



EPRI Materials Reliability Program Fatigue Issue Task Group

Thermal Fatigue Program

MRP/NRC Thermal Fatigue Meeting

NRC Headquarters
Rockville, MD
May 28, 2003



Agenda/Presentation Outline

- MRP Thermal Fatigue ITG
 - Objectives
 - Background of Fatigue ITG
 - Fatigue ITG thermal fatigue program
 - Program elements
 - Brief status
 - Configuration testing/model development activities
 - MRP thermal fatigue management guidelines
 - Schedule for completion
- NRC Feedback



Meeting Objectives

- Re-establish communications between MRP and NRC on thermal fatigue management activities
- Update staff on MRP Fatigue ITG activities
- Obtain NRC feedback on Fatigue ITG activities and future NRC thermal fatigue activities
- Review opportunities for future information meetings between the MRP and the NRC

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Background Historical Overview

- Several instances of pipe failures due to cyclic thermal fatigue identified in 1988
 - Farley, Tihange safety injection lines
 - Genkai residual heat removal suction line
- Additional thermal fatigue failures occurred in foreign and domestic plants (1992-1997)
 - Dampierre, Biblis, Mihama
 - TMI, Oconee

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Background Historical Overview

- Fatigue ITG established in 1999 in response to NRC request for industry action to:
 - Provide leadership to the US nuclear fleet for thermal fatigue issues
 - Address ASME Code inspection inconsistencies between small bore Class 1 and Class 2 lines

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Background Strategic Approach

- Provide industry leadership in proactive management of thermal fatigue
- Provide guidelines/methodology to manage thermal fatigue
- Validate guidelines/methodology against known failures

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Background Program Goals

- Build upon previously completed work in this area
 - EPRI thermal stratification, cycling and striping (TASCS) program (1989-1994)
 - Individual utility efforts in responding to NRC Bulletin 88-08 and more recent leakage events
- Provide utilities with a consistent set of guidelines and methodology for addressing piping thermal fatigue issues
 - Thermal stratification
 - Thermal cycling from valve in-leakage toward the RCS
 - Non-isolable line swirl penetration effects

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Background Program Scope

- Initial scope included thermal fatigue issues for ASME Code Class 1 piping systems in PWRs that are:
 - Connected to the reactor coolant pressure boundary
 - Normally stagnant and not isolable from the reactor coolant pressure boundary
 - Included: Safety Injection, Core Residual Heat Removal, RCS Drains, Alternate Charging and Alternate Letdown Lines
 - Excluded: loop piping, Surge Lines, Spray Lines, Normal Charging Lines, Thermal sleeve problems in B&W plant Makeup Lines
- Environmental fatigue added to ITG scope in 2000



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MRP Fatigue ITG Thermal Fatigue Program Elements

- Compile industry operating experience
- Screening and evaluation methodology
- Monitoring guidance (in plant instrumentation)
- Thermal fatigue NDE technology
- Operations/maintenance modifications
- Coordination with international activities
- Thermal fatigue management guidelines
- Training

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MRP Fatigue ITG Compile Industry Operating Experience

- Developed industry experience database
 - Identified leakage events and monitoring observations
 - Database available online for utility review
 - Allows for user entry of new information
 - Accompanying EPRI technical report
 - *Operating Experience Regarding Thermal Fatigue of Unisolable Piping Connected to PWR Reactor Coolant Systems (MRP-25)*, December 2000 (EPRI report 1001006)
 - Updated online database in 2002
 - Added experience related to isolable safety class lines attached to RCS
 - Revised MRP-25
 - *MRP-85* (EPRI report 1007761), March 2003

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MRP Fatigue ITG Screening and Evaluation Methodology

- Original goal was to develop a predictive model to:
 - Screen non-susceptible components
 - Determine thermal fatigue loadings
 - Perform piping fatigue analysis
- Initial screening methodology based on experience, line geometry, and temperature conditions
 - Incorporated into Interim Thermal Fatigue Management Guidelines (to be discussed later)
- Improved methodology under development

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MRP Fatigue ITG Screening and Evaluation Methodology

- Initial evaluation approach was to use Computational Fluid Dynamics (CFD)
 - CFD unable to predict turbulence-driven flow
 - Program rescoped to develop improved technology
- Research conducted to enhance understanding of swirl penetration and cycling mechanisms
 - Identifying Thermal Cycling Mechanisms in Two Piping Configurations (MRP-54), November 2001 (EPRI Report 1003081)
 - Interim Report on Thermal Cycling Model Development for Representative Un-Isolable Piping Configurations (MRP-81), November 2002 (EPRI Report 1003527)
- Ongoing investigations will be described in later presentation today

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MRP Fatigue ITG Monitoring Guidelines

- Compiled guidelines for thermal fatigue monitoring
 - Provides practical guidance for in-plant monitoring of suspect lines
 - *Thermal Fatigue Monitoring Guidelines (MRP-32)*, April 2001 (EPRI Report TR-1001016)

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MRP Fatigue ITG NDE Technology

- Evaluated NDE technology for application to thermal fatigue
 - Evaluated methods to detect thermal fatigue cracking/crazing on small diameter piping
 - *NDE Technology for Detection of Thermal Fatigue Damage in Piping (PWRMRP-23)*, September 2000 (EPRI Report 1000152)
 - Accompanying computer-based training module developed for training inspectors about uniqueness of thermal fatigue
 - *Computer Based NDE Training for Thermal Fatigue Cracking (MRP-36)*, June 2001 (EPRI Report 101317 version.1.0)

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MRP Fatigue ITG NDE Technology

- Recent thermal fatigue piping failures prompted a review of examination practices for detection of thermal fatigue damage in piping
 - Previous NDE development had focused on detection of IGSCC cracking in larger diameter piping (nominal diameter > 4 inches)
 - Most examinations of small-diameter piping (< 4 inches nominal diameter) were limited to surface examinations
 - Volumetric examinations are difficult
 - Detection of relatively shallow thermal fatigue cracking or crazing presented a challenge
- Guidance for NDE examiners needed

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MRP Fatigue ITG NDE Technology

- Reviewed relevant U.S. and international thermal fatigue cracking experience to quantify the types and extent of cracking morphology that might be expected
- Candidate NDE technologies reviewed for thermal fatigue crack detection and length sizing
 - Evaluated effectiveness using NDE mockups based on observed cracking experience
 - Established general requirements for examination with 'best' technique

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MRP Fatigue ITG NDE Technology

- Six mockups constructed with implanted thermal fatigue damage
 - Crazing with depth of 0.02-0.04 inches surrounded deeper cracks
 - Deeper crack depth = 2 x crazing depth
 - Mockups were 3.5" OD straight pipe and elbows
 - All mockups constructed from stainless steel
 - One mockup simulated Oconee HPI/makeup safe-end
- Several conventional and advanced techniques evaluated
 - Manual pulse-echo ultrasonics (UT)
 - Time of flight diffraction (TOFD)
 - Conventional radiography (RT)
 - Ultrasonic spectroscopy
 - Pulse eddy current
 - Vibro-modulation
 - Conventional eddy current

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MRP Fatigue ITG NDE Technology

- Manual pulse-echo UT performed best
 - Viable for detection and length sizing of cracks
- TOFD is viable for scanning large areas semiautomatically
- RT is viable for detecting thermal fatigue cracks deeper than 10% of wall thickness
- Ultrasonic spectroscopy, pulsed eddy current, vibro-modulation
 - Would require further development

