Materials Reliability Program: Thermal Cycling Screening and Evaluation Model for Normally Stagnant Non-Isolable Reactor Coolant Branch Line Piping with a Generic Application Assessment (MRP-132-NP)

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Final Report, December 2004

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PRODUCT DESCRIPTION

Swirl penetration thermal fatigue has been identified as a mechanism that can lead to cracking in dead-ended branch lines attached to pressurized water reactor (PWR) primary coolant piping. To perform evaluations of this thermal fatigue mechanism, utilities needed screening methods to determine which lines are potentially affected and evaluation methods to determine the magnitude, frequency, and location of thermal loadings. The development of such a methodology required a combination of testing and analysis. This report summarizes the screening and evaluation methodology derived from extensive testing and analysis, including its application in a generic assessment of the state of the U.S. PWR plants with regard to thermal cycling and fatigue.

Results & Findings

Results documented in this report provide engineering models for use in predicting the onset of thermal cycling and in characterizing the thermal loading boundary conditions for structural assessment of non-isolable, normally stagnant branch lines attached to reactor coolant piping. Engineering models have been derived from extensive testing and analysis, resulting in a model that is applicable to two general piping configurations. In one branch line piping configuration, designated up-horizontal (UH) due to the typical orientation relative to the reactor coolant piping, thermal cycling occurs due to both cold water in-leakage through the upstream branch line valve and a swirl flow structure in the branch line established by the flow through the reactor coolant line. The model for this configuration is also applicable to piping configurations that are entirely horizontal (H). In the second configuration, designated down-horizontal (DH), thermal cycling occurs due to cyclic penetration and retreat of a thermal interface that is driven by a swirl flow structure. The screening and evaluation methodology documented in this report provides a load definition that is conservative based on model benchmarking against plant data.

Challenges & Objectives

Predicting thermal cycling in normally stagnant lines has historically proven to be challenging due to the complex nature of the fluid dynamic and thermal-hydraulic interactions, requiring testing and analysis conducted over several extensive test programs. The primary objectives of this report are:

- To combine test results, analyses, and semi-empirical models from previous test programs into a single, comprehensive thermal loading prediction methodology for plant thermal cycling (fatigue) screening and evaluation

- To apply this screening and evaluation methodology in a generic branch line assessment to determine industry susceptibility to thermal cycling, as well as verify the applicability of the methodology.

Applications, Values & Use

In January 2001, the Materials Reliability Program (MRP) published the *Interim Thermal Fatigue Management Guideline* (MRP-24; EPRI report 1000701), providing the industry with a common approach for assessing the potential for thermal fatigue cracking. It is the intention of the MRP to develop a final guideline in 2005, which will incorporate this screening and evaluation methodology. To support preparation of the final guideline, the engineering models developed from extensive testing have been incorporated into the comprehensive methodology documented in this report and demonstrated in the assessment of approximately 70% of non-isolable branch lines in U.S. PWR plants, thus providing guidance for the application of the methodology. Example calculations demonstrating the methodology are also provided for guidance for industry use.

EPRI Perspective

The models for predicting the onset and thermal-hydraulic boundary conditions for thermal cycling in normally stagnant lines will form the basis of an improved screening method for evaluating the likelihood of thermal cycling in PWR systems. Benchmarking results have shown the model to be effective in predicting the location of thermal cycling in a branch line attached to primary coolant piping, and the thermal loads have also been defined for input to separate structural analysis. This model will be used for evaluation in accordance with the final Thermal Fatigue Management Guideline.

Approach

The project team designed test facilities and methods to simulate thermal cycling observed in several representative non-isolable, normally stagnant piping configurations of operating PWRs. Test results and supporting analysis for developing the thermal cycling screening and evaluation methodology have been documented separately. Engineering models developed from several previous test series have been combined with correlations developed during the EPRI Thermal Stratification, Cycling, and Striping (TASCS) program, in addition to general engineering analyses, resulting in the current thermal cycling screening and evaluation methodology. The methodology includes screening criteria based on piping geometry and methods to estimate the cyclic thermal loading due to cycling for stress/fatigue evaluations. Some components of the thermal cycling model have been developed since previous test reports and benchmarked against several PWR plant configurations with known thermal stratification and cycling. Comparison of the current methodology to the previous TASCS methods has also been performed.

Keywords

Fatigue
Thermal Fatigue
Thermal Cycling
Thermal Stratification
Reactor Coolant Piping
NRC Bulletin 88-08

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Pat Strauch – Westinghouse
Ken Wolfe – EPRI

The comparison study between the TASCS and current thermal cycling evaluation methodologies described in Appendix E of this report was performed by Pat Strauch of Westinghouse.

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1 INTRODUCTION AND OVERVIEW

This report summarizes a screening and evaluation methodology for swirl penetration thermal cycling/fatigue (also referred to as thermal cycling/fatigue in normally stagnant lines). The report also presents the results of an application of that methodology to a generic assessment of the applicable piping found in pressurized water reactor (PWR) plants in the United States.

The primary components of the thermal cycling screening and evaluation methodology are models to predict if and where thermal cycling would occur in a branch line piping system and to provide conservative cyclic thermal loads (magnitude and frequency) that would be applied to the pipe wall. The methodology includes pre-screening criteria based on simple geometric and fluid dynamic conditions. Many lines can be shown not susceptible to thermal cycling by application of these simple rules. For lines not eliminated from concern based on the geometric screening rules, the methodology provides a detailed procedure for calculating the location in each pipe where thermal cycling will occur. If this detailed calculation indicates that thermal cycling will occur in an area of the piping susceptible to damage from cyclic thermal loads, the methodology can be used to develop parameters required for performing a stress analysis (e.g., cycling frequency, temperature differences and heat transfer coefficients).

The thermal cycling model is described in the following section, tying together model elements (i.e., predictive formulae and semi-empirical correlations) derived from test results and engineering modeling. Two principal sources for the thermal cycling model components are:

- MRP-97 [1]
- TASCS [2]

These references include results in which the model components are benchmarked against data. In addition, general engineering correlations, in particular for heat transfer coefficients, are defined for use in thermal cycling/fatigue evaluations.

Section 2 of this report summarizes the thermal cycling screening and evaluation methodology for normally stagnant lines. Section 3 summarizes results from a generic assessment of typical piping geometries for U.S. PWR plants with regard to swirl penetration thermal cycling. Example calculations illustrating the application of the screening and evaluation methodology are summarized in Section 4. Section 5 summarizes quality assurance aspects of the program, and references cited in this report are provided in Section 6.

Nomenclature definitions are provided in Appendix A. Technical bases for elements of the thermal cycling model not previously published are summarized in Appendices B and C. Additional details of the generic assessment described in Section 3 are provided in Appendix D.

A summary of a study comparing methods from TASCS and this report is provided in Appendix E.

2 THERMAL CYCLING APPLICATION MODEL DESCRIPTION

2.1 Methodology Overview

A general methodology for assessing branch line susceptibility to swirl penetration thermal cycling is described in this section. The central element to the methodology is the thermal cycling application model, which has been developed from several extensive test programs.

Swirl penetration thermal cycling in dead-ended branch lines occurs due to several physical phenomena. A fundamental mechanism leading to thermal cycling is the establishment and penetration of a well-defined, swirling vortical flow structure in the branch line due to effects of primary flow through the reactor coolant line (RCL) header. This hot, swirling flow interacts with colder water in the branch line and, under certain conditions, can result in cyclic thermal loads on the branch line piping. The thermal cycling application model, therefore, requires several input parameters such as the RCL flow (water) velocity, temperature boundary conditions, and heat transfer characteristics, in addition to the geometry of the branch line piping configuration. The outputs of the application model provide the thermal loading (time-varying boundary conditions) to the pipe, which is caused by the motion of the interface between hot and cold stratified fluid regions in the pipe. Assessment of thermal cycling susceptibility first consists of determining where cycling would occur based on the model. If thermal cycling is predicted to occur in a region of the pipe that could be susceptible to damage from thermal fatigue (e.g., at an elbow or in a horizontal pipe segment), the model can be used to develop a thermal load definition that may be used for structural analysis. The thermal load is defined by the fluid temperatures, heat transfer coefficients, and a periodic function (waveform) representing the motion of the thermal stratification interface.

Branch lines are generally attached to the top or bottom of loop piping, but some lines intersect at the side or other orientations. Thermal stratification is affected by piping orientation. Thermal cycling mechanisms in branch line piping configurations may be broadly classified based on line geometry. This classification results in two generic configurations: the up-horizontal/horizontal (UH/H) configuration[1], which includes lines with up-horizontal (UH) geometry (Figure 2-1) and lines with strictly horizontal (H) geometry (Figure 2-2); and the down-horizontal (DH) configuration (Figure 2-3) (see Appendix A for notation conventions). Classification of attached piping is based on geometric considerations, with each having a

[1] Due to the similarity of the thermal cycling mechanisms, UH and H configurations will be considered together in Section 2.2 of this report. The UH/H notation will be used to identify model components that are applicable to both UH and H line configurations.

fundamentally different mechanism for thermal cycling. Thermal stratification and cycling in UH/H configurations is caused by the interaction between the swirling vortical flow and in-leakage of cold water from a leaking, normally-closed valve between a high-pressure source and the RCL piping. In contrast, no valve in-leakage is necessary in DH configurations, where thermal cycling occurs due to the cyclic penetration and retreat of a swirling vortical flow structure that brings hot water into the branch line, combined with heat transfer to the environment that cools the lower horizontal section of the line.

Application of the thermal cycling model first requires identification of the branch line based on the geometric configuration and potential for valve in-leakage. Branch lines with in-leakage potential and geometry that are above or at the same elevation as the reactor coolant system piping fall within the UH/H model configuration. Branch lines with no in-leakage potential and geometry that are below the reactor coolant system piping fall within the DH model configuration. The UH/H and DH configuration application models are described in Section 2.2 and Section 2.3, respectively. Extensions of the model for use in more complex branch line configurations (e.g., HDH, DHDH, lines with reducers/expanders) are described in Section 2.4.

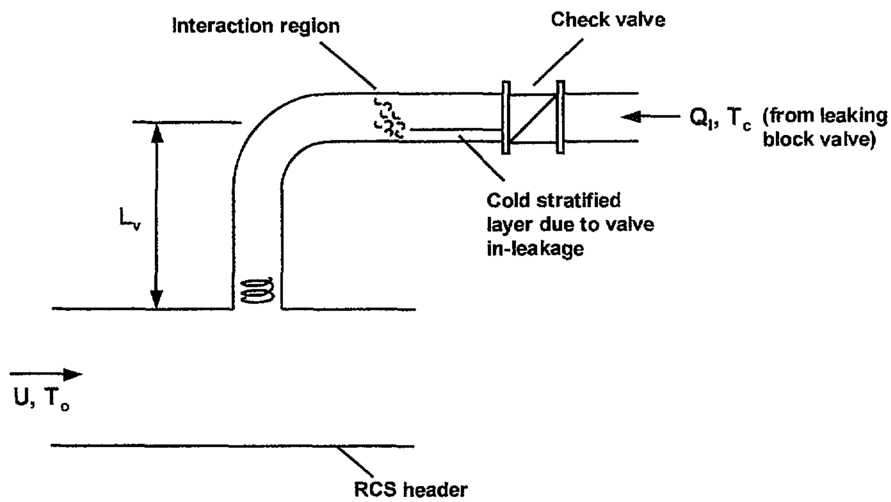

Figure 2-1
Illustration of UH Branch Line Piping Configuration

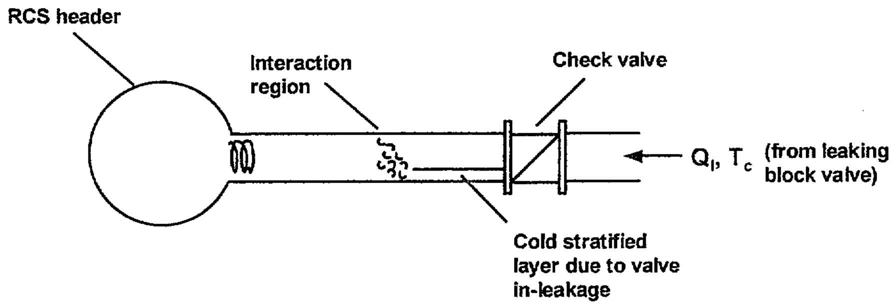

Figure 2-2
Illustration of H Branch Line Piping Configuration

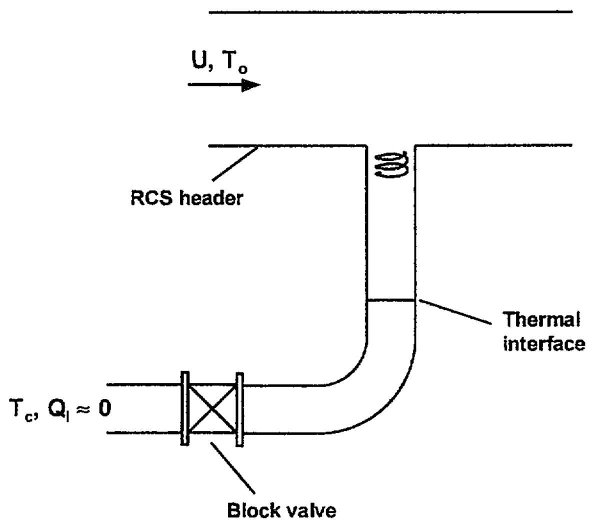

Figure 2-3
Illustration of DH Branch Line Piping Configuration

2.2 UH/H Configuration Thermal Cycling Application Model

For piping configurations that fall within the UH/H classification, thermal cycling, and hence the thermal load, occur due to the periodic axial motion of the cold stratified layer due to a leaking valve (Figure 2-4). Valve in-leakage establishes a cold stratified layer in a horizontal pipe run, which interacts with branch line swirl resulting in cyclic thermal loads applied to a region of the horizontal pipe segment. The average thermal cycling location ($\bar{x}_m$) is dependent on the branch line swirl, valve in-leakage flow rate and temperature, RCL temperature, and geometry. The associated thermal load is determined based on a simplification of the complex fluid dynamic structure in the thermal cycling interface region, as illustrated in Figure 2-4.

