

# Materials Reliability Program: Integrated Fatigue Management Guideline (MRP-148)



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# **Materials Reliability Program: Integrated Fatigue Management Guideline (MRP-148)**

**1011957**

Final Report, September 2005

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This report describes research sponsored by the Electric Power Research Institute (EPRI).

The report is a corporate document that should be cited in the literature in the following manner:

*Materials Reliability Program: Integrated Fatigue Management Guideline (MRP-148)*. EPRI, Palo Alto, CA: 2005. 1011957.



# REPORT SUMMARY

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The EPRI Materials Reliability Program (MRP) formed the Fatigue Issue Task Group (ITG) to evaluate fatigue related issues at nuclear power plants. Fatigue is part of the design basis for reactor coolant systems. In addition, fatigue failures have occurred at nuclear power plants, and in some cases, have caused unplanned shutdowns. This document describes how an integrated plan for fatigue management can be established both to meet licensing requirements related to fatigue and to minimize unplanned shutdowns related to fatigue.

## **Background**

In 1991, work was started to develop the EPRI Fatigue Management Handbook (TR-104534, Vols. 1-4) to address key issues related to fatigue damage in operating nuclear power plant piping systems and components, vibrational fatigue failures in small-bore piping, and thermal fatigue failures due to thermal stratification. This EPRI handbook was developed to help utility engineers at operating plants understand and act upon fatigue-related issues. Since its publication, there have been ongoing industry efforts related to fatigue; and this work is reflected in this integrated fatigue management guideline.

A major area of effort has been related to license renewal. Since fatigue is an age-related degradation mechanism, commitments were required in license renewal submittals to assure that fatigue was being adequately addressed for operation in the license renewal period. Certain commitments were also required related to the effects of light-water reactor environment. Since 1999, work has been underway to develop improved methods for addressing the effects of swirl penetration and valve in-leakage effects for normally stagnant lines attached to PWR main loop piping. Implementation of these methods will allow utilities to assure that fatigue is not an issue in these lines, previously managed only by commitments made following issuance of NRC Bulletin 88-08. Vibration-induced fatigue failures have also continued to be a major contributor to unplanned outages. These failures have occurred in both reactor coolant attached piping and components as well as in balance of plant piping.

## **Objective**

To provide an integrated approach for fatigue management that can be implemented by individual utilities.

## **Approach**

Relying mainly upon other guidelines prepared under the EPRI MRP Fatigue ITG, the project team developed this guideline to provide overall guidance for effectively managing fatigue, including special requirements during an extended license-operating period.

## **Results**

This guideline serves to provide a comprehensive roadmap, integrating various programs and elements for fatigue management. It also discusses the interfaces and inter-relations among the individual programs and fatigue management elements. When implemented, the approach discussed in this guideline will assure that an effective fatigue management program is in place at individual plants.

## **EPRI Perspective**

Establishment of effective plant fatigue management will assist plant owners in maximizing plant safety and availability while assuring that license conditions can be met for the current and/or extended license operating period.

This document provides overall guidance for utilities in establishing an integrated approach for fatigue management or assessing the effectiveness of the approach currently used. When its guidance is followed, the potential for component leakage and unplanned outages due to fatigue should be greatly reduced.

## **Keywords**

Fatigue  
Environmental fatigue  
Swirl penetration  
High cycle fatigue  
Thermal fatigue  
Vibration  
Material degradation  
Fatigue management

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# 1

## INTRODUCTION

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### 1.1 Fatigue Overview

Fatigue is the structural deterioration that can occur as the result of repeated stress/strain cycles caused by fluctuating loads or temperatures. After repeated cyclic loading and sufficient accumulation of localized micro-structural damage, crack initiation can occur at the most highly affected locations. Subsequent cyclic loading and/or thermal stress can cause crack growth. The relevant fatigue-related degradation regimes, with example mechanisms, include:

1. High-cycle fatigue – The most ‘classical’ fatigue-related degradation is high-cycle fatigue. High cycle fatigue involves a high number of stress cycles at a relatively low stress amplitude (typically below the material’s yield strength but above the fatigue endurance limit of the material). High cycle fatigue may be
  - a. mechanical in nature, i.e. vibration or pressure pulsation or due to flow-induced vibration. It may also be
  - b. thermally induced due to mixing of cold and hot fluids where local instabilities of mixing lead to low-amplitude thermal stresses at the component surface exposed to the fluid.
2. Low-cycle fatigue – Low cycle fatigue is due to relatively high stress range cycling where the number of cycles is less than about  $10^4$  to  $10^5$ . To induce cracking at this number of cycles, the stress/strain range causes plastic strains that exceed the yield strength of the material, and the cycling causes local plasticity leading to more rapid material fatigue degradation. The stress cycling that contributes to low cycle fatigue is generally due to the combined effects of pressure, attached component loadings (e.g., piping moments) and local thermal stresses that result during normal operation. Thermal stratification in piping systems can produce low-cycle fatigue due to cycling between stratified and non-stratified conditions.

Types of fatigue mechanisms include:

1. Mechanical fatigue – Mechanical fatigue is due to cyclic stresses that result from application of pressure or other mechanical loads. Of special significance in nuclear plants is fatigue resulting from vibration of components and/or piping systems due to equipment motion or fluid induced forces. It is generally observed as a high-cycle fatigue phenomenon.
2. Thermal fatigue – Thermal fatigue is due to cyclic stresses that result due to changing temperature conditions in a component or in the piping attached to the component. Thermal fatigue may involve a relatively low number of cycles at a higher stress (e.g., plant operational cycles or injection of cold water into a hot nozzle) or be due to a high number of cycles at low stress amplitude (e.g. local leakage effects with cyclic stratification).

3. Environmental effects – The environmentally enhanced fatigue effect is the reduction in fatigue life in a reactor water environment compared to that in a room temperature air environment. Environmental fatigue involves two primary elements: the effects of a reactor water environment on fatigue crack initiation and the potential accelerated growth of an identified defect due to reactor water environments.
4. Fatigue crack initiation and crack growth may be governed by a number of material, structural and environmental factors, such as stress range, temperature, fluid oxygen content, mean stress, loading frequency (strain rate), surface roughness and number of cycles. Cracks typically initiate at local geometric stress concentrations, such as welds, notches, other surface defects, metallurgical anomalies and structural discontinuities. The presence of an oxidizing environment or other deleterious chemical species can accelerate the fatigue crack initiation and propagation process.

Design requirements to protect against fatigue damage for reactor coolant system pressure boundary components are based on fatigue curves in Section III of the ASME Boiler and Pressure Vessel Code. These curves indicate the number of allowed stress cycles at a given amplitude of stress intensity. The fatigue curves are based on test data taken in air at room temperature reduced by a factor of 2 on stress or a factor of 20 on cycles to failure, whichever is most conservative, to account for scatter of data, size effects, roughness, and industrial environment. For carbon and alloy steel materials, the most adverse conditions of mean stress are included to correct the test data prior to applying these factors. The ASME Code includes analytical approaches and criteria for determining usage factors for Class 1 components. For Class 1 Code components, the usage factor must be shown to be less than or equal to 1.0 for the component life. However, a calculated fatigue usage factor of unity does not imply crack initiation because of the safety factors applied to the stress amplitude or number of allowed cycles for the Code fatigue curves. At the same time, the Code curves were based on room temperature testing in air, so do not explicitly address environmental effects associated with light water reactor coolant.

