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Life Cycle Management in the US Nuclear Power Industry

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ABSTRACT

With the gradual transition of the world-wide electric power industry from economically regulated to competitive, nuclear plants or fleets of plants in the US are being viewed as individual business enterprises rather than as simply production units within a monopoly with an obligation to serve. In the new environment, a key to business success in both the near and long term is asset management, which addresses both physical assets (plant facilities and equipment) and financial assets (plant value and profit). Broadly speaking, life cycle management is the process by which nuclear power plants integrate operations, maintenance, engineering, regulatory, environmental, and business activities that (1) manage plant condition (equipment reliability, aging, and obsolescence), (2) optimize operating life (including the options of early retirement and license renewal), and (3) maximize plant value while, above all, maintaining plant safety. This paper discusses the equipment LCM technology development being sponsored by US utilities through EPRI. LCM identifies the optimum long-term maintenance and replacement plan for reducing the risk that aging degradation and obsolescence make the plant vulnerable to shutdowns and derates. The paper also describes work in financial asset management (also known as Nuclear Asset Management or NAM). A NAM framework for determining plant value and allocating resources to maximize plant value is presented. The framework is what is needed to perform equipment LCM on an integrated plant basis, which should addresses uncertainty and risk to the degree it is cost-beneficial.

KEY WORDS: life-cycle management, nuclear asset management, benefit/investment ratio, equipment reliability, aging risk reduction.

INTRODUCTION

The international movement to shift the business structure of electric power providers from monopolies to market-driven competitive enterprises was slowed, but not stopped, by the poorly implemented attempt at restructuring by the US State of California in 2001. Increasingly, nuclear power plants or fleets of plants in the US are being viewed as individual businesses rather than as production units with an obligation to serve. In conjunction with this restructuring movement world wide, the nuclear power industry continues to explore ways to maximize the profitable utilization of existing nuclear assets, while it supports the promotion and deployment of new nuclear technology. The role of the Electric Power Research Institute (EPRI) is to provide its US and international customers with technology (methods and software tools) to meet these objectives. Although all technology development by EPRI's Nuclear Power Sector supports efficient utilization of plants, the asset management activities of EPRI discussed in this paper focus directly on efficient utilization and profitability of existing nuclear assets.

In a competitive environment, a key to business success in both the near and long term is asset management, which addresses both physical assets (plant facilities and equipment) and financial assets (plant value and profit). Asset management is a process based on quantitative consideration of uncertainty and risk for making resource allocation decisions at every level of every business unit of an energy provider's organization. One of the most important aspects of asset management is life cycle management (LCM) defined as the integration of aging management and economic planning to:

- Optimize the operation, maintenance, and service life of equipment;[1]
- Maintain an acceptable level of performance and safety; and
- Maximize return of investment over the service life of the plant.

This paper gives an overview of EPRI technology development in the areas of equipment LCM and nuclear asset management (NAM).

[1] In this paper, "equipment" denotes systems, structures, and components (SSCs).

LIFE CYCLE MANAGEMENT

LCM is an effective long-term planning method for optimizing unplanned generation loss, maintenance cost, and capital investments consistent with plant safety and a target plant operating term (the original licensed term or an extended term). Note that the goal is *not* to minimize generation loss and maintenance cost, because, carried too far, this goal could lead to the worst-case scenario of permanent plant shutdown due to economic failure. Once an acceptable safety level is achieved, the goal is to maximize plant value by tradeoffs between plant performance and costs, and ensuring that the plant operates at full capability during times of peak usage.

Equipment LCM planning addresses such issues as aging management, preventive maintenance, technical obsolescence, and the replacement or redesign of equipment important to safety and plant operation. An equipment LCM plan consists of activities (preventive maintenance, predictive maintenance, corrective maintenance, redesign, etc.), schedules for these activities, and projections of long-term yearly expenditures.

Since 1998, EPRI has been developing the LCM process and collaborating with eleven plants to apply the process to equipment deemed important by those plants [1-5]. A paper at the 16th SMiRT Conference [6] discussed early results from LCM planning on six equipment types at two plants.

LCM PLANNING PROCESS OVERVIEW

The EPRI LCM planning process consists of the steps in Fig. 1.

