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DATE OF MEETING
11/29/2000

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Docket Number(s)	**PROJECT NO. 669**
Plant/Facility Name	**EPRI**
TAC Number(s) (if available)	
Reference Meeting Notice	**11/7/00**
Purpose of Meeting (copy from meeting notice)	**TO DISCUSS STATUS OF EPRI MATERIAL RELIABILITY PROJECT'S THERMAL FATIGUE PROGRAM**

NAME OF PERSON WHO ISSUED MEETING NOTICE	TITLE
L. N. OLSHAN	**PROJECT MANAGER**

OFFICE
NRR

DIVISION
DLPM

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EPRI MRP Thermal Fatigue ITG and USNRC Meeting

November 29, 2000
USNRC Headquarters
Rockville, MD

Agenda

I.	Introductions, Opening Comments	K.Cozens,NEI M.Robinson, DPC
II.	MRP Thermal Fatigue Program Overview & Task Status	M.Robinson, DPC
III.	Thermal Fatigue Operating Experience, Task 3	A.Deardorff, SIA
IV.	Thermal Cycling Model development, Task 4	A. Bilanin, CDI
V.	NDE for Thermal Fatigue, Task 6	P.Lara, EPRI
VI.	Mitigation of Thermal Fatigue, Task 7 & 9	A. Deardorff, SIA
VII.	Interim Thermal Fatigue Management Guidelines Task 11a	A. Deardorff, SIA
VIII.	Conclusions & Final Comments	All

Background

- NRC proposed Generic Letter on augmented inspection of PWR Class 1 HPSI piping, March '98
- EPRI MRP Issue Task Group formed in mid '99 to:
  - develop confidence in analytical models, start w/ EPRI TASCS and perform validation testing as required
  - enhance guidance on where and how often to perform NDE
  - develop guidance on best NDE techniques for detection of thermal fatigue cracks in small diameter piping
  - develop guidance on how and where to perform monitoring
  - develop recommendations to enhance O&M practices to reduce potential of TF cracking

Thermal Fatigue ITG

Project Plan Review

Project Goal

- Provide utilities with a consistent set of guidelines and methodology for addressing piping thermal fatigue issues in 2001(non-design basis thermal cycling/thermal stratification)

Project Scope

- Thermal fatigue issues for those portions of ASME Code Class 1 piping systems that are connected to the Reactor Coolant Pressure Boundary AND are not isolatable from the Reactor Coolant Pressure Boundary. (Includes those thermal fatigue effects due to cyclic thermal stratification)

Strategic Approach

- Respond to NRC request for industry leadership and action
- Provide the industry w/ tools to manage thermal fatigue concerns through current license life and any renewal periods
- Take advantage of earlier thermal fatigue work performed and supplement that with enhanced capabilities
- Establish relationships & partnerships that allow access to new data and information

MRP Thermal Fatigue Task Listing & Summary Status

Task Number	Task Description	Vendor	Status	Comments
3	**Industry Operating Experience** - Series of case histories, LER, plant monitoring experience, and lower level thermal anomalies, contained in a simple database and installed on the EPRI web site	SIA	Comp	Final report approved by ITG, ready for EPRI publication. Web site installed and available for utility use.
4	**Thermal Fatigue Screening** – Screening tool to assess the susceptibility of attached piping to significant stratification driven thermal fatigue	CDI	12/01	Preliminary T/H model prepared & proceeding w/ selected experiments to either prove or dis-prove theories
5	**Thermal Fatigue Monitoring Guidelines** - Provides guidance to assure an effective monitoring program is in place to detect temperature distributions which could result in thermal stresses that could lead to cracking	FTI	3/01	Final comments being incorporated into report
6	**NDE Inspection Guidelines** - Thermal fatigue inspection guidance on NDE methodologies, procedures, and qualifications of NDE examiners to detect TF damage. Task focuses on volumetric inspection of less than 4" diameter lines.	NDEC EPRI	Comp	Final report approved by ITG. Final EPRI report has been published. Inspection guidance included in Task 11a.
7	**O&M Guidelines** - Identifies plant operational and maintenance practices that contribute to potential cyclic thermal conditions and modifying those practices to minimize the potential for the phenomena to occur	SIA	Comp	Final report approved by ITG and ready for EPRI publication.
8	**Thermal Fatigue Evaluation** - Quantifies the fatigue damage in lines screened as susceptible.	On Hold	On Hold	Activity on hold pending results of revised Task 4 results
9	**Plant Modification Guidelines** - Identifies plant modifications that would eliminate the potential for thermal fatigue	SIA	Comp	Final report approved by ITG and ready for EPRI publication.
10	**International Technical Exchange** - Focuses on the identification and participation in important foreign R&D activities which could contribute to resolution of thermal fatigue issues. Allows US access to MHI thermal cycling simulation data; access to extensive EDF in-plant thermal monitoring data; participation in JSME joint PWR/BWR Thermal Fatigue Research Program	EPRI	On-going	Co-sponsored Intern'l Fatigue Conference; Tentative plans for 2nd Intern'l Conference in 2002. Continuing exchange w/ EDF on monitoring data of interest
11(a)	**Interim Thermal Fatigue Management Guidelines** – Interim pipe inspection guidance from screening, monitoring, and NDE. Interim report focuses on those known industry events that have resulted in actual leakage events, both domestic and foreign.	SIA	Comp	Final report approved by ITG & sent to MRP IIG, MRP Execs, & NEI APCs for review & approval. Resolving industry comments.
11(b)	**Thermal Fatigue Management Guidelines** - Principal product of the ITG and is a compilation of methods for assessment, screening, monitoring, analysis and management of thermal fatigue	SIA	2002	Final report to include conclusions from Task 4 which is still under development.
12	**Develop & Deliver Training Plan** - Develops and delivers the training for utility engineers and others in applying the results of this project	EPRI SIA	2002	NDE CBT available in 12/00. Site specific training of Guidelines targeted for '01 & '02.