Mitigation of fatigue damage for existing components may be accomplished by reducing the magnitude of the applied loads or thermal conditions or by reduction of the number of cycles of loading. For thermal transients, reduction in the rate of temperature change for extreme temperature cycles can be effective. However, the normal operating cycles are not generally the actual source of significant fatigue damage in nuclear plants. Further, the observed fatigue cracking has generally been due to high cycle fatigue as a result of conditions not known at the time of original plant design.

## **1.2 Overview of Supporting EPRI Fatigue Activities**

In 1991, work was started to develop the EPRI Fatigue Management Handbook [1] to address key issues related to fatigue damage in operating nuclear power plant piping systems and components. The work at that time primarily addressed vibrational fatigue failures in small-bore piping and thermal fatigue failures due to local thermal cycling and stratification. The handbook was developed to help utility engineers at operating plants understand and act upon fatigue-related issues. A key supporting document was the TASCs (Thermal Stratification, Cycling and Striping) report [2], prepared to assist utilities in understanding and evaluating issues identified in NRC Bulletin 88-08 [3].

Since 1999, work has been underway to develop improved methods for addressing the effects of swirl penetration and valve in-leakage for normally-stagnant lines attached to PWR main loop piping. An interim guideline [4] to address these effects was provided to utilities in 2001. A final guideline [5] was made available in 2005. Following the final guideline will allow utilities to assure that fatigue is not an issue in this class of lines, previously managed only by commitments made following issuance of NRC Bulletin 88-08.

In March 2000, the first license renewal of a U.S. plant was approved by the NRC. Many others have followed. Since fatigue is an age-related degradation mechanism, commitments were required in license renewal submittals to assure that fatigue was being adequately addressed in the license renewal period. A guideline has been prepared for establishing an effective program for tracking design-basis cycles and/or usage factors for components with an explicit fatigue design basis [6]. In addition, certain commitments were also required related to the effects of light-water reactor environment. A guideline for addressing these environmental effects in an extended operating license period has also been provided [7].

Appendix A provides a listing of EPRI MRP Fatigue Issue Task Group (ITG) reports.

### **1.3 Objective and Requirements**

The objective of this report is to define attributes of an effective approach for fatigue management at individual plant sites. This guideline serves to provide a comprehensive roadmap integrating and establishing the inter-relationships between the various programs and elements for fatigue management. The elements and interactions for effective fatigue management are described in Section 2.0. As described in Section 3.0, this document is provided only as good practice and contains no ‘mandatory’ or ‘needed’ requirements as defined for the Nuclear Energy Institute (NEI) materials initiative [8, 9].



# 2

## EFFECTIVE FATIGUE MANAGEMENT

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Effective fatigue management needs to meet license requirements related to fatigue design and minimize crack initiation, leakage and plant outages due to fatigue damage. In the following, the elements and attributes of effective fatigue management are described.

### 2.1 Overview

The objective of fatigue management is to prevent the occurrence of fatigue failures during plant operation that could breach a pressure boundary, especially the reactor coolant boundary, or any other fatigue failure that could cause plant outages. As a minimum, all license commitments must be met, as committed in the original plant license or any modification thereto by way of NRC generic communications or changes to the plant license (e.g., license renewal).

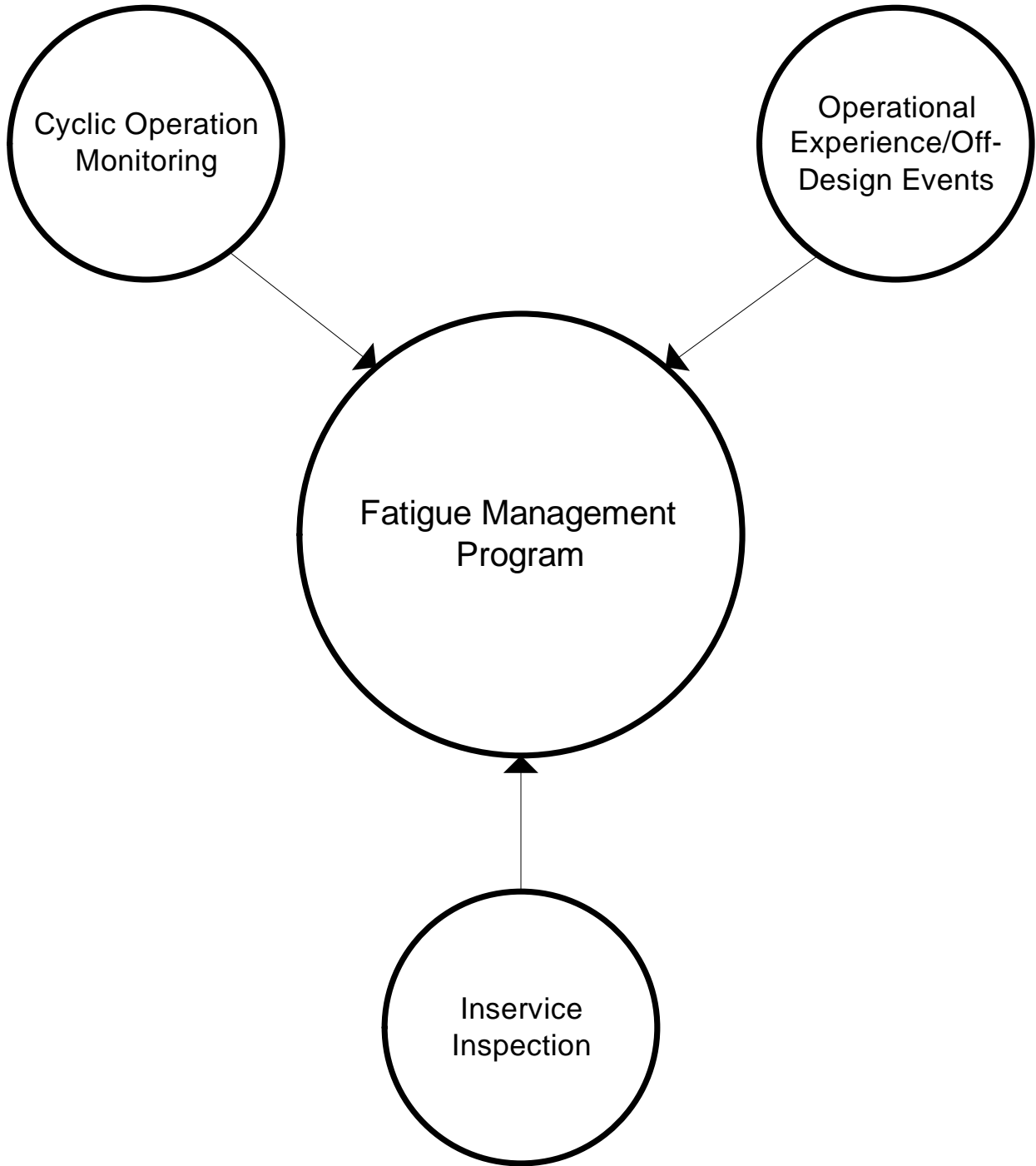
Key input to effective fatigue management is from

- plant cyclic operation monitoring,
- results of plant inspections, and
- industry operational experience.