For thermal cycling screening and evaluation, the thermal cycling model, outlined in this section, provides several parameters for use in branch line evaluations, which are defined in Figure 2-4[2]. These outputs are:

- the average cycling location, measured from the RCL inside diameter, of the interaction region between hot and cold fluid regions $\bar{x}_m$;
- the axial and azimuthal variation of fluid temperatures in the hot and cold stratified fluid regions T_1, T_2;
- heat transfer coefficients associated with hot and cold fluid regions h_1, h_2;
- the height of the cold stratified layer H; and
- the time-varying position of the interaction region (stratification interface) $x_m(t)$, which is defined by a prescribed cyclical waveform.

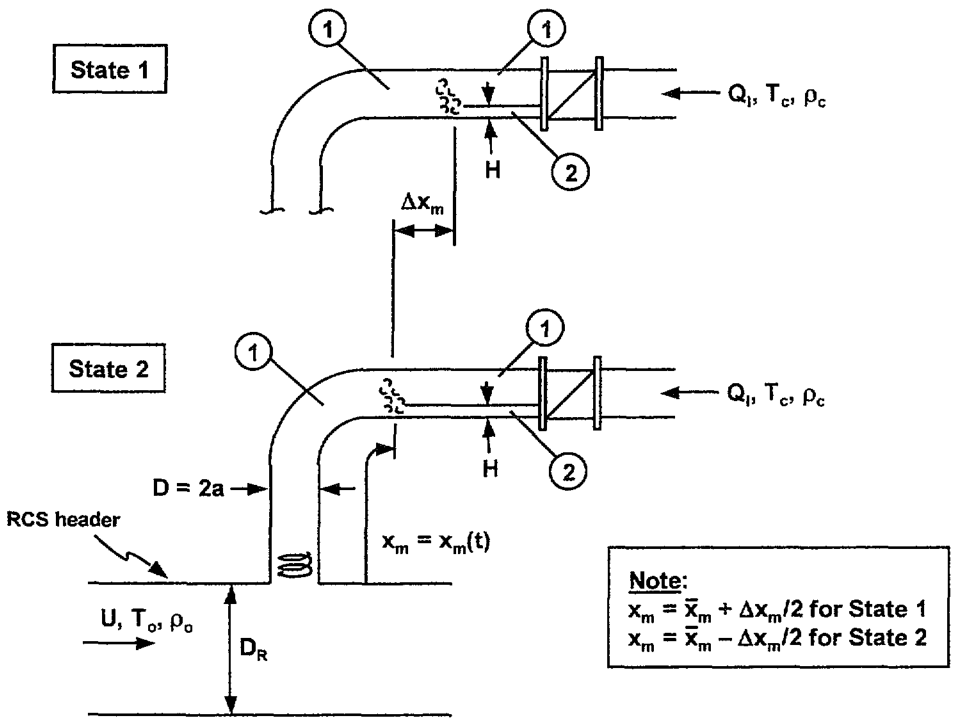

Figure 2-4
Thermal Cycling Model Parameter Definitions and Fluid Boundaries for UH/H Branch Line Configurations

[2] Note that circled numbers indicated fluid regions where the relevant thermodynamic and transport properties are approximately constant. The labels "State 1" and "State 2" indicate the extremal limits of the thermal cycling interface motion as a function of time.

Line geometries that are addressed by the model are summarized below. Report sections in which the evaluation procedure is defined are also indicated:

- UH lines, where the horizontal length can consist of multiple piping segments (Sections 2.2.2, 2.2.4, 2.2.5, and 2.2.6)
- Inclined UH lines, which are considered a UH configuration if the branch line nozzle is perpendicular to the RCL axis. The model does not strictly apply for lines that are inclined relative to the RCL flow direction.
- H lines with constant diameter (Sections 2.2.2, 2.2.5, and 2.2.6)
- H line with larger diameter nozzle at the RCS (Sections 2.2.2, 2.2.5, 2.2.6, and 2.4)
- HUH lines, which should be analyzed as a UH configuration (Section 2.4.1)

Down-horizontal lines with short vertical drops and in-leakage potential may also be considered a variation of the horizontal line configuration, although no specific branch line configurations such as these are known to exist in U.S. PWR plants.

An approach to evaluate UH/H piping configurations is outlined in Figure 2-5. Specific model components are described in the following sub-sections. Note that the valve in-leakage rate may not be known and may be varied parametrically (corresponding to the dashed block in Figure 2-5). A suggested approach for analysis of cases when valve in-leakage is not known is discussed in Section 2.2.3.

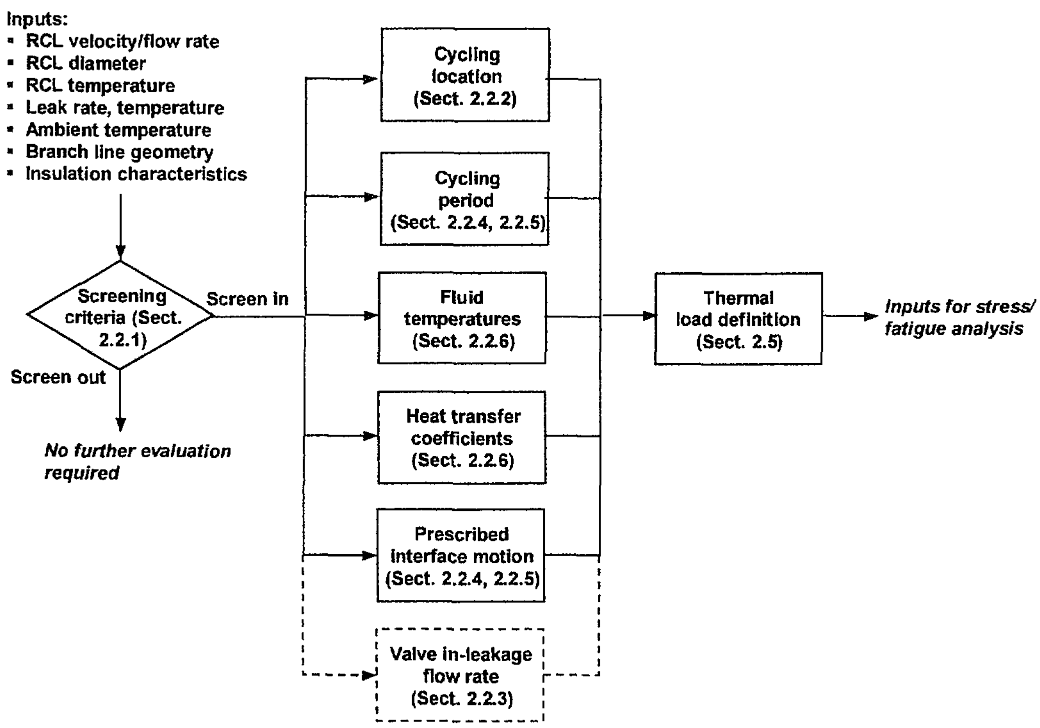

Figure 2-5
UH/H Thermal Cycling Model Evaluation Approach

Guidance on transforming the boundary conditions described by the following paragraphs and referred to from the flow chart into load definitions for stress analysis is given in Section 2.5.

2.2.1 UH/H Screening Criteria

Before proceeding to the estimation of the cycling location and thermal loading in a particular piping configuration, screening criteria can be used to eliminate certain lines from further consideration. Screening rules have been derived in terms of simple geometric and operational criteria for which thermal cycling will not occur.

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Figure 2-6
Geometric Screening Criteria for UH Piping Configurations

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2.2.2 UH/H Cycling Location

For lines that are not screened out based on the criteria given in the previous section, it is necessary to determine the cycling location and thermal loading for further analysis. The location of thermal cycling in UH/H piping configurations is defined by its time-averaged position from the RCL-branch line nozzle, measured from the inner surface of the RCL header. The average location of thermal cycling $\bar{x}_m$ is determined from the following relationship [1]:

Content Deleted -
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[3] The approximate solution for the cold layer height is discussed in Appendix E.

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2.2.3 Analysis Procedure for Unknown Valve In-leakage Flow Rate

From the previous section, it should be apparent that an important parameter for determining where thermal cycling could occur in UH/H piping configurations is the volumetric flow rate of cold water due to valve in-leakage (Q_l). This parameter also affects the thermal load amplitude and period of the prescribed interface motion, as shown in the following sections. The valve in-leakage rate may not be known accurately when conducting plant-specific piping evaluations. If the valve in-leakage rate is not available from plant measurements, it is necessary to perform an analysis to determine the range of in-leakage flow rate that results in the thermal cycling in a susceptible region of the piping segment (i.e., a horizontal segment). If justification can be provided that the in-leakage rate will not occur within these bounds, then the line may be removed from consideration. This approach was used in the generic branch line assessment in Section 3.

2.2.4 Cold Stratified Layer Prescribed Motion in UH Configurations

If a branch line has been determined to be susceptible to thermal cycling (i.e., cycling is predicted to occur within the horizontal segment), it is necessary to determine the thermal-hydraulic inputs for structural analysis. The thermal loading is determined from the prescribed, cyclic motion of the interface between hot and cold fluid regions (see Figure 2-4) and the temperatures and heat transfer coefficients in the hot and cold fluid regions.

The spatial and time dependence of where and when the fluid temperatures are applied to the inside pipe wall are determined by the motion of the interface between hot and cold stratified layers. In UH piping configurations, thermal cycling results from the cyclic entrainment of the cold stratified layer by the swirl followed by a purging process that scales with the in-leakage flow rate, referred to as the "fill and spill" mechanism (additional details are provided in separate reports [1, 3, 4]). While extensive observations of the fill and spill mechanism reveal that the region where the cold layer is picked up and mixed rapidly with the hot swirling flow is very complicated, the extent of the region is short with the dominant cyclic motion occurring along the pipe axis. Furthermore, observation does not indicate that the height of the cold layer varies significantly along the pipe axis. Thus, an idealized prescribed motion waveform (constant layer height) is defined below based on test observations.

Testing has also indicated that the "fill and spill" thermal cycling mechanism cannot be supported in branch line configurations with strictly horizontal geometry for practical plant operational conditions. Thus, the discussion in this sub-section only applies to UH piping configurations. An alternate prescribed waveform applicable to horizontal lines is discussed in a Section 2.2.5.

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Figure 2-8
Fill and Spill Prescribed Interface Motion Definition in UH Configurations

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2.2.5 High-Frequency, Turbulence-Driven Cold Stratified Layer Prescribed Motion

As noted in the previous section, the interface motion in UH configurations consist of two components: a large-amplitude motion component (fill and spill) with frequency that scales with the in-leakage flow rate and a high-frequency, turbulence-driven component. For entirely horizontal branch line configurations, the fill and spill mechanism is only supported in a region close to the RCL, and for most practical configurations, the waveform definition given in Eqs. (2-15) and (2-16) is not applicable since the dominant thermal cycling mechanism is characterized by only the turbulence-driven mechanism. For horizontal line configurations, the following waveform definition should be used:

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2.2.6 UH/H Fluid Temperatures and Heat Transfer Coefficients

Models to predict the fluid temperatures and heat transfer coefficients in UH/H piping configurations are described in this section. The fluid temperatures and heat transfer coefficients in the swirl penetration region and cold layer region are provided below using models that provide conservative estimates of the thermal loading.

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Figure 2-9
Definition of Parameters for Cold Layer Heat-up Model

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2.3 DH Configuration Thermal Cycling Model

In this section, the thermal cycling screening and evaluation methodology for DH piping configurations is summarized. The general approach is similar to the UH/H methodology described previously. In the DH configuration, thermal cycling primarily occurs due to cyclic penetration, break down, and retreat of a thermal stratification interface that is formed by the interaction between swirl penetration and fluid in the branch line that has lower temperature (higher density) than the RCL header due to heat transfer to the environment (i.e., "cold-trapped" lines). Cyclic motion of the thermal interface provides a thermal load to the pipe, which may lead to thermal fatigue.