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MRP Fatigue ITG NDE Technology

- UT is still the best inspection alternative
 - Generic examination procedure developed
 - Procedure tested on a field-extracted 1.5-inch diameter elbow
- Inspections should be performed by qualified examiners
 - Qualified to industry standard
 - Indoctrinated as to specifics of thermal fatigue in small diameter piping (different than IGSCC)

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MRP Fatigue ITG Operations/Maintenance/Modifications

- Provided guidance for improved plant operations, maintenance and modification activities to mitigate thermal fatigue effects
 - Valve program maintenance
 - Addition of insulation to un-insulated lines susceptible to cyclic interactions of hot and cold fluids
 - Etc.
 - *Mitigation of Thermal Fatigue in Unisolable Piping Connected to PWR Reactor Coolant Systems (MRP-29), December 2000 (EPRI Report 1001017)*

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MRP Fatigue ITG Coordination with International Efforts

- Established collaborative efforts to share information to increase our understanding of thermal fatigue issues
- EdF in-plant data was obtained
 - EdF Thermal Fatigue Monitoring Experience on Reactor Coolant System Auxiliary Lines (MRP-69), April 2002 (EPRI Report 1003082)
- Fatigue ITG sponsors series of international fatigue conferences
 - July 2000 – Napa, California
 - Proceedings of International Conference on Fatigue of Reactor Components (MRP-46), June 2001 (EPRI Report 1006070)
 - July 2002 – Snowbird, Utah
 - Proceedings of Second International Conference on Fatigue of Reactor Components (MRP-84), April 2003 (EPRI Report 1003536)
 - October 4-6, 2004 – Seville, Spain (tentative)
- Participating with NRC to complete OECD questionnaire on thermal fatigue

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MRP Fatigue ITG Interim Thermal Fatigue Management Guideline

- Developed a thermal fatigue management guideline (TFMG) for use by utilities
 - *Interim Thermal Fatigue Management Guideline (MRP-24)*, issued January 2001 (EPRI Report 1000701)
 - Provided to NRC for information
 - Final guidelines will summarize entire program and methods for fatigue management
 - Tentatively scheduled to be complete by mid-2004

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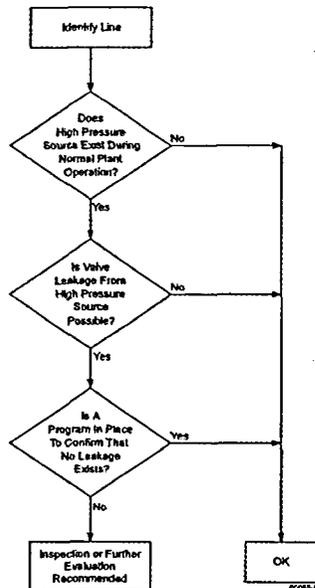
MRP Fatigue ITG Interim TFMG

- Provides interim recommendations regarding assessment and examination
 - Represents a common industry approach to effectively reduce occurrence of leakage
 - Scope includes lines which have demonstrated potential for cracking
 - SI lines with potential inleakage
 - Drain lines/excess letdown lines
- Evaluation/Inspection guidance aimed at avoiding leakage
 - Risk-informed inspection programs do consider these, or similar, considerations in element selection

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MRP Fatigue ITG Interim TFMG-Logic for Evaluation of SI Lines

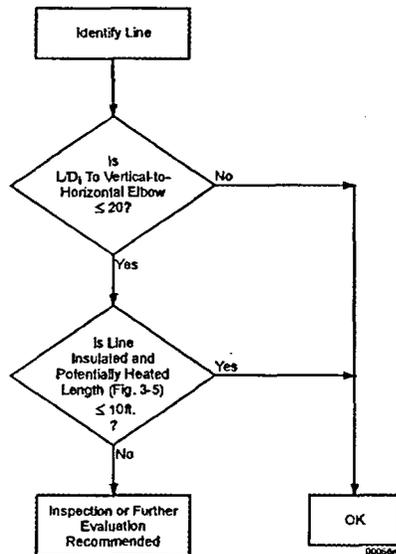


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- Charging/make-up pumps are only high pressure source
- Direct leakage from high pressure source not possible in many plants
- Continued monitoring or leakage trending may confirm that leakage is not significant



MRP Fatigue ITG Interim TFMG-Logic for Evaluation of Drain Lines



- Long vertical run would prevent heating of elbow
- Short/insulated segments would not lose heat, such that ΔT would be small

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MRP Fatigue ITG Interim TFMG-Additional Guidance

- Interim TFMG provides information to assist in evaluation of thermal fatigue potential
 - Assessment guidance
 - Evaluate high pressure sources
 - Assess leakage potential
 - Evaluate monitoring results
 - Trend valve leakage (to show leakage not significant)
 - Inspection guidance per MRP-23
 - Inspection interval not provided in interim TFMG
 - Monitoring guidance per MRP-32

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MRP Fatigue ITG Training

- Goal is to develop and deliver training for plant personnel in applying TFMG
 - Workshops held at nearly all PWR sites
 - Provided general training on thermal fatigue, MRP Fatigue ITG activities and application of interim TFMG
 - Causes of thermal fatigue in non-isolable lines
 - Effects of leakage in SI lines
 - Effects of swirl penetration in drain lines
 - Actions to avoid thermal fatigue occurrence
 - Numerous lessons learned from the on-site training
 - *Lessons Learned From PWR Thermal Fatigue Management Training (MRP-83)*, December 2002 (EPRI Report 1003666)
- Workshop training material currently being converted to an e-media application for continued utility on-site training

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MRP Fatigue ITG Training-Plant Workshops

- Performed plant-specific review per interim TFMG
 - Reviewed flow diagrams (P&IDs) to determine if in-leakage of cold water to RCS is possible
 - Reviewed piping isometrics for all lines
 - Assessed SI lines and drain lines
 - Assessed potential for thermal fatigue in other lines
- Conducted workshop for plant personnel
 - Described MRP Fatigue ITG tasks in detail
 - Provided training on fatigue mechanisms/industry experience
 - Reviewed plant-specific evaluation

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MRP Fatigue ITG Training-Observations

- Safety Injection lines
 - In-leakage not possible for CE-designed plants
 - In-leakage not possible on a portion of Westinghouse-designed plants
 - 4-loop plants have 1 ½-inch SI lines (no leakage event)
 - Only 3-loop plants have larger lines (like Farley)
 - Some B&W plants can have in-leakage to HPI lines
 - Where in-leakage is possible, almost all plants have a program to ensure no leakage or no thermal cycling (committed following NRC Bulletin 88-08)

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MRP Fatigue ITG Training-Observations

- Drain lines
 - Almost all drain lines are insulated and length <10 feet to first isolation valve
 - Few cases identified where isolation valves were slightly greater than 10 feet from vertical drain line piping
- In-leakage potential generally identified for alternate charging lines (Westinghouse plants) and auxiliary spray lines
 - No observed cracking or adverse monitoring in alternate charging (low ΔP)
 - No observed cracking or thermal cycling (from monitoring) in auxiliary spray lines

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Configuration Testing Outline

- Background and Motivation:
 - Approach
 - Generic piping configurations (UH, DH)
- UH Configuration Test Series Overview
- DH Configuration Test Series Overview
- Swirl Penetration Test and Model Development
- Screening Tool Application and Benchmarking
- Summary and Remaining Work