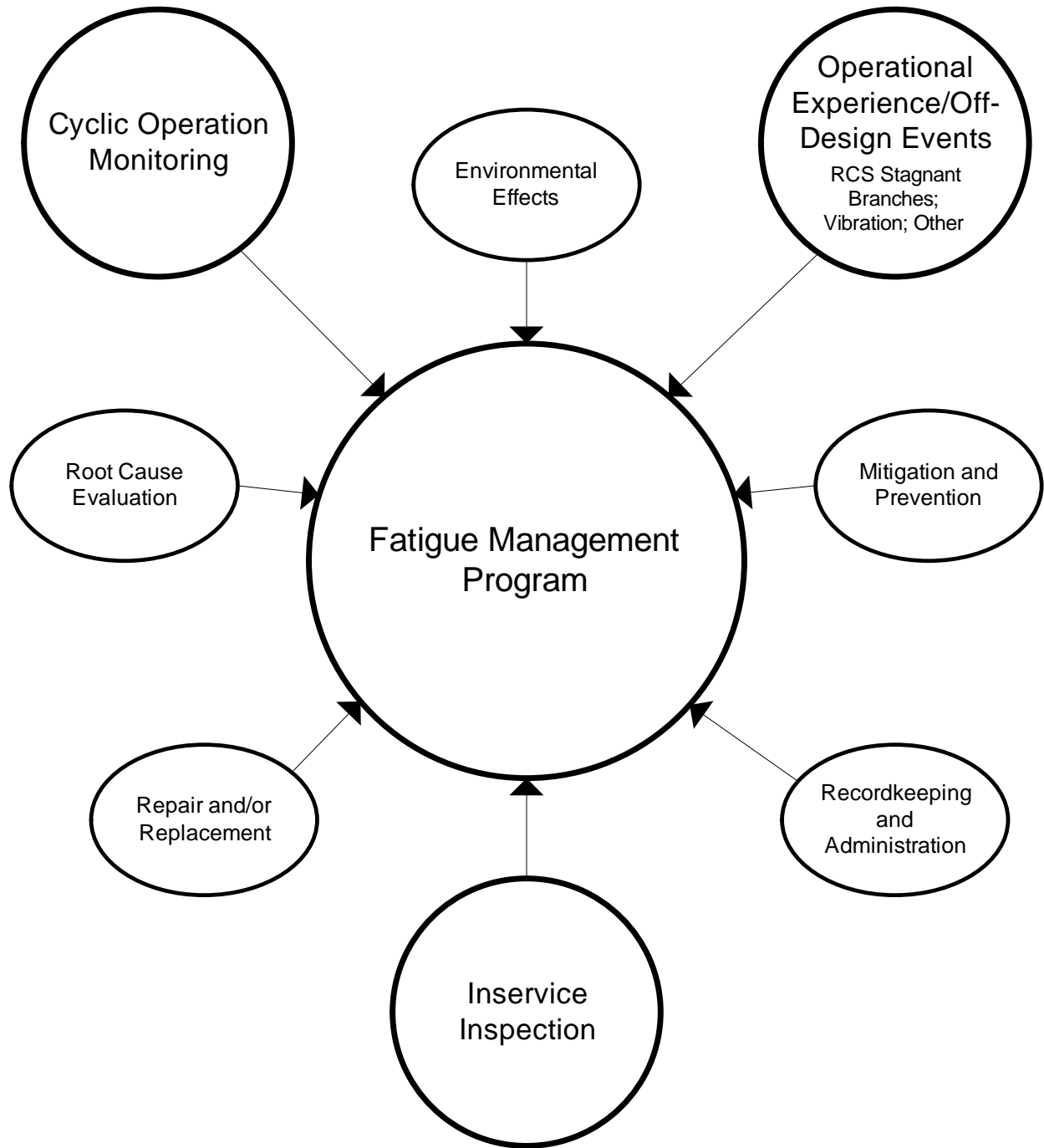
These three elements, which are often administered separately at many plants, can be considered as constituting the *principal elements* of effective fatigue management. Figure 2-1 illustrates this. Other elements, considered as *expanded elements*, also contribute to effective integrated fatigue management, as illustrated in Figure 2-2. The principal elements and the remaining expanded elements are discussed separately in following sub-sections, as are the special requirements for interface and inter-relational ties among the principal elements. EPRI publications are cited where they apply to the elements.

Execution of an effective fatigue management plan may spawn activities to perform evaluations or to conduct additional inspections or tests. The results of these activities may either assure that fatigue is not a significant issue, or they may show that further actions are required. When significant fatigue issues are identified, mitigation, maintenance or prevention may be undertaken to extend the lifetime of affected components. In some cases, it may be necessary to implement repair or replacement activities to allow continued plant operation.

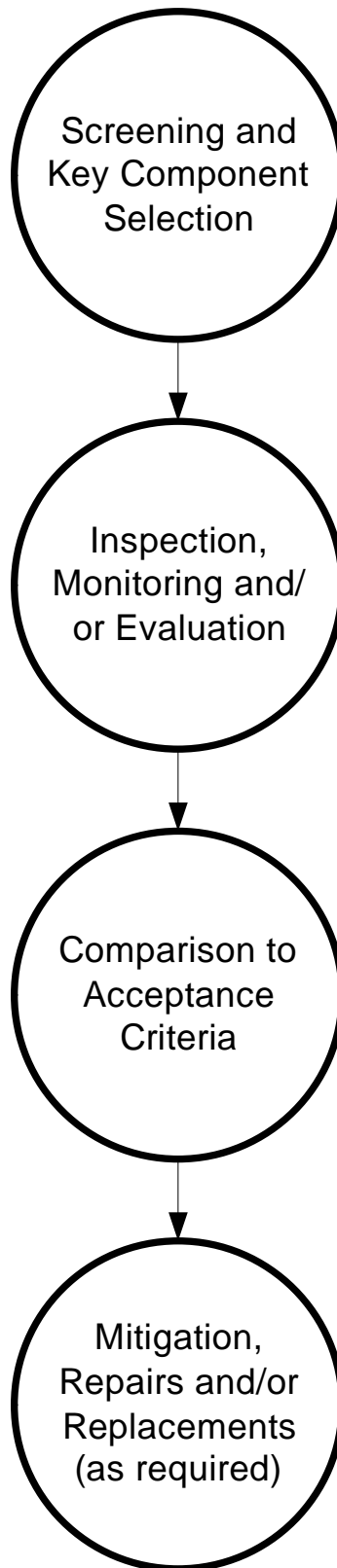
Figure 2-3 shows a process that can be followed to focus fatigue management efforts. First, a screening process can be undertaken to identify key components where fatigue might be a concern. Then, inspections, monitoring and/or evaluations can be undertaken to assure that the components meet developed acceptance criteria. Then, if required, additional activities can be undertaken to assure that the acceptance criteria can be met for the life of the plant. This generic process model is directly applicable to the principal elements, as will be discussed for each below. Some of the expanded elements also appear in the process model, but are discussed separately.



**Figure 2-1**  
**Principal Elements**



**Figure 2-2**  
**Principal and Expanded Elements**



**Figure 2-3**  
**Generic Process Tasks**

## **2.2 Elements of Effective Fatigue Management**

In the following, additional description is provided for the key elements comprising effective fatigue management.

