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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Presentation Outline

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- Schedule

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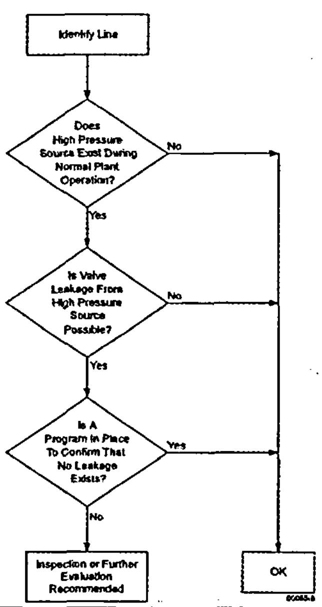
MRP Fatigue ITG
Interim TFMG-Logic for Evaluation of SI Lines



- 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

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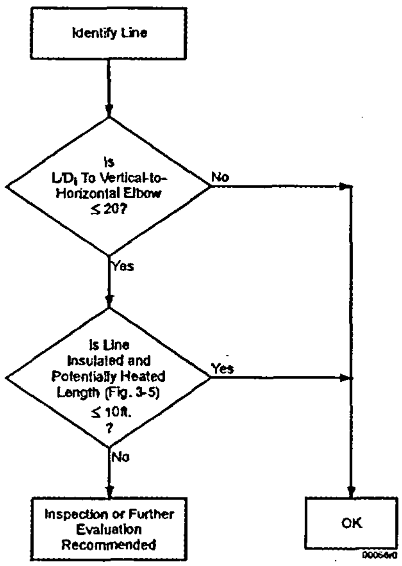
MRP Fatigue ITG
Interim TFMG-Logic for Evaluation of Drain Lines



- 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)

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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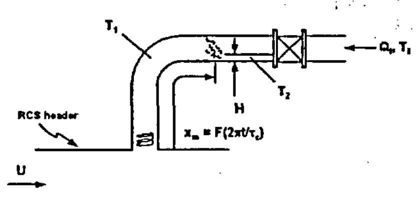
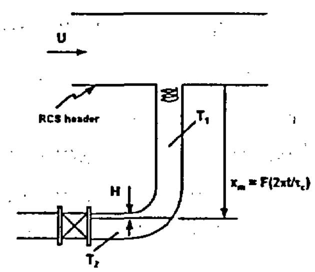
Background
Piping Configurations and Classifications

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



Up-Horizontal (UH) Configuration

Down-Horizontal (DH) Configuration



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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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Configuration Testing Outline

- Background and Motivation:
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- ***UH Configuration Test Series Overview***
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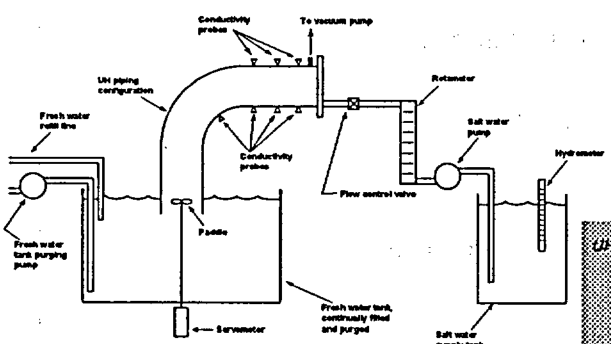
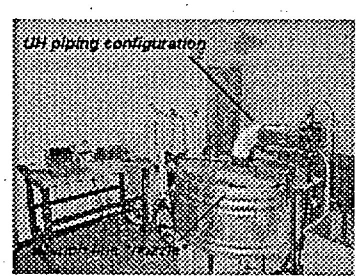
UH Configuration Test Series
Test Objectives and Methodology

- 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

UH Configuration Test Setup



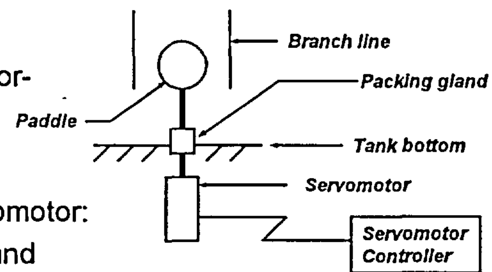


Key features of test setup:

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

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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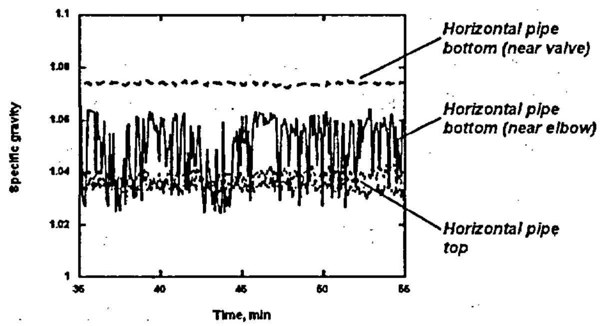
Representative UH Configuration Data

0.3 gpm in-leakage flow rate

$\rho_i/\rho_o = 1.2$

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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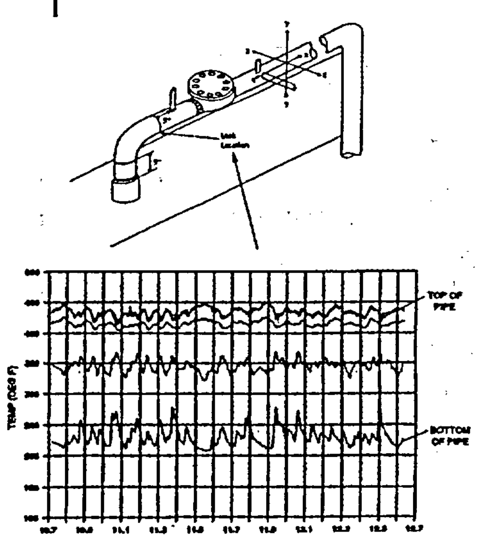
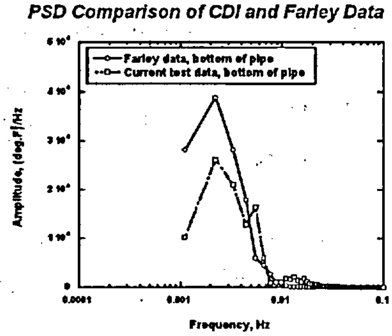
Comparison with Full-Scale Plant Data





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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):

Cycling period -- $$\frac{T_c Q_l}{D^2 L_H} = f_1\left(\frac{\Omega D^3}{Q_l}, \frac{Q_l^2}{gD^5}, \frac{\rho_l - \rho_o}{\rho_l}, \text{geometric parameters}\right)$$

Cycling amplitude -- $$\frac{\Delta\rho}{\rho_l} = f_2\left(\underbrace{\frac{\Omega D^3}{Q_l}}_{\Pi_1}, \underbrace{\frac{Q_l^2}{gD^5}}_{\Pi_2}, \underbrace{\frac{\rho_l - \rho_o}{\rho_l}}_{\Pi_3}, \text{geometric parameters}\right)$$

where the non-dimensional groups are defined as follows:

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

$\Pi_2 = \frac{Q_l^2}{gD^5}$ = *Froude number based on leak velocity*

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

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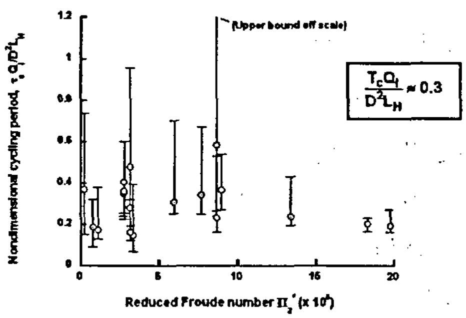
UH Thermal Cycling Period Correlation

- 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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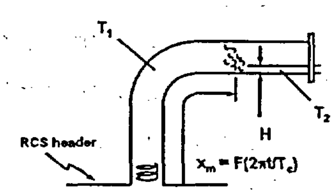
Application of UH Thermal Cycling Model