Unlike the UH/H methodology, valve in-leakage is not required for thermal cycling to occur in DH line configurations. Note that while cyclic valve out-leakage has previously been attributed to through-wall cracking in one DH configuration (i.e., Genkai RHR described in NRC Bulletin 88-08 Supplement 3), it is generally believed that the cyclic penetration and retreat of the thermal interface is instead the fundamental mechanism for thermal cycling and fatigue failures in drain lines, residual heat removal (RHR) suction lines, and similar lines in U.S. PWR plants. Valve leakage effects are not considered in the methodology described herein, although limited test data examining the effects of valve in-leakage in DH line configurations are provided in a separate report [1].

As with the UH/H configuration, the thermal load is determined based on the motion of the thermal interface separating two fluid regions: the swirl penetration region (1) and the cold-trapped region (2) (see Figure 2-10). The thermal cycling model provides the following parameters:

- the maximum penetration of the thermal interface from the RCL inside diameter x_m;
- the height of the hot stratified layer H;
- the axial and azimuthal variation of fluid temperatures in the hot and cold stratified fluid regions T_1, T_2;
- heat transfer coefficients associated with hot and cold fluid regions h_1, h_2; and
- the time-varying position of the thermal stratification interface $x_m(t)$, which is defined by a prescribed cyclical waveform.

Note that the region (1') shown in Figure 2-10 identifies the fluid region in which the temperature increases as the thermal interface penetrates into the branch line and decreases after retreat of the thermal interface.

An approach to evaluate DH piping configurations is outlined in Figure 2-11. The methodology described in this section is applicable to simple DH line configurations. Alternate line configurations, including inclined down-down-horizontal lines (e.g., IDzDH) and multiple drop lines (e.g., DHDH) can be evaluated using the methods described in this section in combination with Section 2.4. Specific model components are described in the following sub-sections.

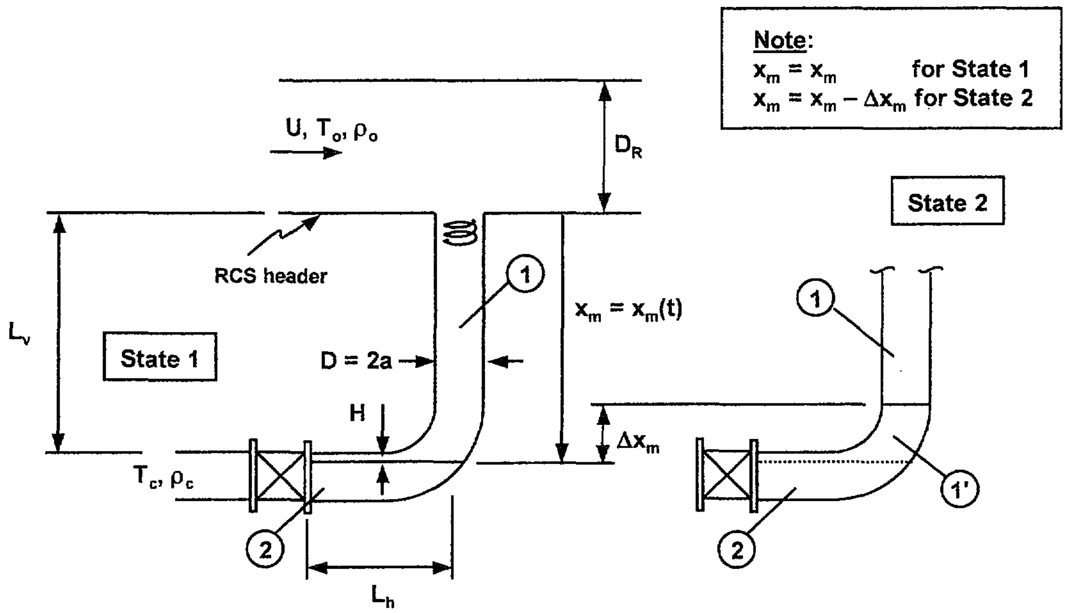

Figure 2-10
Thermal Cycling Model Parameter Definitions and Fluid Boundaries for DH Branch Line Configurations

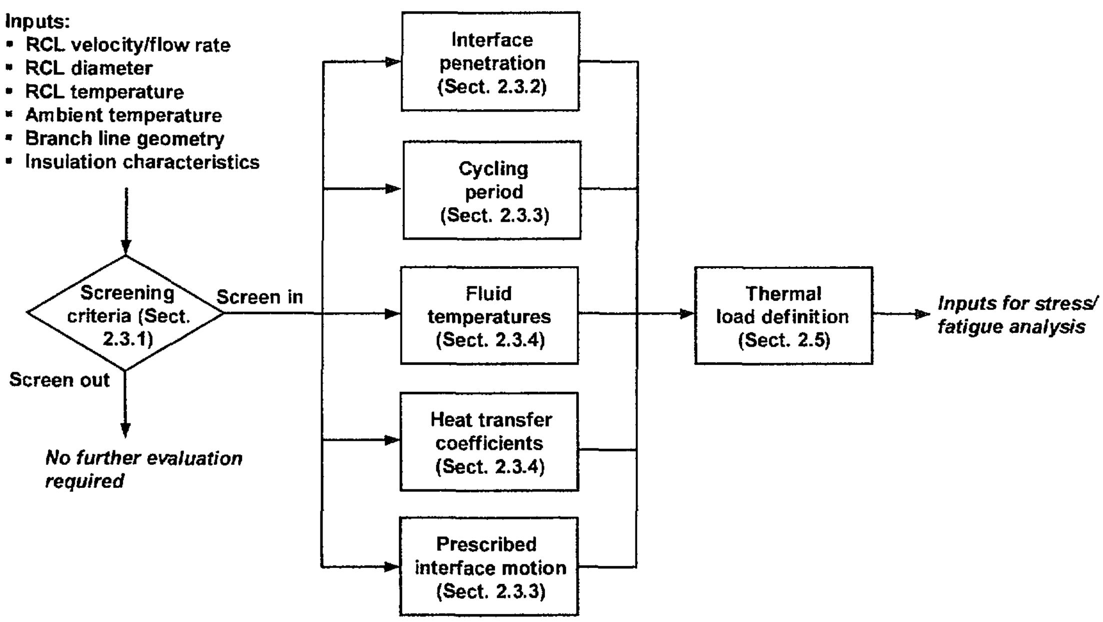

Figure 2-11
DH Thermal Cycling Model Evaluation Approach

Guidance on transforming the boundary conditions described by the following paragraphs and referred to from the flow chart into load definitions for stress analysis is given in Section 2.5.

2.3.1 DH Screening Criteria

Screening criteria, based on line geometry and operational conditions, have been developed for DH configurations that can be used to eliminate certain lines from further consideration. Additional details on the development of these criteria are provided in Appendix C.

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Figure 2-12
Geometric Screening Criteria for DH Piping Configurations

2.3.2 DH Thermal Interface Penetration

Assessment of thermal cycling susceptibility is made by comparison of the maximum penetration of the thermal interface with the branch line geometry. The maximum penetration is determined from consideration of the stability of the stratification interface due to the gradient in the swirl velocity. For straight vertical branch lines (i.e., no elbow), an expression is given below to predict the maximum thermal interface penetration:

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2.3.3 DH Thermal Interface Prescribed Motion for Cycling Loading

A thermal load definition is provided for structural analysis of DH piping configurations, which is defined by prescribed, cyclic motion of the thermal interface and the fluid temperatures and heat transfer coefficients in the hot and cold fluid regions. As noted previously, thermal cycling is considered insignificant when $H/D|_{DH}$ is predicted to be greater than or equal to 1.0. The thermal loading defined by Sections 2.3.3 and 2.3.4 are only applicable for lines with H/D less than 1.0.

The spatial and time dependence of where and when the fluid temperatures are applied to the inside pipe wall are determined from a waveform that captures the basic features of the thermal interface motion as observed from testing. The prescribed motion, shown in Figure 2-13, is functionally described as:

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Figure 2-13
Prescribed Interface Motion Definition in DH Configurations

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2.3.4 DH Fluid Temperatures and Heat Transfer Coefficients

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Figure 2-14
Illustration of Potentially Heated Length in Simple DH Configurations

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Figure 2-15
Illustration of Potentially Heated Length in Multiple Drop DH Configurations

2.4 Effects of Branch Line Geometry on Swirl Penetration

Flow through the primary reactor coolant piping system leads to the formation of a swirl vortex structure in the branch line that can penetrate many diameters from the RCL-branch line junction. The swirl velocity in the branch line is largest near the branch line inlet at the RCL and decays along the branch line, and may be further modified by variations in the branch line geometry. The models for predicting the cycling location/maximum penetration given in the previous sections were developed under the assumption that swirl penetration occurs in a straight pipe segment with no diameter variation. Extensions of the basic models given previously to account for more complex branch line configurations are discussed in this section. Additional details are provided in a separate report [1].

2.4.1 Additional Elbows in Branch Line Configurations

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Figure 2-16
Illustration of Potentially Affected Region in HUH and UHUH Configurations

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previously. Note that this approach applies to all generic DH piping configurations, including HDH lines and lines with inclined down sections preceding vertical pipe drops.

2.4.2 Branch Line Reducers and Expanders

Changes in the branch line diameter, due to a reducer or an expander, affect the swirl penetration characteristics and cycling location. This effect must be factored into the models described previously.

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Figure 2-17
Geometric Definitions for Analysis of Branch Line Reducer or Expander

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Figure 2-18
Interpolation of Reducer and Expander Loss Factor

2.4.3 Branch Line Tees

An additional component that may potentially affect thermal cycling in branch lines is a straight tee. Test data to determine the effect of a straight tee (i.e., equal branch and run diameters) on swirl penetration have shown that the branch line swirl is significantly reduced when a tee is present in the branch line piping configuration (see Figure 2-19). Swirl was observed to penetrate into both the run side and branch side of the tee but greatly reduced due to separation and other losses. The thermal cycling model, as described previously, is not applicable beyond a branch line tee.

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Figure 2-19
Straight Tee Branch Line Piping Configuration

2.4.4 Branch Line Thermal Sleeves

The geometry of the branch line inlet, in particular the presence of a thermal sleeve, has been shown to affect the generation of swirl in a branch line, which may ultimately influence the thermal cycling loading. Testing has previously been performed to quantify the thermal sleeve effect on the branch line entry swirl and swirl penetration characteristics [1]. It has been shown that a thermal sleeve will have little effect on the branch line when positioned flush to the RCL inside diameter, so that the models described previously will be applicable.

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2.5 Thermal Loading Definition for Piping Stress Analysis

The previous sections of this report provide methods to predict thermal cycling characteristics for evaluation of a normally-stagnant branch line. For susceptible branch line configurations, a thermal load is defined in terms of the fluid temperatures, heat transfer coefficients, and the prescribed motion of the interface separating these hot and cold fluid regions. This section discusses how these parameters can be translated into fluid boundary conditions for piping stress analysis, for example, using finite element structural analysis.

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Figure 2-20
Illustration of Fluid Temperature Time History at Several Axial Stations in UH Branch Line Configuration

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2.6 Sensitivity of Thermal Cycling Model Parameters

This section of the report concludes with a discussion of the sensitivity of the thermal cycling model parameters. The objective of this section is to provide qualitative discussion of the physical parameters that may be changed to affect the thermal cycling location and/or thermal loading for a given branch line configuration, if it is determined to be susceptible to swirl penetration thermal cycling.

Branch line physical parameters that may be modified to affect the thermal cycling characteristics include: vertical and horizontal segment lengths, insulation characteristics (type and thickness), in-leakage flow rate, and in-leakage (ambient) temperature. For this discussion, it is assumed that the in-leakage temperature is directly controllable, although in practice, this temperature would be effectively modified by local heating elements or augmented cooling. It is desired to effect a change in the swirl penetration characteristics to eliminate susceptibility to thermal cycling and/or the thermal loading by reducing the hot-to-cold fluid temperature difference or increasing the cycling period. Qualitative parametric sensitivities are summarized in Table 2-1 and Table 2-2 for UH/H and DH configurations, respectively, where the following notation is used to define the relative sensitivity between input and output parameters:

- Strong – parameter has strong influence on thermal cycling location/loading, i.e., variations of this parameter may be used to mitigate a potentially susceptible piping configuration
- Weak – parameter has weak influence on thermal cycling location/loading
- N/A – parameter has negligible or no effect on thermal cycling location/loading

Note that the "Swirl penetration" column in Table 2-1 and Table 2-2 represents the sensitivity of the predicted cycling location with respect to the parameters in question (i.e., Eqs. 2-1 and 2-41). The predicted cycling location does not depend on the line dimensions (length) in UH/H configurations; for DH configurations, the swirl penetration distance is affected by the vertical segment length only when swirl extends to the horizontal segment. As indicated by Figure 2-6 and Figure 2-12, however, the vertical segment length may be modified to mitigate thermal cycling in a susceptible line by effectively moving the susceptible region (i.e., a horizontal segment) relative to the swirl penetration. The discussion in this section does not account for this general behavior.