### **2.2.1 Principal Elements**

#### **2.2.1.1 Plant Cyclic Operation Monitoring**

Certain components in nuclear plants have been designed to Codes that may limit component lifetime based on the number and severity of cyclic operation. There generally are specific licensee commitments to assure that the number of cycles does not exceed that considered in the original design.

The following types of components are typical of those that have a fatigue design basis:

- Reactor coolant pressure boundary components, where the design has generally been to the requirements of the ASME Code, Section III, Class 1, and can include vessels, piping, pumps and valves;
- Reactor coolant piping that may have been designed to ASME/ANSI B31.7, the predecessor code to that currently contained in ASME Section III for Class 1 piping;
- Piping designed to ANSI B31.1, although the allowable number of cycles is generally very large compared to those experienced in a nuclear power plant;
- Certain Class 2 vessels that may have been designed to the requirements of Section VIII, Division 2 where a fatigue analysis, similar to that for ASME Section III for Class 1 vessels, was conducted;
- Containment penetrations, designed to ASME Section III, Class MC requirements. For older plants, other similar design requirements may have been used that included an explicit fatigue design basis;
- Main and Auxiliary Feedwater nozzles in Steam Generators, designed to the requirements of ASME Class 1, even though not required by the assigned Code Class.

Certain components may also have been explicitly evaluated for cyclic duty associated with Leak Before Break or Fracture Mechanics Analyses or Non-Design Events. These analysis requirements, when combined with the Design Basis Analysis requirements, constitute the Fatigue Licensing Basis.

To assist in monitoring the actual plant operation and making comparisons to the fatigue licensing basis of these components, a fatigue licensing basis monitoring guideline has been developed [6]. This guidance document also provides further discussion of the fatigue licensing basis. It also describes how licensing basis fatigue monitoring can be performed to adequately and economically track the effects of fatigue through an extended license period. This guidance can be used to implement licensing basis fatigue monitoring to meet the fatigue criteria of the GALL report [10] and comply with plant technical specifications and 10CFR50 requirements to operate within the bounds of plant component fatigue analyses. Use of this guideline will reduce the inconsistency between the approaches used by various plants in approaching this issue.

The Reference [6] guidance document defines a program to monitor and track the number and severity of significant thermal, mechanical and pressure transients for the components where fatigue is significant. These licensing basis fatigue monitoring activities should include both the locations identified in NUREG/CR-6260 [11], as well as other components that have a fatigue licensing basis. A range of methods is included, including direct cycle counting and techniques that convert the cycle severity directly to CUF based upon measured temperature, pressure, and flow data associated with actual plant operation.

The Reference [6] guidance document assists the user in performing tasks such as the following:

- Determining the design basis for all Class 1 components and others with an explicit fatigue time limited aging analysis (TLAA)
- Selection of the key components and/or the significant transients/events for monitoring
- Determination of transients/events that do not need to be monitored based on: 1) quantity, 2) severity, or 3) no associated TLAA
- Comparison of the actual plant operating conditions to those assumed in the plant design
- Base-lining of the past fatigue cycles
- Establishing methods for determining actual fatigue effects based on cycle counting, use of actual plant data, etc.

Referring to Figure 2-3, the generic tasks are completed by performance of the above actions as follows:

Screening and Key Component Selection is accomplished by determining all components with an explicit fatigue time limited aging analysis (TLAA), selecting key components and/or the associated significant transients/events for monitoring, and determining those transients/events that do not need to be monitored based on: 1) quantity, 2) severity, or 3) no associated TLAA.

Inspection, Monitoring and/or Evaluation is accomplished by observations of actual key plant operating parameters used to recognize and characterize each of the events being monitored or each of the location CUFs being computed. Events are logged or CUF is calculated.

A Comparison to Acceptance Criteria is accomplished by comparing the logged/computed conditions to those assumed in the analyses, for both quantity and severity. The quantity (or the directly computed CUF) is projected into the future using the past cycles and the extrapolated value is used to determine an allowable period for future operation by comparison to the allowable. The severity is compared to the controlling as-evaluated severity for each event logged.

Mitigation, Repairs and/or Replacements activities are performed as needed as discussed in Reference [6]. These can include: removal of the non-compliance by refining either the observation or the acceptance criteria, or taking steps to reduce or eliminate the occurrence of damaging fatigue by revising appropriate plant operational practices and procedures. Section 2.2.3.4 has further discussion on Repair/Replacement.

### 2.2.1.2 Results of Plant Inspections

Inspection is an integral part of assuring that fatigue cracks do not propagate to a size where component integrity would be challenged. Inspections can be one time or recurring. Recurring inspections are typically administered under the plant's ISI Plan. Recurring inspections can be grouped into

- Code inspections,
- Augmented inspections, and
- Elective inspections.

Code inspections are those specified by ASME Section XI, as in Table IWB-2500-1, which for B-J welds includes:

- a) terminal ends at vessels,
- b) terminal ends/joints that are either highly stressed or highly fatigued (“stressed welds”),
- c) dissimilar metal welds,
- d) other welds up to 25% of the applicable population, and
- e) beginning at the 2001 Code year] an extra 10% of the circumferential welds in PWR HPI piping NPS 1.5” up to but not including NPS 4”, where valve leakage or turbulence effects [swirl penetration, see Section 2.2.1.3] may be causing thermal fatigue.

Code inspections will also include inspections at frequencies based on flaw tolerance at fatigue sensitive locations where usage factors less than 1.0 cannot be demonstrated analytically [5, 19, 21].

Most plants have implemented risk-informed inservice inspection that can alter the inspections noted above. For this approach, inspections are focused on those locations where failure consequences and/or potential for failure are relatively high. When implementing risk-informed inspection, appropriate consideration should be given to high-potential mechanisms such as hot/cold water mixing, swirl penetration, stratification and normally-closed valve leakage that could contribute to thermal fatigue. MRP provides specific guidance on inspection interval for normally-stagnant lines attached to reactor coolant system main loop piping [5]. Risk informed inspections are also included in the Code Inspections category described above. Related discussion is given in Section 2.2.2.2.

Augmented inspections are any recurring inspections committed to the regulator or for adherence to MRP “mandatory” or “needed” requirements.

Elective inspections are any others that are being repeatedly performed under plant commitments to MRP “good practice” guidelines, or others that the plant has voluntarily and prudently elected to perform and which may be rescinded under plant specific internal guidelines or practices.

Referring to Figure 2-3, the generic tasks are completed by performance of specific actions as follows:

Screening and Key Component Selection for Code inspections is dictated by the plant's commitment to a particular ASME edition and for Augmented inspections by commitments to the regulator or for adherence to MRP mandatory requirements. Elective inspection locations are selected via voluntary processes.

Inspection, Monitoring and/or Evaluation for Code inspections is accomplished by performance of ISI as required by PDI. Similar standards would be expected for Augmented inspections. Elective inspections may be performed by methods at the discretion of the plant. For inspections being performed as described in *Management of Thermal Fatigue in Normally Stagnant Non-Isolable Reactor Coolant System Branch Lines (MRP-146)* [5], the techniques as described in *NDE Technology for Detection of Thermal Fatigue Damage in Piping (PWRMRP-23)* [22] are expected to be followed. Fracture Mechanics Evaluations would be performed in accordance with the rules of the particular ASME Section XI edition committed to by the plant, or later as appropriate.