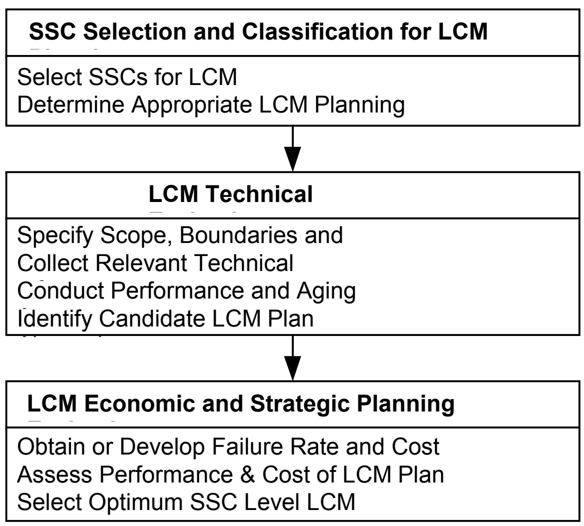

Figure 1 Major Steps in the EPRI LCM Planning Process.

The LCM process begins by screening and classifying all the systems and major components in a plant. The screening involves application of criteria including risk-significant/safety-related, important to power production (can trip or derate plant), costly if failed, subject to significant degradation or obsolescence, or chronically in need of corrective maintenance. A structured process called "EPRI-lite" [7] for interviewing plant experts can also be used to identify equipment types that warrant LCM planning. Such systems and components are classified as "critical" or "important." Both classifications are similar to the Institute of Nuclear Plant Operations (INPO) category of "critical" (failure defeats or degrades a function important to safety, reliability, or power generation), or "non-critical" (failure represents a significant economic or maintenance concern) [8]. Less important equipment does not warrant development of a long-term LCM plan. In the future, LCM planning should adopt the INPO definitions for importance categorization of equipment.

Following the screening and final selection of the candidate SSCs, LCM planning technical and economic evaluations are performed using the following basic steps:

- Reviewing the plant operating and performance history of the equipment
- Reviewing the generic industry operating and performance history for the equipment

- Reviewing the current long-term maintenance plan for the equipment
- Performing an aging, obsolescence and performance assessment
- Identifying candidate LCM approaches compatible with plant operating term strategies:
  - No changes to the current maintenance plan
  - Optimize the current maintenance plan
  - Make design changes or modifications
  - Replace or refurbish parts or components
  - Designate the component as run-to-failure
- Specifying alternative LCM plans, one of which is the "base case" (the current plan with no additional investment)
- Compiling failure rate and cost data for the alternative LCM plans
- Estimate performance and yearly costs of alternative LCM plans
- Calculate the net present value (NPV) of the following four cost elements for each LCM plan
  - Cost of lost power generation due to SSC failure.
  - Corrective maintenance (CM) cost
  - Preventive maintenance (PM) cost
  - Other "consequential" costs (e.g. regulatory cost)
- Select optimum LCM plan alternative for the SSC

LCM software tools [9, 10] are used to calculate the total NPV cost and the benefit-to-investment ratio (B/I) of each alternative plan. The total NPV cost is the sum of NPVs of the four cost elements identified above. The value of an alternative is measured by the amount it lowers the base case total NPV cost. The investment is an alternative plan's NPV PM cost over-and-above that of the base case. The benefit is the increase in power generation revenues in excess of the base case revenues, less any increases in CM and consequential costs. An alternative plan is economically worthwhile if its benefit-to-investment ratio, B/I, exceeds one. This means that the return on investment in the LCM "project" over the life of the plant is greater the company's cost of capital, which is used as the discount rate for future revenues and costs in the calculation of the increase in plant net present value (NPV) due to the plant's investment in PM (including replacements). Generally, the optimum alternative LCM plan is the one with the greatest B/I ratio.