MRP THERMAL FATIGUE PROJECT
TASK 3
Thermal Fatigue Operating Experience

Art Deardorff
Structural Integrity Associates

NRC / MRP / NEI MEETING

November 29, 2000

THERMAL FATIGUE OPERATING EXPERIENCE SCOPE

- **Collect Details of Non-Isolable Line Leakage Events Worldwide**
- **Survey Domestic Utilities**
  - **Obtain results from:**
    - **Monitoring programs**
    - **Identify conditions that could be precursors to thermal fatigue cracking**
    - **Capture non-reportable events and observations**
- **Present information in a database format, to be maintained on EPRI website**

THERMAL FATIGUE OPERATING EXPERIENCE SOURCES OF DATA

- Questionnaire Sent to Domestic PWR Plants
  - Identified Plant Technical Contacts
  - Telephone Followup
- Three Databases Previously Compiled by EPRI
  - RI-ISI, SKI, Fatigue Management Handbook
- Licensee Event Reports
- Operating Experience Reports
- NUREGs, Conference Proceedings
- Published Technical Papers
- Evaluations by Utilities and Consultants

THERMAL FATIGUE OPERATING EXPERIENCE RESULTS OF REVIEW - GENERAL

- 14 Leak Events Have Occurred Worldwide:
  - 7 were due to the scenarios cited in Bulletin 88-08
    - Except for Farley, none of these 7 occurred in domestic plants
  - Of the other 7 events:
    - 2 were specific to B&W plants (non-stagnant lines)
    - 2 were attributed to designs unique to European plants
    - 3 were in drain/excess letdown lines

THERMAL FATIGUE OPERATING EXPERIENCE
PLANT RESPONSES TO BULLETIN 88-08

- Two-thirds of Survey Respondents Instrumented One or More Systems to Measure Thermal Stratification
  - Most monitored for one or two cycles
- One-quarter Perform Some Form of Valve Leakage Monitoring
- One-eighth Have Means to Monitor and Control System Pressures
- 40% Took Other Actions to Prevent Thermal Fatigue Failures
  - Modified piping geometry
  - Improved valve maintenance
  - Added or changed valves

PRS-00-088/5

THERMAL FATIGUE OPERATING EXPERIENCE
HP SAFETY INJECTION LEAK EVENTS

- Farley (1987) - HAZ of Elbow to Pipe Weld
- Tihange (1988) - Elbow Base Metal
- Dampierre 2 (1992) - Valve to Pipe Weld
- Dampierre 1 (1996) - Straight Pipe Base Metal (cracked again in 9 months)
- Obrigheim (1986) - Nozzle to Elbow Weld
- Biblis (1995) - Tee Connecting Hot and Cold Injection Lines
- None in Westinghouse 1 1/2" SI Lines, CE Plants or B&W Plants (Stagnant Lines)

PRS-00-088/6

THERMAL FATIGUE OPERATING EXPERIENCE HP SAFETY INJECTION MONITORING EXPERIENCE

- Monitoring Indicated That Stratification Was Insignificant During Normal Operation Unless a Valve Was Leaking
- Several Plants Reported Stratification During Heatup Due to Backflow Through the Check Valve When the Associated RCP Was off and Others Were Running
- CE and B&W Plants Are Generally Not Subject to Inleakage
- Some Plants Installed Pressure Control Systems to Prevent Upstream Pressure From Exceeding RCS Pressure

THERMAL FATIGUE OPERATING EXPERIENCE LP SAFETY INJECTION

- No Leak Events
- Several Plants Reported a Moderate Amount of Stratification
  - Caused by natural convection; no cycling

THERMAL FATIGUE OPERATING EXPERIENCE
RHR / SHUTDOWN COOLING / DECAY HEAT SUCTION

- **Only Leak Event Was at Genkai**
  - **Attributed to intermittent out-leakage through isolation valve stem packing**
- **Some Plants Reported Thermal Stratification**
  - **Stratification attributed to turbulence penetration and not the Genkai leak-off line mechanism – steady to very low frequency**
  - **A few plants reported significant stratification during power reduction**

THERMAL FATIGUE OPERATING EXPERIENCE
CHARGING / MAKEUP / ALT. CHARGING

- **Leak Events:**
  - **Crystal River (1983) and Oconee 2 (1997)**
  - **In Makeup / HPI system, B&W plants only. Caused by leakage past thermal sleeves**
  - **Managed by a B&W Owners Group program**
- **Monitoring Experience:**
  - **No stratification unless crossflow occurs during heatups due to pressure differences from RC pump cycling**
  - **Alternate charging had insignificant stratification**
  - **Some plants use both charging and alternate charging, or equalize their use**

THERMAL FATIGUE OPERATING EXPERIENCE PRESSURIZER SPRAY / AUXILIARY SPRAY

- Leak Event at Loviisa
  - Crack in auxiliary spray isolation valve due to internal thermal cycling. The valve design is not used in the U.S.
- Stratification is not Significant During Normal Operation Unless Isolation Valve Leaks
- No Stratification Cycling Observed at Main Spray to Aux. Spray Junction
- Stratification Has Been Observed In Main Spray, During Heatups and Cooldowns, When RCPs Are Off and Main Spray Flow Is Insufficient to Fill the Pipe

PRS-00-088/11

THERMAL FATIGUE OPERATING EXPERIENCE REACTOR COOLANT LOOP DRAINS / EXCESS LETDOWN

- Leak Events:
  - TMI 1 (1995), Mihama (1999), Oconee 1 (2000)
- Attributed to High Cycle Fatigue Due to Turbulence Penetration
  - Horizontal portion stratifies due to loss of heat to ambient and intermittent incursion of hot reactor coolant
- Vertical Length Was About 8 - 12 Diameters From RCS
- Horizontal Portion of Drain Line Was Uninsulated, or Insulated but Isolation Valve Was Far Away
- Very Little Monitoring Done on These Lines

PRS-00-088/12

THERMAL FATIGUE OPERATING EXPERIENCE CONCLUSIONS

- Mechanisms for Thermal Stratification and Cycling Induced Fatigue Failures Are Still Possible
- Concern Primarily in High Pressure Safety Injection and RCL Drains
- Operating Experience Database Is Available to Utilities on EPRI website
- EPRI Report is in Publication

Thermal Cycling Model Development

Task 4.0

Prepared for

Electric Power Research Institute - MRP
Thermal Fatigue Issue Task Group

Prepared by

Continuum Dynamics, Inc.

November 29, 2000
USNRC Headquarters
Rockville, Maryland

Alan J. Bilanin
Jeffrey D. Keller
Milton E. Teske
Donald B. Bliss

Objective

Develop a physics based tool when given thermal, hydraulic and mechanical parameters of a piping system will predict whether or not thermal cycling will occur. If cycling does occur predict the frequency of cycling and pipe temperature distributions.

Modeling Effort

Phase I

Task I - Physical Basis

a. Review existing data for vertical upward to horizontal branch line ending in a leaking valve.

b. Review existing data for vertical downward to horizontal.

c. Postulate physical mechanisms that result in observed time scales of oscillation and cyclic distribution of temperature.

d. Rank mechanisms as to postulated importance.

Modeling Effort (cont.)