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Background

Motivation for Screening Tool Development

- Primary objectives for engineering model development:
 - To provide screening tool to predict if and where cycling will occur in a generic branch line
 - To model thermal-hydraulic boundary conditions for separate piping structural analysis
- Engineering models formulated from phenomenological test results and first-principles modeling
- Model development to support fatigue management guidelines under preparation by EPRI MRP by adding physical basis to current "rules of thumb"

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Background

Test Program Approach and Philosophy

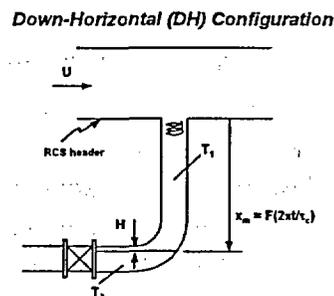
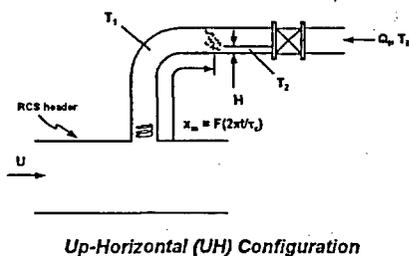
- Physical insight into thermal cycling phenomena is limited in full scale tests with RCS flow driven excitation; full scale tests are expensive and yield limited data
- Split the problem:
 - Branch line configuration testing with forced excitation
 - Prototypical branch line/RCS flow penetration tests
- Branch line configuration testing examined thermal cycling mechanisms with emphasis on obtaining quantitative and qualitative data for phenomena identification and model development
- Prototypical branch line/RCS flow penetration test provided data for tying configuration tests to actual plant conditions

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Background Piping Configurations and Classifications

- Two ways to categorize attached piping configurations:
 - Geometry
 - Thermal stratification/cycling mechanism
- Use “geometric” classification:



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Background Piping Configurations and Classifications

- UH configuration:
 - Examples: SI lines[†] (Farley-2, Tihange-1)
 - Stratification/cycling due to valve in-leakage
- DH configuration:
 - Examples: drain, RHR suction lines (TMI-1, Oconee-1, Mihama-2, Genkai-1)
 - Stratification/cycling due to heat loss to environment with cyclic “turbulence” penetration

[†] – Some SI lines have other geometries, resulting in a “hybrid” line classification.

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Background

Test Program Overview and Summary

- UH Configuration Test Series:
 - Mock-up of SI line with mechanical branch line excitation
 - Heat transfer effects are secondary
- DH Configuration Test Series:
 - Mock-up of RHR suction line, with separate smaller scale rig representative of drain lines
 - Heat transfer effects are important
- Swirl Penetration Test Series:
 - Prototypical branch line flow excitation due to primary flow through coolant line
 - Test conducted in high Reynolds number test facility with additional “low pressure” tests to extend data/model

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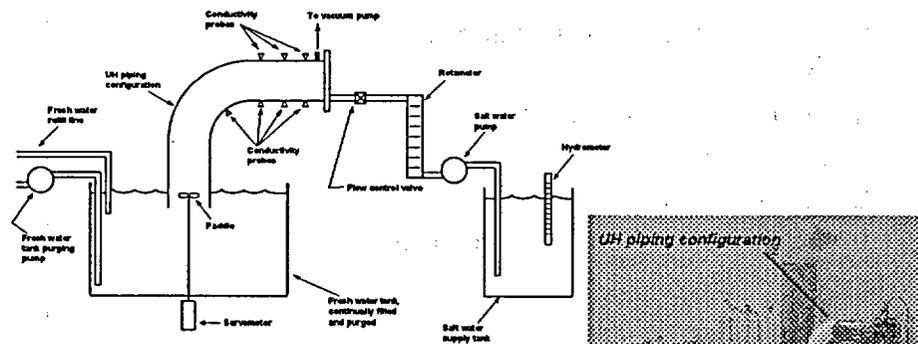
UH Configuration Test Series Test Objectives and Methodology

- Test performed in transparent plastic pipe to facilitate flow visualization (mechanism identification)
- In-leakage has minimal influence on RCL-branch line junction flow structure, so that flow structure may be simulated mechanically
- Branch line excitation simulated using servomotor-driven "paddle" – provides control over flow excitation
- Stratification effects simulated with salt solution:
 - Turbulent mixing dominates laminar thermal diffusion
 - Heat transfer through the pipe is secondary effect
 - Density fluctuations monitored with surface-mounted conductivity probes to augment flow visualization

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UH Configuration Test Setup



Key features of test setup:

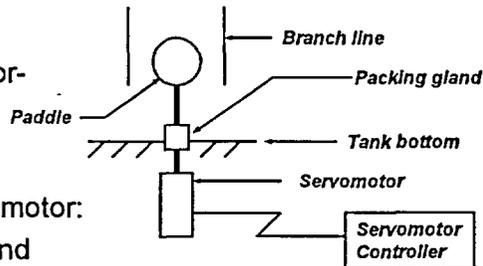
- 1) In-leakage flow rate and density varied
- 2) Branch line flow excitation varied
- 3) Branch line density fluctuations monitored

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Branch Line Flow Excitation

- Branch line excitation is simulated using servomotor-driven paddle
- Motion controlled by servomotor:
 - Oscillatory frequency and magnitude (random turbulence)
 - Constant rotation rate (swirl vortex)
- Paddle geometry also varied:
 - 3-inch diameter circular disk
 - 4-inch diameter propeller



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UH Configuration Test Conditions and Data

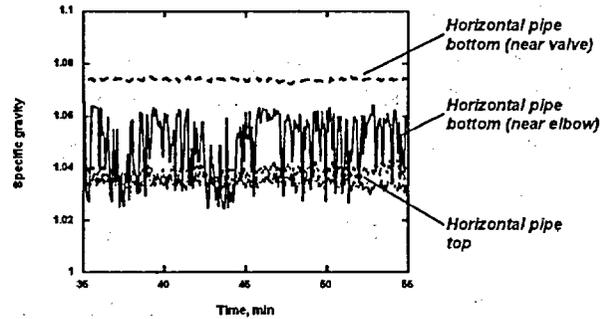
- Test matrix developed to provide data for semi-empirical model formulation
- Test parameters varied include:
 - Leak flow rate
 - Leak density
 - Branch line excitation (excitation type and source strength)
 - Branch line geometry
- Results presented herein:
 - Conductivity probe time history traces
 - PSD analysis of test data
 - Scaling analysis correlation

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Representative UH Configuration Data

0.3 gpm in-leakage flow rate
 $\rho_l/\rho_o = 1.2$
 Steady paddle rotation (swirl excitation)

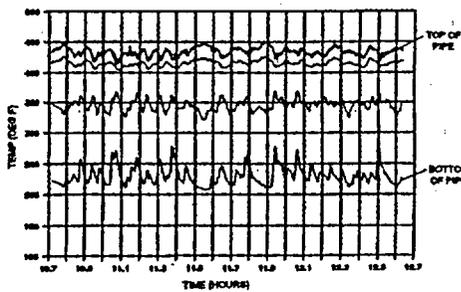
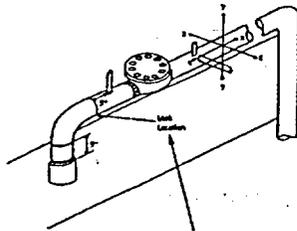


- Long period cycling in horizontal pipe with period of approximately 5 minutes
- Random turbulence excitation does not cause cycling (does not penetrate past elbow)