- 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
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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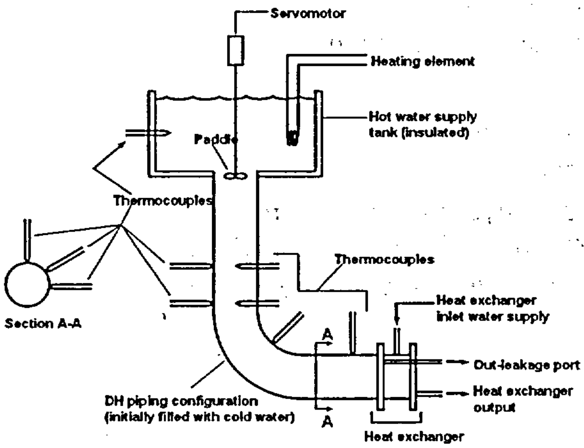
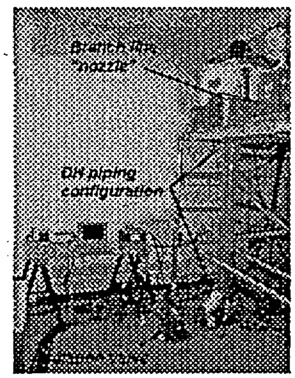
DH Configuration Test Setup

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





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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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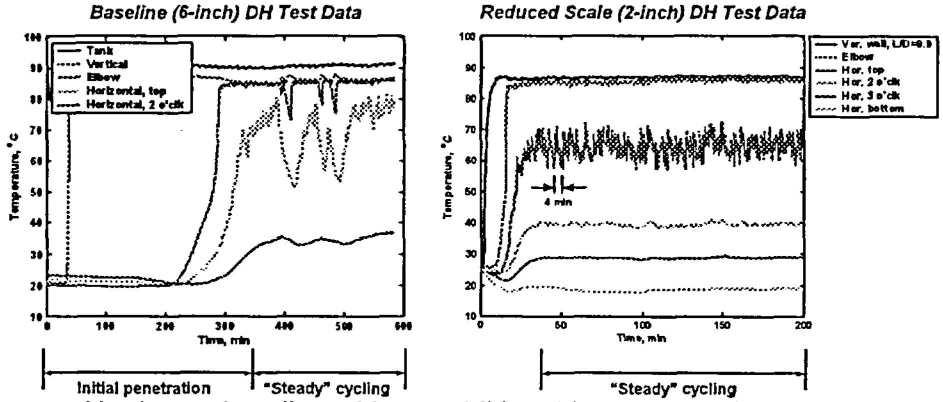
Representative DH Configuration Data

Baseline (6-inch) DH Test Data *Reduced Scale (2-inch) DH Test Data*



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

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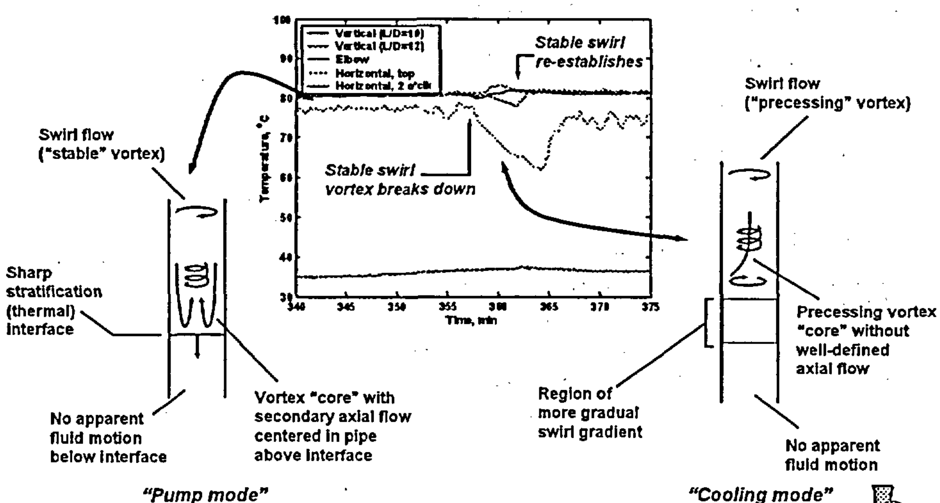
Thermal Cycling Mechanisms
DH (Heat Transfer) Configuration