Table 2-1
Summary of Qualitative Sensitivities of UH/H Thermal Cycling Parameters

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3
MODEL APPLICATION TO A GENERIC BRANCH LINE ASSESSMENT

3.1 Overview

The thermal cycling screening and evaluation methodology described in the previous section of this report was applied in a generic assessment of non-isolable, normally-stagnant branch lines in U.S. PWR plants. The approach and results of this generic branch line assessment are presented in this section of the report. The generic branch line assessment was performed with the following objectives:

- To exercise the thermal cycling screening and evaluation methodology using actual line geometries that exist within U.S. PWR plants;
- To determine the population of branch lines that may or may not be susceptible to thermal fatigue, as well as configurations that are indeterminate due to insufficient knowledge of the input parameters or limitations within the methodology; and
- To obtain generic thermal-hydraulic load definitions for lines identified as susceptible to thermal fatigue.

The branch line assessment also provides a means to qualitatively assess the thermal cycling screening and evaluation methodology. By comparing the population of branch lines determined to be susceptible to thermal cycling and fatigue from industry operating experience, end-users can gauge conservatism in the methodology for practical applications.

3.2 Generic Branch Line Assessment Approach

3.2.1 Summary of RCS Attached Piping Survey

The primary input for the generic branch line assessment is a survey of normally-stagnant lines with nominal diameter greater than 1-inch (25-mm) attached to the primary coolant system of PWR plants [9]. This survey, which was developed from EPRI-sponsored Thermal Fatigue Workshops, documents the line type, size, segment lengths, orientation, and RCS attachment point. Lines with the potential for valve in-leakage were also identified. A total of 540 lines are represented in this survey, which are estimated to account for approximately 70% of all such lines in the U.S. domestic PWR fleet.

Note that some configurations in the branch line survey did not include sufficient details (e.g., unspecified line dimensions or unknown attachment point) and were excluded from the analysis.

Sixteen lines were excluded based on insufficient line geometry details; leaving 524 unique branch line configurations in the assessment.

3.2.2 Approach to Performing Calculations

The general approach used in performing the generic branch line assessment is outlined. Branch line piping survey inputs were categorized based on orientation and in-leakage potential so that the thermal cycling methodology could be applied. Screening and evaluation calculations were performed for configurations with in-leakage potential (UH/H methodology) and bottom-connected downcomer (cold-trapped) line configurations (DH methodology). A summary of the branch line configuration groupings for assessment calculations is provided in Table 3-1. Calculations were performed to determine the cycling location/penetration, fluid temperatures, and heat transfer coefficients, in addition to parameters defining the cyclic motion of the interface between hot and cold fluid regions that can be used to provide the thermal loading inputs for structural analysis. Sample thermal load definitions are also given (see Section 4).

Table 3-1
Summary of Generic Branch Line Assessment Configurations

Model configuration	Number of lines	Example line types
DH	224	Drain, excess letdown, residual heat removal
DH (IDx geometry)	4	Decay heat removal
UH	176	Safety injection, charging
UH (IUx geometry)	24	Safety injection
H	44	Safety injection
No calculation required (insufficient swirl penetration)	39	Pressurizer auxiliary spray
No calculation required (geometry)	13	

Note that branch line configurations that are not oriented normal to the RCS axis at the loop attachment point (i.e., IUx and IDx configurations, see Figure 3-1[5]) are identified separately in Table 3-1. For these configurations, the swirl penetration model does not strictly apply, but branch line assessment calculations have been performed using the models given in Section 2 of this report. These configurations represent a small fraction (approximately 5%) of the total population. Furthermore, most safety injection lines with IUx geometry have been identified to have no valve in-leakage potential and may be eliminated from further consideration.

[5] Branch line piping configuration nomenclature is explained in Appendix A.

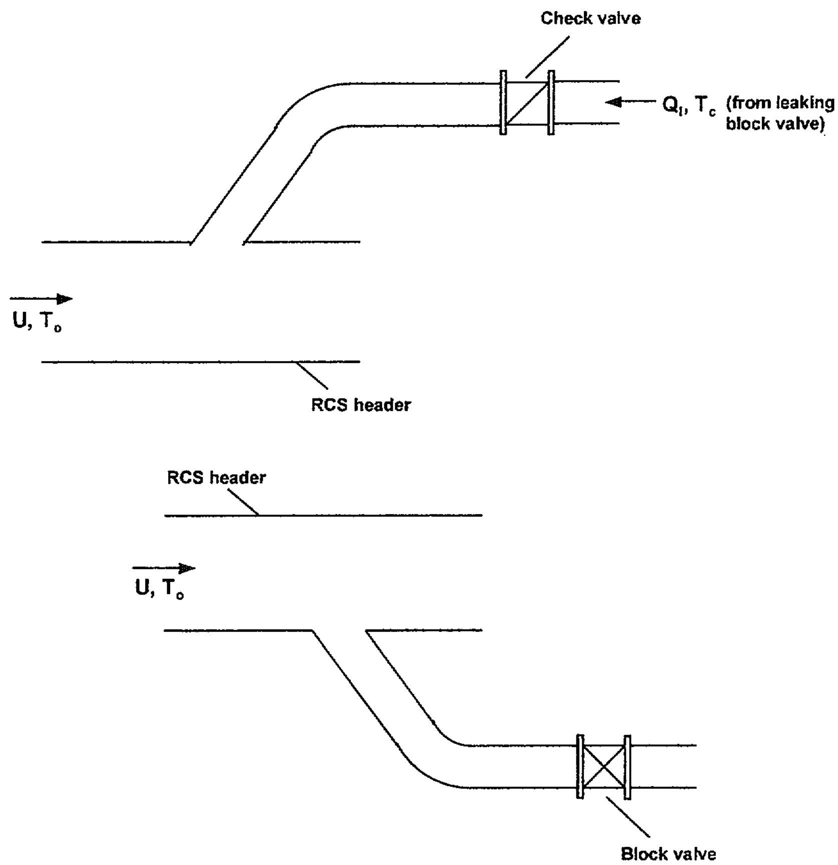

Figure 3-1
Illustration of IUx and IDx Configuration Layouts

A subset of the total population of lines was also eliminated from the branch line assessment (i.e., no swirl penetration thermal fatigue susceptibility) without performing direct calculations. Branch line configurations not attached to primary loop piping (e.g., pressurizer auxiliary spray lines) were eliminated since the velocity in the pressurizer spray piping is low during normal plant operational conditions and does not provide a source for significant swirl penetration in the attached branch line (see Section 3.2.3). Other configurations were eliminated based on geometry as summarized below:

- Drain/excess letdown lines in DV configuration (4 configurations);
- Safety injection lines in HDV configuration and no valve in-leakage potential (6 configurations); and
- Loop bypass lines in HUV configuration (3 configurations).

Bottom-connected downcomer lines that terminate at a valve with no intermediate horizontal segment (i.e., DV and HDV lines) were eliminated since swirl penetration thermal cycling in the vertical segment has not been shown to be problematic (DH configurations). The loop bypass lines in HUV configuration were eliminated based on engineering judgment, since valve in-leakage, if present, would not result in stratification in the horizontal segment due to mixing in the vertical segment.

Additional lines can be eliminated based on geometry and valve in-leakage considerations (for UH/H configurations). The following sections provide additional discussion to this end.

Some input parameters for the thermal cycling model were not defined from the piping survey, for example, the RCL flow properties and geometry (i.e., inside diameter), temperature boundary conditions, and branch line insulation characteristics. For the RCL parameters, representative values were assumed based on the branch line attachment point and NSSS vendor. These assumed parameters are summarized in Table 3-2.

Table 3-2
Summary of RCL Parameters for Branch Line Assessment

Vendor	Attachment point	RCL inside diameter, in (m)	RCL temperature, °F (°C)	RCL velocity, ft/sec (m/sec)
Westinghouse	Hot leg	29 (0.74)	620 (330)	45 (14)
Westinghouse	Crossover leg	31 (0.79)	560 (290)	40 (12)
Westinghouse	Cold leg	27.5 (0.70)	560 (290)	50 (15)
CE	Hot leg	42 (1.07)	600 (320)	45 (14)
CE	Crossover/cold leg	30 (0.76)	550 (290)	40 (12)
B&W	Hot leg	36 (0.91)	600 (320)	60 (18)
B&W	Crossover/cold leg	28 (0.71)	550 (290)	45 (14)

The ambient (cold) temperature was assumed to be 100 °F (38 °C) for all calculations. Line insulation characteristics were also missing in the survey. All calculations were performed assuming lines were insulated with representative thickness and thermal conductivity characteristics. This assumption may potentially lead to the under-estimation of the fluid temperature difference in some DH calculations, although sensitivity calculations have been performed and indicate that the difference in the fluid temperatures due to this assumption is typically no larger than 20 °F (10 °C).

Generic branch line assessment results for in-leakage (UH/H) configurations are summarized in Section 3.3. Results for cold-trapped (DH) branch line configurations are summarized in Section 3.4.

3.2.3 Pressurizer Auxiliary Spray Lines

Auxiliary spray lines attached to the pressurizer spray system represent a subclass of normally stagnant lines that have the potential for cold-water in-leakage. During normal plant operational conditions, the flow rate through pressurizer spray piping is low such that there is insufficient swirl penetration for thermal cycling to occur. In this section, a representative calculation is provided to illustrate this case.

For this calculation, the following input parameters are used:

Main spray line inside diameter: 5.2 inches (130 mm)

Auxiliary spray line inside diameter: 1.7 inches (43 mm)

Main spray flow rate: 5 gpm (20 l/min)

Main spray velocity: 0.08 ft/sec (0.02 m/sec)

Main spray temperature: 550 °F (290 °F)

In-leakage temperature: 100 °F (38 °F)

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3.3 UH/H Configuration Results

Results of generic branch line assessment calculations for lines with in-leakage potential (i.e., UH/H line configurations) are presented in this section. Branch lines from the survey can be subdivided based on the geometric layout into UH configurations (which also include IUzH and other more complex configurations), H configurations, and IUxH configurations. Line types covered by these calculations include safety injection (SI), charging, and loop bypass lines[6]. As noted previously, the thermal cycling model is not strictly applicable to lines with IUxH geometry (i.e., the branch line axis is not perpendicular with the RCS axis). Most lines with IUxH layout typically do not have the potential for valve in-leakage as noted in the branch line survey. The potential for valve in-leakage was indeterminate for two IUxH line configurations, however, and these lines were analyzed in addition to the UH and H configurations.

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[6] Loop bypass lines are present in some Westinghouse plants, connecting the hot and cold legs.

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[7] Includes IUzH, IUxUH, HUH, etc. line configurations.

Similar results are also observed for the H configuration lines, summarized in Table 3-5 representing the unique configurations for the 25 remaining H lines in Table 3-3. For H configurations with small diameters, the minimum valve in-leakage was typically determined by the minimum temperature difference limit between the hot and cold fluids. Valve in-leakage ranges for thermal cycling in H line configurations were generally larger than those for comparable UH configurations.

Calculation results for UH configurations categorized by nominal pipe size and line type are also summarized in Figure 3-2, corresponding to results tabulated in Table 3-4, in which the valve in-leakage range for cycling to occur in the horizontal segment is plotted versus pipe diameter. A similar plot for H configuration lines is shown in Figure 3-3, corresponding to results tabulated in Table 3-5. The shaded regions indicate the median range of valve in-leakage for cycling to occur in the horizontal segment for all lines in the given population subset, where the median in-leakage range is defined as the range between the median of the maximum in-leakage rate and the median of the minimum in-leakage rate for all lines in the subcategory. The vertical lines in Figure 3-2 and Figure 3-3 indicate the range between the overall minimum and maximum in-leakage flow rates for all lines in the population subcategory. Note that some lines in the branch line assessment, in particular the larger diameter lines, were found to undergo thermal cycling for very large in-leakage flow rates on the order of 10 gpm (40 l/min) or greater. The maximum flow rates in the plots are limited to 2.5 gpm (9.4 l/min) to be more representative of the flow rates that would be expected for a leaking valve.

Table 3-4
Summary of Branch Line Assessment Calculations for Cycling Susceptible UH Line Configurations

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Table 3-5
Summary of Branch Line Assessment Calculations for Cycling Susceptible H Line Configurations

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Figure 3-2
In-leakage Range for Thermal Cycling in Cycling Susceptible UH Configurations

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Figure 3-3
In-leakage Range for Thermal Cycling in Cycling Susceptible H Configurations

The hot-to-cold fluid temperature differences for the results tabulated in Table 3-4 and Table 3-5 are also illustrated in Figure 3-4 for UH configurations and Figure 3-5 for H configurations. These plots summarize the calculated temperature difference at the minimum and maximum in-leakage flow rates for thermal cycling to occur in the horizontal segment, which can be used to quantify the thermal loading. Results are presented in a similar manner as the in-leakage range, with the median temperature difference for the minimum and maximum in-leakage rates shown by the shaded region and overall range (i.e., smallest temperature difference to largest temperature difference) indicated by the vertical line. Note that the narrow temperature range for the 6-inch (150-mm) SI lines in Figure 3-4 indicates that the variation in the temperature loading in these configurations did not vary significantly between configurations and with in-leakage flow rate. The temperature difference is generally smaller for the minimum in-leakage bound due to heat-up of the cold layer in the pipe. The maximum in-leakage rate provides the most conservative load, which is typically on the order of the overall temperature difference $T_0 - T_C$, where T_0 is the RCL temperature and T_C is the in-leakage temperature. In general, the thermal loading that would be expected in small diameter (less than 3-inch or 75-mm) lines is less severe than large diameter lines.

