Integrated Life Cycle Management for Nuclear Power Plant Long Term Operation

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Abstract: High capacity factors and low operating costs have contributed to making commercial nuclear power plants (NPPs) some of the most economical low carbon emission power generators in the world. As a result of both economic and environmental (e.g. climate change) imperatives, it is envisioned that operation of the current fleet of NPPs will extend significantly beyond their original period of licensed operation. However, a decision to extend NPP life involves inter-related technical, economic, regulatory and public policy issues. Due to the long timeframes involved there are large uncertainties associated with the elements that are evaluated to arrive at such a decision. This is particularly important given the potentially large capital expenditures that could be necessary to maintain high levels of safety, operational and economic performance over the intended extended period of operation. In this paper we describe development of an Integrated Life Cycle Management (ILCM) approach that provides methods to assess asset life probabilities through physics of failure based analyses that are then used to develop optimal component refurbishment and replacement strategies that can be implemented at either the plant or fleet level.

Keywords: Integrated Life Cycle Management, Physics of Failure, Genetic Algorithm

1. INTRODUCTION

Environmental, regulatory and market realities coupled with sizeable capital costs associated with new nuclear plant construction have made long term operation (LTO) of existing nuclear power plants (NPPs) economically and practically favorable over new builds. To achieve this desired state, NPP operators must maintain, enhance and ensure high levels of plant safety, reliability and economic performance over the projected extended operating timeframes. Major capital assets designed to operate over the initial license period, and whose failure might jeopardize continued operation, must now be evaluated for these extended operational timeframes. When deciding whether to extended NPP life or not, long term operating plans must be developed, investment strategies considered, and major asset replacement and / or refurbishment options examined. Plant operators need to be equipped with sound scientific, and consistent technical knowledge bases to provide them with critical information to support optimal asset management and investment decisions. Over the past several years the Electric Power Research Institute (EPRI) has conducted research to develop an approach to provide NPP operators with methods and tools to cost effectively perform these evaluations and to optimize the capital asset allocation for the operating fleet of plants over their postulated extended operating lifetimes. This research resulted in the development of the Integrated Life Cycle Management (ILCM) methodology. ILCM methods are intended to result in scientifically, technically, and economically based asset life probabilities, which then, in turn, feed optimization and risk calculations. Integration of asset failure likelihood with economic impact to quantify plant operating financial risks are used to provide credible scenarios for input into long range plant and / or fleet strategic technical and business decision models. The objective of ILCM is to provide plants with better information to improve the quality of major asset refurbishment / replacement decisions that are based upon quantitative scientific and engineering principles that are site specific and generate analyses that support repeatable and justifiable decision-making.

ILCM consists of three basic elements. First, the anticipated lifetime of structures, systems and components (SSCs) that have high capital costs and high consequences of failure are evaluated. For these SSCs a physics of failure (PoF) approach is used to develop representative “Likelihood of Failure” (LoF) curves. These curves are modified to account for the material properties, aging effects and operating stressors to which the SSCs have been subjected over the operating lifetime of the plant.

From the plant historical data Monte Carlo analyses are used to obtain plant specific probabilistic failure curves for each SSC that is evaluated as part the ILCM program. These LoF curves provide the basic information used to evaluate the risk tradeoffs that are inherent in the capital asset allocation process. The second necessary element associated with a NPP's ILCM program is the need to assess the projected life cycle costs. To evaluate these costs for each of the SSCs the LoF information serves as the technical element of the assessment. Then cost and financial models are used to evaluate the key financial attributes (e.g. cash flow and net present value (NPV)) for different life cycle management strategies associated with each plant SSC. The final component of ILCM is to provide a decision support structure to evaluate alternatives and select optimal SSC replacement or refurbishment strategies. In our work a genetic algorithm has been used to evaluate alternative investment strategies within the constraints imposed (either internally or externally) to arrive at an optimal investment plan over the remaining life of the plant.

In this paper we describe the basic ILCM framework and its foreseen use in the NPP LTO decision making framework. We also provide examples from several initial proof of concept pilot applications at operational US NPPs. Finally we discuss insights obtained from these pilot applications and describe plans to enhance and mature the ILCM approach.

2. COMPONENT EVALUATIONS – LIKELIHOOD OF FAILURE

The first question that needs to be addressed in an evaluation of a NPP life extension decision is what are the level and timing of the projected capital costs will be required to enable the extended operation of the plant. Because these costs are dominated by a relatively small number of high cost / high consequence structures, systems and components (SSCs) ILCM is intended to be applied primarily to this subset of SSCs. In addition to individual components and structures, ILCM also considers "classes" of these SSCs such as cables or buried piping. Because the SSCs included in an ILCM evaluation consist of many diverse characteristics (e.g. active and passive electrical and mechanical components, reinforced concrete structures, etc.) the ILCM methodology is designed to provide a consistent basis for evaluating these disparate SSCs.