Comparison to Acceptance Criteria for Code inspections is performed in accordance with the rules of the particular ASME Section XI edition committed to by the plant. Similar standards would be expected for Augmented and Elective inspections.

Mitigation, Repairs and/or Replacements activities are performed as needed. Section 2.2.3.4 has further discussion on Repair/Replacement.

### 2.2.1.3 Industry Operational Experience/Off Design Events

It is recognized that industry instances of through-wall fatigue cracking have generally resulted from high cycle fatigue as a result of conditions not anticipated at the time of original plant design, and not because of un-conservatism in either quantity or severity in specifying plant design conditions. For this reason it is essential that proper attention be paid to industry fatigue failures where similarities may make a particular plant susceptible to the same or similar failure.

Events may be discovered that exceed the conditions considered in a plant's original design. The appropriate action path from among the options of inspections, monitoring, and/or modeling/evaluation should be chosen. A distinction is made between the cases of "active mechanism" as discussed under Risk Informed inspection where a 10 year frequency is allowed, and Operational Experience ("OE") events where a cyclic phenomena has been observed in that plant's lines or similar industry lines and the proper inference is to consider that it is potentially applicable where similarities exist.

The following options are recommended when beyond-design events are discovered at a particular plant or susceptibility exists when such events are detected at another plant:

1. Monitoring to show that the suspected phenomena are not present;
2. Monitoring/Modeling to generate loads to perform CUF analyses to show acceptance for no further actions; or
3. Monitoring/Modeling to generate loads for Flaw Tolerance analyses to show acceptance based on additional and/or more frequent inspections.

When increased inspections are performed to provide assurances of low susceptibility for fatigue failure for off-design events, the volumes to be inspected, the techniques employed, the acceptance criteria, and especially the inspection frequency should be justified. Simple addition of susceptible locations to the risk informed inspection program is insufficient.

The following paragraphs provide discussion on operational experience involving swirl penetration into normally-stagnant reactor coolant system attached lines, vibrational fatigue, and other high-cycle thermal fatigue. The generic process model of Figure 2-3 is discussed for the first two of these.

#### *2.2.1.3.1 Normally-Stagnant Reactor Coolant System Attached Lines Assessment*

In 1988, several leaks in RCS-attached piping resulted in the issuance of NRC Bulletin 88-08 [3]. This bulletin required that utilities assess the potential for in-leakage toward the RCS that might lead to thermal cycling similar to that causing the through-wall cracking at the Farley and Tihange plants. In addition, the potential for cyclic out-leakage through normally-closed valves, similar to the residual heat removal line at the Genkai, plant had to be addressed. Utilities responded by performing assessments and implementing monitoring at some plants. Because through-wall cracking later occurred at several other plants, the NRC proposed to the ASME Section XI Code committees that additional inspection be performed of all safety injection piping. Industry responded by developing additional guidelines for managing thermal fatigue in all normally-stagnant lines attached to RCS main loop piping. Interim guidelines were issued in 2001 [4] followed by a final guideline in 2005 [5].

The final guideline [5] includes an assessment for both top-connected or side-connected horizontal lines (“UH/H”, e.g. safety injection lines) and bottom-connected lines (“DH”, e.g. drain and residual heat removal suction lines). For lines potentially affected by thermal fatigue cycling, methods are provided to define the thermal loadings (magnitude and number of cycles) and the physical extent of susceptible piping. General instructions for performing the analyses are also provided. Depending on the results of analytical evaluations, specific recommendations are provided for inspection frequency.

The thermal load definition methodology is defined in Reference [12], along with a generic application to show which lines will most likely be affected. Screening methods are provided that identify the lines not affected.

Referring to Figure 2-3, the generic tasks are completed by performance of specific actions as follows:

Screening and Key Component Selection is performed in accordance with the rules in *Management of Thermal Fatigue in Normally Stagnant Non-Isolable Reactor Coolant System Branch Lines (MRP-146)* [5].

Once Component selection is performed, Inspection, Monitoring and/or Evaluation may be chosen according to the following: First, either modeling or monitoring using the techniques of the *Thermal Cycling Screening and Evaluation Model for Normally Stagnant Non-Isolable Reactor Coolant Branch Line Piping with a Generic Application Assessment (MRP-132)* [12] or

*Thermal Fatigue Monitoring Guidelines (MRP-32)* [23], respectively, as described in Reference [5] is performed. Second, an analytical evaluation is performed using the techniques of Reference [5] to determine an inspection frequency. Third, inspections are performed for locations described in Reference [5] in accordance with *NDE Technology for Detection of Thermal Fatigue Damage in Piping (PWRMRP-23)* [22].

Comparison to Acceptance Criteria for inspections is performed in accordance with the rules of the particular ASME Section XI edition committed to by the plant.

Mitigation, Repairs and/or Replacements activities are performed as needed. Mitigation options are discussed in *Mitigation of Thermal Fatigue in Unisolable Piping Connected to PWR Reactor Coolant Systems (MRP-29)* [20]. Section 2.2.3.4 has further discussion on Repair/Replacement.

#### *2.2.1.3.2 Vibrational Fatigue*

High cycle fatigue due to vibration may result in fatigue crack initiation, component support wear, or leakage. Based on a recent assessment [13], this may occur in a broad range of plant systems. Although this degradation is most prevalent in small diameter lines, recent experience with plant power uprate and component changes shows that new issues with larger components are still being experienced.

Specific guidance for vibrational fatigue was prepared in the EPRI Fatigue Management Handbook [1], dealing primarily with small-bore piping issues. The following guidance is provided with respect to vibrational fatigue:

1. When upgrading systems to modified flow rates or temperature conditions (e.g., power uprate), special attention should be given to the potential for increasing vibration amplitudes. Increased fluid dynamic loadings and changes in base vibrational frequencies can result in increased vibrational response at vent and drain lines, other attached piping and component supports.
2. Although vibrational fatigue failures typically occur early in plant life, the plant modes of operation that result in vibration may occur for only a few hours in each operational cycle. This can lead to failures later in plant life.
3. When replacing or modifying systems, consideration should be given to the fact that vibrational characteristics may change, leading to component failure.

Tracking industry experience is especially important in identifying potential vibrational fatigue issues.

Referring to Figure 2-3, the generic tasks are completed by performance of the above actions as follows:

Screening and Key Component Selection will identify components/systems to experience increased flow or otherwise susceptible to modifications that may change the excitation or the response. Systems/components infrequently used should be considered for fatigue failures later in life if the modes of actual operation that may result in vibration are infrequent.

Inspection, Monitoring and/or Evaluation and Comparison to Acceptance Criteria are accomplished by performing vibration monitoring in accordance with Reference [1].

Mitigation, Repairs and/or Replacements activities are performed as needed. Repair or modification options for socket welded piping are discussed in References [24] or [25]. Section 2.2.3.4 has further discussion on Repair/Replacement.

#### *2.2.1.3.3 Other High-Cycle Thermal Fatigue*

Periodically, other issues related to thermal fatigue have been identified, such as

- High-cycle thermal fatigue due to leakage past thermal sleeves. This occurred in boiling water reactor feedwater nozzles in the early 1980s [14]. Similar instances of cracking have been observed in PWR steam generator feedwater inlet nozzles due to on/off flow cycling and stratification [15].
- Stratification in pressurizer surge lines [16].
- High-cycle thermal fatigue due to mixing of hot and cold water. Specific instances of note include:
  - B&W plant HPI/Makeup nozzles and thermal sleeves
  - Mixing tees downstream of residual heat removal heat exchangers such as occurred at the French Civaux plant.