Phase I

Task II - Panel Review

a. Prepare a white paper reviewing phenomenon and physical basis for oscillation including data and references for panel review.

b. Attend a one-day panel review meeting in Baltimore in September.

Modeling Effort (cont.)

Phase I

Task III - Modeling

a. Construct integral, one dimensional unsteady, and/or semi empirical models as appropriate to simulate thermal cycling.

b. Compare model predictions with test data where appropriate and identify deficiencies in the models and means to rectify by CFD and/or Tests

Modeling Effort (cont.)

Phase I

Task IV - Documentation

a. Document Phase I effort.

Modeling Effort (cont.)

Phase II

1. Carry out experiments to improve and supplement models developed in Phase I.

2. Extend models to alternate configuration/geometries.

3. Determine Thermal Hydraulic model transfer means, PC based software, etc.

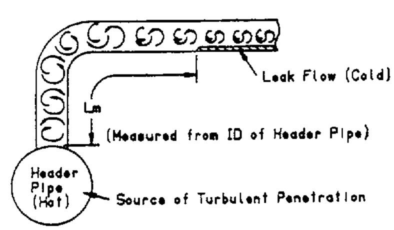
4. Software QA
   - Spec
   - V & V
   - Sample Calculations

5. Software Users Manual
   - Technical Basis
   - Sample Calculations

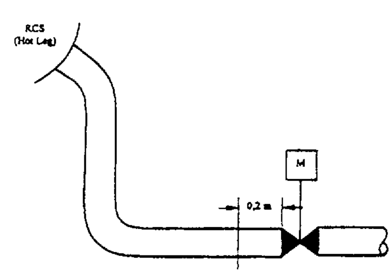
(Items 4–5 are bracketed together with the note: } or alternate transfer means)

Piping Configurations in Thermal Cycling

- UH Configuration:



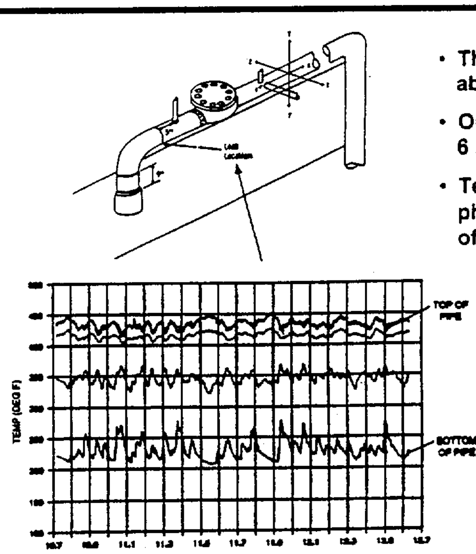
- DH Configuration:



Thermal Cycling Phenomenon -- Data

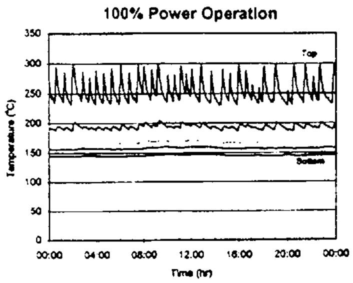
- Piping configurations considered:
  - up-and-horizontal (UH configuration)
  - down-and-horizontal (DH configuration)
- Thermocouple data:
  - Farley plant (UH configuration)
  - Angra 1 plant (DH configuration)

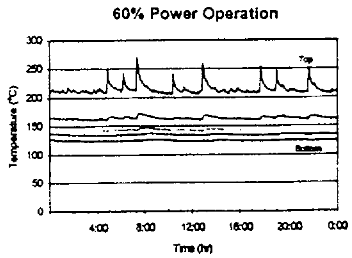
UH Configuration Data -- Farley Plant



- Thermocouple data at five locations about pipe circumference
- Observed thermal cycling period of 6 minutes (periodic but not harmonic)
- Temperature at top of pipe out of phase with temperature at bottom of pipe

DH Configuration Data -- Angra 1 Plant





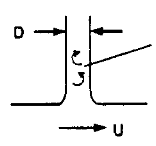
- Thermocouple data at five locations about pipe circumference
- Observed thermal cycling period of 40 minutes at 100% power; temperature fluctuations are periodic but not harmonic
- When power level reduced to 60%, temperature fluctuations are less regular in period

Time Scales

- **Turbulence**

$$t_t \sim O\left(\frac{\Lambda}{q}\right) = \frac{D}{0.1U}$$

$$\sim 0.1\ sec$$



q ~ O(0.1U)
Λ = eddy size ~ O(D)

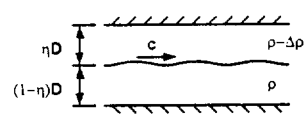
D = 0.5 ft
U = 40 ft/sec

- **Internal waves in stratified layer**

$$c^2 = g\frac{\Delta\rho}{\rho}\left[\frac{\eta(1-\eta)D}{(1-\eta)+\left(1-\frac{\Delta\rho}{\rho}\right)\eta}\right]$$

$$t_w = \frac{L}{c} \sim 3\ sec$$

$$L \sim O(3\ ft)$$



η	c (ft/sec)
0	0
0.3	1.2
0.5	1.8
0.7	1.6
0.9	0.7
1	0

$$\frac{\Delta\rho}{\rho} = 0.2$$

Time Scales (cont.)

- Pipe purge by leak

$$\left.\begin{aligned} L &= 6.7\ D \\ D &= 0.5\ ft \\ V &\sim 2\ ft^3 \\ \rho &\sim 60\ lbm/ft^3 \end{aligned}\right\} \qquad \begin{aligned} \dot{M}_L &= 200\ lbm/hr \\ t_p &= \frac{\rho V}{\dot{M}_L} = 4\ min \end{aligned}$$

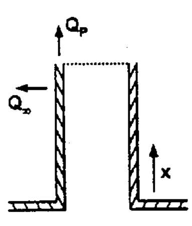
- Conduction time

$$\alpha = \textit{thermal diffusivity of stainless steel}$$
$$= 0.15\ ft^2/hr$$
$$t_c = \frac{\alpha}{(\eta D)^2} = 12\ min, \quad \eta D = 2\ in$$

Note: Cycle time in Farley plant ~ 6 min

Turbulence Penetration in a Vertical Leg

- Example: Zone 1 integral model



From Second Order Closure turbulence model –

$$\frac{dq^2}{dt} = \frac{2g}{\Theta}\overline{u\theta} - \frac{2b}{\Lambda}q^3 + diff. \qquad \text{where } q^2 = \sqrt{\overline{u_i' u_i'}}$$

$$\frac{d\overline{u\theta}}{dt} = -\frac{q^2}{3}\frac{d\Theta}{dx} + \frac{g}{\Theta}\overline{\theta^2} + diff. + disp.$$

$$\frac{d\overline{\theta^2}}{dt} = -2\overline{u\theta}\frac{d\Theta}{dx} + diff. + disp.$$