Once the critical set of SSCs to be included in the ILCM evaluation is identified, the next step is to determine the likelihood of failure for each of them between now and the projected end of operation of the plant as a useful economic asset. Generally, within a physics of failure framework the remaining operating life of an SSC is considered to be related to the amount of time it already has been in service. The particulars associated with the remaining SSC life and the timing of the likely occurrence of "failure" are dependent on the degradation mechanisms that are acting on it. For many SSCs, the failure likelihood is classically defined by a "bathtub curve." If the stress experienced by the SSC increases, the likelihood of its failure at any given time will be statistically greater and the wear-out period, the time period in which the slope of the failure rate curve increases, will begin earlier. In this model, after an early life "run-in" period with a higher likelihood of failure (infant mortality), SSC performance is commonly characterized by many years of low and a relatively flat rate of failure (and which typically are taken to be random events). It should be noted that performance in this portion of the curve is highly dependent on preventive maintenance and condition monitoring practices applied to the SSC. Because of the effective maintenance and monitoring applied to plant SSCs, this is the typical operational regime that characterizes SSCs at commercial NPPs. Thus, an inherent assumption of the ILCM approach is that a generally accepted and effective preventive maintenance (PM) program is in place at the NPP [1].

A critical assumption of the ILCM approach is that the maintenance and monitoring practices applied to plant SSCs will continue to be effective and even improved over time. We note that this is a reasonable assumption as all operating NPPs are stringently regulated. For example, in the United States all operating NPPs are subject to the requirements of the maintenance rule which requires systematic assessments of SSC performance [2].

However, even with ongoing maintenance, the likelihood of failure of all SSCs will eventually start to increase over time. This “wear-out” period characterizes the time when the likelihood of failure begins to increase. The stressors (use practices, duty cycles, temperature, etc.) cause the likelihood of failure to increase despite the preventive maintenance activities that are conducted. This situation occurs because the typical bathtub curve in reality is the composite of all of the failure distribution curves for all of the active failure mechanisms that occur on a SSC. Thus the bathtub curve is the “failure envelope” line that envelops all of the curves that characterize the individual degradation mechanisms. This is shown schematically in Figure 1. In general the mechanisms that occur during the “run-in” period are different from those that occur during wearout. For example, during the run-in period, failures typically occur due to misalignment, manufacturing defects, and other similar mechanisms. In the wear-out period, the mechanisms are more likely to be those that are a function of the SSCs service life and environment such as fatigue, corrosion, stress corrosion cracking, and irradiation embrittlement. It is these mechanisms that will eventually degrade a well-made and well-maintained SSC. For the purposes of the ILCM approach it is the rate of increase and the timing of occurrence of these mechanisms that are critical and that must be characterized and evaluated within the NPPs investment decision making process.

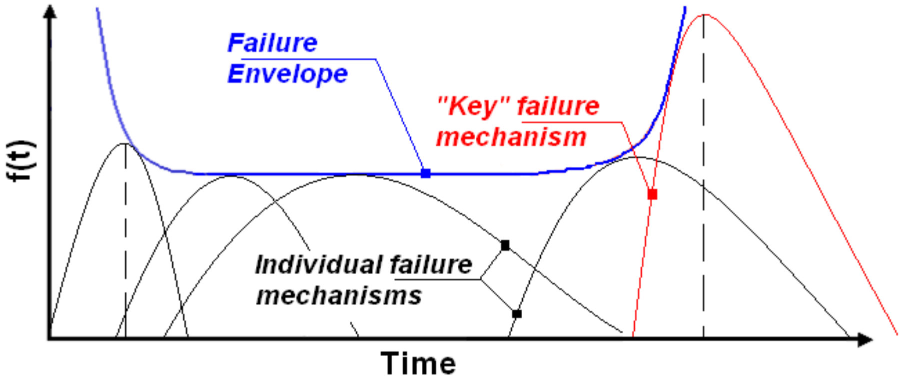
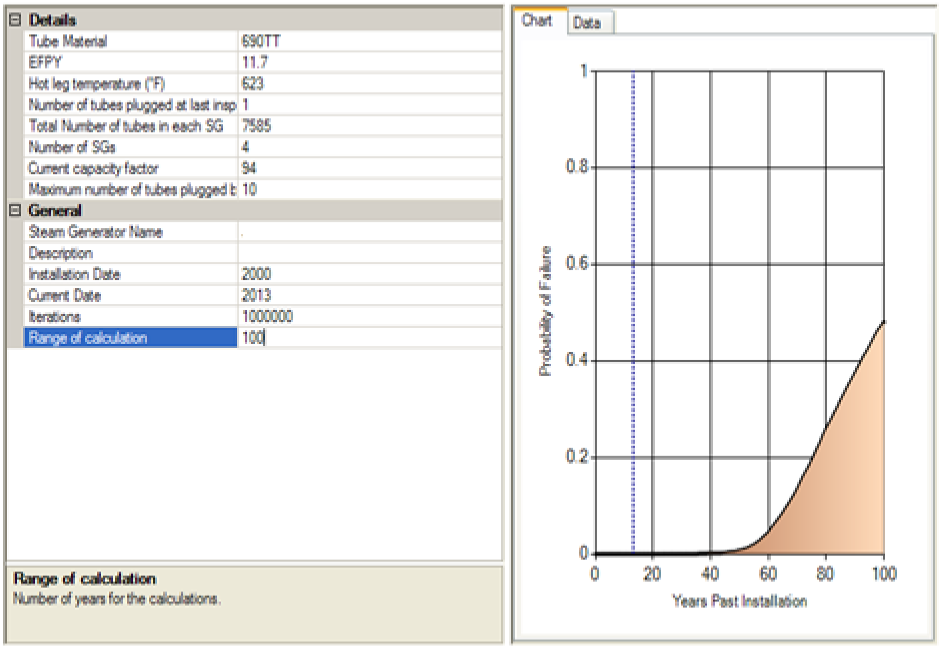