In the past four years, the EPRI LCM process has been applied in plant studies to the following equipment types:

- Large Diameter Buried Piping
- Low Voltage Electrical System (Circuit Breakers)
- Buried Cable
- Main Generator
- 480V Electrical System
- Reactor Protection System
- Station Air
- Radiation Monitoring System
- Nuclear Instrumentation System
- Feedwater Heater Controls
- Main Condenser
- Chilled Water System
- Main Steam & Feedwater Isolation Valves
- Emergency Diesel Generators

EPRI LCM studies are of two types. For the above equipment types, a plant-specific LCM plan was prepared in collaboration with plant engineers in eleven plants [1-5]. Expert consultants visited sites to collect the needed equipment performance and cost data for one or more specific equipment items in each plant. For other equipment types, a subject matter expert prepared an "LCM Sourcebook" [11-18]. An LCM Sourcebook is a compilation of the *generic* information, data, and guidance an engineer typically needs to produce a plant-specific LCM plan for an equipment item. A sourcebook enables plant engineers or outside experts to develop a plant-specific plan for the subject equipment type with substantially less effort than they would need to spend without it. The sourcebook adds valuable industry information to the plant's own equipment performance and maintenance experience.

Table 1 shows the PM investments and benefits from five examples from LCM planning at three plants. The table indicates the recommended optimum alternative LCM plan and the substantial return on investment for each. Note that for some plant items the LCM evaluation may show that none of the new alternative plans are optimum – the current PM plan (base case) should be followed.

Governing NPV cost drivers are typically power price and predicted lost generation, which decreases revenues and increases corrective maintenance costs.

Table 1 Example Estimated Payoffs from Optimum LCM Plans at Three Plants

Equipment Type (Plant) [LCM Plan]	Investment in PM (NPV - $K)	Benefit (NPV - $K)	Benefit/ Investment Ratio
Station Air (Prairie Island) [change to rotary compressors]	760	6,200	8.2
Emergency Diesel Generators (Wolf Creek) [replace controls]	450	2300	5.2
Main Steam/ Feedwater Isolation Valves (Wolf Creek) [replace valve actuators]	180	1,700	9.3
Chilled Water System (V. C. Summer) [retrofit chillers]	350	11,000	32.4
480 / 600 V Non- Safety Breakers (Prairie Island) [replace with solid state]	630	1,700	2.6

Relationship of Equipment LCM to Other Plant Initiatives

In the last several years, all of a plant's activities and programs to enhance equipment reliability have been placed under the umbrella of INPO's Equipment Reliability Process. Long-term life-cycle planning is just one of them. Others include PM optimization, reliability centered maintenance (RCM), aging management, and obsolescence management. In addition, equipment reliability includes engineering actions like design, qualification, and failure analysis and operations actions like surveillance, carrying out operational procedures within specified limits, and measuring plant/component environments.

Originally, maintenance programs were established mainly on the basis of equipment manufacturer, NSSS, and architect-engineer recommendations. The equipment that received primary attention and resources were those important to safety (covered by, for example, ASME in-service inspection rules and equipment qualification requirements) and those important to reliable production (for example, reactor coolant pumps and turbine-generators). As time went on, the original maintenance programs were adjusted to reflect experience, reliability centered maintenance (RCM), and, in the US, the NRC Maintenance Rule [19]. Another step in the evolution of maintenance practices has been EPRI's Preventive Maintenance (PM) Basis project [20]. Based on consensus of industry expert panels, the PM Basis is centered on a "template" giving recommended maintenance tasks and task intervals for a wide range of common major equipment types. The technical basis for the recommended tasks consists of the reasons each task is performed and the relationship between the component's failure locations, failure mechanisms, the stressors producing degradation, and the timing of failures. This EPRI initiative has completed PM templates for about fifty component types.

The goal of the LCM process is to integrate vendor recommendations, Maintenance Rule, License Renewal Rule, equipment qualification, RCM, LCM, and PM Basis to arrive at one comprehensive living maintenance program that improves reliability, availability, and safety at reduced life cycle cost. In recognition of this, LCM activities at EPRI are being transferred to be a part of equipment reliability and plant technology programs.

Addressing Uncertainties and Plant-Level Life Cycle Management

The LCM process and planning discussed above uses a best-estimate, point-value approach to performing LCM economic studies. It has been shown that, not unexpectedly, assumed or projected power prices, along with predicted long-term failure rates are important drivers in the decision process. These two factors are also subject to large uncertainties; i.e. the crystal ball is blurred and becomes even more blurred for the later years of licensed operation.