Solution form – $\begin{Bmatrix} \overline{q^2} \\ \overline{u\theta} \\ \vdots \end{Bmatrix} = \begin{Bmatrix} q \\ \vdots \end{Bmatrix} e^{\alpha t} = \begin{Bmatrix} q \\ \vdots \end{Bmatrix} e^{\alpha t}$

- Stability relationship:

$$\alpha = -\frac{bq}{\Lambda}\left[1 \pm \sqrt{1 - \frac{2}{3}\frac{d\Theta}{dx}\left(\frac{\Lambda}{bq}\right)^2}\right] \implies \frac{d\Theta}{dx} < 0 \text{ results in an exponential growth of turbulence}$$

- Unstable temperature gradient is assured due to leak flow and heat transfer from pipe

Steady-State Turbulence -- Analytical Solutions

- No convective velocity and $d\Theta/dx = 0$: $q^2 = q^2(0)e^{-0.745x/\Lambda}$
- Destabilizing temperature gradient in the presence of gravity ($d\Theta/dx < 0$ which implies cold fluid sitting above hot fluid):

  Steady state turbulence $$q^2 = -\frac{\left(1+\frac{2}{18}\right)}{0.1875}\frac{g}{\Theta_o}\frac{d\Theta}{dx}\Lambda^2$$

- Note that turbulence penetration is infinite; contradicts earlier conclusion in (Palusamy 1994)
- Stabilizing temperature gradient results in significantly shortened penetration length

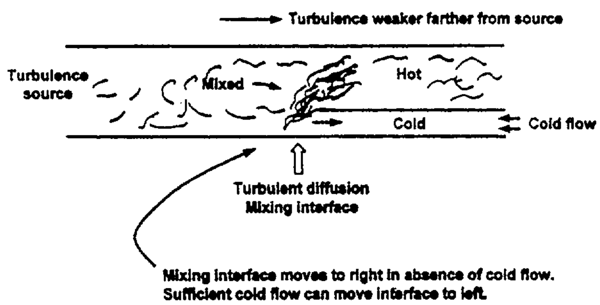
Ranking of Mechanisms - Thermal Cycling

- UH Configuration
  - Fill & Spill *
  - Periodic turbulence in vertical leg
  - Driven hydraulic jump
  - Periodic valve leakage
  - Other?
- DH Configuration
  - Fill & Splash/Cool
  - Other?

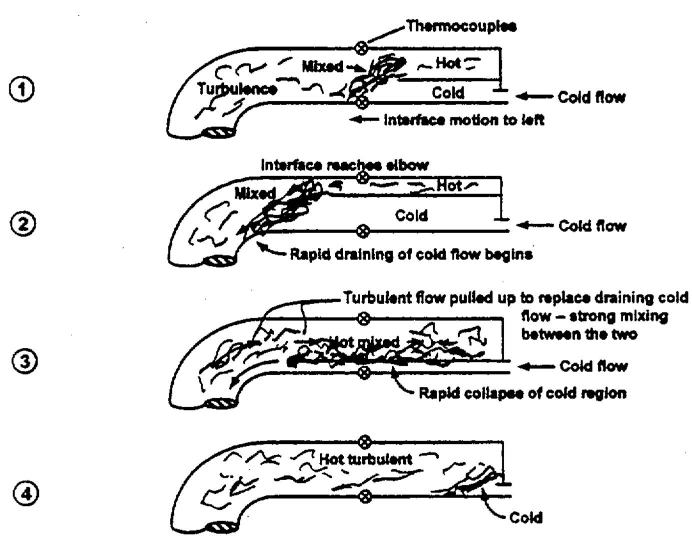
* Only mechanism to be discussed today.

Fill and Spill

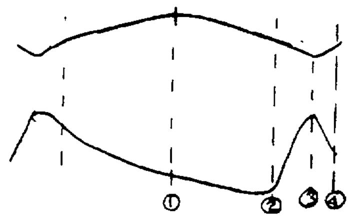
- Thought experiment:



Fill and Spill -- Postulated Mechanisms



Thermocouple Readings



1. Top thermocouple starts to fall gradually as mixing zone passes.

Bottom Temperature falls as mixing zone and cold flow pass by.

2. Top temperature keeps falling.

Bottom temperature approaches lowest value.

3. Interface reaches elbow. Rapid cold drainage begins. Turbulent flow is pulled up. Rapid mixing of some cold flow due to overturning, mixing, shear, as it drains. Top temperature reaches minimum. Bottom temperature rises abruptly due to mixing and drainage.

4. Top temperature begins to rise as hot turbulent flow diffuses into regions warming it up. Bottom temperature hangs on and then begins gradual fall as cold water seeps into region. Mixing interface begins to return at closed end where cold leaks - initially not much mixing since turbulence is weakest here, and leakage water coldest.

Time Scales

Fill & Spill

$\dot{q}_\ell$ = volumetric flow of cold water

L_H = length of vertical pipe

D = pipe diameter

h = height of cold water

$A(h)$ = cross sectional area of partially filled pipe

Time to fill

$$t_{fill} > \frac{L_H}{\dot{q}_\ell} A(h), \quad A(h) = \frac{D^2}{4}(\theta - 1/2\sin 2\theta) \qquad \cos\theta = 1 - 2h/D$$

Time Scales (cont.)

Time to spill

$$u \sim \sqrt{\frac{\Delta\rho}{\rho} gh}$$

$$\dot{q}_s = uA(h)$$

$$t_{spill} = \frac{L_h A(h)}{uA(h)}$$

$$\frac{t_{fill}}{t_{spill}} = \frac{A(h)u}{\dot{q}_\ell} = \frac{\pi D^2}{4\dot{q}_\ell}\sqrt{\frac{\Delta\rho}{\rho} gD}$$

$\dot{q}_\ell = 0.5$ gpm (Nakamori, et al.)