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Figure 3-4
Range of Hot-to-Cold Fluid Temperature Differences for Cycling Susceptible UH Configuration In-leakage Range for Cycling

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Figure 3-5
Range of Hot-to-Cold Fluid Temperature Differences for Cycling Susceptible H Configuration In-leakage Range for Cycling

Branch line assessment calculation results for the two IUxH line configurations of Table 3-3, attached to the cold leg of a CE plant, are summarized as follows. Analysis of these 12-inch (300-mm) IUxH lines, with L_v/D and L_h/D of 3.1 and 19.7, respectively, was performed using the same methodology as used for the previous analysis. Results for these configurations were similar to the H configuration results for large diameter, SI line types, which is not surprising given that these IUxH lines consist of short inclined segments followed by long horizontal segments. Due to the limited number of lines in this configuration, no general statements can be made for thermal cycling susceptibility of these branch line configurations.

3.4 DH Configuration Results

Results of generic branch line assessment calculations for bottom-connected downcomer (DH) piping configurations are presented and discussed in this section. Calculations have been performed for 224 DH configurations, which include lines with HDH, DHDH, IDzDH, and IDzH layouts. Line types in the branch line assessment include drain/excess letdown lines, residual heat removal (RHR) lines, and loop bypass lines. As noted previously, four lines with IDxH layout are also present in U.S. PWR plants. While the thermal cycling model does not strictly apply to these line configurations, analysis has been performed with results discussed at the end of this section.

A high level summary of generic branch line assessment results for DH and IDxH configurations is given in Table 3-6. This table summarizes the total number of lines, as well as the number of lines that were screened out based on the geometric criteria given in Section 2.3.1 (i.e., Figure 2-12). Specific line details for the configurations screened out are provided in Appendix D. The remaining lines in the population represent those with potential for thermal cycling, and line details for these cases are given below.

Table 3-6
Summary of DH Branch Line Assessment Calculations

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The remaining potentially susceptible configurations were evaluated to determine the thermal interface penetration and thermal load. Line details and results for generic DH branch line assessment calculations are summarized in Table 3-7 for small diameter (less than 6 inch or 150 mm) lines and in Table 3-8 for larger-bore piping. Of the 224 DH line configurations in Table

[8] Includes IDzH, IDxDH, HDH, etc. line configurations.

3-1, the 90 unique configurations represented in Table 3-7 and Table 3-8 have been identified as susceptible to thermal cycling. Susceptible lines are identified by comparing predicted thermal interface penetration lengths with the line geometry.

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Table 3-7
Summary of Branch Line Assessment Calculations for Cycling Susceptible Small Diameter DH Line Configurations

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Table 3-8
Summary of Branch Line Assessment Calculations for Cycling Susceptible Large Diameter DH Line Configurations

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Table 3-9
Summary of Potentially Susceptible DH Branch Line Configurations, by Nominal Pipe Size

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Figure 3-6
DH Branch Line Population with Potential Thermal Cycling Susceptibility

Table 3-10
Summary of DH Branch Lines Eliminated for Insignificant Top-to-bottom Temperature Difference

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Figure 3-7
Predicted Top-to-Bottom Temperature Differences in Potentially Susceptible DH Lines

Four IDxH configurations were noted in the branch line survey, which exist in some B&W plants. These lines are decay heat removal lines with 12-inch (300-mm) nominal pipe diameter. Analysis was performed for these configurations, and no thermal cycling susceptibility was found. These lines were eliminated from consideration based on geometry (i.e., due to insufficient swirl penetration and/or complete penetration through the horizontal segment).

4
THERMAL CYCLING APPLICATION MODEL EXAMPLE CALCULATIONS

Example calculations for the thermal cycling evaluation methodology are provided illustrating application of the thermal cycling model to representative line configurations.

4.1 Safety Injection Line Example (UH Configuration)

Example calculations illustrating methods to determine the cycling location and load definition for a representative UH configuration line are given in this section. Input parameters are selected to correspond to the Farley Unit 2 safety injection (SI) line, which is a 6-inch Schedule 160 line that runs vertical for 28.6 inches (0.73 m) from the RCS cold leg followed by a horizontal run of 21 inches (0.53 m) to a check valve. Parameters for this example calculation are given in Table 4-1 [1]. Note that no direct measurement of the valve in-leakage flow rate was available, and the tabulated parameter is an estimated value based on flow diversion testing at Farley.

Table 4-1
Thermal Cycling Model Input Parameters for Farley SI Line Example

Parameter	Description	Value	Units
U	RCL average velocity	48 (15)	ft/sec (m/s)
T_o	RCL temperature	560 (290)	°F (°C)
D_R	RCL inside diameter	27.5 (0.70)	in (m)
D	Branch line inside diameter	5.19 (132)	in (mm)
Q_I	In-leakage flow rate	0.5 (1.9)†	gpm (l/min)
T_c	In-leakage temperature	120 (49)†	°F (°C)
t_w	Pipe wall thickness	0.72 (18)	in (mm)
k_w	Pipe wall thermal conductivity	10 (17)	Btu/hr·ft·°F (W/m·K)

† Approximate or assumed value

4.1.1 Cycling Location Calculation

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Figure 4-1
Illustration of Predicted and Observed Cycling Locations in Example SI Line

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4.1.2 Fluid Temperature and Heat Transfer Coefficient Calculation

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4.1.3 Thermal Loading Calculation

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Figure 4-2
Fluid Temperature Time History for SI Example Case, x/D = 8.3

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Figure 4-3
Fluid Temperature Time History for SI Example Case, x/D = 7.6

4.2 RHR Suction Line Example (DH Configuration)

Example calculations illustrating methods to determine the thermal interface penetration and load definition for a representative DH configuration line are given in this section. Input parameters are selected to correspond to the Angra residual heat removal (RHR) suction line. This line is an 8-inch Schedule 160 line that is inclined downward at a 45-degree angle for 25.5 inches (0.65 m) followed by a vertical run of 118 inches (3.0 m) before turning horizontal for 24.8 inches (0.63 m) and ending at a valve (IDzDHV). While no fatigue cracking has occurred at Angra, published data were available for this configuration in which thermal cycling was observed [12]. Input parameters for the Angra benchmark case are summarized in Table 4-2 [1]. The insulation thermal conductivity used for benchmarking could not be confirmed, and a representative value was assumed.

Table 4-2
Thermal Cycling Model Input Parameters for Angra RHR Suction Line Example

Parameter	Des cription	Value	Units
U	RCL average velocity	44.7 (13.6)	ft/sec (m/s)
T_o	RCL temperature	595 (313)	°F (°C)
D_R	RCL inside diameter	29 (0.74)	in (m)
D	Branch line inside diameter	6.81 (173)	in (mm)
T_c	Temperature beyond valve	200 (93)	°F (°C)
T_{amb}	Ambient temperature	100 (38)	°F (°C)
A_c	Pipe wall (metal) area	22.0 (14,200)	in^2 (mm^2)
t_w	Pipe wall thickness	0.91 (23)	in (mm)
k_w	Pipe wall thermal conductivity	10 (17)	Btu/hr·ft·°F (W/m·K)
t_i	Insulation thickness	2.5 (64)	in (mm)
k_i	Insulation thermal conductivity	0.036 (0.062)†	Btu/hr·ft·°F (W/m·K)

4.2.1 Thermal Interface Penetration Calculation

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† Approximate or assumed value

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Figure 4-4
Illustration of Thermal Interface Penetration and Cycling Range in Example RHR Suction Line

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4.2.2 Thermal Cycling Period Calculation

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4.2.3 Fluid Temperature and Heat Transfer Coefficient Calculation

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4.2.4 Thermal Loading Calculation

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Figure 4-5
Fluid Temperature Time Histories for RHR Example Case at Several Axial Locations

4.3 Thermal Interface Penetration in DHDH Configuration

An example calculation is provided in this section illustrating application of the DH thermal interface penetration model to a multiple drop (DHDH) configuration. This example also illustrates application of the model for the hot stratified layer height to determine when the horizontal segment "runs hot". Calculations of the fluid temperatures and thermal load are not given since this aspect of the model is identical to the previous example. Furthermore, some details, which are identical to the previous example, are omitted.

Numerical parameters used in the example, which are representative of a 12-inch (300-mm) RHR line, are summarized below:

D = 10.5 in (267 mm)

D_R = 30 in (0.76 m)

U = 40 ft/sec (12 m/sec)

T_o = 550 °F (290 °C)

T_c = 100 °F (38 °C)

ρ_o = 47 lb/ft^3 (750 kg/m^3)

ρ_c = 62 lb/ft^3 (990 kg/m^3)

The line segment lengths (see Figure 4-6) are given as:

First vertical segment: L_1 = 60 in (1.5 m)

First horizontal segment: L_2 = 110 in (2.8 m)

Second vertical segment: L_3 = 90 in (2.3 m)

Second horizontal segment: L_4 = 55 in (1.4 m)

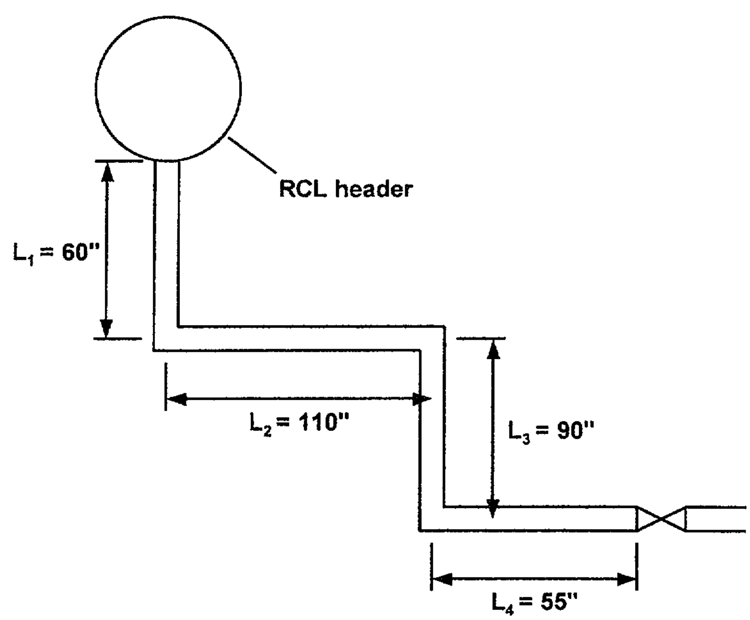

Figure 4-6
DHDH Line Geometry for Thermal Interface Penetration Example

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4.4 Cycling Location in H Configuration with Reducer

An example calculation is provided to demonstrate methods to evaluate lines with a reducer or expander. The example calculation examines a representative horizontal SI line with larger diameter nozzle at the RCS. Representative input parameters are used (see also Figure 4-7).

D_1 = 3.44 in (87 mm)

D_2 = 1.69 in (43 mm)

D_R = 27.5 in (0.70 m)

U = 50 ft/sec (15 m/sec)

T_o = 550 °F (290 °C)

T_c = 100 °F (38 °C)

Q_l = 0.1 gpm (0.03 l/min)

ρ_o = 47 lb/ft^3 (750 kg/m^3)

ρ_c = 62 lb/ft^3 (990 kg/m^3)

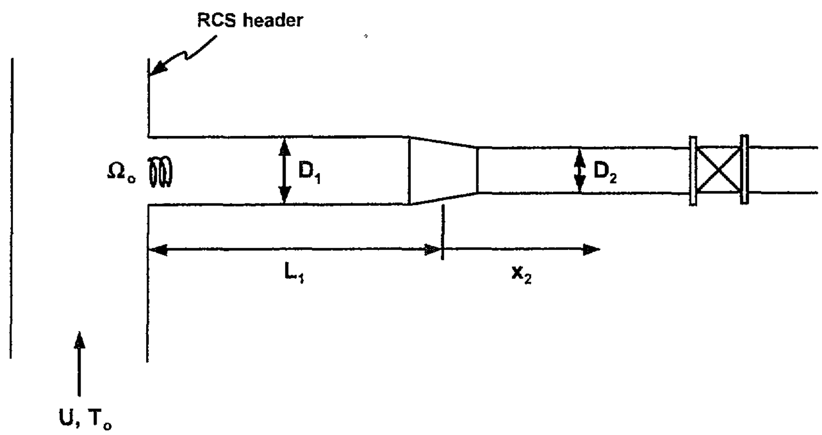

Figure 4-7
Geometric Parameter Definitions for Reducer Analysis

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5
QUALITY ASSURANCE

All quality-related activities were performed in accordance with the Continuum Dynamics, Inc. Quality Assurance Manual, Revision 13 [13]. Quality-related activities documented in this report include model development, validation, and documentation. Calculations for the generic branch line assessment (Section 3 and Appendix D) were not conducted as part of the CDI Quality Assurance Program. CDI's Quality Assurance Program provides for compliance with the reporting requirements of 10 CFR Part 21 and 10 CFR 50 Appendix B. All data analysis procedures and results are contained in a Design Record File that will be kept on file at CDI offices.