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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

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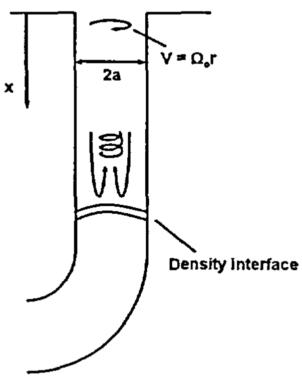
Swirl Velocity Penetration/Decay Model

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



$$\boxed{\frac{\Omega(x)}{\Omega_o} \cong \frac{1}{\left(1+\frac{x}{L_\Omega}\right)^{\beta}}}$$

$\Omega(x)$ – swirl velocity in branch line
x – distance along branch line
Ω_o – 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:

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

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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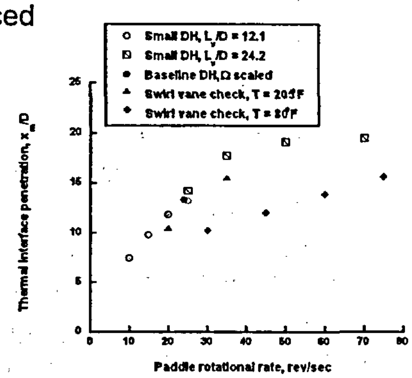
Maximum Thermal Interface Penetration

- 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:

$$\tau = \frac{\rho_c c_p \left(\frac{\pi}{4} D^2\right)(\beta D)\Delta T}{q_o}$$

where (βD) is fraction of branch line to be cooled

q_o is net heat transfer out of system

- Typical values (baseline DH configuration):

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

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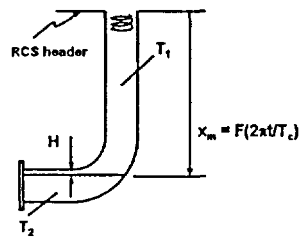
Application of DH Thermal Cycling Model

- 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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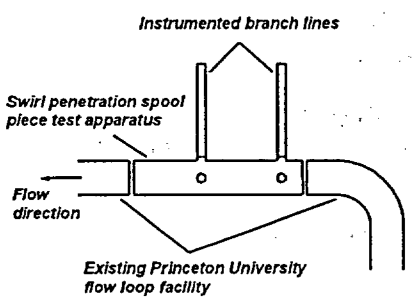
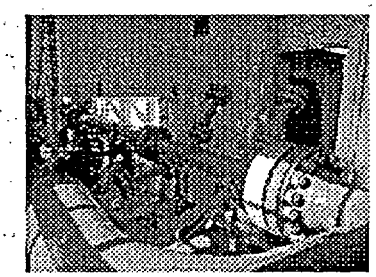
High Reynolds Swirl Penetration Test
Facility and Setup

- 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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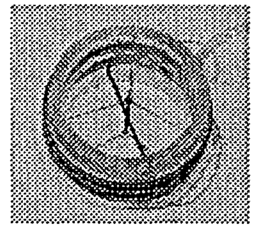
Swirl Penetration Test Instrumentation

- 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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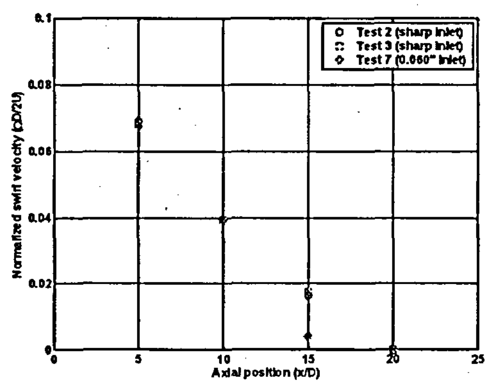
Representative Swirl Penetration Test Data

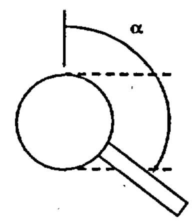
Normalized Swirl Velocity for 2-Inch Branch Line



