allowed limit is envisaged as a withdrawal solution, waiting for a SG replacement, and in preference to other maintenance options (sleeving, etc…) for economic considerations.

6- CONCLUSION AND METHODOLOGY TO FOLLOW UP THE AGING MANAGEMENT

The development of methodology to follow up the evolution of life management of each components, equipments and structures requires a good knowledge of the evolution of mechanical and metallurgical parameters for initial properties and the increasing of characteristics during time in operation.

The identification of different modes of degradation and the combination with normal maintenance program or exceptional maintenance strategic view are main guidelines for life management.
Fig 1 – Aging management Diagram
Fig 2 - RPV integrity assessment Diagram of methodology

RPV SPECIFIC EVALUATION