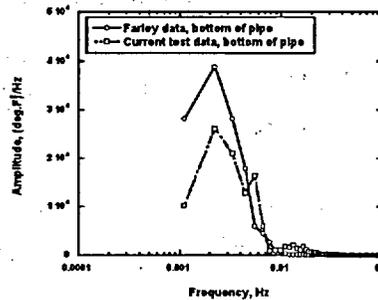
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Comparison with Full-Scale Plant Data



PSD Comparison of CDI and Farley Data



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Thermal Cycling Mechanisms UH (In-leakage) Configuration

- In-leakage creates stratified layer in horizontal pipe; swirl “breaks up” layer if sufficient to penetrate past elbow
- Interface characterized by turbulent mixing with small fluctuations (short period fluctuation)
- Long-period thermal cycling fluctuation:
 - Stratified layer overcomes swirl and “spills” over elbow
 - Swirl re-establishes and breaks up layer in horizontal pipe
 - Period scales with ratio of horizontal pipe volume to in-leakage flow rate

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UH Thermal Cycling Model Development

- Engineering model formulated from application of scaling analysis with physical insight into phenomena
- UH scaling analysis (salt water analogy):

$$\begin{aligned}
 \text{Cycling period} &\sim \frac{T_c Q_l}{D^2 L_H} = f_1 \left(\underbrace{\frac{\Omega D^3}{Q_l}}_{\Pi_1}, \underbrace{\frac{Q_l^2}{g D^5}}_{\Pi_2}, \underbrace{\frac{\rho_l - \rho_o}{\rho_l}}_{\Pi_3}, \text{geometric parameters} \right) \\
 \text{Cycling amplitude} &\sim \frac{\Delta p}{\rho_l} = f_2 \left(\underbrace{\frac{\Omega D^3}{Q_l}}_{\Pi_1}, \underbrace{\frac{Q_l^2}{g D^5}}_{\Pi_2}, \underbrace{\frac{\rho_l - \rho_o}{\rho_l}}_{\Pi_3}, \text{geometric parameters} \right)
 \end{aligned}$$

where the non-dimensional groups are defined as follows:

$$\Pi_1 = \frac{\Omega D^3}{Q_l} = \text{ratio of swirl-to-leak velocity}$$

$$\Pi_2 = \frac{Q_l^2}{g D^5} = \text{Froude number based on leak velocity}$$

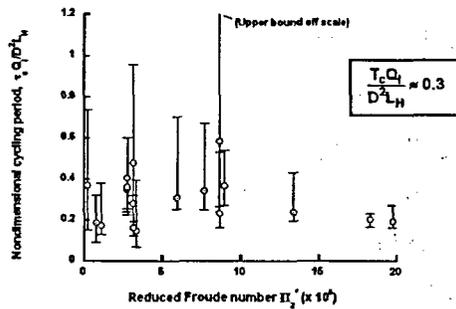
$$\Pi_3 = \frac{\rho_l - \rho_o}{\rho_l} = \text{density ratio}$$

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UH Thermal Cycling Period Correlation

- Non-dimensional cycling period correlation:



- >> Period scales with time to "fill" fraction of horizontal pipe
- >> Confirmed scaling correlation over a range of geometric configurations

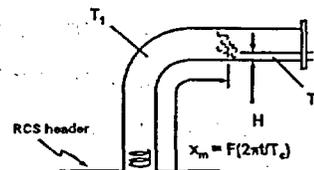
- Additional correlations for density fluctuation amplitude and interface location/bounds have been formulated for modeling thermal cycling in UH configurations

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Application of UH Thermal Cycling Model

- Thermal cycling model to provide loading/boundary conditions for thermal-structural analysis
- Required inputs:
 - Geometry
 - Leak flow rate/temperature
 - RCS temperature
 - Swirl velocity "source" (from swirl penetration test)
- Model outputs include cycling onset prediction, period, and thermal loading profile



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- *DH Configuration Test Series Overview*
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DH Configuration Test Series Test Objectives and Methodology

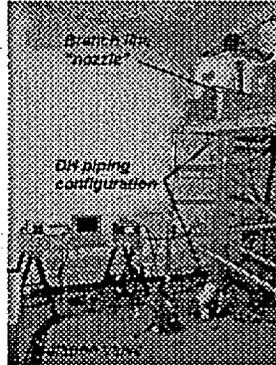
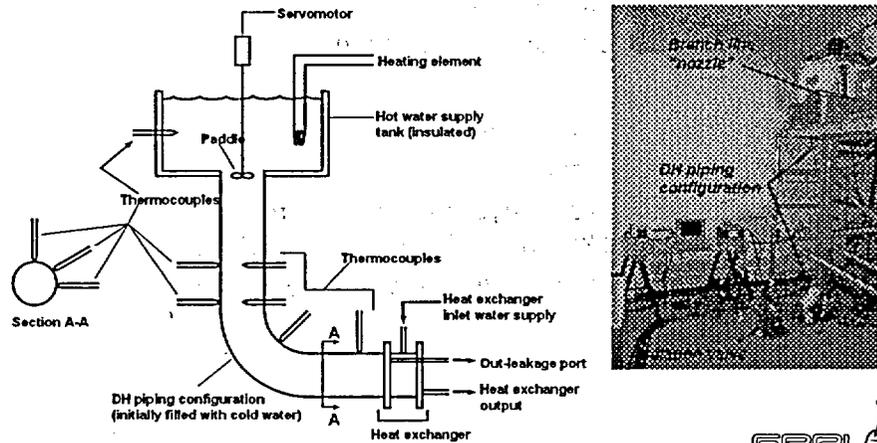
- DH configuration test objectives similar to UH tests:
 - Identify mechanisms and phenomena (flow viz.)
 - Provide test facility to vary controlling parameters
 - Obtain data for engineering model development
- Use mechanically-generated branch line excitation
- Mechanisms fundamentally different:
 - Geometry
 - No appreciable valve in-leakage or out-leakage
 - Insulated vs. non-insulated (heat transfer effects)
- Geometric scale effects also examined using 6-inch and 2-inch diameter test rigs

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DH Configuration Test Setup

- Baseline rig: 3/4-scale mock-up of RHR suction line
- Geometrically scaled rig constructed from 2-inch pipe



DH Configuration Instrumentation

- Paddle rotation rate
- Thermocouples:
 - Reservoir temperature – typically 200 °F (90 °C)
 - Vertical pipe (near pipe wall and pipe center)
 - Elbow
 - Horizontal pipe (top, 2 o'clock, 3 o'clock, bottom)
- Additional instrumentation to infer heat transfer rate from heat exchanger

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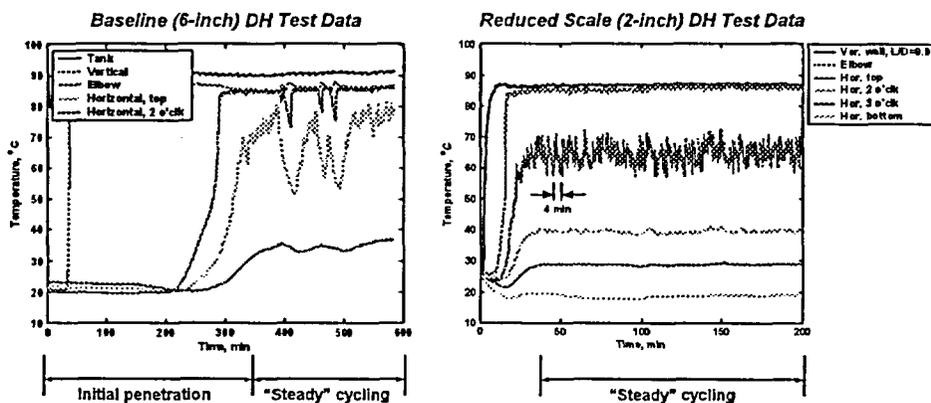
DH Configuration Test Conditions and Data