Reynolds number ~ 10^7

Station B-B: $(L/D)_R = 7.8$

$\alpha = 105°$

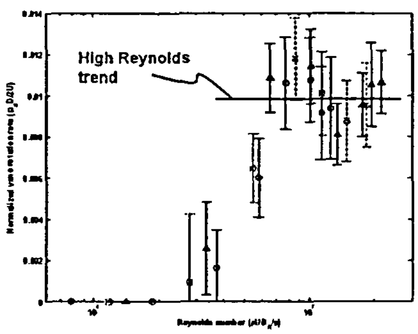


Swirl Penetration Test Data Reduction

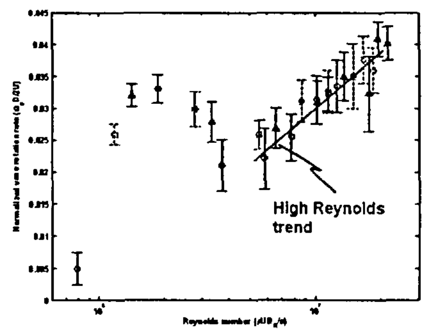
- Primary goals for data reduction:
  - Trends in swirl data at high Reynolds number
  - Estimation of swirl model parameters from data
- Summary of key findings in swirl test data:
  - Weak dependence on Reynolds number
  - Swirl decay in branch line relatively insensitive to geometry
  - Branch line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

High Reynolds Number Trends in Swirl Data

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



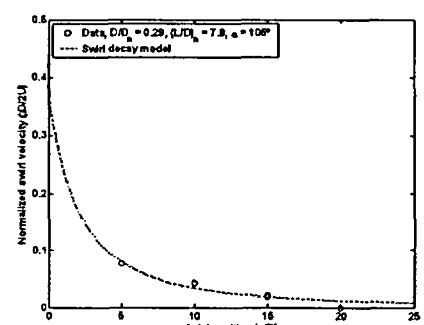
2-inch Branch Line, $(L/D)_R = 2.6$, $\alpha = 60°$



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 ⟹ $\frac{\Omega D}{2U} \sim K Re^{\gamma}$

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



<u>*Fitted model*</u> – $\frac{\Omega D}{2U} = \frac{\Omega_o D}{2U} \frac{1}{\left(1 + \frac{x/D}{L_\Omega/D}\right)^{\beta}}$

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

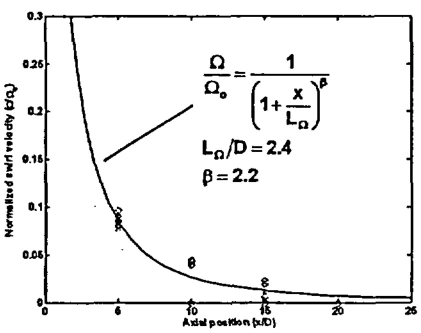
$$\frac{L_\Omega}{D} = 4.0$$

$$\beta = 1.9$$

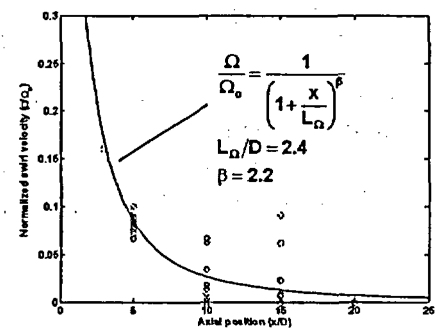
Swirl Decay Model Estimation Summary

- 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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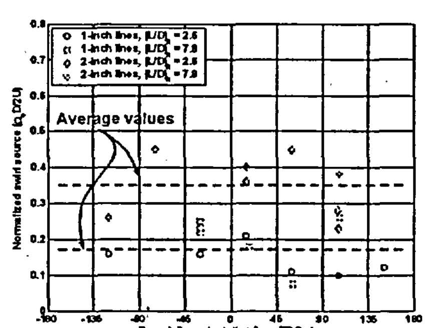
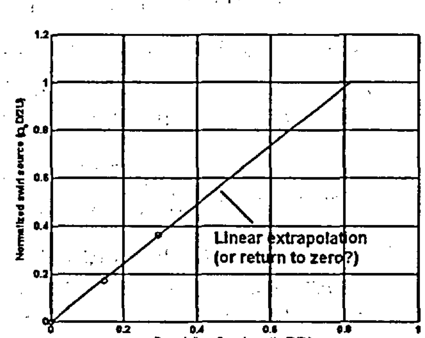
Reactor Coolant Line Geometric Effects on Branch Line Entry Swirl