Figure 1: Envelope of the failure probability curves.

In the application of ILCM, the first activity is to collect plant specific operational data and to calculate a plant-specific LoF curve for each SSC evaluated. The result of this activity for each SSC is development of a curve that defines the probability of failure in any year out to the projected end of life of the plant. Once appropriate details of the SSC are gathered, including past operating experience (OE), a physics of failure approach is applied to calculate the likelihood that a failure could occur over a specified time range during the projected remaining life of the plant. For each SSC evaluated, the possible active degradation mechanisms are tabulated based on information available that incorporate industry operating experience, typical materials used, the environment or stressors experienced. These data are combined to develop a generic LoF curve for the SSC which is then reviewed by an expert panel for validation. We note that in this context, the use of the term validation is specific to indicating that the generic LoF curves developed for use in the ILCM process are representative of industry experience and are applicable to long term business / investment planning decisions. In particular these curves are not intended to be used to support short term applications such as preventive maintenance program development or optimization.

When these results are applied to investment planning at a particular plant, the generic LoF data need to be adjusted to reflect the operational experience at that particular NPP. A SSC being evaluated at a particular plant may be more or less susceptible to specific degradation mechanisms and the LoF curve will need to be modified accordingly. As a typical example, if the specific materials or operating environment make it more susceptible, the likelihood of failure will be increased. As mentioned previously, the outcome of this plant specific evaluation is to develop a LoF curve that is applicable to that plant and can be used in its investment planning process. An example of a plant specific LoF curve for the steam generators that was developed during one of the pilot applications (discussed more fully in Section 4 below) is shown in Figure 2 [3]. This figure shows the cumulative density function for failure of the SSC with time zero corresponding to the date of initial operation of the SSC. The vertical dashed line at t = 15 yrs indicates where the SSCs currently is in its operational life. These results are used to provide input of the SSC's likelihood of failure at different times in the future for evaluation of the impact of alternative investment strategies over the remaining postulated life of the plant.



Details	
Tube Material	690TT
EFPY	11.7
Hot leg temperature (°F)	623
Number of tubes plugged at last insp	1
Total Number of tubes in each SG	7585
Number of SGs	4
Current capacity factor	94
Maximum number of tubes plugged b	10
General	
Steam Generator Name	.
Description	
Installation Date	2000
Current Date	2013
Iterations	1000000
Range of calculation	100

Range of calculation
Number of years for the calculations.

Figure 2: Steam Generator LoF curve from ILCM pilot application at pilot NPP1 [3].

Due to limitations of space, a detailed discussion of the process used to develop LoF curves will not be provided in this paper. Reference [1] describes in detail results of a proof of concept application of the approach to large electrical transformers and spent fuel pool structures for the ability to predict long term SSC degradation. This was accomplished by performing the following activities for each of these SSCs:

1) defining the critical degradation modes,
2) developing an understanding of how those modes progress – i.e. developing analytical expressions that represent the "physics of failure",
3) obtaining specific LoF curves for each SSC that is commensurate with the plant specific data and operational experience.

In this paper we provide a very brief synopsis of this work. As a result of the initial applications described in [1] it was concluded that a degradation-based modeling approach could be effective in determining a plant-specific life of a SSC for the purposes of long range investment planning.

A critical aspect of developing a LoF curve that is useful for decision making is to evaluate and characterize the failures that have been observed for the SSC of interest. In the ILCM approach the documented operating experience (OE) for each SSC was reviewed. For the case of large transformers the frequency of failure as a function of in service time is shown in Figure 3. For this SSC the predominant failures were due to the core, winding, insulation, and internal wiring. In failures that occurred after twenty years of operation, 17 occurred in these subcomponents and 6 occurred in the bushings.