- Test parameters varied include:
 - Flow excitation source (swirl vs. turbulence, paddle type)
 - Swirl velocity magnitude (sweep)
 - Heat transfer (heat exchanger, insulation)
- Primary test results:
 - Thermal cycling obtained with swirl excitation and augmented heat transfer
 - Flow visualization indicate cycling occurs as repeated penetration and breakdown of stratification interface
 - Phenomena sensitive to small changes in boundary conditions

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Representative DH Configuration Data

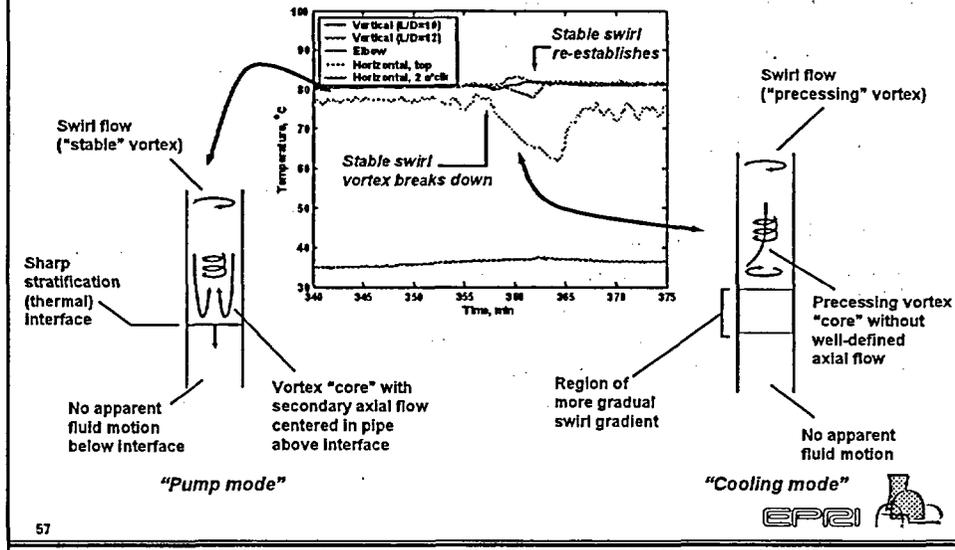


- No thermal cycling without additional heat removal from heat exchanger
- Cycling period scales with branch line diameter

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Thermal Cycling Mechanisms DH (Heat Transfer) Configuration



DH Configuration Engineering Model

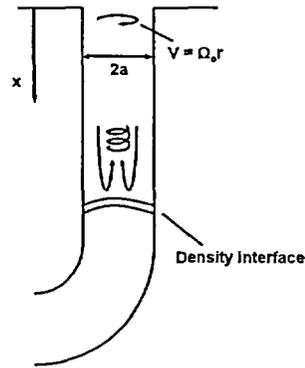
- Visualization indicates cycling occurs over very limited set of flow variables
- Penetration due to stable vortex operates as "pump"; asymmetric geometry of elbow/horizontal breaks up penetration (acts as "non-linear switch")
- Cooling to environment required to re-establish stratification interface
- Model development examined:
 - Swirl decay in uniform density/temperature fluid
 - Penetration rate/distance of stratification interface
 - Cycling period scaling

Swirl Velocity Penetration/Decay Model

- RCL flow induces vortex in branch line
- Orderly (laminar) flow field observed
- Control volume analysis:
 - Angular momentum
 - Boundary layer model
- Swirl velocity decay law:

$$\frac{\Omega(x)}{\Omega_0} = \frac{1}{\left(1 + \frac{x}{L_\Omega}\right)^\beta}$$

$\Omega(x)$ – swirl velocity in branch line
 x – distance along branch line
 Ω_0 – swirl “source” magnitude
 L_Ω – swirl decay length scale
 β – decay law exponent (theory = 1/2)



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Thermal Interface Penetration

- Penetration distance in branch line determined from analysis considering balance of:
 - gravitational forces (due to density gradient)
 - turbulent stresses at swirl flow interface
- Richardson number in terms of swirl in branch line:

$$Ri = \frac{g}{\rho_h} \frac{\partial \rho}{\partial z} \approx \frac{g \frac{\Delta \rho}{\rho_h} \delta}{(a\Omega)^2}$$

where

$\Delta \rho / \rho_h$ – normalized density difference
 Ω – branch line swirl at interface
 δ – interface boundary layer length scale
 a – branch line radius
 g – acceleration of gravity

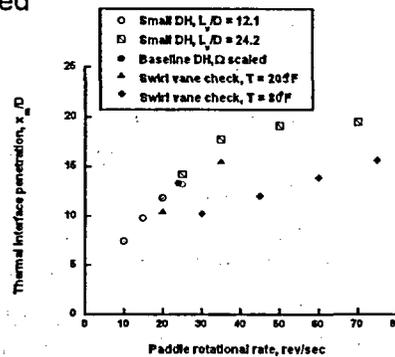
- Maximum penetration determined when $Ri_{crit} = 1/4$; combine with swirl decay relationship for predictive model

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Maximum Thermal Interface Penetration

- Thermal interface penetration measured in baseline & reduced diameter DH; correlated with paddle rotation
- Maximum penetration limit observed with "cycling" in vertical segment



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Thermal Cycling Period Estimate

- Conservative estimate of period is time required to "pump" plus "cooling" time
- Neglect penetration (pump) time:

$$\tau = \frac{\rho_c c_p \left(\frac{\pi D^2}{4} \right) (\beta D) \Delta T}{q_o} \quad \text{where } (\beta D) \text{ is fraction of branch line to be cooled}$$

q_o is net heat transfer out of system

- Typical values (baseline DH configuration):

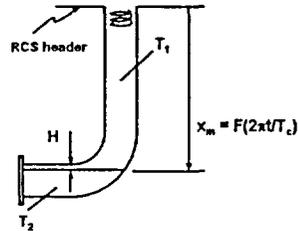
$$\begin{aligned} D &= 0.5 \text{ ft} \\ \Delta T &= 100 \text{ deg.F} \\ q_o &= 600 \text{ BTU/hr} \\ \beta &\approx 1 \end{aligned} \quad \Rightarrow \quad \tau = 1 \text{ hr}$$

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Application of DH Thermal Cycling Model

- Similar outputs as UH model (structural analysis bc's)
- Required inputs:
 - Geometry
 - Temperature BC's
 - Heat transfer from system (lumped effect)
 - Swirl velocity source (from swirl penetration test)
- In-leakage effects on cycling in DH configurations to be examined ("hybrid" lines)



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Configuration Testing Outline

- Background and Motivation:
 - Approach
 - Generic piping configurations (UH, DH)
- UH Configuration Test Series Overview
- DH Configuration Test Series Overview
- **Swirl Penetration Test and Model Development**
- Screening Tool Application and Benchmarking
- Summary and Remaining Work

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Swirl Penetration Test Series Test Objectives and Methodology