The LCM process and planning discussed above is performed at the equipment level; i.e. it treats individual systems or components in isolation. For each of them, the optimum alternative LCM plan is selected on the basis of benefit-to-investment ratio. A preferred approach would be to treat all important plant equipment at once for several reasons. First, plant-level planning can account for two or more systems that interact physically. For example, a change in water chemistry in the secondary system would affect LCM planning for both steam generator and condenser of a PWR. Second, plant-level planning ensures that lost generation or costs are not double counted when plant totals are calculated. For example, any errors made in attributing lost generation to a single system would become evident when the total lost generation for all systems is benchmarked against experience with plant level capacity factors and unplanned capability loss factors. Third, it will generally not be possible to implement the optimum LCM alternative plan for all equipment items because of limited O&M and capital budgets. A plant-level LCM method needs to have criteria and a technique for selecting the optimum set of equipment LCM alternative plans that would give the maximum increase in plant NPV for a given budget limit.

As soon as we attempt to expand LCM planning to treating uncertainty and performing it at the plant level, the techniques required go beyond straightforward NPV calculations, which involve simple equations for inflating single-valued costs to future costs and then discounting future costs to the present using a discount factor (usually a plant's weighted cost of capital). The needed techniques involve range estimates and Monte Carlo calculations and plant models that can predict the impact on plant generation loss from a particular plant system or component. Such techniques are developed more in the field of financial Nuclear Asset Management, than in the field of equipment LCM.

NUCLEAR ASSET MANAGEMENT

NAM is the process of making resource allocation and risk management decisions at all levels of a nuclear generation business to maximize value/ profitability for all stakeholders while maintaining plant safety. NAM methods and tools support management decisions related to

- Plant investments and operational strategies that maximize value to all stakeholders
- Resource allocation within and among plants in a fleet
- Reduction of production costs while maintaining safety
- Optimized capital additions to maintain or improve availability of aging plants

The EPRI NAM program is providing US and international members with NAM methods and tools.

The framework into which all NAM technologies fit is shown in Fig. 1. The goal is to calculate the NPV of a plant or fleet of plants. This value, being the integral of cash flows (revenues minus costs) over the remaining service life of the plant(s) is one direct measure of profitability. It is important for making buy/sell, generation mix, and operating term decisions (early retirement or plant life extension). By calculating NPV with and without the effect of a project such as an LCM plan or any non-hardware project, the NPV (or benefit-to-investment ratio based on it) can be used to prioritize proposed projects.

As indicated in the framework, revenues are the product of power price and power output (rated power times capacity factor). Capacity factor depends to a large extent on equipment and plant reliability and availability. The latter also are drivers of cost (e.g. preventive and corrective maintenance cost). Production cost results from summing materials and labor costs. Many US plants are shifting from functional labor categorization (i.e. based on organizational units or cost centers) to "activity based costing," which is process-based, lumping costs based on activity types, regardless of what organizational unit performs them.

The LCM process discussed in the first part of this paper follows the framework in Fig. 2 for evaluating LCM plans (LCM projects) and the increment they produce in plant NPV. If all equipment is addressed and each of the elements in the framework are treated as uncertain variables, the framework becomes so-called "Nuclear Asset Risk Management" or "risk-informed asset management." EPRI is beginning to take steps to provide its utility members with methods and tools that facilitate asset risk management. The following paragraphs give a brief description of some of development efforts.

LCM Using Uncertainty Analysis

A modest step in going from the best-estimate LCM method and software described above to a risk-based method is to couple the point-value spreadsheet economic software [10] with a commercial off-the-shelf random sampling probabilistic analysis software such as Crystal Ball® or @Risk®. EPRI applied this approach to examine the aspect of uncertainty in an LCM planning study for a main generator at South Texas Project [10]. The uncertainty analysis tools use a sensitivity study to identify those parameters that are important drivers to deciding on an optimum LCM alternative plan. These parameters are then treated as uncertain variables, with probability distributions constructed by subject matter experts used as input to the random sampling calculations. The analysis yields probability density functions of the increase in NPV or benefit-to-investment ratios corresponding to candidate LCM alternative plans. This information allows managers to factor probabilistic confidence levels into their choice of optimum LCM plans.