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A
NOMENCLATURE

Notation used throughout this report is defined below. Typical units, including both English engineering and SI units, are also denoted (n.d. = non-dimensional).

a	Branch line internal radius (in, mm)
A_t	Pipe wall (metal) cross-sectional area (in^2, mm^2), $\pi\left(D_o^2 - D^2\right)/4$
A_H	Cold layer cross-sectional area in UH/H configurations (in^2, mm^2)
A_y	Cold layer cross-sectional area based on critical depth (in^2, mm^2)
C_p	Specific heat (Btu/hr lb °F, W/kg K)
D	Branch line internal diameter (in, mm)
D_i	Insulation outside diameter (in, mm)
D_o	Pipe outside diameter (in, mm)
D_R	RCL header internal diameter (in, mm)
F	Periodic function (n.d.)
f_s	Swirl fraction parameter for DH fluid temperature model (n.d.)
g	Acceleration of gravity (ft/sec^2, m/sec^2)
Gr	Grashof number (n.d.)
H	Stratified layer height (in, mm)
h_1	Heat transfer coefficient between pipe hot fluid and pipe wall (Btu/hr ft^2 °F, W/m^2 K)

h_2	Heat transfer coefficient between pipe cold fluid and pipe wall (Btu/hr ft^2 °F, W/m^2 K)
h_a	Heat transfer coefficient between pipe/insulation outer surface and ambient air (Btu/hr ft^2 °F, W/m^2 K)
k	Fluid thermal conductivity (Btu/hr ft °F, W/m K)
k_i	Insulation thermal conductivity (Btu/hr ft °F, W/m K)
k_w	Pipe wall thermal conductivity (Btu/hr ft °F, W/m K)
L	Total branch line length from RCL to valve (in, mm)
L_h	Horizontal segment length (in, mm)
L_H	Horizontal segment length including elbow (in, mm)
L_{ph}	Potentially heated segment length (in, mm)
L_v	Vertical segment length (in, mm)
L_V	Length of vertical segment from RCL inside diameter to top of horizontal segment inside diameter (in, mm)
l_Ω	Swirl penetration decay length scale (in, mm)
Pr	Prandtl number (n.d.)
Q_l	In-leakage flow rate (gpm, l/min)
$\hat{Q}_l$	Non-dimensional in-leakage flow rate (n.d.)
R_e	Elbow bend radius (in, mm)
Re	Reynolds number (n.d.)
Ri	Richardson number (n.d.)
t_1	Hold time for hot fluid region temperature in UH/H load definition (sec)
t_2	Hold time for cold fluid region temperature in UH/H load definition (sec)

t_i	Insulation thickness (in, mm)
t_w	Pipe wall thickness (in, mm)
$\overline{T}$	Average temperature in DH configuration horizontal segment (°F, °C)
T_o	RCL header temperature (°F, °C)
T_1	Temperature in hot stratified fluid region (°F, °C)
T_2	Temperature in cold stratified fluid region (°F, °C)
T_{amb}	Ambient temperature (°F, °C)
T_c	In-leakage temperature or temperature beyond valve (°F, °C)
U	RCL average header velocity (ft/sec, m/sec)
U_a	Overall axial heat transfer coefficient (Btu/hr ft^2 °F, W/m^2 K)
U_{l_H}	Average velocity in cold stratified layer (in/sec, mm/sec)
U_r	Overall radial heat transfer coefficient (Btu/hr ft^2 °F, W/m^2 K)
U_v	Equivalent heat transfer coefficient through valve (Btu/hr ft^2 °F, W/m^2 K)
W_y	Cold layer width based on critical depth (in, mm)
x	Axial distance from RCL inner surface (in, mm)
x_1	Axial distance from check valve in cold layer heat-up model (in, mm)
x_m	Thermal interface location (in, mm)
Δx_m	Thermal interface displacement during cycle (in, mm)
$\overline{x}_m$	Time-averaged location of thermal interface, measured from run piping (in, mm)
y_c	Critical depth for cold layer height correlation (in, mm)
α_H	Angle subtended by cold stratified layer in UH/H configurations (rad)

α_y	Angle subtended by cold stratified layer based on critical depth (rad)
β	Swirl penetration decay exponent (n.d.)
β_T	Coefficient of thermal expansion (1/°F, 1/K)
ε	Uncertainty in model estimate
ϕ_1	Half angle bounding hot stratified layer in the DH configuration (n.d.)
κ	Reducer/expander loss factor (n.d.)
κ_{ts}	Swirl multiplicative factor for thermal sleeve (n.d.)
ρ	Fluid density (lb/ft^3, kg/m^3)
ρ_o	Fluid density evaluated at RCL header temperature (lb/ft^3, kg/m^3)
ρ_c	Fluid density evaluated at temperature T_c (lb/ft^3, kg/m^3)
$\Delta\rho/\rho_o$	Normalized density difference, $\Delta\rho/\rho_o = (\rho_c - \rho_o)/\rho_o$ (n.d.)
ν	Kinematic viscosity (ft^2/sec, m^2/sec)
τ_1	Purging time scale in fill and spill interface prescribed motion (sec)
τ_c	Thermal cycling period (min)
τ_{hf}	Period of high-frequency interface motion (sec)
τ_p	Penetration time scale for DH interface prescribed motion (min)
χ	Thermal cycling correlation parameter in UH/H configurations (n.d.)
Ω	Branch line swirl rate (rad/sec)
Ω_o	Branch line entry swirl (rad/sec)
$\Omega_{o_{eff}}$	Effective branch line entry swirl for branch lines with reducer, expander, or thermal sleeve (rad/sec)

$\widetilde{\Omega}_o$	Scaled branch line entry swirl (rad/sec)
$\widetilde{\Omega}_{o_H}$	Scaled branch line entry swirl for thermal interface penetration to horizontal pipe (rad/sec)

Notation used to define the branch line geometric layout is adopted from [14]. Specific notation used in this report is summarized below.

D	Downward (vertical) segment
H	Horizontal segment
IDx	Downward inclined segment in direction of RCS flow
IDz	Downward inclined segment perpendicular to direction of RCS flow
IUx	Upward inclined segment in direction of RCS flow
IUz	Upward inclined segment perpendicular to direction of RCS flow
U	Upward (vertical) segment
V	Valve

Example:

IDzDHV denotes a branch line with geometry (moving from the RCS header) as downward inclined perpendicular to the RCS flow direction, followed by a downward segment that turns horizontally before ending at a valve.

B
TECHNICAL BASIS FOR THERMAL CYCLING MODEL COMPONENTS

The technical basis for most components of the thermal cycling model has been previously documented in separate reports [1, 2]. Additional model extensions have been made since publication of these reports, and the technical basis for these model extensions is summarized in this appendix. Specific model extensions include the heat transfer coefficient in the swirl penetration region of the branch line and fluid temperatures in the horizontal segment for DH configurations. A method for correcting the DH thermal cycling period for the heat loss through the horizontal segment is also presented. Development and benchmarking of these model components are summarized below.

B.1 Heat Transfer Coefficient Model for Swirl Penetration Region

Evaluation of the loading due to thermal cycling requires an estimate of the cyclic fluid temperatures and heat transfer coefficients. Previous test programs [1, 2] did not provide data that could be used to directly estimate the heat transfer coefficient in the hot fluid region where the branch line swirl was present (i.e., the swirl penetration region). Review of the open literature also does not provide guidance for a suitable heat transfer correlation for the fluid dynamic phenomenon in this region of a dead-ended branch line.

In this section, a model for the heat transfer coefficient in the swirl penetration region is formulated by adapting standard correlation relationships. Comparison with estimated heat transfer coefficients from plant monitoring data demonstrates that this model is conservative by a factor of 3 to 8 (i.e., the model over-predicts the estimated heat transfer coefficients from plant data). Other methods to determine the heat transfer coefficient in the swirl penetration region may be used if technically justified.

B.1.1 Model Formulation

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B.1.2 Model Benchmarking

Comparisons are made with plant monitoring data to confirm that the model described in the previous section is in fact conservative. The heat transfer coefficient in the swirl penetration region is estimated from external pipe wall temperature measurements and compared with model predictions. The estimation procedure uses an inverse heat transfer analysis in which the internal film coefficient is determined from the fluid temperature, which is assumed to be equal to the RCL temperature, measured pipe wall temperature, and ambient conditions. Only radial heat transfer is considered in the analysis. Additional geometric and physical parameters required for the analysis are taken from model benchmarking inputs summarized in a separate report [1].

Temperature monitoring data for Angra and Mihama benchmarking cases are used for the present study. These data are obtained at locations in the vertical segment outside the cycling region where swirl is always present. Table B-1 summarizes the comparison of predicted and estimated heat transfer coefficients in the swirl penetration region, where the heat transfer coefficients are tabulated as a non-dimensional coefficient (Nusselt number) based on the pipe diameter. Comparison of predicted and estimated values is also shown in Figure B-1. As expected, the model provides a conservative prediction of the heat transfer coefficient.

Table B-1
Comparison of Predicted and Estimated Heat Transfer Coefficients in Swirl Penetration Region

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Figure B-1
Comparison of Predicted and Estimated Heat Transfer Coefficients in Swirl Penetration Region

B.2 DH Fluid Temperature Model

Revisions to the model for estimating the fluid temperatures in DH piping configurations are described in this section of the Appendix. The fluid temperature model described herein can be used to estimate the temperature below the thermal interface when the interface has penetrated into the horizontal piping segment, accounting for heat loss to the environment through the horizontal segment and valve.

B.2.1 Model Development

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Figure B-2
Parameter Definitions Used in DH Configuration Fluid Temperature Model

[9] The general form of this model was suggested by Art Deardorff of Structural Integrity Associates.

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B.2.2 Estimation of Potentially Heated Length

The average temperature in the horizontal pipe depends upon the potentially heated length, which is defined as the length of pipe within which hot water from the RCL and vertical segment extends into the horizontal segment. While the temperature in the vertical pipe is relatively uniform due to the mixing from swirl penetration, the swirl flow structure does not extend into the horizontal segment, and the temperature above the thermal interface (i.e., $T_{I'}$ in Figure B-2) will not be constant. Axial heat conduction through the pipe wall and convective cells in the horizontal pipe that are established due to the fluid temperature gradient provide mechanisms to draw heat into the horizontal segment and increase the potentially heated length. The latter mechanism is difficult to model, however, and test data are limited so that an empirical model of this phenomenon cannot be formulated.

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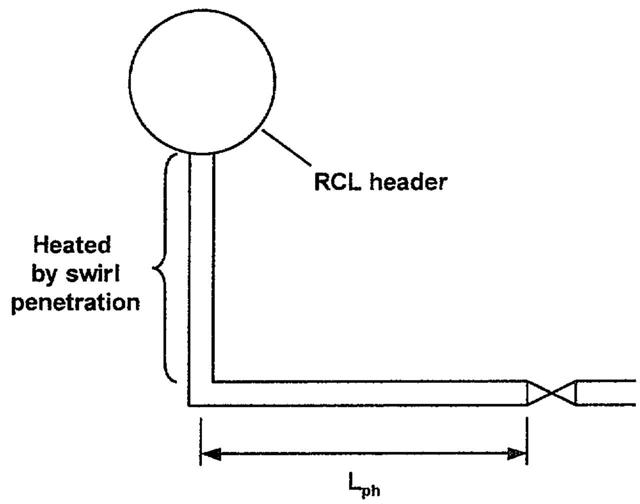

Figure B-3
Definition of Potentially Heated Length in DH Configuration

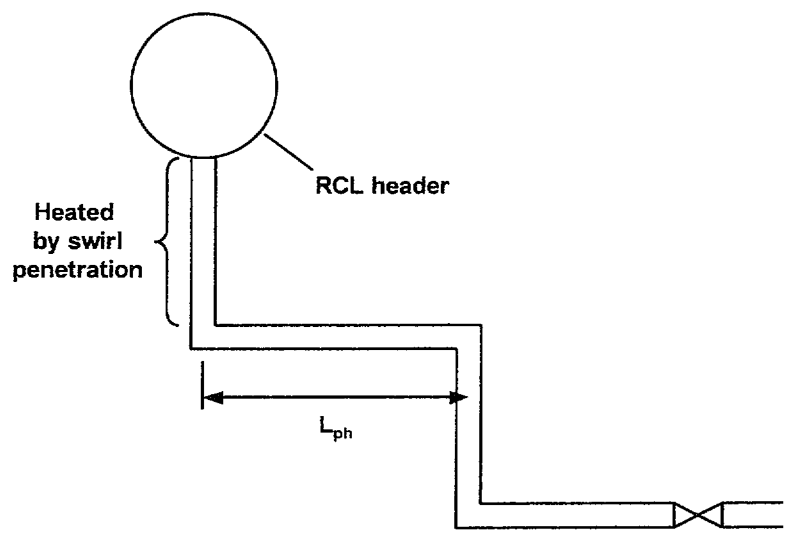

Figure B-4
Definition of Potentially Heated Length in Multiple Drop (DHDH) Configuration

B.2.3 Estimation of Total Heat Transfer Coefficients

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B.2.4 Estimation of Swirl Fraction Parameter

The remaining parameter in the DH fluid temperature model is the swirl fraction parameter f_s. The swirl fraction affects the energy transfer to the horizontal pipe due to swirl penetration, and as indicted by Eq. (B-10), the average temperature in the horizontal pipe is directly proportional to the swirl fraction. Physical intuition suggests that the swirl fraction should depend on the penetration into the horizontal segment, i.e., the swirl fraction should be zero with no penetration and increase with the hot layer thickness H/D. When the hot layer is thin, it is expected that the swirl fraction will increase proportionally to the layer thickness,

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Figure B-5
Estimation of Swirl Fraction from Scaled Test Data

B.2.5 Model Benchmarking

Benchmarking of the DH fluid temperature model described above was performed to verify the model and to provide guidance on its application to plant thermal cycling load evaluation. Benchmarking cases included small bore (drain) and larger diameter (RHR suction) lines from several plants. Line geometry details and model input parameters for these benchmarking cases are summarized in a separate report [1]. Benchmarking results comparing the top-to-bottom temperature difference are summarized in Table B-2 and Figure B-6, using the recommended values for the constant $K = 1$ and $n = 2$ in Eq. (B-19).