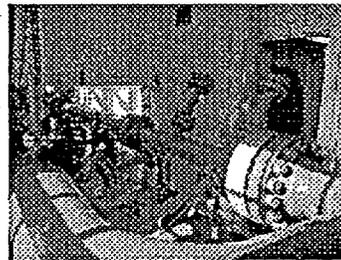
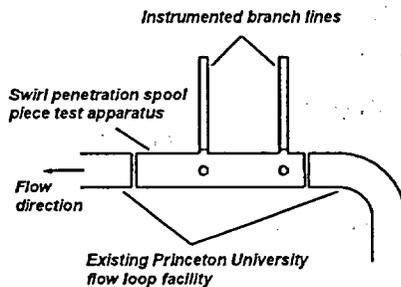
- Swirl penetration identified as critical mechanism for thermal cycling in both UH and DH configurations
- Limited data from previous tests indicate potential Reynolds number effect on branch line swirl generation; current test program run in specialized flow loop facility
- Swirl penetration test performed for prototypical flow conditions and geometry
- Formulate swirl model by relating model parameters to:
 - Reynolds number
 - Primary coolant piping geometry
 - Branch line inlet geometry/thermal sleeve effects
- Additional branch line geometry effects on swirl penetration studied separately

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High Reynolds Swirl Penetration Test Facility and Setup

- Testing performed in Princeton University "Superpipe" facility using pressurized air as working fluid



High Reynolds Swirl Penetration Test Setup

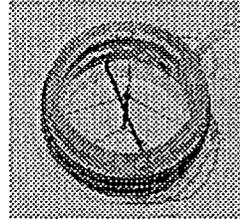
- Reynolds number controlled by varying working pressure (up to 2400 psi) and velocity (up to 50 ft/sec)
- Test geometry (branch locations, orientation, etc.) varied

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Swirl Penetration Test Instrumentation

- Primary test instrumentation consisted of integrated swirl measurements in branch line "inserts"
- Swirl sensor fabricated from rotating vane with optical detectors to infer rotation rate and direction
- Primary focus on steady swirl in branch line; also recorded data to analyze swirl direction and "unsteadiness"
- Swirl sensor friction effects corrected:
 - Pressure/temperature range for free operation
 - Pre- and post-test characterization of sensor performance



2-Inch Swirl Vane Sensor from High Reynolds Number Tests

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Swirl Penetration Test Conditions

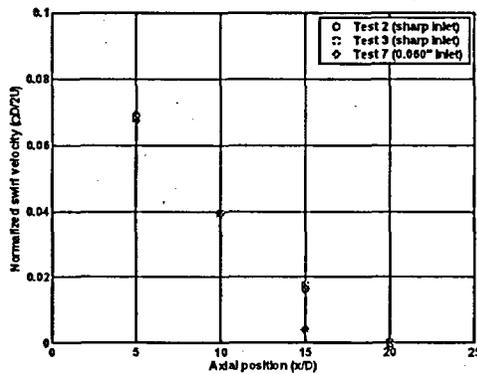
- Test geometry varied:
 - Branch line diameter
 - Branch line location/orientation in test section
 - Inlet geometry (radius, thermal sleeve)
- Tests performed with flow instrumentation (axial velocity/yaw angle survey) in place of instrumented branch line to characterize primary flow profile
- Also performed repeat tests to confirm data repeatability and to bound vane interference effects
- Working pressure and velocity varied to provide order of magnitude sweep in Reynolds number

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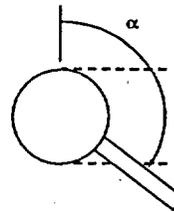


Representative Swirl Penetration Test Data

Normalized Swirl Velocity for 2-Inch Branch Line



Reynolds number $\sim 10^7$
Station B-B: $(L/D)_R = 7.8$
 $\alpha = 105^\circ$



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Swirl Penetration Test Data Reduction

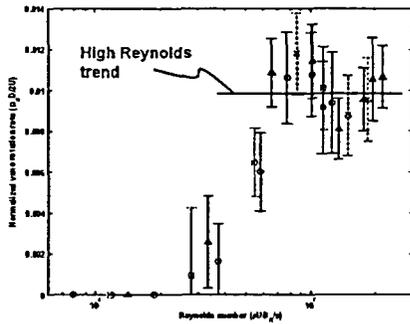
- Primary goals for data reduction:
 - Trends in swirl data at high Reynolds number
 - Estimation of swirl model parameters from data
- Summary of key findings in swirl test data:
 - Weak dependence on Reynolds number
 - Swirl decay in branch line relatively insensitive to geometry
 - Branch line entry swirl primarily depends on branch line diameter ratio
 - Thermal sleeve provides large increase in entry swirl when inserted into primary flow

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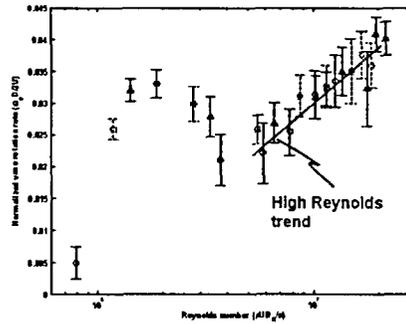


High Reynolds Number Trends in Swirl Data

1-inch Branch Line, $(L/D)_R = 7.8$, $\alpha = 60^\circ$



2-inch Branch Line, $(L/D)_R = 2.6$, $\alpha = 60^\circ$



Trend at high Reynolds number can be approximated as power law with exponent estimated to be on the order of 0.2 to 0.3

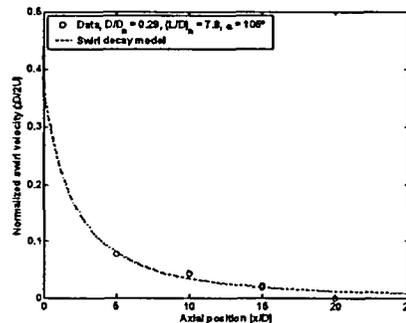
$$\Rightarrow \frac{\Omega D}{2U} \sim KRe^\beta$$

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Swirl Decay Model Estimation Approach

- Parameters in swirl model determined using non-linear least-squares estimation
- Analysis of several lines with indicate that parameters affecting swirl decay rate are independent of geometry
- Branch line entry swirl estimated from remaining test data while fixing decay length scale and exponent at average values



$$\text{Fitted model} - \frac{\Omega D}{2U} = \frac{\Omega_0 D}{2U} \frac{1}{\left(1 + \frac{x/D}{L_\Omega/D}\right)^\beta}$$

$$\frac{\Omega_0 D}{2U} = 0.37$$

$$\frac{L_\Omega}{D} = 4.0$$

$$\beta = 1.9$$

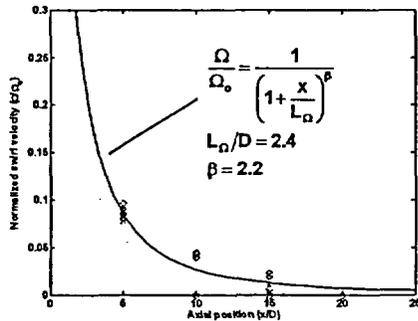
72



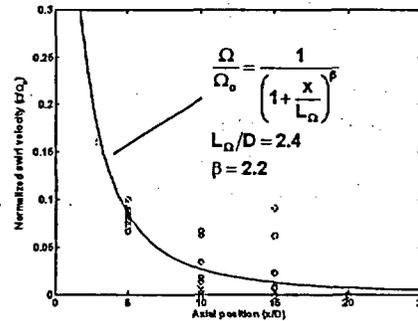
Swirl Decay Model Estimation Summary

- Data from multiple tests collapsed to single model fit:

2-Inch Branch Line Test Data



1-Inch Branch Line Test Data



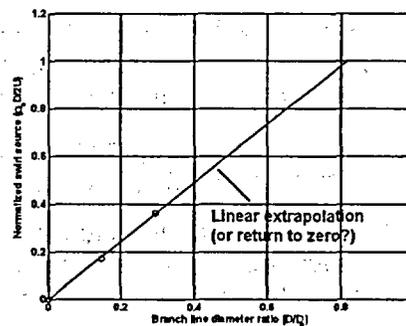
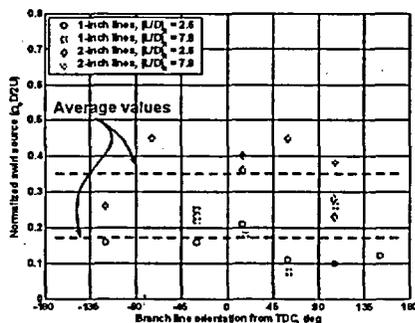
- Branch line entry swirl (Ω_0) is a function of geometry

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Reactor Coolant Line Geometric Effects on Branch Line Entry Swirl

- “Carpet” plot of entry swirl versus geometric parameters
- Weak influence of RCL geometry – branch line entry swirl is a function of branch line-to-RCL diameter ratio only

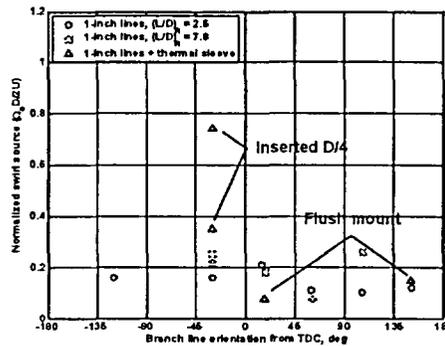


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Thermal Sleeve Geometric Effects on Branch Line Entry Swirl

- Thermal sleeve provides increment in branch line swirl when inserted into RCL
- Flush mounted thermal sleeve has minimal impact on entry swirl (but may affect penetration)



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Thermal Cycling Swirl Model Summary

- Model provides prediction of branch line swirl in terms of RCL flow conditions and geometry
 - Entry swirl function of branch line diameter (weak dependence on Reynolds number)
 - Swirl decay independent of geometry
 - Thermal sleeve increases entry swirl when inserted in RCL; may affect decay characteristics
- Testing underway to quantify influence of additional branch line geometric effects (elbows, reducers, etc.) on swirl
- Data also to be acquired to relate branch line entry swirl to an "equivalent paddle rotation" to tie configuration test results to plant operating conditions

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Configuration Testing Outline

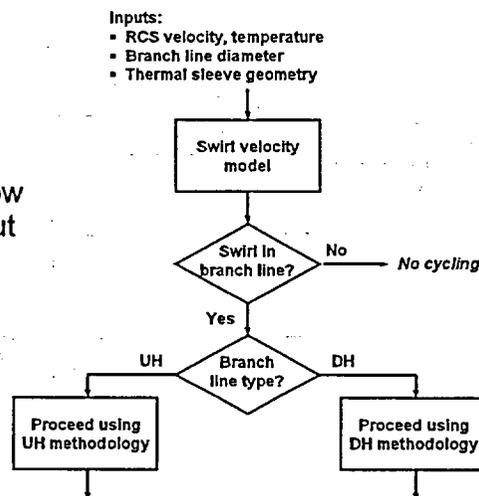
- Background and Motivation:
 - Approach
 - Generic piping configurations (UH, DH)
- UH Configuration Test Series Overview
- DH Configuration Test Series Overview
- Swirl Penetration Test and Model Development
- **Screening Tool Application and Benchmarking**
- Summary and Remaining Work

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Thermal Cycling Screening Model Flowchart

- Initial step in model application to determine swirl magnitude in branch line
- If branch line swirl is below threshold TBD, screen out line (first-level screening)

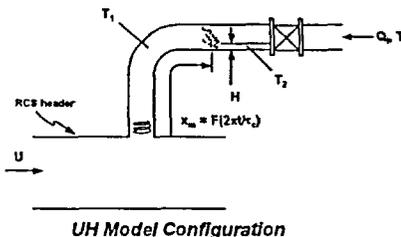


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UH Thermal Cycling Model Requirements

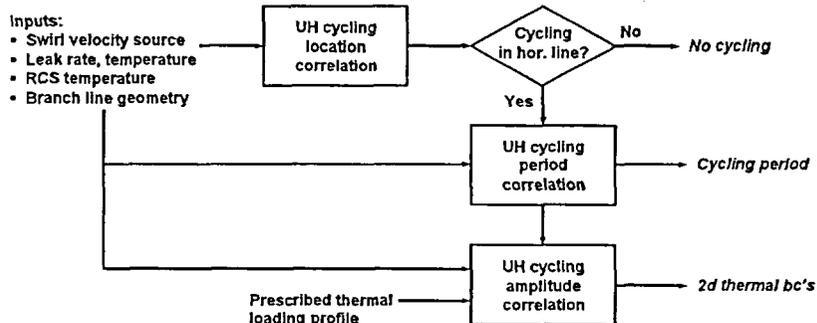
- UH model applies to lines with:
 - Horizontal segment with down-turning elbow
 - Valve in-leakage
- Required inputs:
 - Swirl “source”
 - Leak rate and temperature
 - RCS temperature
 - Branch line geometry (diameter, lengths)
- Model to provide:
 - Cycling (Y/N)?
 - Cycling period
 - Fluid thermal boundary conditions



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UH Thermal Cycling Model Flowchart

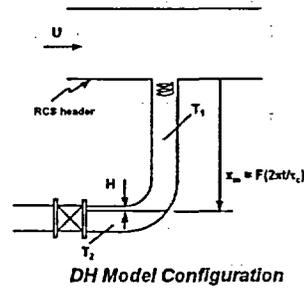


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DH Thermal Cycling Model Requirements

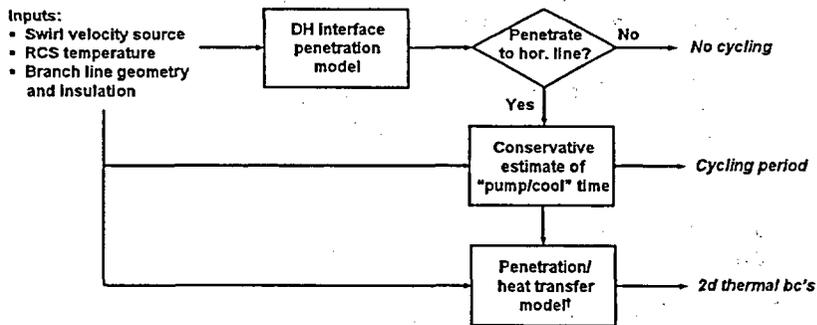
- DH model applies to lines with:
 - Horizontal segment with up-turning elbow
 - No valve in-leakage or nominal out-leakage
- Required inputs:
 - Swirl “source”
 - RCS temperature
 - Branch line geometry
- Model to provide similar outputs as UH model



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DH Thermal Cycling Model Flowchart