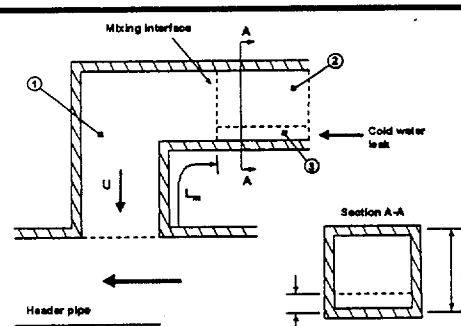
$D = 0.5$ ft

$$\frac{\Delta\rho}{\rho} \sim 0.2$$

$$\frac{t_{fill}}{t_{spill}} \simeq 300$$

$t_{fill} > 5$ min at 0.5 gpm and h=D/2. Since all cold flow does not fill, time given is minimum time.

Integral Thermal Cycling Code Formulation (TC^2) -- UH Configuration (same for DH config.)



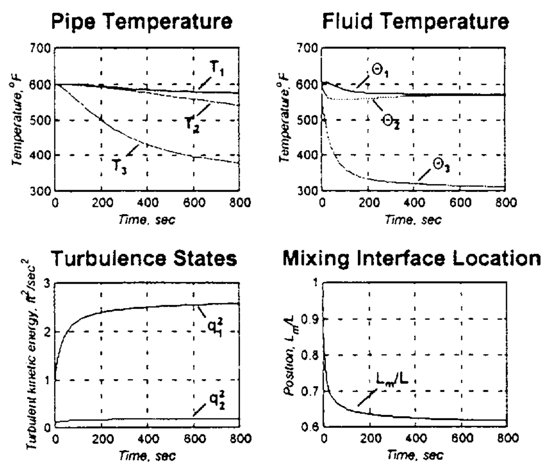
- **Model states:**
  - pipe temperature (T_1, T_2, T_3)
  - fluid temperature (Θ_1, Θ_2, Θ_3)
  - turbulence in regions 1 & 2
  - mixing interface location (L_m)
- **Boundary conditions:**
  - fluid temp in header pipe (Θ_0)
  - fluid temp of cold leak (Θ_4)
  - turbulence in header pipe
- **Model equations in region 1 (similar equations for regions 2 & 3):**

$$\frac{dT^1}{dt} + [T^1 - T(L_m)]\frac{1}{L_m}\frac{dL_m}{dt} = -\frac{1}{\tau}(T^1 - \Theta^1)$$

$$\frac{d\Theta^1}{dt} + [\Theta^1 - \Theta(L_m)]\frac{1}{L_m}\frac{dL_m}{dt} = \frac{U}{L_m}[\Theta(L_m) - \Theta^1] + \frac{1}{\tau}(T^1 - \Theta^1) + \frac{\overline{u\theta(0)} - \overline{u\theta(L_m)}}{L_m}$$

$$\frac{dq^2}{dt} + [q^2 - q^2(L_m)]\frac{1}{L_m}\frac{dL_m}{dt} = \frac{U}{L_m}[q^2(L_m) - q^2] + \frac{2g}{\Theta_{ref}}\left(\frac{U}{L_m}\right)\overline{u\theta} - \frac{2b}{\Lambda}q^3 + \frac{\nu}{L_m}\left\{\left(q\Lambda\frac{\partial q^2}{\partial x}\right)_{L_m} - \left(q\Lambda\frac{\partial q^2}{\partial x}\right)_0\right\}$$

TC² Model Representative Results



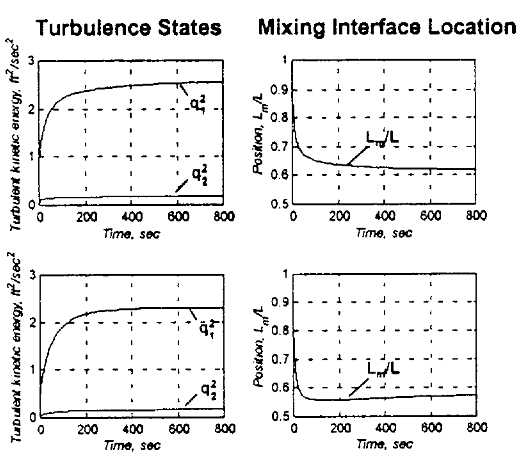
Boundary conditions for calculation:

$T_0 = \Theta_0 = 600$ °F

$\Theta_4 = 300$ °F

3.5 ft³/hr leak rate

TC² Model Sensitivity to Boundary Conditions



RCL turbulence = 4 ft/sec

RCL turbulence = 2.8 ft/sec

>> Changing turbulence boundary condition results in different steady state but no oscillatory behavior (similar findings when changing leak rate and temperature boundary conditions) <<

Conclusions from UH Integral Model Formulation

- Model does not contain physical mechanism that results in oscillation
- All solutions are exponentially damped
- Turbulent transport between Volumes 2 & 3 neglected; Volume 3 height not permitted to vary with time
- Model neglects turbulence spatial dependence in vertical pipe
- Testing to identify and confirm thermal cycling mechanisms needed at this time

Cycling Mechanism Test Justification (Phase II -- Task 1)

- CDI modeling effort identified several thermal hydraulic phenomena that can cause thermal cycling
- Data is needed to confirm these mechanisms and guide implementation into existing fully nonlinear integral formulation (i.e., TC^2 code)
- CFD not viable at this time
- Review panel conclusions:
  - Confirm that proposed cycling mechanisms are possible
  - Recommend and support testing to confirm and quantify physical mechanisms

Objectives of Phase II Test Program

- Perform *simple* tests to confirm cycling mechanisms for continued model development
- Obtain quantitative *and* qualitative (i.e., flow visualization) data for fluid dynamic and turbulent mass transfer in piping configurations
- Explore sensitivity of piping geometry to underlying mechanisms for additional modeling extensions in alternate piping configurations
- Testing will be structured in a multi-tiered program to provide a rapid turn-around of desired results:

  A -- Thermal Cycling Mechanisms
  B -- Turbulence Penetration

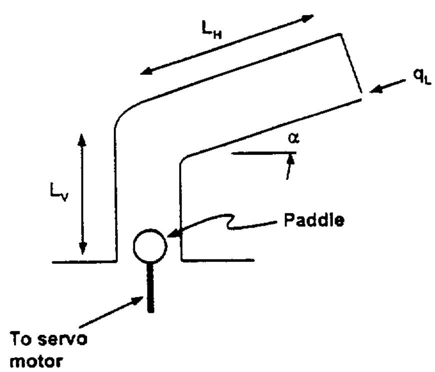
Experiment A -- Thermal Cycling Mechanisms

- Motivation:
  - Testing to date has not allowed identification of fluid phenomena responsible for cycling.
  - Most measurements are surface mounted thermocouples on full pressure systems.
  - Internal mixing, splashing, sloshing, etc. are not easily inferred from thermocouple data since these phenomena are fast compared to pipe wall thermal lag.
- Completion of TC^2 model of thermal cycling requires insight into phenomena before implementing