The model provides reasonable estimates for the fluid temperatures and is conservative in all benchmarking cases except for Palo Verde SDC suction line. It is beneficial to discuss the sources of discrepancy for this case, given that the fluid temperature model implicitly depends on predictions of the thermal interface penetration and cycling period. For the Palo Verde case, which is a DHDH configuration line, the thermal interface penetration was predicted to extend almost entirely through the second horizontal segment. Examination of plant temperature measurements indicate that the thermal interface penetrates to the second vertical segment and does not reach the second horizontal segment, which suggests that the discrepancy in the fluid temperature prediction is caused by over-prediction of the thermal interface penetration.

Table B-2
Comparison of Predicted and Observed Top-to-Bottom Temperature Differences

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Figure B-6
Comparison of Predicted and Observed Top-to-Bottom Temperature Differences

B.3 Method to Correct DH Thermal Cycling Period for the Effect of Horizontal Length

A semi-empirical model has been previously developed and documented for estimating the thermal cycling period for DH piping configurations [1]. This model has been developed as a correlation with thermal cycling period observations in plant operational data. The semi-empirical model was given in Section 2.3.3 as Eq. (2-45) and is repeated below:

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C
DERIVATION OF THERMAL CYCLING SCREENING CRITERIA

C.1 Overview

Details of the development of geometric screening criteria for UH and DH piping configurations are summarized in this appendix. The objective is to determine geometric conditions in which thermal cycling does not occur in a susceptible region (i.e., a horizontal segment) of a given branch line configuration. Screening criteria are derived from predicted cycling location and thermal interface penetration metrics only. Since limits on the thermal loading amplitude are not factored into the criteria, results presented below are conservative.

C.2 Derivation of UH Screening Criteria

To derive criteria for screening UH configuration lines, it is necessary to examine the behavior of the average cycling location relationship given in Eq. (2-1). When the RCL diameter, velocity, and temperature boundary conditions are fixed, the average cycling location ($\bar{x}_m$) is determined by two parameters: the branch line inside diameter (D) and the velocity in the cold stratified layer (U_{l_H}), which can be related to the in-leakage flow rate. To determine if a particular UH line configuration is potentially susceptible to thermal cycling, the average cycling location must fall within the horizontal segment, which occurs when

$$L_v < \bar{x}_m < L$$

where L_v is the vertical segment length and L is the total line length from RCL to valve. Note that this relationship does not account for uncertainty in the predicted average cycling location or the range of interface motion during cycling. These effects will be accounted for later in the analysis by shifting the screening curves by 2 diameters.

For fixed line geometry, it is possible to eliminate thermal cycling in the horizontal segment by increasing the in-leakage rate, which will result in steady-state stratification in the horizontal segment but no unsteady thermal load variations. In a similar manner for fixed in-leakage rate, increasing the vertical segment length will also result in steady-state stratification since the swirl penetration distance is determined by the ratio of the branch line to RCL diameters. The effects of in-leakage rate and vertical segment length are inversely related; thermal cycling can be eliminated in the horizontal segment if vertical segment length is increased as the in-leakage rate is decreased. It should be noted, however, that although thermal cycling may be eliminated in the horizontal segment, mixing of hot and cold water in the vertical segment could also lead to adverse thermal stresses in the vertical segment.

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Figure C-1
Vertical Segment Length Boundaries for Horizontal Segment Thermal Cycling in UH Configurations

C.3 Derivation of DH Screening Criteria

Screening criteria for DH configurations are derived in a similar manner. The methodology outlined in Section 2.3.2 is used to determine the thermal interface penetration, which is then used to perform screening based on one of the following conditions: (1) if the thermal interface does not penetrate to the horizontal segment, cycling will not occur in a susceptible region of the line; or (2) if the thermal interface penetrates entirely through the horizontal segment, the horizontal segment will "run hot" if the vertical segment is sufficiently short. By fixing the RCL diameter, RCL velocity, RCL temperature, and ambient conditions, penetration of the thermal interface depends only upon the branch line inside diameter so that screening can be performed based on the vertical segment length and branch line diameter, as shown previously for UH piping configurations.

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Figure C-2
Vertical Segment Length Boundaries for Thermal Cycling in DH Configurations

D
DETAILS FOR BRANCH LINES NOT SUSCEPTIBLE TO THERMAL CYCLING

This appendix provides a summary of line details for branch line configurations that were determined not to be susceptible to thermal cycling as part of the generic branch line assessment. Details for DH configurations that were screened out based on the geometric screening criteria are summarized in Table D-1 through Table D-3. A summary of line details and screening results is provided in Table D-4 through Table D-6 for UH configurations and in Table D-7 for H configurations.

Note that lines screened based on geometric considerations (i.e., Table D-1 through Table D-3 and lines indicated by "Y" in the "Screened – geometry" column of Table D-6) result by comparison of the line geometry (L_v/D, D) with the screening criteria given in Figure 2-6 for UH configurations and Figure 2-12 for DH configurations. For example, the first entry in Table D-1, a DH line with $L_v/D = 94.7$, $D = 1.34$ in (34 mm), and cold leg attachment, is screened out based on Figure 2-12 since the normalized vertical segment length of 94.7 falls above the upper "Cold leg" line (approximately 13 diameters for $D = 1.34$ in or 34 mm). Similarly, the first entry in Table D-6, a UH line with $L_v/D = 14.2$, $D = 1.34$ in (34 mm), and cold leg attachment, is screened out based on Figure 2-6 since the normalized vertical length of 14.2 falls above the "Cold leg" line (approximately 9 diameters for $D = 1.34$ in or 34 mm).

Table D-1
DH Configuration Line Details for Lines Screened Out Due to Insufficient Swirl Penetration

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Table D-2
DH Configuration Line Details for Lines Screened Out Due to Insufficient Swirl Penetration (Continued from Table D-1)

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Table D-3
DH Configuration Line Details for Lines Screened Out Due to Complete Penetration Through Horizontal Segment

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Table D-4
Geometric Details and Assessment Results for UH Branch Line Configurations

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Table D-5
Geometric Details and Assessment Results for UH Branch Line Configurations (Continued from Table D-4)

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Table D-6
Geometric Details and Assessment Results for UH Branch Line Configurations (Continued from Table D-4)

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Table D-7
Geometric Details and Assessment Results for H Branch Line Configurations

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E
COMPARISON OF TASCS AND CURRENT THERMAL CYCLING MODEL METHODOLOGIES

A study has been performed in which predictive models developed during the EPRI TASCS program were compared with the current methodology outlined in this report. Results from this study are presented in this appendix. The methodology comparison focused on the thermal cycling model components that were substantially different (i.e., models predicting the thermal cycling location). In addition, additional benchmarking of the model was performed with respect to the thermal load prediction, with results summarized herein.

Comparison of EPRI Thermal Stratification, Cycling, and Striping (TASCS) Methodology and EPRI MRP Thermal Fatigue Methodology

Prepared by:

Westinghouse Electric Company LLC
Pat L. Strauch, Principal Investigator

E.1 Introduction

Thermal stratification, cycling and striping are mechanisms that have caused fatigue cracking, permanent pipe deformation, pipe support damage, and equipment clearance problems in pressurized water reactors (PWR) and boiling water reactors (BWR) worldwide. Utilities need a screening method for determining which branch lines may be susceptible to such phenomena and an evaluation methodology to assess fatigue implications for the lines that are susceptible. Models to support screening and evaluation have been developed based on a combination of testing and analysis.

The Electric Power Research Institute (EPRI) Thermal Stratification, Cycling, and Striping (TASCS) program, documented in Reference 1, was primarily initiated in response to fatigue failures that occurred in unisolable sections of piping in the 1988 timeframe. "Unisolable" refers to the section of piping between the reactor coolant system (RCS) and the first isolation or check valve. This piping cannot be isolated from the RCS, which is especially important in the event of cracking. These fatigue failures are noted below:

- The Farley Unit 2 safety injection (SI) piping failure resulted from cold leakage through an isolation valve entering the hot, unisolable piping between the reactor coolant system (RCS) cold leg piping, and the adjacent check valve in the branch piping, as described in the original issuance of Nuclear Regulatory Commission (NRC) Bulletin 88-08 (Reference 2). A similar failure was noted at Tihange Unit 1.
- The Genkai Unit 1 residual heat removal (RHR) piping failure resulted from a periodically leaking RHR isolation valve admitting hot RCS water into the cold trapped portion of unisolable RHR piping, as described in Supplement 3 of NRC Bulletin 88-08.

Several events similar to the Farley, Tihange and Genkai failures have occurred over the past 15 years. However, some recent failures have occurred in downward oriented piping (e.g. drain and excess letdown lines) that were not associated with isolation valve leakage, but rather with the periodic progression and recession of hot RCS turbulence into the cold trapped section of unisolable piping. These events have again focused attention on unisolable piping failures, and the limitations of previous methodologies in evaluating this failure mode. As a result of a need to determine improved inspections for these lines, another EPRI program was initiated under the support and guidance of the EPRI Materials Reliability Program (MRP) Fatigue Issue Task Group (ITG) to better understand the phenomena leading to thermal cycling, and to provide enhanced screening and evaluation methods. These methods are documented in Reference 3, and in the current report. Throughout this report, this will be referred to as the "MRP" methodology.

This report compares the most recently formulated methodology from the MRP program (Reference 3 and the current report) to the study performed in the TASCS program (Reference 1). Both programs developed engineering models to support thermal fatigue screening and susceptibility assessment. In addition, benchmark calculations are provided for several lines for which temperature monitoring is available. It is noted that the calculations presented in this report are for comparative purposes only, and do not include any uncertainties that would typically be used in actual application to operating plants.

E.2 Methodology Comparison

Critical mechanisms that contribute to thermal cycling in branch line piping include fluid stratification due to temperature gradients within the piping configuration, branch line penetration of vortical flow structures resulting from the junction flow between the header and branch line, in-leakage from branch line check valves, and heat transfer from the piping system.

The TASCS and MRP programs both provide methodologies for predicting the location and frequency of thermal cycling in branch lines. Some of the key elements of the two methodologies are compared below.

The methods developed in the TASCS program (Reference 1) include the following:

1. Turbulent (swirl) penetration
2. Height of a stratified flow
3. Heat transfer of a leak flow
4. Turbulent penetration thermal cycling
5. Thermal striping
6. Heat transfer from conduction and flows without stratification
7. Free convection heat transfer
8. Stratification heat transfer coefficients
9. Turbulent penetration length

Items 2, 3, 5, 6, 7, and 8 are either not considered in the MRP methodology or are carried over directly from TASCS. Items 1, 4 and 9 were redeveloped in the MRP methodology based on recent testing and analytical results. These revised methodology elements are compared to the original TASCS implementation in the following subsections. Data points from Farley and Genkai are included on the comparative figures, where appropriate. Note that unless specifically noted on the comparative figures, uncertainties associated with the MRP methodology are not factored into the model calculations in this appendix.

In the MRP program, the branch piping configurations investigated are broadly classified as either up-horizontal (UH) or down-horizontal (DH), in describing their orientation from the header pipe connection. The UH category includes the Farley safety injection piping, and also piping that is purely horizontal. The DH category includes the Genkai residual heat removal piping, and piping that is substantially downward from the header pipe connection (e.g., drain lines, excess letdown lines).

Throughout this appendix, the following typical base case values are used:

Header velocity (U) = 52 feet/second
Header temperature (T_o) = 560 °F
Header pipe inside diameter (D_R) = 27.5 inches
In-leakage temperature (T_c) = 120 °F
Branch pipe inside diameter (D) = 5.2 inches
In-leakage flow rate (Q_l) = 0.5 gpm

These values correspond (approximately) to the Farley Unit 2 safety injection line, which is a UH configuration. These base case values are also used for DH configuration comparisons, for consistency. Note however that for DH configurations, Q_l is not used and T_c is the temperature beyond the valve.