These and other instances of thermal fatigue cracking are described in MRP-85 [17].

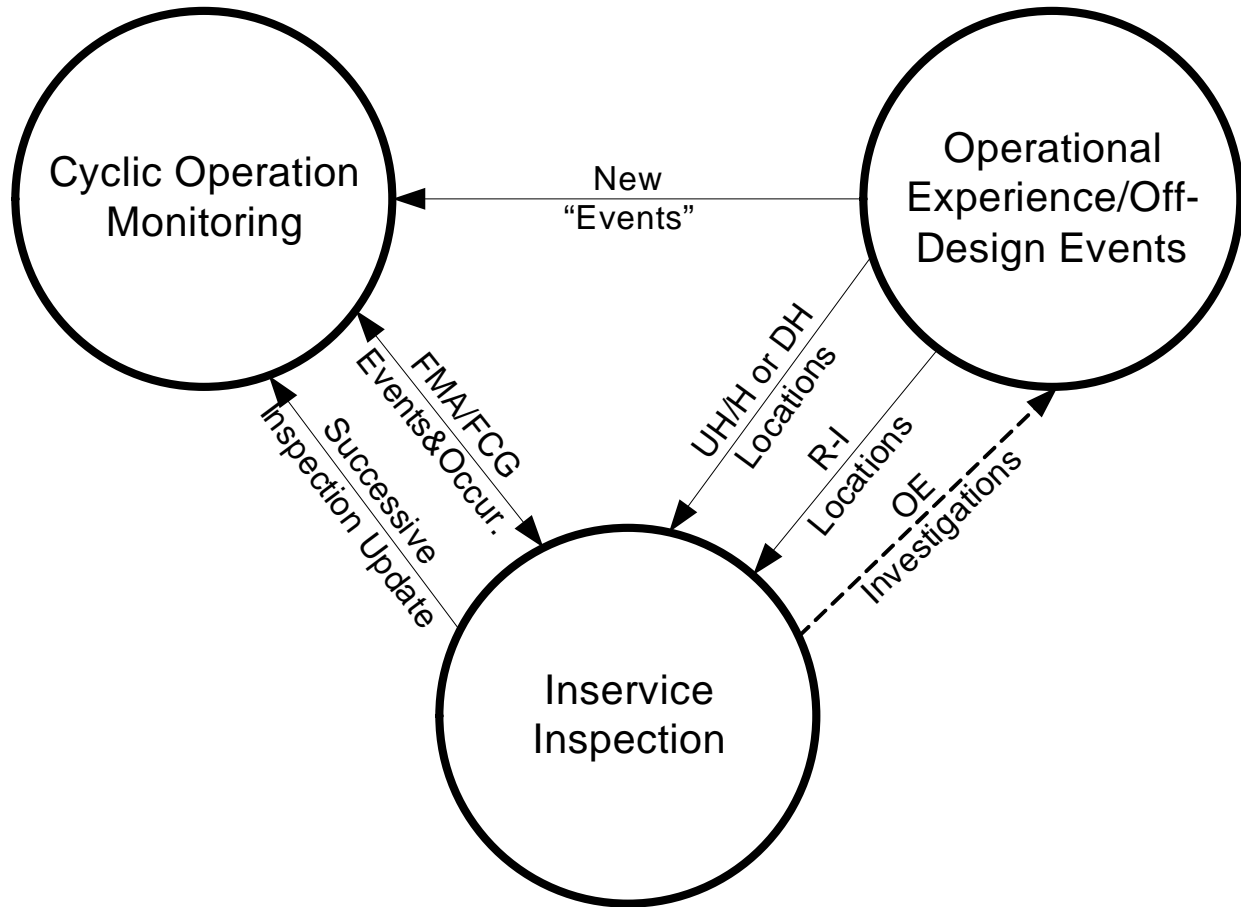
An earlier survey document, prepared by the Section XI Task Group on Fatigue in Operating Plants, describes the above and additional fatigue issues identified prior to 1992 [18].

### **2.2.2 Interactions Among Principal Elements**

The principal elements, Licensing Basis Monitoring, ISI, and OE, have important cross-ties and interfaces that need to be considered when designing a plant Fatigue Management System and as conditions change in the future. These interfaces are illustrated schematically in Figure 2-4 and are described below.

#### **2.2.2.1 Plant Inspections to Cyclic Operation Monitoring Interfaces**

If flaws are discovered in the course of ISI that are justified by Fracture Mechanics Analysis (FMA) as in accordance with ASME IWB-3600, such an evaluation must include a fatigue crack growth analysis (FCG). This FCG is performed using an assumed future set of plant cyclic events, defined in terms of severity and number of occurrences, both of which must then be continually confirmed as enveloping actual plant events. In other words, the assumed input transient set of the FMA then becomes a direct input to the Screening and Key Component Selection task of the Plant Cyclic Operation Monitoring element.



**Figure 2-4**  
**Interfaces Among Principal Elements**

In computing the allowable monitored occurrences for the transient events, a special case may occur if only a fraction of the full life allowable number of occurrences for a particular transient has been justified to allow operation to the next Section XI required successive inspection, i.e., used in the FMA. In this case, the plant lifetime allowable for this transient is reduced (at least) to that lower quantity plus the quantity already logged for that transient at the time of the last inspection. Then at the future inspections of the controlling flaw, if no crack growth is noted, the updated plant lifetime allowable is the total quantity logged for that transient at the time of that inspection plus the quantity considered in the fracture mechanics analysis (up to the lower allowed by all other analyses.)

It is, however, desired that the FMA not introduce a new controlling lower occurrence limit for any monitored event. To facilitate this, the assumed set of plant cyclic events to be used in the FMA, defined in terms of severity and number of occurrences, is taken from the previously compiled Cyclic Operation Monitoring (Fatigue Licensing Basis Monitoring) set, typically using the severities and occurrences as originally defined for the component design. Such definitions would already have been used in the Screening and Key Component Selection task of the Plant Cyclic Operation Monitoring element, thus will not introduce any new controlling conditions. Alternatively, if the component with the flaw cannot be qualified for the full occurrences, then a

lesser quantity can be used. The lowest quantity not to introduce a new controlling condition is the lifetime allowable from the Screening and Key Component Selection task of the Plant Cyclic Operation Monitoring element, minus the total quantity logged for that transient at the time of that inspection. The lowest quantity to be able to utilize FMA to return the component to service is the prorated expected number of occurrences until the next successive inspection as required by, for example, IWB-2420. This quantity is determined by a trending of the history based on Licensing Basis Fatigue Monitoring.

Another potential interface between the Plant Inspections element and the Cyclic Operation Monitoring element involves the definition of the stress welds for ISI, as described in Section 2.2.1.2. The determination of which welds meet these criteria is dependent on the same transient set being considered for monitoring in the Plant Cyclic Operation Monitoring element. This interface is, however, likely not considered active since the Code (or Code Cases) have deemed that the same Code inspection locations should be inspected each interval, and there is no expectation that more than 25% be inspected.