† – Temperature boundary conditions in DH configuration to be determined from lumped heat transfer model

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Thermal Cycling Model Benchmarking Scaled Test Data (DH Configuration)

- In response to Mihama failure, scaled tests have been performed by JSME resulting in data set for benchmarking thermal penetration model (DH configuration)
- Data published in Proceedings of Second Int'l Fatigue Conference (MRP-84) includes thermal interface penetration versus:
 - RCL flow velocity
 - Branch line diameter
 - RCL temperature
- Data allows benchmarking of DH penetration model

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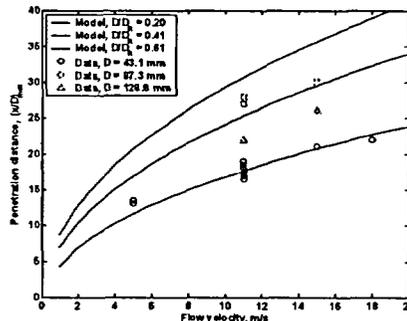


Prediction of Thermal Interface Penetration

- Combining swirl and thermal interface penetration models results in an algebraic expression interface penetration:

$$\frac{x}{D} \Big|_{\max} = \text{fcn} \left(\underbrace{\frac{Q_w a}{U}, \frac{L_a}{D}, \beta, \frac{\Delta p g D}{\rho_h U^2}, \frac{\delta}{D}}_{\text{From swirl decay model}} \right)$$

- Boundary layer length scale held constant
- Use linear extrapolation for branch line entry swirl – model over-predicts data for large branch lines

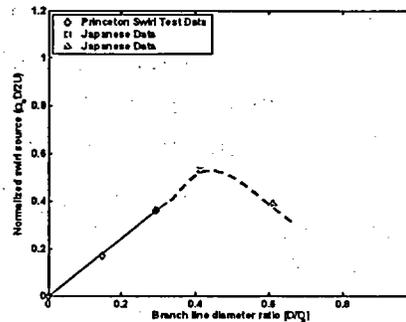
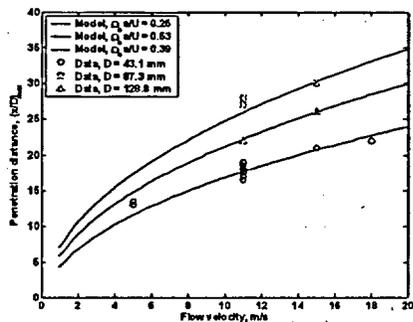


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Refinement to Swirl Model Large Branch Line Diameter Limit

- Adjust branch line entry swirl to match scaled test data
- Large diameter trend is reduction in branch line swirl



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Additional Model Benchmarking

- Thermal cycling model benchmarking proceeding in a two-tier approach
- Preliminary benchmarking to examine “simple” branch line configurations (e.g., straight pipe run + elbow between RCS and affected region), for example:
 - Farley, Blayais (UH configuration)
 - Angra, Japanese test data (DH configuration)
- “Advanced” benchmarking to focus on “general” branch line configurations
- Emphasis on correlating thermal-hydraulic metrics (i.e., penetration distance, temperatures)

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Configuration Testing Summary and Conclusions

- Physical mechanisms responsible for cycling in UH & DH configurations have been identified
- Swirl penetration into branch lines provides thermal cycling driver in both configurations (not random turbulence)
- Thermal cycling mechanisms differ:
 - UH configuration: “fill & spill”
 - DH configuration: “pump/cooling”
- Swirl penetration test results yielded model for swirl decay in branch line (branch line entry swirl insensitive to branch line location)
- Initial benchmarking has shown good correlation with scaled test data in DH configuration

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Configuration Testing Remaining Work

- Completion of configuration tests:
 - Additional swirl penetration data (branch line geometry)
 - Alternate SI line configurations
 - Horizontal configuration
 - Down-horizontal configuration
- Completion of benchmarking
- Final report to be published December 2003

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Presentation Outline

- Objectives
- Background of Fatigue ITG
- Fatigue ITG thermal fatigue program
 - Program elements
 - Brief status
- Configuration testing/model development activities
- MRP thermal fatigue management guidelines
- Schedule for completion

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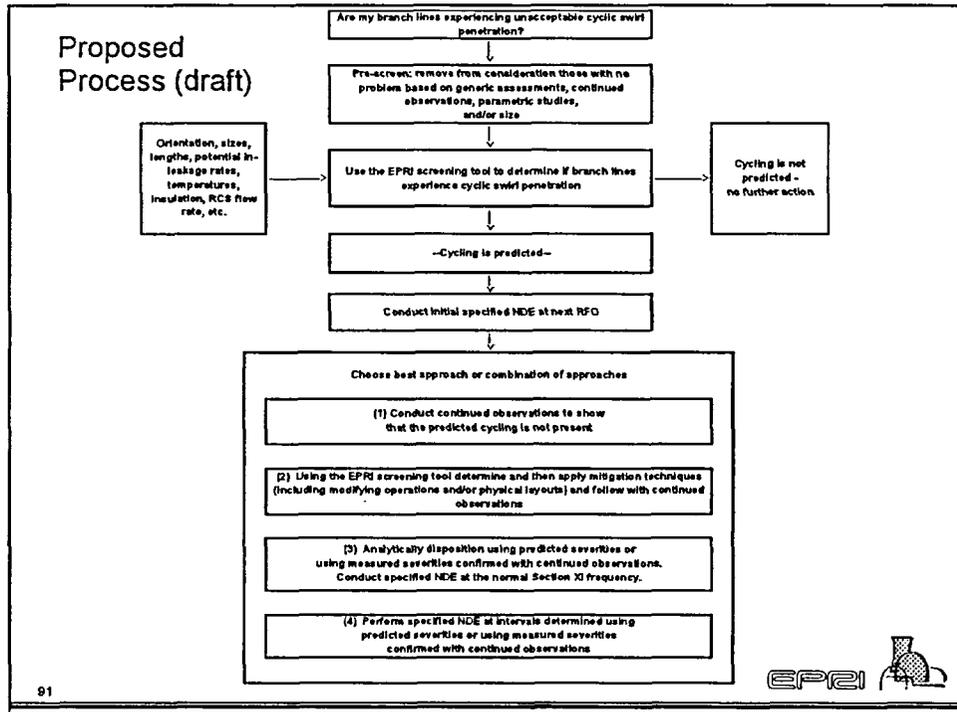


MRP Fatigue ITG Final Thermal Fatigue Management Guideline

- Expand on guidance provided in Interim TFMG (MRP-47)
 - Consider all RCS-attached non-isolable piping
- Summarize relevant results of MRP Fatigue ITG activities
- Detailed screening and evaluation methodology
- Provide NDE guidance, including inspection frequency
- Evaluation methodology and thermal fatigue management approach process under development

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- ## Presentation Outline
- Objectives
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 - Schedule for completion
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- 

MRP Fatigue ITG Schedule

- Final TFMG to be completed mid-2004
- Evaluating appropriate industry implementation
- NRC review will be requested
- Propose future information meetings between the MRP and the NRC

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Agenda/Presentation Outline

- MRP Thermal Fatigue ITG
 - Objectives
 - Background of Fatigue ITG
 - Fatigue ITG thermal fatigue program
 - Program elements
 - Brief status
 - Configuration testing/model development activities
 - MRP thermal fatigue management guidelines
 - Schedule for completion
- NRC Feedback

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