E.2.1 Turbulent (Swirl) Penetration

The TASCS and MRP programs both studied the effects of branch line vortical flow structure penetration, or swirl. In the TASCS program, this was referred to as turbulent penetration. Comparisons of the swirl at the entry of the branch, and the decay of the swirl into the branch line are provided in Figures E-1 through E-3. In Figure E-1, it is seen that the entry swirl is higher using the TASCS methodology for branch to header pipe diameter ratios less than 0.56. However, the swirl decay is higher using the TASCS methodology, as seen in Figures E-2 and E-3. Note that in Figure E-3, "u" is the local swirl velocity along the pipe.

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Figure E-1
Normalized Entry Swirl as a Function of Pipe Inside Diameter Ratio

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Figure E-2
Swirl Decay into the Branch Line

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Figure E-3
Swirl Velocity Decay into the Branch Line

E.2.2 Height of a Stratified Flow

TASCS

The TASCS program provided a method to determine the stratification interface height. The critical height (y_c) of the interface between hot and cold fluids of a thermally stratified flow in a pipe may be determined from an iterative solution of the following equation:

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Figure E-4
Normalized Stratification Interface Height and Inverse Pipe Richardson Number (TASCS Methodology)

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Figure E-5
Non-Dimensional In-leakage Flow Velocity and Inverse Pipe Richardson Number (TASCS Methodology)

E.2.3 Heat Transfer of a Leak Flow

TASCS

The TASCS program provided methods to determine the temperature change of a thermally stratified flow in the steady-state condition. Applicability of this procedure is recommended for cold leakage into horizontal pipe sections containing hot ambient fluid, which is assumed to be at a constant temperature. The heat transfer coefficients provided must be used for this method to remain valid.

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E.2.4 Turbulent Penetration Thermal Cycling

<u>TASCS</u>

The TASCS program provided a method to bound the location in a pipe where thermal cycling could occur as a result of the interaction of header pipe turbulence with thermal stratification flow:

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MRP

The MRP methodology provides a method to determine the average location of thermal cycling $\bar{x}_m$, due to cold water in-leakage, which is given by the following relationship:

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Figure E-6
Effect of Header Velocity on Cycling Location (Up Horizontal)

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Figure E-7
Effect of Header Pipe Size on Cycling Location (Up Horizontal)

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Figure E-8
Effect of Branch Pipe Size on Cycling Location (Up Horizontal)

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Figure E-9
Effect of Header Temperature on Cycling Location (Up Horizontal)

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Figure E-10
Effect of In-leakage Temperature on Cycling Location (Up Horizontal)

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Figure E-11
Effect of In-leakage Flow Rate on Cycling Location (Up Horizontal)

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Figure E-12
Effect of Branch Pipe Size on Low Frequency Cyclic Period (Up Horizontal)

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Figure E-13
Effect of Horizontal Branch Pipe Length on Low Frequency Cyclic Period (Up Horizontal)

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Figure E-14
Effect of In-leakage Flow Rate on Low Frequency Cyclic Period (Up Horizontal)

E.2.5 Thermal Striping

TASCS

Thermal striping is a cyclic mechanism caused by instabilities in the hot-cold fluid interface in a stratified loading (i.e., hot and cold water coexisting within the pipe) during relatively steady flow conditions. The TASCS program provided a method to evaluate thermal striping loads in typical piping applications with thermal stratification:

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E.2.6 Heat Transfer from Conduction and Flows without Stratification

TASCS

The TASCS program provided a one-dimensional, closed form solution to determine the axial temperature distribution in a pipe from conduction. This method may be used to determine the boundary conditions for TASCS evaluations. It is not applicable if other heat transfer mechanisms are present, e.g. convective heating or turbulent penetration heating.

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E.2.7 Free Convection Heat Transfer

TASCS

The TASCS program provided a method to determine the temperature distribution in a pipe as a result of free convection from a high temperature heat source at one end of the pipe. This method does not include a detailed evaluation of free convection heat transfer, but rather provides guidance to assist power plant engineers in evaluating free convection heat transfer.

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E.2.8 Stratification Heat Transfer Coefficients

TASCS

The TASCS program provided methods to determine heat transfer coefficients for TASCS related calculations, specifically thermal stratification loads. The coefficient can be applied to the entire pipe inner surface for the steady-state solution.

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E.2.9 Turbulent Penetration Length

TASCS

The TASCS program provided estimates for the effect of turbulent penetration as a mechanism to heat up a pipe section.

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Figure E-15
Effect of Header Velocity on Turbulent Penetration Length (Down Horizontal)

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**Figure E-16
Effect of Header Pipe Size on Turbulent Penetration Length (Down Horizontal)**

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Figure E-17
Effect of Branch Pipe Size on Turbulent Penetration Length (Down Horizontal)

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Figure E-18
Effect of Header Temperature on Turbulent Penetration Length (Down Horizontal)

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Figure E-19
Effect of Branch Pipe Size on Thermal Cycling Period (Down Horizontal)

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Figure E-20
Effect of Header Temperature on Thermal Cycling Period (Down Horizontal)

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Figure E-21
Effect of Temperature Beyond Valve on Thermal Cycling Period (Down Horizontal)

E.3 Benchmark Study

In this section, the recent MRP screening and evaluation methodology is benchmarked to several unisolable lines for which temperature monitoring is available. These lines are discussed in the following subsections.

E.3.1 Farley Unit 2 Safety Injection Piping Failure

The Farley Unit 2 safety injection line was used as the base case in Section 2 of this report. The description and evaluation of the Farley cracking incident are documented in References 2 and 4, and are summarized below.

Farley Unit 2 began commercial operation in July 1981. The safety injection line crack was discovered on December 9, 1987. The cracked pipe spool piece was replaced on December 15, 1987, and the piping was instrumented with temperature and vibration monitors. The monitoring location was about 7.5 branch pipe inside diameters from the cold leg connection. The top to bottom pipe outside wall temperature differential was about 215°F, with large fluctuations at the bottom sensor. Three cases were evaluated in Reference 4, reflecting the various magnitudes of outside wall temperature fluctuations seen in the monitoring data:

Case A:	74°F	12 cycles per day, or a period of 120 minutes
Case B:	45°F	98 cycles per day, or a period of 14.7 minutes
Case C:	19°F	220 cycles per day, or a period of 6.5 minutes

Therefore, there were a total of about 330 cycles per day, or about one cycle every 4.4 minutes.

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Figure E-22
Farley Safety Injection Monitoring Data

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Figure E-23
Farley Safety Injection Assumed Loading at Monitoring Location

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Figure E-24
Farley Safety Injection Bottom of Pipe Temperature Correlation

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E.3.2 Genkai Unit 1 Residual Heat Removal Piping Failure

The description of the Genkai Unit 1 RHR piping failure is included in Reference 2. This piping extends approximately 24 pipe inside diameters to the horizontal piping, and then an additional 5 pipe inside diameters to the isolation valve. This piping is 8 inch Schedule 140, with an inside diameter of about 7.0 inches, and a wall thickness of 0.812 inch.

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E.3.3 South Texas Project Units 1 and 2 Residual Heat Removal Piping

The description of and evaluation of the South Texas Project RHR piping is documented in Reference 5. This piping is 12 inch Schedule 140, with an inside diameter of 10.5 inches. The piping extends downward from the RCS hot leg approximately 5 branch pipe inside diameters, and then horizontally to a valve.

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E.3.4 South Texas Project Units 1 and 2 Charging Piping with Leakage

The description and evaluation of the South Texas Project alternate charging piping is documented in Reference 6. The alternate charging piping is 4 inch Schedule 160, with an inside diameter of 3.438 inches. The piping extends from the regenerative heat exchanger to the RCS cold leg. It is one of two possible flow paths, the other being the normal charging line, which will be in service during normal power operation. Under maximum charging conditions, the temperature of the charging flow is nearly 500°F, based on the regenerative heat exchanger outlet temperature.

As a means to relieve excessive pressure which could potentially occur when the normal and alternate charging line isolation valves are closed, a bypass line was included in the design of the alternate charging line. This design included a spring loaded check valve which would open at a set pressure differential, but would not admit flow under normal power operating conditions.

The spring loaded check valve called for in the design was not initially installed. Rather, a lift check valve was used. The effect of this configuration was to admit bypass flow around the isolation valve and into the RCS. This resulted in stratification of about 20°F to 40°F, and a maximum of 140°F, when charging flow was secured. The in-leakage flow rate was not determined, but a value of 0.5 gpm will be used here. Considering this in-leakage flow rate, a cold leg temperature of approximately 560°F, and an in-leakage temperature of 480°F (based on Reference 6 calculated temperature at the non-isolable piping inlet, and monitoring data from the pipe bottom sensor), the cycling location is about 9 pipe inside diameters from the cold leg.

Cycling was not observed at the monitoring location, which was about 16 pipe inside diameters from the cold leg, which somewhat substantiates the calculated thermal cycling location using the MRP methodology.

E.3.5 Vogtle Unit 2 Residual Heat Removal Piping

The description and evaluation of the Vogtle Unit 2 RHR piping is documented in Reference 7. This evaluation involves cyclic stratification due to turbulent penetration, without leakage. For train B of the RHR system, the distance from the RCS hot leg connection to the horizontal piping is only about 6 pipe inside diameters. The monitoring location is located within the horizontal piping, approximately 28 pipe inside diameters from the hot leg, and experienced a maximum stratification temperature differential of 186°F. Considering the short vertical distance and the high potential for convective currents in the horizontal piping, it is unusual that the monitoring location is experiencing such high stratification (277°F top and 95°F bottom). This stratification and cycling would not be predicted by the current methodology.

E.4 Conclusions

The table given on the following page summarizes the comparisons from the figures presented in this appendix.

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As shown, the recent MRP program provides additional methodology to supplement the TASCS methodology, most significantly the average location of thermal cycling and the cycling period for up horizontal configurations, and a better estimation of thermal penetration and the cycling period for down horizontal configurations. The parameters studied did not trend along the same curve for the two methods, but they did trend in the same direction in all cases in which a parameter had an effect.

Most failures involving in-leakage have occurred within approximately 15 branch pipe inside diameters from the header pipe connection. The EPRI programs correlate well with known failures and monitoring data.

Failures involving turbulent/swirl penetration thermal cycling into lines that extend from the bottom of the RCS piping also correlate well with known failures and most monitoring data.

E.5 Tabular Listing of Values Used in Figures

This section provides the tabulated values used to generate the figures throughout this appendix.

The Farley base case parameter values were used to generate the plots for both the up horizontal (UH) and the down horizontal (DH) configurations. These approximate values are as follows, and are shown in italics in the tables:

U = 52 feet/second (RCS velocity)

D_R = 27.5 inches (RCS inside diameter)

D = 5.2 inches (Branch line inside diameter)

T_o = 560°F (RCS cold leg temperature)

$T_c = T_a$ = 120°F (In-leakage temperature or temperature beyond valve, ambient temperature)

Q_l = 0.5 gpm (In-leakage flow rate)

x_m/D = 6.5 (Location of crack, in branch pipe inside diameters from RCS cold leg)

k_i = 8.33E-07 BTU/sec-in-°F (Insulation thermal conductivity)

k_w = 2.31E-04 BTU/sec-in-°F (Branch line wall thermal conductivity)

t_w = 0.718 inches (Branch line wall thickness)

t_i = 2.5 inches (Insulation thickness)

L_H = 26.1 inches (Branch line horizontal pipe length, including the elbow)

Figure E-1:

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Figures E-2 and E-3:

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Figures E-4 and E-5:

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Figures E-6 and E-15:

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Farley crack was at 6.5 branch pipe inside diameters from the RCS loop.

Figures E-7 and E-16:

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Figures E-8, E-12, E-17, and E-19:

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Figures E-9, E-18, and E-20:

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Figures E-10 and E-21:

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Figures E-11 and E-14:

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Figure E-13:

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E.6 References

1. Thermal Stratification, Cycling, and Striping (TASCS), EPRI, Palo Alto, CA: 1994. TR-103581.

2. United States Nuclear Regulatory Commission Bulletin 88-08, "Thermal Stresses in Piping Connected to Reactor Coolant Systems", 06/22/88; Supplement 1, 06/24/88; Supplement 2, 08/04/88; and Supplement 3, 04/11/89.

3. Materials Reliability Program: Development of a Thermal Cycling Model for Un-isolable Branch Line Piping Configurations (MRP-97), EPRI, Palo Alto, CA, and U.S. Department of Energy, Washington, DC: 2003. 1003209.

4. Westinghouse report WCAP-11786, "J. M. Farley Unit 2 Engineering Evaluation of the Weld Joint Crack in the 6" SI/RHR Piping," April 1988, Westinghouse Proprietary Class 2.

5. Westinghouse report WCAP-12108, "Evaluation of Thermal Stratification for the South Texas Unit 1 and 2 Residual Heat Removal Lines," January 1989, Westinghouse Proprietary Class 2.

6. Westinghouse report WCAP-12598, Supplement 1, "NRC Bulleting 88-08 Evaluation of Auxiliary Piping for South Texas Project Units 1 and 2," November 1993, Westinghouse Proprietary Class 2.

7. Westinghouse report WCAP-14834, "Structural Evaluation of the Vogtle Units 1 and 2 Residual Heat Removal Lines Considering the Effects of Thermal Stratification," January 1997, Westinghouse Proprietary Class 2C.