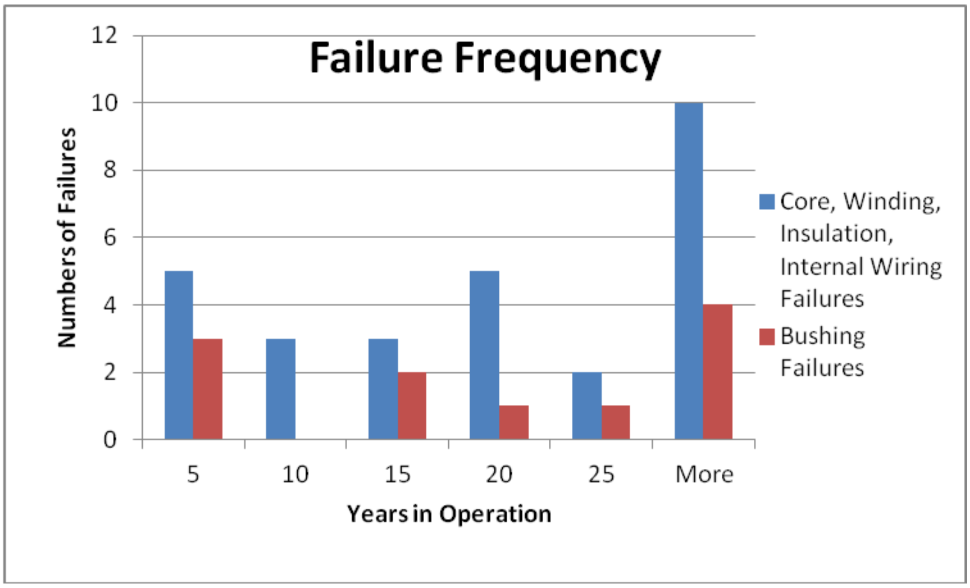


Figure 3: Transformer failures by years in service [1].

With the identification of the subcomponents and categorization of their OE, the next step in the ILCM approach is to identify the degradation mechanisms applicable to each subcomponent and to formulate a physics of failure model applicable to it. Based on the transformer OE and knowledge of the source of end-of life events, the core and internals provide the greatest threat to successfully achieving extended life of the transformer. Therefore, it was posited that an assessment of the degradation that occurs in the core and internals would provide an effective surrogate to predict the effective end of the SSC's service life.

Based on review of the relevant literature, failure degradation algorithms were developed for the transformer subcomponents. To validate these models data were collected from six operating NPPs. The data are shown in Table 1.

Plant	**Transformer**	**Load**	**Summer Oil Temperature (°C)**			**Winter Oil Temperature (°C)**		
			Min	Mean	Max	Min	Mean	Max
1	A	95%	70	80	95	50	60	70
	B	92%	70	80	95	50	60	70
2	A and B	90%	70	80	95	50	60	70
3	A	80%	70	80	90	50	60	70
4	A, B, and C	86%	70	80	90	50	60	70
5	A and B	50%	70	80	95	44	60	70
6	A	88%	55	60	70	35	50	55

Table 1: Transformer operational data [1].

The input for the Monte Carlo analysis to construct the LoF curves requires that statistical distributions be assigned for the expected range of each variable. Based on the available data the following distributions were developed and are shown in Table 2. We note that the reader is referred to reference [1] to obtain details of the development of the degradation algorithms, statistical distributions and outcomes from the Monte Carlo runs to generate the LoF curves for this SSC. We also note that we anticipate publishing similar information (relevant SSC OE, degradation algorithms and generic LoF curves) for each SSC within the ILCM scope in a future EPRI technical report.

Variable	Nominal Value	Statistical Variation
Transformer Life	180,000	Normal distribution with standard deviation of 9000
Load as a percentage of Rating	As stated for specific transformer	Normal distribution with standard deviation of 1%
Summer Temperature	Average Summer Temperature	Weibull Distribution with the scale of 9, with the shape of 1.7, and with the minimum temperature equal to the summer minimum temperature
Winter Temperature	Average Winter Temperature	Normal distribution with standard deviation of 4

Table 2: Transformer input distributions for LoF development [1].

3. INVESTMENT OPTIMIZATION

As mentioned previously, the ultimate objective of ILCM is to optimize the planning of long term investments to support decisions for NPP long term operation. A critical element necessary to support this objective is to obtain estimates of specific plant cost data that will be required to support capital asset planning evaluations. These data include the cost of replacement or refurbishment for each SSC evaluated, the cost of capital to the organization, maintenance costs before and after replacement or refurbishment, and the consequences / costs that would occur if an SSC would fail while in operation. In addition to the relevant costs, the implementation of the potential investment strategies is subject to numerous constraints. Some of these constraints are due to issues associated with particular SSCs. Because ILCM addresses investment planning for large capital equipment (such as steam generators and large electrical transformers) there often are limitations related to the supply chain for these SSCs and which are manifest in the necessary lead times needed to procure and obtain replacements. There also are constraints associated with the business aspects associated with the operation of the NPP. As one example of such a constraint, NPP refuel outages are scheduled many years in advance and reflect constraints on the timing of when particular investment strategies can be implemented in the field. In the planning process these constraints also can be complicated by the fact that they may be interrelated (i.e. they represent coupled constraints). These conditions result in a very complicated problem from the viewpoint of developing a solution that is optimal from a financial perspective (such as maximizing a metric such as net present value – NPV) while simultaneously satisfying all of the constraints that are imposed over (potentially) many decades of planned NPP operation.