  Fill & Spill -- UH configuration
  Fill & Splash/Cool -- DH configuration
- Conduct tests to visualize fluid phenomena during cycling
  - Confirm if Fill & Spill mechanism is responsible for cycling in UH configuration
  - Confirm if Fill & Splash/Cool is responsible for cycling in DH configuration

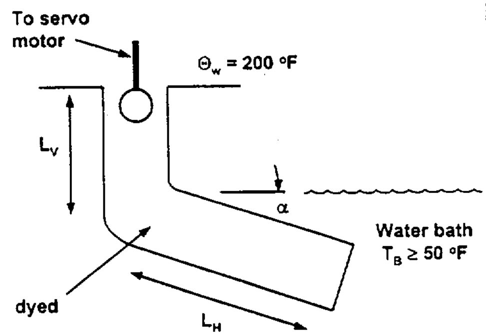
Schematic for Experiment A -- Cycling Mechanisms

- UH Configuration:



  - Test conducted at atmospheric pressure and temperature
  - Saltwater leak flow (q_L) dyed

- DH Configuration:



  - Test conducted at atmospheric pressure
  - Cold water dyed

Experiment A -- Test Plan and Measurements

- Construct full scale (~6 inch diameter) UH and DH branch leg configuration from Lexan pipe.
- Introduce range of controlled amount of vorticity and/or turbulence at RCL-branch leg junction:
  - For UH configuration, simulate cold water leak with dyed saltwater
  - For DH configuration, use hot and dyed cold water
- Measurements:
  - Vortical and turbulent velocity in vertical legs (UH & DH)
  - Flow visualization recorded on video camera (interface geometry and position)
  - (UH config) Density of salt water, salt water flow rate, and position/geometry of interface with conductivity probes
  - (DH config) Fluid and pipe temperature distributions with thermocouples

Experiment A -- Configuration Variations and Anticipated Results

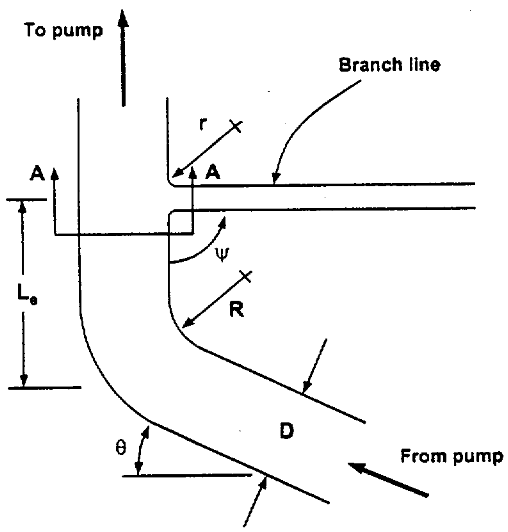
- Initially consider (for both UH and DH setups):
  - two different angular configurations
  - two different length configurations

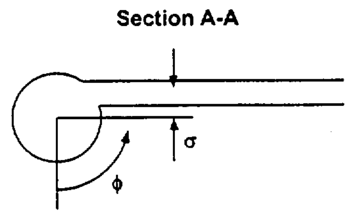
- Quantitative and qualitative description of interface will be determined as a function of:
  - time
  - inlet conditions
  - limited geometric variations

Experiment B -- Turbulence Penetration

- Motivation:
  - Observations have shown that turbulent penetration may reach 25D yet analysis suggests truly turbulent flow in neutral density water should only penetrate several pipe diameters
  - Plants with two nearly identical branch lines have one with thermal cycling and one without
- Postulate:
  - Quasi-steady flows are being established in branch lines (M. Robert, Corkscrew Flow Pattern in Piping System Dead Legs, Sept. 1992) and/or gravitationally-aligned thermal gradients control penetration depths
  - Branch line location relative to upstream elbows or nozzles establishes energy transport at branch line junction with RCL
- Conduct tests to:
  - Establish flow condition at inlet to branch line
  - Relate RCL flow condition to branch flow conditions required to generate cycling

Schematic for Experiment B -- Turbulence Penetration





<u>Configuration parameters</u>:

- Elbow geometry (R, θ)
- Branch line geometry (φ, σ, ψ)
- Distance between branch line and elbow (L_e)
- Junction geometry (r)
- Diameter changes (D)

Experiment B -- Test Plan and Measurements

- Conduct scaled experiment (~4 inch pipe) varying some configuration parameters and flow rate to determine turbulent penetration length as a function of geometry and conditions
- Pump water through RCL pipe loop
- Measurements:
  - geometry
  - flow rate
  - turbulent penetration in branch leg (velocity probes and flow visualization)

Experiment B -- Configuration Variations and Anticipated Results

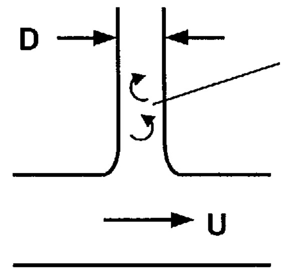
- Initially consider:
  - two different branch line radii (r)
  - four different branch line orientations to elbow (ϕ)
  - three different elbow distances (L_e)

- Demonstrate sensitivity of turbulence penetration to upstream piping configuration characteristics

Time Scales

- **Turbulence**

$$t_t \sim O\left(\frac{\Lambda}{q}\right) = \frac{D}{0.1U}$$
$$\sim 0.1\ sec$$



q ~ *O*(0.1U)
Λ = eddy size ~ *O*(D)

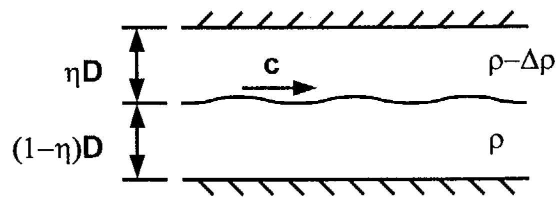
D = 0.5 ft
U = 40 ft/sec

- **Internal waves in stratified layer**

$$c^2 = g\frac{\Delta\rho}{\rho}\left[\frac{\eta(1-\eta)D}{(1-\eta)+\left(1-\frac{\Delta\rho}{\rho}\right)\eta}\right]$$