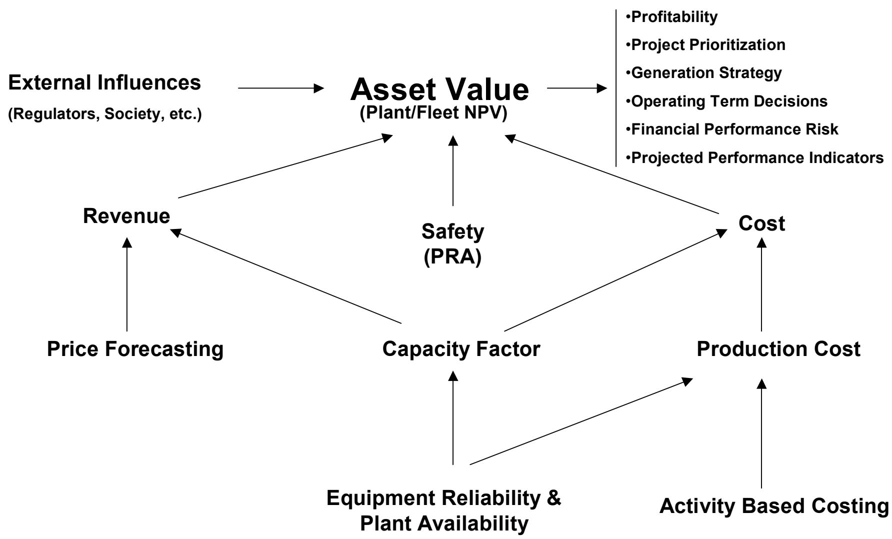

Figure 2 Nuclear Asset Risk Management Framework

Risk-Informed Asset Management (RIAM)

The general concept of RIAM is to use a rigorous systematic risk-informed approach for assessing, analyzing, predicting, and monitoring power plant economic (i.e., financial) performance while maintaining high confidence that NRC-established safety limits will not be breached (see Fig. 2). The RIAM process [22] involves the modeling and probabilistic quantification of decision support performance indicators to aid plant decision-makers in determining not only which plant improvement investment options should be implemented, but also how to prioritize plant resources for their implementation based on their predicted levels of profitability.

RIAM uses a risk-informed approach to project these kinds of performance indicators. Unlike most conventional asset management approaches, RIAM includes the contribution of low-frequency, high-consequence events that can occur over the long term, as well as shorter-term "expected" events, activities, and conditions, into its performance indicator prediction process. Thus, using the RIAM approach, these performance indicators incorporate predicted cost aversion issues as well as the more conventional direct operations and maintenance (O&M) and capital cost issues. In this way, the RIAM performance indicators are effectively "risk-informed" and can be applied in evaluating cost aversion and revenue-impacting issues as well as conventional cost savings issues.

RIAM generates predictions probabilistically so that performance indicator information can be supplied to managers in terms of probability distributions as well as point estimates. This enables managers and other decision-makers to apply the concept of "confidence levels" in their critical decision-making processes.

In addition to primary economic performance indicators, the RIAM methodology provides safety performance indicators, like core damage frequency and large early release frequency, that give the decision-makers high confidence that investment implementation will not breach NRC-established safety criteria for the plant (i.e., core damage frequency or core damage probability limits). In this way, decisions can be made to implement investments with positive impact on long-term profitability and reliability, while also ensuring that plant safety is not unacceptably impacted. A RIAM process has been applied to LCM decisions evaluated by the STP Nuclear Operating Company (STPNOC). EPRI plans to provide the industry with a generic form of RIAM software in the next few years.

Generation Risk Modeling

Plants need tools to assist management in making decisions involving the operation and maintenance of equipment whose failure can cause reactor trips or down-power events. One important tool for treating generation risk is a trip model. A trip model is similar in function and construction to that used for Probabilistic Risk Assessment (PRA) with the exception that the end-state of the trip model is the frequency of plant trip as opposed to the frequency of core damage. The trip model is generally used to determine the instantaneous trip and down-power frequency at the plant based on actual plant configuration and condition. Another important tool is a Generation Risk Model (GRM). It is the module of the RIAM tool that translates equipment failure to generation loss. A GRM uses the results of the trip model, time dependent reliability correlations, and repair and unit down times associated with potential trips to provide the probability of generation loss. Therefore, the GRM relates the failure of a system or component to the probability of generation loss at the present or during the remaining life of the plant. The GRM can also be used to calculate the "generation risk reduction worth" in a manner similar to the way PRAs calculate safety risk reduction worth. This allows the establishment of priorities for preventive and corrective maintenance in terms of both safety and production. Detailed PRA models for all plants are used to assess safety risk, but few plants have developed an equivalent capability for assessing down-power, trip or generation risk, which entails extending reliability models from safety systems to balance of plants systems (BOP). EPRI is in the process of providing plants with guidance for constructing plant-specific trip and generation risk models. This will initiate an extension of PRA to a new powerful use of event-tree risk-based methods -- Generation Risk Assessment (GRA).