To develop an optimal long-term investment plan to support LTO, ILCM utilizes an integrated Investments Portfolio Optimal Planning (IPOP) tool. The IPOP tool was initially developed by Électricité de France to apply an appropriate financial metric (typically NPV) to optimize investments for major components of a fleet of NPPs. To achieve this objective, IPOP consists of three modules to perform the necessary calculations:

1) Mean NPV Valuation Module to evaluate the measure of the profitability of a portfolio of investments,
2) Optimization Module to identify an optimal set of investments,
3) Probabilistic NPV Valuation Module to evaluate the measure of the risk associated with a portfolio of investments.

The articulation of these modules is described in Figure 4.

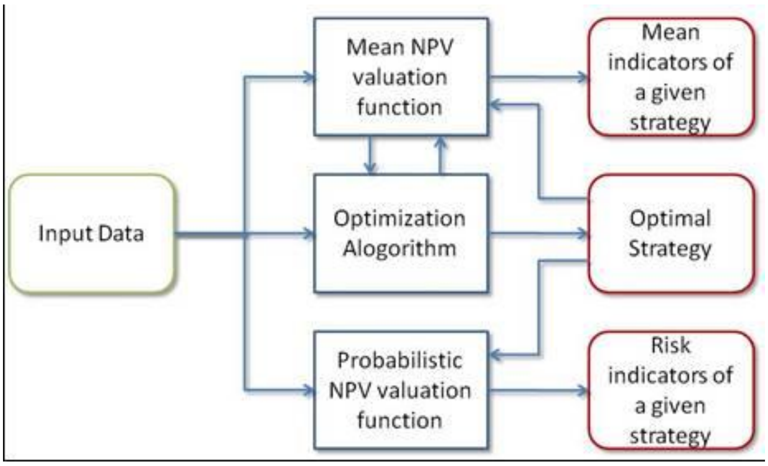


Figure 4: Articulation of the different steps in the optimization and the risk assessment of long-term NPP investments with IPOP.

In the IPOP approach each SSC that is evaluated is characterized by its reliability which results in the LoF characterization described in Section 2 above. A failure of a component generates different types of consequences (such as direct costs, loss of production, power derate, etc.). In IPOP these consequences are evaluated as financial cash flows. The risk associated with a given SSC is then defined in the standard manner as the product of probability of occurrence and the resultant consequence of the event. The profitability of a particular investment is then the difference in the accumulated discounted cash flows for the two conditions where the particular investment is made and the case where it is not. Typically this is quantified through a representative financial metric (most frequently chosen to be net present value (NPV)). Figure 5 shows an example for which the preventive replacement of a component is profitable between the years 2014 and 2026 (characterized by a positive NPV) with an optimal investment occurring in 2020 (characterized by a maximal value of NPV) [3].

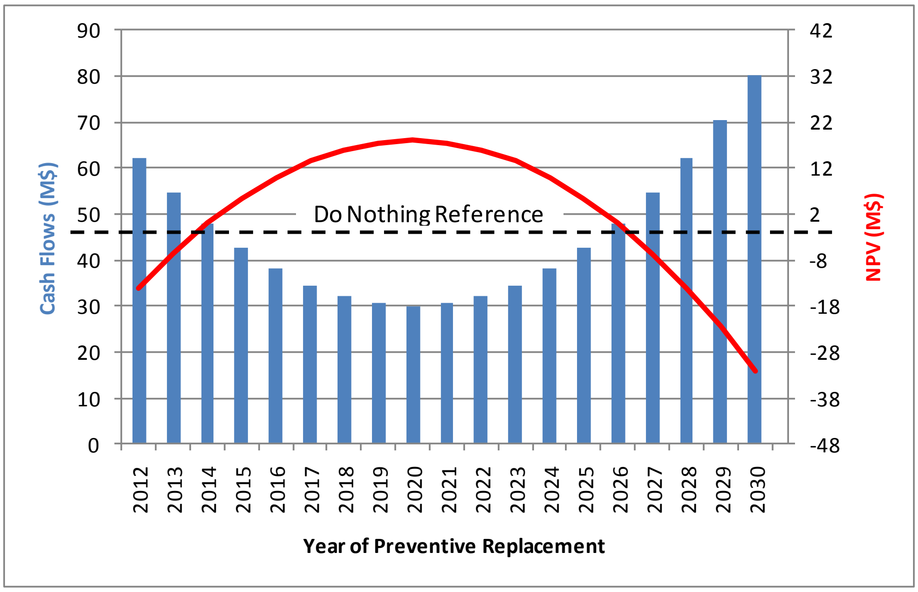


Figure 5: Example NPV results for different years of preventive SSC replacement.

When attempting to achieve an optimal portfolio of investments, the global optimum usually is not a result of taking a selection of optimal decisions which are taken independently (that is, a series of investment decisions that are optimized individually does not generally lead to an optimization of a portfolio that includes all of the individual investments). This situation is complicated by the observation that such a portfolio often is unacceptable from a business perspective when constraints are imposed. These constraints may be economic (for example, global and annual budget allocation limits), logistical (such as a delay between performing an activity because it requires personnel or equipment that are already employed in other activities), or external (such as actions needed to meet regulatory requirements). In addition to these conditions, attempting to arrive at a portfolio of capital investments that is implemented over very long time periods also is complicated by the presence of significant uncertainties in the information (inputs and outputs) necessary to support effective decision making.