### 2.2.2.2 Plant Inspections to Operational Experience Interfaces

As described generically in Section 2.2.1.2, and in Section 2.2.1.3 for the case of Normally-Stagnant Reactor Coolant System Attached Lines Assessments, a fatigue problem may be managed alternatively by performing inspections at intervals based on a flaw tolerance analysis.

As a result of such an approach, such a decision to implement extra inspections as a means of managing fatigue defines an interface between the OE program and the ISI program. As described in the ISI discussion (Section 2.2.1.2), new locations are defined in the ISI Plan for either Augmented or Elective periodic inspections, along with associated volumes, frequencies, and specific inspection procedures. (If these are being defined as a result of following MRP mandated or needed guidelines, then they are Augmented. If as a result of MRP good practice guidelines, or other plant initiated “precautionary” actions, then they are Elective.)

For example, if in the process of implementing the EPRI guideline *Management of Thermal Fatigue in Normally Stagnant Non-Isolable Reactor Coolant System Branch Lines* [5], extra inspections are recommended for susceptible locations, defined by volumes and enhanced techniques and by either normal 10 year or every refueling outage frequency, then new entries would be defined in the ISI Plan as needed.

Another interface between the Plant Inspections element and the Operational Experience element involves the determination of locations for inspection based on Risk Informed processes. As discussed in Section 2.2.1.3, a distinction is made between “active mechanism” phenomena and OE identified phenomena. For the “active mechanism” case, i.e., the mechanism is much less well understood and thus “unquantifiable”, generic knowledge, perhaps stemming from OE, would be used as input in selecting locations following a Risk Informed process.

If ISI indications are discovered, a metallurgical examination may determine fatigue as a contributor and a root cause investigation may be initiated to determine if a new non-design event is occurring, as shown by the dotted line in Figure 2-4.

### 2.2.2.3 Operational Experience to Cyclic Operation Monitoring Interfaces

As briefly discussed in Section 2.2.1.3, and as discussed in ASME Section XI IWB-3740 and Appendix L [19], one option for dispositioning fatigue effects of off-design events is via analytical evaluation. Such an evaluation will use an assumed past and future set of plant cyclic events, defined in terms of severity and number of occurrences, both of which must then be continually confirmed as enveloping actual plant events. This set will include the original design set for the particular location of concern plus new events defined to envelope the off-design phenomena. The assumed input transient set of the fatigue analysis then becomes a direct input to the Screening and Key Component Selection task of the Plant Cyclic Operation Monitoring element.

For example, if in the process of implementing the EPRI guideline *Management of Thermal Fatigue in Normally Stagnant Non-Isolable Reactor Coolant System Branch Lines* [5], CUF or Flaw Tolerance FCG analyses are performed, then the set of transient events thus used then becomes part of the set to be monitored in the Plant Cyclic Operation Monitoring element.

### **2.2.3 Expanded Elements**

The following sections discuss other aspects of effective integrated fatigue management, which are referred to here as “expanded” elements.

#### 2.2.3.1 Environmental Effects

Research has identified that fatigue is affected by the temperature and fluid environmental conditions of reactor water. Environmental effects may accelerate both fatigue initiation and crack growth. Although it is difficult to mitigate these effects, they should be considered in any failure analysis where fatigue is a contributor. In addition, the effects of environment must be specifically considered during license renewal operating periods [7].

Extensive discussion is provided in the *Thermal Fatigue Licensing Basis Monitoring Guideline* [6] regarding modifications to the Plant Cyclic Operation Monitoring element to accommodate the regulatory requirements concerning reactor water effects on the fatigue life of affected components in the license renewal period.

#### 2.2.3.2 Root Cause Evaluation

When component failures are observed in plants, root cause evaluations are generally conducted to understand the reasons for the failures and to avoid similar occurrences either later in life or in other similar systems. When conducting such analyses, fatigue should always be one of the potential contributors. Specific considerations should be given to:

- Potential for hot/cold water mixing, including cold water leakage past normally closed valves;
- Potential for swirl penetration and/or cyclic stratification;

- Contributions of environmental effects that could have accelerated initiation and/or crack growth; and
- Vibration due to adjacent pumps or valves, or fluid dynamic loadings.

Where possible, examination of cracked components should be undertaken. Laboratory examination can generally quantify the crack growth history and show if it is due to low-cycle or high-cycle mechanisms or if other corrosion-related mechanisms were responsible for the component failure.

### 2.2.3.3 Mitigation and Prevention

Where fatigue mechanisms are identified, mitigation of loadings, system modifications, and/or maintenance should be considered to prevent future occurrences. Appropriate plant operational practices and procedures should also be reviewed for potential revision to reduce or eliminate the occurrence of damaging fatigue. MRP-29 [20] provides guidance related to mitigation of thermal fatigue issues.

### 2.2.3.4 Repair and/or Replacement

In certain cases, repair/replacement may be an appropriate solution for a fatigue problem, especially if a fatigue failure has occurred. When replacing components, considerations should be given to proper material selection and component geometry that could reduce the potential for future fatigue failure. Examples might include:

- Use low-sulfur carbon or low-alloy steels, since these would be much less susceptible to environmental effects
- Reduce stress concentrations due to counter-bores or other geometric discontinuities

The *EPRI Fatigue Management Handbook* [1] provides extensive discussion on design changes to eliminate or reduce fatigue vulnerabilities. See also discussions regarding vibration in Section 2.2.1.3.

### 2.2.3.5 Recordkeeping and Administration

Records of component fatigue failure investigations or other fatigue assessments should be retained in plant permanent records.

Records should also be maintained regarding the following fatigue subjects and others as deemed necessary:

- Determination of the collective and controlling Fatigue Licensing Basis as described in Reference [6],
- Results of Plant Cyclic Operation Monitoring as described in Reference [6],

- Basis documentation for the determination and specification of Code “stress welds”, Augmented ISI locations, and Elective ISI locations,
- OE Assessments, including as described in Reference [5], and
- Records of special fatigue monitoring and other observations, for instances where anomalies were both absent and present.

Record retrieval methods should be available so the plant experience can be available to engineers not involved in earlier fatigue assessments.

A plant administrative document and/or program description document should be prepared which discusses how the recommendations in this guideline should be and/or are fulfilled. It should serve as a roadmap to the separate administrative controls and fatigue management description documents where such exist for the various elements as discussed herein. It should describe how the interfaces are maintained among the various elements. It should also describe the various fatigue related records as described above.

# 3

## RECOMMENDATIONS

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This guideline is provided as a top-level document for managing fatigue and is provided as a good practice guideline as defined in MRP-130 [8] and NEI 03-08 [9]. Some of the elements for integrated fatigue management may have more specific requirements in other license commitments or other MRP/NEI materials initiative documents. These include:

1. Monitor and track fatigue status for components with an explicit analysis of fatigue effects including design, LBB, FMA, OE analyses or other cyclic duty evaluation. Assure that the fatigue licensing basis is not exceeded by re-evaluations, mitigation, and/or repair/replacement activities. Specific details are outlined in MRP-149 [6].
2. Manage thermal fatigue in RCS lines potentially affected by thermal cycling resulting from in-leakage toward the reactor coolant system and/or swirl penetration effects not considered in original plant design. Specific details are outlined in MRP-146 [5].
3. When operating in an extended license period, license renewal commitments relative to fatigue must be included in item 1 above. An approach to meet commitments for addressing environmental fatigue is discussed in MRP-47 [7].