- "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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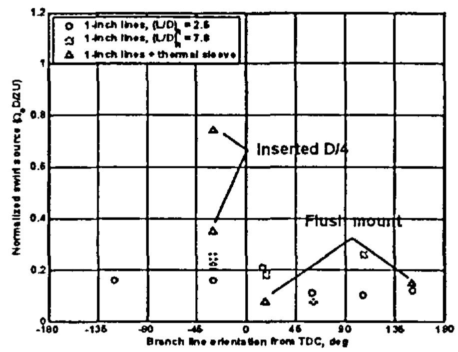
Thermal Sleeve Geometric Effects on Branch Line Entry Swirl

- 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:
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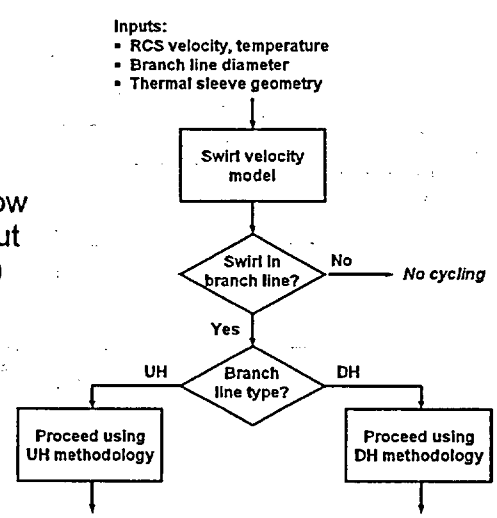
Thermal Cycling Screening Model Flowchart

- 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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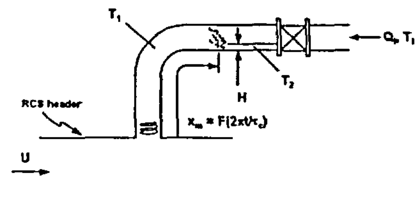
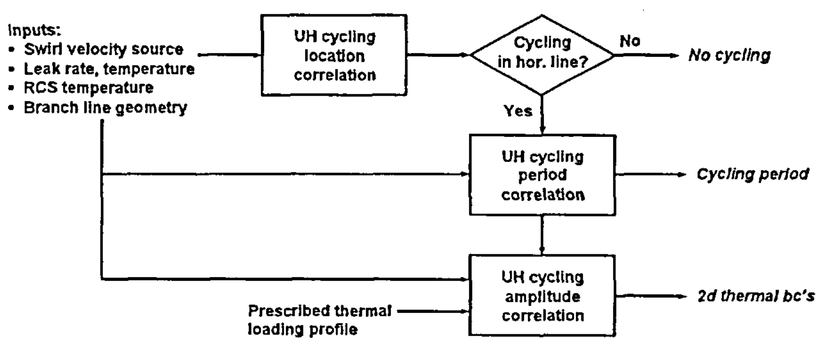
UH Thermal Cycling Model Requirements

- 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



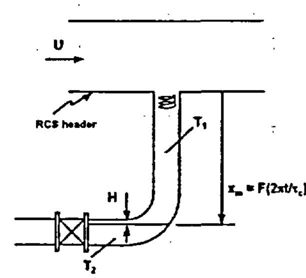
UH Model Configuration

UH Thermal Cycling Model Flowchart



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



DH Model Configuration

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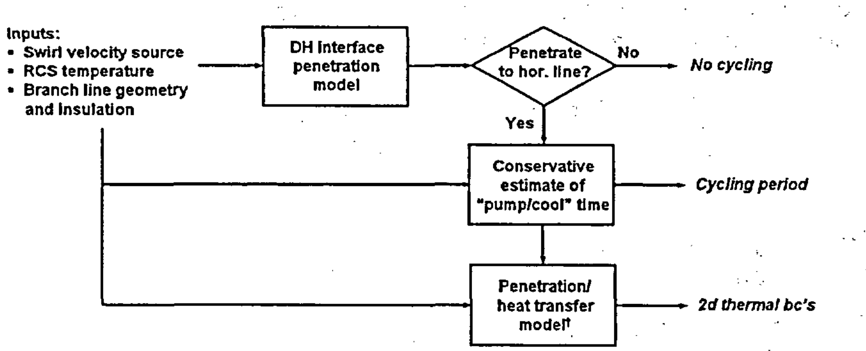
DH Thermal Cycling Model Flowchart