Given the large number of SSCs that need to be evaluated, the diverse nature of constraints that must be met, the long timeframes involved and the large uncertainties in the information needed to support the analyses, obtaining an optimal capital investment portfolio applicable to the LTO of a commercial NPP represents a very challenging problem. One approach that has proven to be a powerful tool applied to optimization problems intended to achieve objectives similar to that of ILCM is the use of a genetic algorithm (GA). In brief a GA is a class of metaheuristics that is widely used in Operations Research; it belongs to the class of evolutionist algorithms that iteratively attempt to improve a population of solutions to a problem [4, 5]. The IPOP tool was developed to apply this approach [6, 7].

In the implementation of IPOP within the EPRI ILCM software application the following steps are performed to arrive at an optimal investment plan [6].

1) Initialization: Many possible solutions are randomly generated and evaluated via a fitness function with results sorted by increasing fitness.
2) Selection: At each generation step two solutions are chosen randomly. These become parent solutions for future generations.
3) Crossover: Two solutions (offspring) are generated using parts from the parents. Of these only one of the children is kept via random selection.
4) Mutation: Randomized modifications to the child solution are made.
5) Update: The resultant child solution is then incorporated in the population in replacement of an old solution that is chosen randomly.
6) Termination: The algorithm loops to step 2 (i.e. the system evolves) until a termination criterion is reached. This termination point represents the optimal investment solution.

A key output of IPOP is the probabilistic distribution of the NPV for each strategy evaluated. These distributions (and key metrics derived from them such as mean NPV and probability of regret) provide the critical information that is supplied to key decision makers for consideration in the strategic capital allocation process. In the implementation of the IPOP algorithms, we note that the NPV, which is the difference between the cumulative cash flows generated compared to the case where the proposed investment strategy is not implemented, may not be calculated from the distribution of each case evaluated separately as the two distributions may be highly correlated. As a consequence IPOP simulates the probabilistic distributions of the NPV using a Monte-Carlo simulation algorithm that evaluates the cumulative cash flows for the two cases. Tables containing the SSC failure dates are initialized randomly depending on the reliability data supplied from the LoF curves for the impacted SSCs and duplicated so that the failures occur at the same dates as long as an investment does not distinguish them [6].

4. PILOT DEMONSTRATIONS

The fundamental objective of ILCM is to combine estimates of the likelihood of failure of critical capital assets with an evaluation of economic impact to quantify plant operating financial risks over the long periods of time envisioned for NPP LTO. This combination creates the potential to define an optimum long-term operating and financial strategy that reduces plant operating risks and improves financial performance. In ILCM, these processes have been implemented through a software platform, the intent of which is to provide plants with better information so that the quality of and management confidence in long-term investment decisions can be improved. The EPRI ILCM software links the SSC LoF algorithms with plant-specific financial information to enable better-informed decisions about the control of capital spending. Key outcomes of the ILCM analyses are providing insights into how to control and reduce capital spending, development and evaluation of models for potential alternative strategies to optimize capital investments for NPP LTO, and providing a consistent framework for prioritizing capital spending. Importantly, the EPRI ILCM software platform is intended to enable the evaluation of multiple,major plant SSCs and provide a consistent basis for making decisions across these components and across multiple plants in a fleet [3].

To demonstrate the approach ILCM pilot plant demonstrations were conducted at two host NPPs in the United States (identified in this paper as NPP1 and NPP2) during the spring of 2013. These demonstrations represented the first plant-wide applications of ILCM. Objectives of the pilot demonstrations included exercising the three key elements of the ILCM methods and software:

1) calculation of LoF curves for selected plant SSCs,
2) application of the IPOP optimization algorithms to determine optimal plant-specific investment strategies to maintain safety and reliability over the projected plant operation lifetime,
3) demonstration of use of the ILCM software.

In this section we provide several representative results obtained from these pilot implementations. We note that details from them are more fully described in reference [3].