$$t_w = \frac{L}{c} \sim 3\ sec$$

$$L \sim O(3\ ft)$$
$$c \sim O(1\ ft/sec)$$

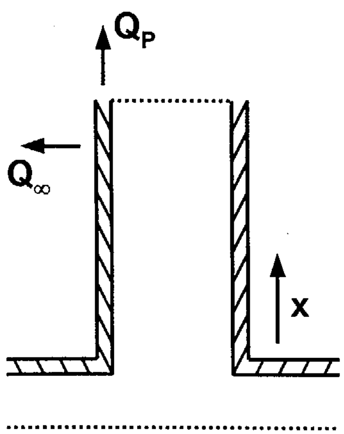


η	c (ft/sec)
0	0
0.3	1.2
0.5	1.8
0.7	1.6
0.9	0.7
1	0

$$\frac{\Delta\rho}{\rho} = 0.2$$

Turbulence Penetration in a Vertical Leg

- **Example: Zone 1 integral model**



From Second Order Closure turbulence model –

$$\frac{dq^2}{dt} = \frac{2g}{\Theta}\overline{u\theta} - \frac{2b}{\Lambda}q^3 + diff. \qquad \text{where} \quad q^2 = \sqrt{\overline{u_i' u_i'}}$$

$$\frac{d\overline{u\theta}}{dt} = -\frac{q^2}{3}\frac{d\Theta}{dx} + \frac{g}{\Theta}\overline{\theta^2} + diff. + disp.$$

$$\frac{d\overline{\theta^2}}{dt} = -2\overline{u\theta}\frac{d\Theta}{dx} + diff. + disp.$$

Solution form –

$$\begin{Bmatrix} q^2 \\ \overline{u\theta} \\ \overline{\theta^2} \end{Bmatrix} = \begin{Bmatrix} \hat{q}^2 \\ \vdots \\ \ \end{Bmatrix} e^{\alpha t} = \begin{Bmatrix} \hat{q}^2 \\ \vdots \\ \ \end{Bmatrix} e^{x\alpha/U}$$

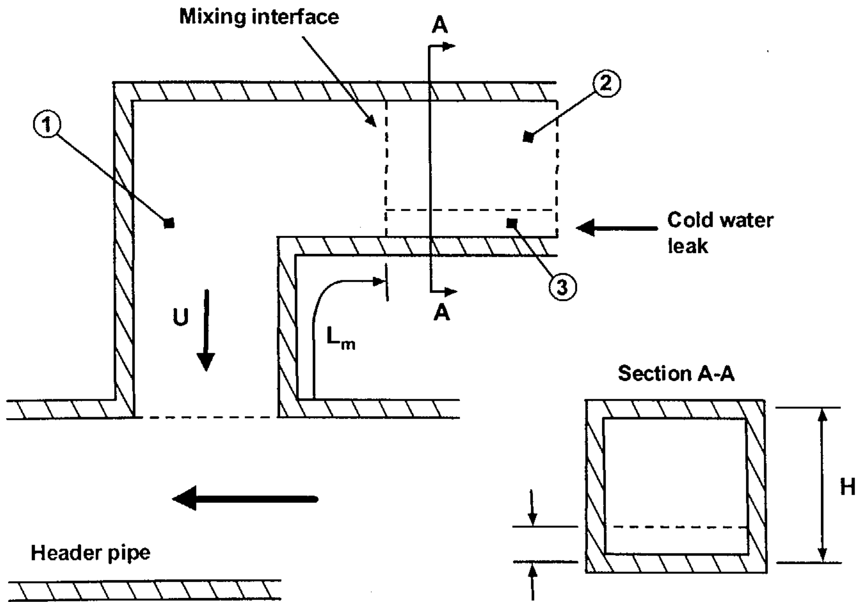
- **Stability relationship:**

$$\alpha = -\frac{bq}{\Lambda}\left[1 \pm \sqrt{1 - \frac{2}{3}\frac{d\Theta}{dx}\left(\frac{\Lambda}{bq}\right)^2}\right] \quad \Longrightarrow \quad \frac{d\Theta}{dx} < 0$$

results in an exponential growth of turbulence

- **Unstable temperature gradient is assured due to leak flow and heat transfer from pipe**

Integral Thermal Cycling Code Formulation (TC^2) -- UH Configuration (same for DH config.)



- **Model states:**
  - ▷ pipe temperature (T_1, T_2, T_3)
  - ▷ fluid temperature (Θ_1, Θ_2, Θ_3)
  - ▷ turbulence in regions 1 & 2
  - ▷ mixing interface location (L_m)
- **Boundary conditions:**
  - ▷ fluid temp in header pipe (Θ_0)
  - ▷ fluid temp of cold leak (Θ_4)
  - ▷ turbulence in header pipe
- **Model equations in region 1 (similar equations for regions 2 & 3):**

$$\frac{dT_1}{dt} + \left[T_1 - T(L_m)\right]\frac{1}{L_m}\frac{dL_m}{dt} = -\frac{1}{\tau_1}\left(T_1 - \Theta_1\right)$$

$$\frac{d\Theta_1}{dt} + \left[\Theta_1 - \Theta(L_m)\right]\frac{1}{L_m}\frac{dL_m}{dt} = \frac{U}{L_m}\left[\Theta(L_m) - \Theta_1\right] + \frac{1}{\tau_{1,w}}\left(T_1 - \Theta_1\right) + \frac{\overline{u\theta}(0) - \overline{u\theta}(L_m)}{L_m}$$

$$\frac{dq_1^2}{dt} + \left[q_1^2 - q^2(L_m)\right]\frac{1}{L_m}\frac{dL_m}{dt} = \frac{U}{L_m}\left[q^2(L_m) - q_1^2\right] + \frac{2g}{\Theta_{ref}}\left(\frac{L_e}{L_m}\right)\overline{u\theta_1} - \frac{2b}{\Lambda}q_1^3 + \frac{\nu_c}{L_m}\left\{\left(q\Lambda\frac{\partial q^2}{\partial x}\right)_{L_m} - \left(q\Lambda\frac{\partial q^2}{\partial x}\right)_0\right\}$$

NDE Technology for Detection of Thermal Fatigue Damage in Piping

Pedro Lara
Stan Walker
Jim Holt

November 29, 2000

EPRI

Introduction

Work Performed For

Thermal Fatigue Issue Task Group
Materials Reliability Program

Task 6 - Produce NDE Inspection Guidelines

Reference: ***NDE Technology for Detection of Thermal Fatigue Damage in Piping (PWRMRP-23)*****, EPRI MRP TF-ITG, Report 1000152, Palo Alto, CA, September 2000.**

Outline

- Technology
  - Objective
  - Crack Morphology
  - Testing Procedure
  - Evaluation of NDE Technologies
- Examiner Qualification
  - Computer Based Training