† – 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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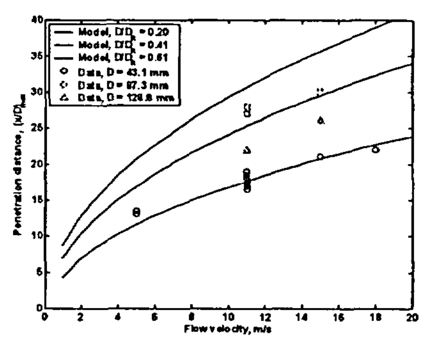
Prediction of Thermal Interface Penetration

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

$$\left.\frac{x}{D}\right|_{max} = fcn\Bigg(\underbrace{\frac{\Omega_o a}{U}, \frac{L_\Omega}{D}}_{\text{From swirl decay model}}, \beta, \frac{\Delta\rho}{\rho_h}\frac{gD}{U^2}, \frac{\delta}{D}\Bigg)$$

- 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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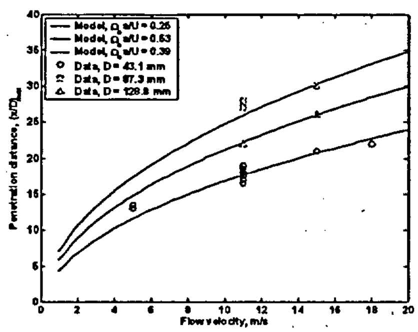
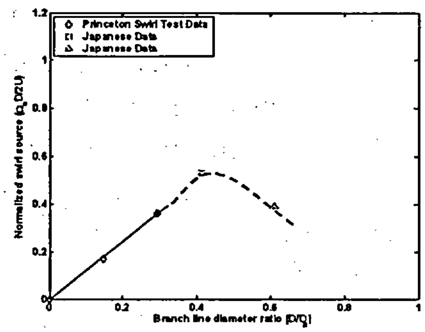
Refinement to Swirl Model
Large Branch Line Diameter Limit

- 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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EPRI

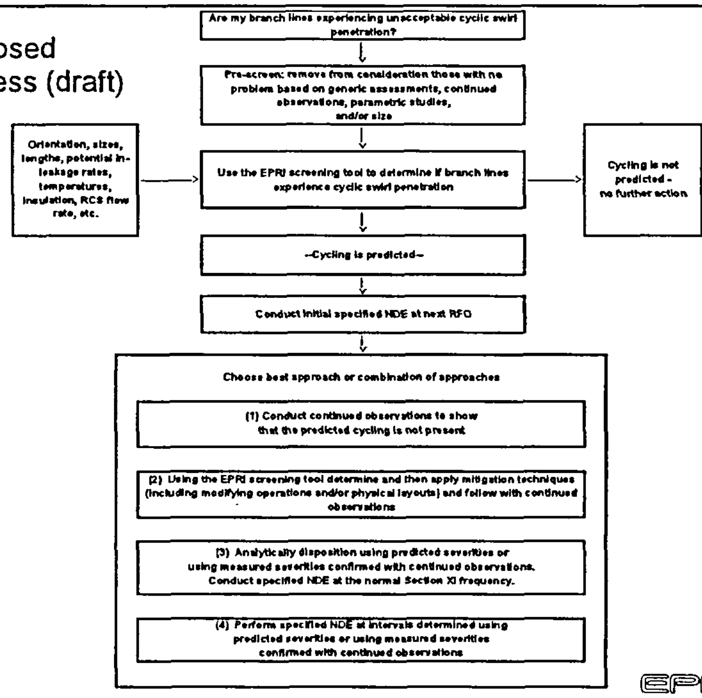
Presentation Outline

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

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

Proposed Process (draft)



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Presentation Outline

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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

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