4.1 Development of SSC LoF Curves

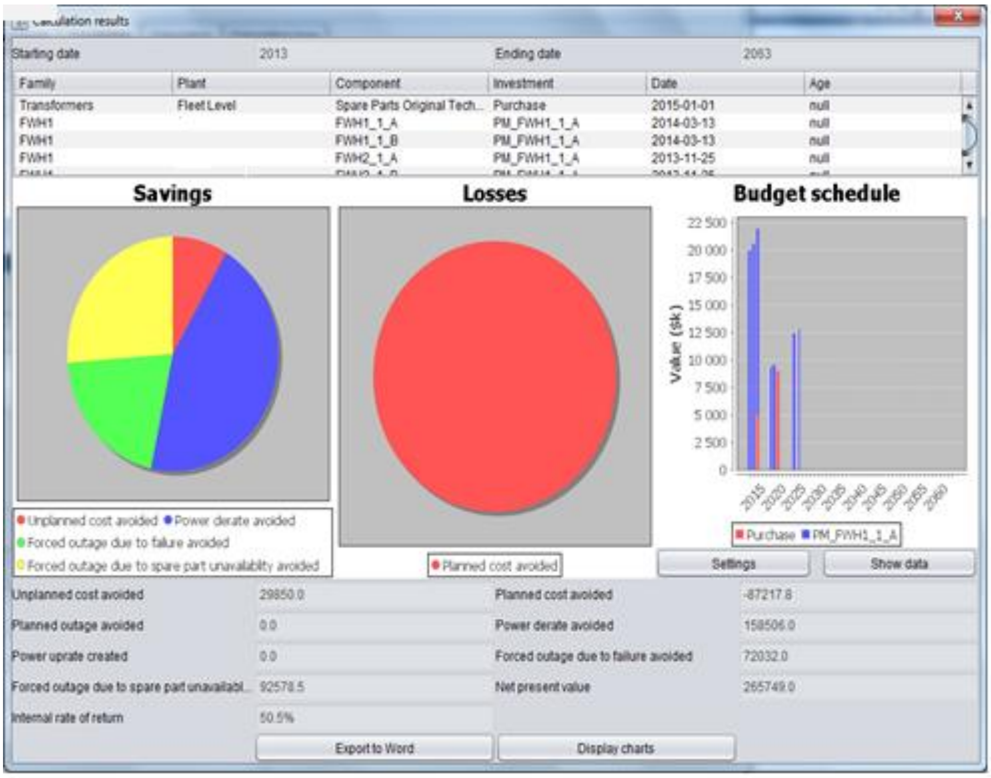
In each pilot application, the responsible system engineers (RSEs) at the station provided plant historical information on the conditions and performance of the SSCs for which they were responsible. These data were input into the ILCM software, and the ILCM algorithms were applied to develop applicable LoF curves for each SSC evaluated. In each case, the RSE performed the following activities:

- Evaluate the appropriateness of the initial decisions about which SSCs were selected to be within the scope of the ILCM process.
- Identify the critical materials that were used by the SSC and their applicable degradation mechanisms.
- Apply plant OE to define any degradation that has been observed to have occurred over the course of the plant operating history.
- Define any stressors that were determined to cause the occurrence or acceleration of the degradation mechanism.
- Defined the life consumption metric for each SSC evaluated.

From the plant data input, an applicable LoF curve for each SSC was developed using the algorithms contained in the ILCM software. The results of these analyses were reviewed by the RSE for applicability to the plant and reasonableness based on their experience. Because this was an initial application of the algorithms that applied physics of failure principles to generate LoF curves, it was expected that enhancements to the failure algorithms would be identified. This situation was, in fact, observed to occur in each of the two pilots. As a result, enhancements to several of the LoF algorithms have been identified and have been incorporated into the ILCM software.

4.2 IPOP Application

After developing the LoF curves for each of the SSCs evalauted, the RSEs worked with the EPRI project team members to develop IPOP results. In each case the RSE provided necessary input on SSC repair / replacement costs, time needed to conduct the repair / replacement, the impact of any required power derate, and other factors that are integrated with plant-specific data on outage schedules and financial parameters for input into optimization algorithms; the output of which is intended to support the NPPs capital investment decision process. The IPOP module was then applied to calculate the NPV for a variety of postulated alternative decision scenarios. An example of graphical output from the IPOP module of the EPRI ILCM software is shown in Figure 6.



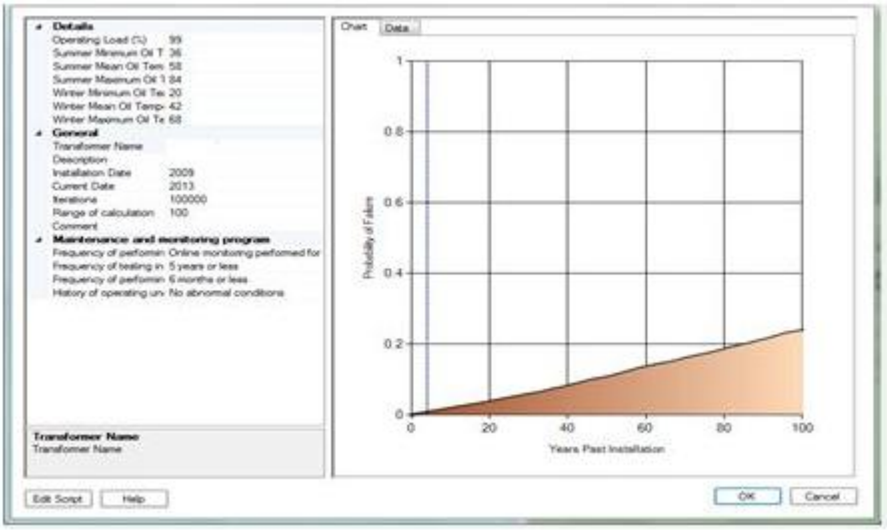
Starting date 2013 Ending date 2063

Family	Plant	Component	Investment	Date	Age
Transformers	Fleet Level	Spare Parts Original Tech...	Purchase	2015-01-01	null
FWH1		FWH1_1_A	PM_FWH1_1_A	2014-03-13	null
FWH1		FWH1_1_B	PM_FWH1_1_A	2014-03-13	null
FWH1		FWH2_1_A	PM_FWH1_1_A	2013-11-25	null