All other recommendations and information provided in this guideline are also considered industry good practice. Other approaches that meet plant license commitments and provide for effective plant fatigue management are equally acceptable.



# 4

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# A

## EPRI MRP FATIGUE ITG REPORTS

**Table A-1**  
**EPRI MRP Fatigue ITG Tasks/Deliverables — General/Thermal Fatigue**

Task Description	Deliverable	Type	Completion Date*
<b>Thermal Fatigue</b>			
Industry Operating Experience	<i>Thermal Fatigue Industry Operating Experience, MRP-25 (1001006)</i>	Report	12/4/2000
	<i>Update of online thermal fatigue operating experience database</i>	Service	10/31/2002
	<i>Materials Reliability Program: Operating Experience Regarding Thermal Fatigue of Piping Connected to PWR Reactor Coolant Systems, MRP-85 (1007761)</i>	Report	4/30/2003
Screening & Evaluation	<i>Identifying Thermal Cycling Mechanisms in Two Piping Configurations, MRP-54 (1003081)</i>	Report	11/20/2001
	<i>Interim Report on Thermal Cycling Model Development for Representative Un-Isolable Piping Configurations, MRP-81 (1003527)</i>	Report	11/27/2002
	<i>Development of a Thermal Cycling Model for Un-isolable Branch Line Piping Configurations, MRP-97 (1003209)</i>	Report	12/19/2003
	<i>Thermal Cycling Screening and Evaluation Model for Normally Stagnant Non-Isolable Reactor Coolant Branch Line Piping with a Generic Application Assessment, MRP-132 (1009552)</i>	Report	12/31/2004
Monitoring Guidelines	<i>Thermal Fatigue Monitoring Guidelines, MRP-32 (1001016)</i>	Report	4/24/2001
NDE Inspection Guidelines	<i>NDE Technology for Detection of Thermal Fatigue Damage in Piping, MRP-23 (1000152)</i>	Report	10/10/2000
O&M Guidelines	<i>Mitigation of Thermal Fatigue in Unisolable Piping Connected to PWR Reactor Coolant Systems, MRP-29 (1001017)</i>	Report	12/4/2000
Management Guidelines	<i>Interim Thermal Fatigue Management Guidelines, MRP-24 (1000701)</i>	Report	1/16/2001
	<i>Management of Thermal Fatigue in Normally Stagnant Non-Isolable Reactor Coolant System Branch Lines, MRP-146 (1011955) E217858 (Draft)</i>	Report	July, 2005

\*Date when report can be ordered from EPRI.

**Table A-1  
EPRI MRP Fatigue ITG Tasks/Deliverables — General/Thermal Fatigue (Continued)**

<b>Task Description</b>	<b>Deliverable</b>	<b>Type</b>	<b>Completion Date*</b>
<b>Thermal Fatigue (Continued)</b>			
Training	<i>Computer Based NDE Training for Thermal Fatigue Cracking, MRP-36 (1001317)</i>	Assembled Package	6/18/2001
	<i>Thermal Fatigue Training</i>	Service	12/2/2002
	<i>Lessons Learned From PWR Thermal Fatigue Management Training, MRP-83 (1003666)</i>	Report	12/5/2002
	<i>Thermal Fatigue Management for RCS-Attached Unisolable Piping, An EPRI/MRP Training Module, MRP-93 (1007849)</i>	CD	12/5/2003
International Program Participation	<i>EDF Thermal Fatigue Monitoring Experience on Reactor Coolant System Auxiliary Lines, MRP-69 (1003082)</i>	Report	4/8/2002
<b>General Fatigue</b>			
Technical Exchange	<i>2000 International Conference on Fatigue of Reactor Components</i>	Service	7/31/2000
	<i>Proceedings of 2000 International Conference on Fatigue of Reactor Components, MRP-46 (1006070)</i>	CD	6/25/2001
	<i>2002 International Conference on Fatigue of Reactor Components</i>	Service	7/29/2002
	<i>Proceedings of 2002 International Conference on Fatigue of Reactor Components, MRP-84 (1003536)</i>	CD	3/5/2003
	<i>2004 International Conference on Fatigue of Reactor Components</i>	Service	10/30/2004
	<i>Proceedings of 2004 International Conference on Fatigue of Reactor Components, MRP-151, (1011958)</i>	CD	9/30/2005
Fatigue Issues Assessment	<i>MRP Fatigue Issues Assessment, MRP-138 (1011442)</i>	Report	2/1/2005
Flow-Induced Vibration	<i>Recommendations for Flow Induced Vibration Analysis and Evaluation Handbook</i>	Draft Paper	1/31/2005
Licensing Basis Monitoring	Thermal Fatigue Licensing Basis Monitoring Guideline, MRP-149 (1012018)	Report	9/30/2005
Integrated Fatigue Mgmt	MRP Integrated Fatigue Management Guideline, MRP-148 (1011957)	Report	9/30/2005

\*Date when report can be ordered from EPRI.

**Table A-2**  
**Fatigue ITG Tasks/Deliverables — Environmental Fatigue**

<b>Task Description</b>	<b>Deliverable Name</b>	<b>Type</b>	<b>Completion Date*</b>
Guidelines Document	<i>Guidelines for Addressing Fatigue Environmental Effects in a License Renewal Application, MRP-47 (1003083)</i>	Report	10/15/2001
	<i>Guidelines for Addressing Fatigue Environmental Effects in a License Renewal Application, MRP-47, Revision 1 (1012017)</i>	Report	9/15/2005
Environmental Fatigue Data Review	<i>Review and Evaluation of Fatigue Reactor Water Environmental Effects Data, MRP-49 (1003079)</i>	Report	12/12/2001
Fatigue Environmental Effects Tests	<i>Environmental Fatigue Testing of Type 304L Stainless Steel U-Bends, MRP-100 (1007853)</i>	Report	12/19/2003
	<i>Environmental Fatigue Testing of Type 304L Stainless Steel U-Bends, MRP-137 (1008207)</i>	Report	12/31/2004
	<i>Effect of Flow Rate on Environmental Fatigue of 304 Stainless Steel Components</i>	Report	7/1/2006
Appendix L Improvements	<i>Recommended Improvements to ASME Section XI Appendix L, MRP-82 (1002814)</i>	Report	12/17/2002
Fatigue Crack Frequency Re-Evaluation	<i>Re-Evaluation of Results in NUREG/CR-6674 for Carbon and Low-Alloy Steels, MRP-74 (1003667)</i>	Report	11/15/2002
	<i>Re-Evaluation of Results in NUREG/CR-6674 for Carbon and Low-Alloy Steels, MRP-74, Revision 1 (1011442)</i>	Report	February, 2005
Fatigue Environmental Effects Technical Basis Document	<i>Interim Staff Guidance (ISG)-11, Environmental Assisted Fatigue**</i>	Service	1/3/2003
Stress Intensification Factors	<i>Investigation of Stress Intensification Factors and Directionality of Loading for Branch Connections (1006227)</i>	Report	9/11/2001
Stainless Steel Crack Growth Rate	<i>Evaluation of Crack Growth Rates in Stainless Steel Considering Reactor Water Environment</i>	Letter Report	11/30/2005

\*Date when report can be ordered from EPRI

\*\*Not accepted by NRC. ISG-11 closed, January 2004.







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