LCM/NAM Database

Regardless of whether one does best-estimate or risk-based LCM planning or one does the planning at the system or plant level, it is important to use as accurate-as-possible characterizations of equipment reliability parameters. These rates have significant effects on life cycle costs of corrective maintenance, replacement, and loss of generation due to component failures, and on the selection of optimum long-term maintenance plans. The objective of the planned LCM/ NAM Database is to provide plants with easy access to data sources of generic reliability parameters important to long-term equipment reliability and other plant performance disciplines. The planning phase has been completed [23], in which a reliability expert identified candidate worldwide databases (three European databases among others) and described the software tools needed to manipulate the data, e.g. combining data from different sources, performing plant-specific updates, and outlining the database structure and suitable software platforms. The planning report also identifies the parameters to be stored (e.g. failure rate, expected life, repair time, failure-related generation loss, and corrective/ preventive maintenance costs) and describes statistical methods for interpreting failure rate data and updating the generic data with plant-specific reliability experience. The second phase will develop software to compile currently available databases. To be available within a year or two, the database will provide improved input values to LCM tools and RIAM.

Project Ranking Method

A particular challenge of nuclear asset management is to recognize that not all forms of value can be measured directly in financial terms, nor are stockholders the only stakeholders in nuclear plants. Some forms of value are "soft" such as public acceptance, worker job satisfaction, etc. Stakeholders include electricity users (safe, reliable, and affordable electricity), nuclear generating companies & shareholders (profitability in a competitive marketplace), company employees (challenging, rewarding, and stable jobs), regulators (public health and safety), and the public (safe, environmentally-clean power production and fair business practices).

All nuclear plants have some kind of method for prioritizing or ranking proposed projects during the budget cycle. However, existing scoring methods are limited in terms of the categories of value they take into account. Generally, they focus on either financial or non-financial (qualitative) value but not both. Current methods tend to be incomplete, perhaps overly influenced by the advocacy of individual managers or perhaps not placing the appropriate weight for decision making on the most appropriate factors. A recent EPRI effort formulated a plant project ranking method that allows both financial measures and soft forms of value to be used to rank projects in annual plant budgeting exercises in terms of value to all stakeholders [24].

The first step in the effort was to have an expert in rating and ranking proposed projects in industry and government examine currently available techniques. The expert identified the Analytic Hierarchy Procedure [25] as most appropriate for rating and ranking proposed power plant projects. Management experts then identified a hierarchy of factors to be used as ranking criteria for projects that range from physical plant changes to process changes, human and cultural effects, and technology advances. Next they formulated two ways to assign weights to the factors, one based on a plant's quartile of performance among all plants, the other based on the relative importance of a set of critical performance indicators.

EPRI is now seeking a pilot plant to perform a trial application of the improved project ranking method.

BENEFITS OF LCM AND NAM

In conclusion, among the benefits of strategic planning for equipment reliability are:

- Promotes forward thinking for long-term problem prevention
- Provides improved economic forecasts to support strategic decision making
- Captures institutional knowledge affecting equipment condition / reliability
- Integrates existing plant programs like maintenance optimization, RCM, PM Basis, maintenance rule, and equipment qualification.
- Captures plant and industry equipment performance experience
- Assesses potential aging mechanisms that add to long-term risks
- Reduced long term vulnerabilities to plant trips and loss of generation.
- Provides software planning tools to assist implementation for all equipment warranting LCM plans

Helps to keep license renewal option open (includes some aging management aspects of the License Renewal Rule)

- Provides documented record of evaluation for continuity in the face of future personnel changes
- Provides improved economic forecasts as input to plant budgeting and strategic decision-making

Improved competitive advantage of individual generating plants or fleets over others.

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