Unplanned cost avoided	29850.0	Planned cost avoided	-87217.8
Planned outage avoided	0.0	Power derate avoided	158506.0
Power uprate created	0.0	Forced outage due to failure avoided	72032.0
Forced outage due to spare part unavailabl...	92578.5	Net present value	265749.0
Internal rate of return	50.5%		

Figure 6: Example IPOP output results.

The capital asset management of one of the components studied at NPP2 represents an interesting application of IPOP for evaluating several different investment alternatives. The value of these alternatives, which focused on an optimization of the spare parts strategy for the SSC, was enhanced by the opportunity to evaluate similar components shared with a sister station where the same manufacturer / model of transformers are used at all four units at the two stations. These transformers had all recently been replaced, so the in-service units are all essentially new. Additionally, the old replaced units that are serviceable were still on site, so there are a total of three potential spares (one at NPP2 and two at the sister unit) that could be installed in the event of a failure. The LoF evaluation (shown in Figure 7) indicates that the likelihood of failure is fairly low.



Details
Operating Load (%) 99
Summer Minimum Oil T 36
Summer Mean Oil Tem 58
Summer Maximum Oil T 84
Winter Minimum Oil Te 20
Winter Mean Oil Temp 42
Winter Maximum Oil Te 68
General
Transformer Name
Description
Installation Date 2009
Current Date 2013
Iterations 100000
Range of calculation 100
Comment
Maintenance and monitoring program
Frequency of perfomin Online monitoring performed for
Frequency of testing in 5 years or less
Frequency of perfomin 6 months or less
History of operating un No abnormal conditions

Transformer Name
Transformer Name

Figure 7: Transformer LoF curve from ILCM pilot application at NPP2 [3].

Given this situation, IPOP was run to identify an optimal investment strategy for these components. Since the in-service components are basically new, the basic investment solution sought was the optimal number of spares for the two sites. In the analysis conducted using IPOP the following assumptions were made:

- One spare transformer is located at NPP2, two spares at the sister site.
- The cost of a spare is $10M with a best case lead time of 18 months.
- In the event of a failure fourteen days are needed to replace the component.

As a result of the IPOP optimization study, it was determined that the optimal stocking level for the component is to maintain one spare for the four units. Additionally, if the decision is made to operate the plants to 80 years, having a second spare would become profitable only in the year 2038. Because there currently are three spares located at the two sites, the LoF results indicate that the likelihood of needing all three spares would be very remote. Thus, an opportunity exists to enhance plant economic value by selling one (or more) of the spares.

Evaluation of this opportunity was identified as a worthwhile application of IPOP. The analysis assumed that each spare could be sold for $5M. The results of this analysis are displayed in Table 3. At the assumed sale price, the analysis clearly indicates that the optimal investment strategy would be to sell two of the three existing spare transformers. In the case of an increase to 80 years of plant operation, further analysis indicated that selling two of the spares would remain the optimal strategy.

No. Spares Sold	**0**	**1**	**2**	**3**
NPV ($M)	0	4.8	10	-9
Probability of Regret of Sale (%)	0	0	3.1	15.6
Risk of Spare Part Unavailable (%)	0	0	3.8	16.5

Table 3: IPOP evaluation of selling spare transformer(s) at pilot NPP2 [3].

5. CONCLUSIONS

In this paper we have described the development and initial pilot demonstrations of an integrated approach to evaluate and optimize large capital investments over extended periods of NPP operation. This ILCM approach developed plant specific estimates of SSC failure likelihoods and combines them with estimated economic impact of failure to quantify plant financial risks. This combination creates the potential to define an optimum long-term operating and investment strategy that can reduce plant operating risks and improve financial performance. These processes have been implemented through a software platform which was developed to provide plant decision makers with better information to enhance the quality of long-term investment decisions and provide a greater level of confidence that the intended results will be achieved. The ILCM software links degradation algorithms for each class of large capital equipment typically evaluated in a long range capital asset management plan with plant-specific financial information to enable better-informed decisions about the control of capital spending over the planned period of extended operation. The ILCM approach provides these decision makers with useful information and insights on how to effectively control capital spending, obtain improved estimates of the projected capital costs and timing of these investments to support NPP long-term operation, and provide a framework for prioritizing capital expenditures. The EPRI ILCM software platform provides a consistent basis to support capital investment decisions associated with high cost plant SSCs. It also provides an approach that supports optimization of these investments within the limitations imposed by constraints (either externally or internally imposed). Finally, the ILCM approach permits application to obtain such optimizations at both a plant and fleet level.

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