Objectives

- Recommend Specific NDE Technologies & Variables for Inspection for Thermal Fatigue Damage for Small-Diameter (≤ 4 Inch), Butt-Welded Piping
- Detection
  - Location
- Identify Additional Qualification Requirements for NDE Examiners

Crack Morphology

- Crazing
  - Shallow, Transgranular Network With Large Aerial Extent & Extensive Branching
    - Cracks are ID Connected
    - No Preferred Direction
      - Checkerboard pattern sometimes observed
- Deeper, Dominant Cracks
  - Preferred Direction Likely (With Exceptions)
    - Circumferential Near Welds
    - Axial (Skewed) Away From Welds
    - Skewed on elbows

Crack Morphology at Tihange (Belgium)

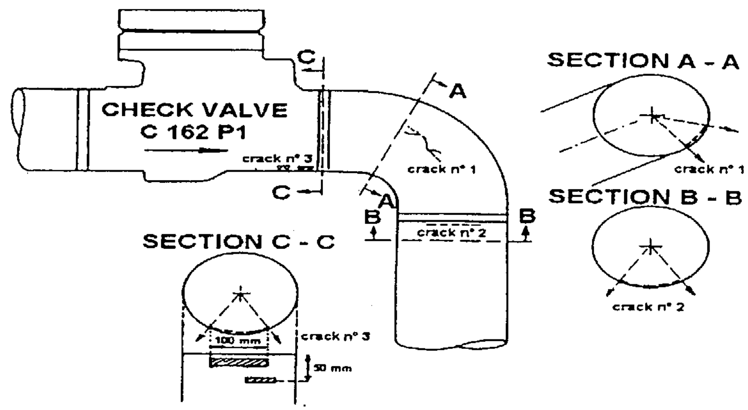


FIGURE 2. Field examination - Location of the cracks

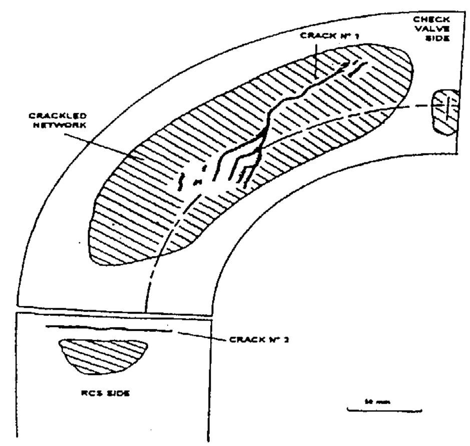
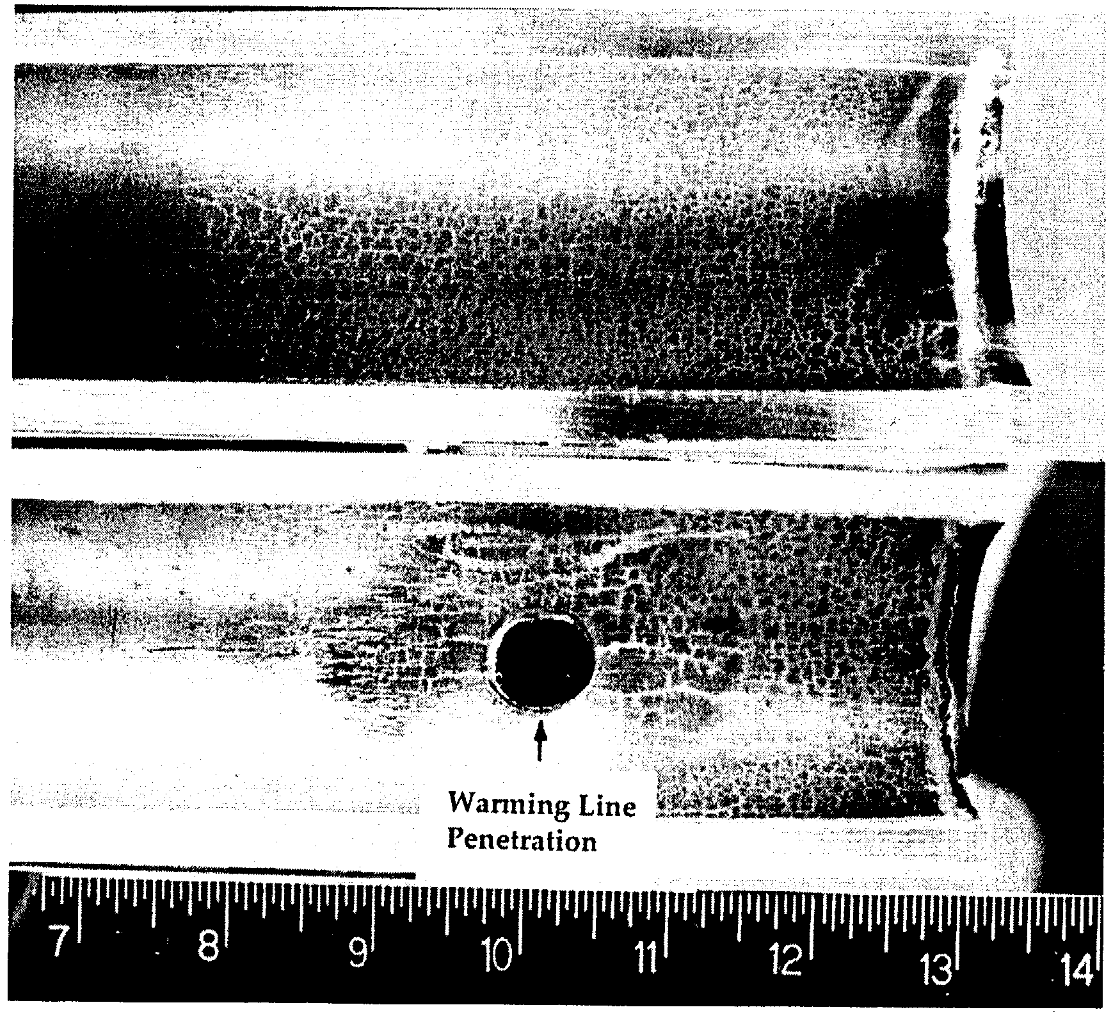


FIGURE 3. Laboratory examination - Location of cracks on ID

10

EPRI

Thermal Fatigue Indications at Oconee 2 HPI/MU Line



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NDE Technologies Evaluated

- Manual Pulse Echo Ultrasonics
- Time-of-Flight Diffraction
- Conventional Radiography
- Ultrasonic Spectroscopy
- Pulsed Eddy Current
- Vibro-Modulation

Evaluation Protocol

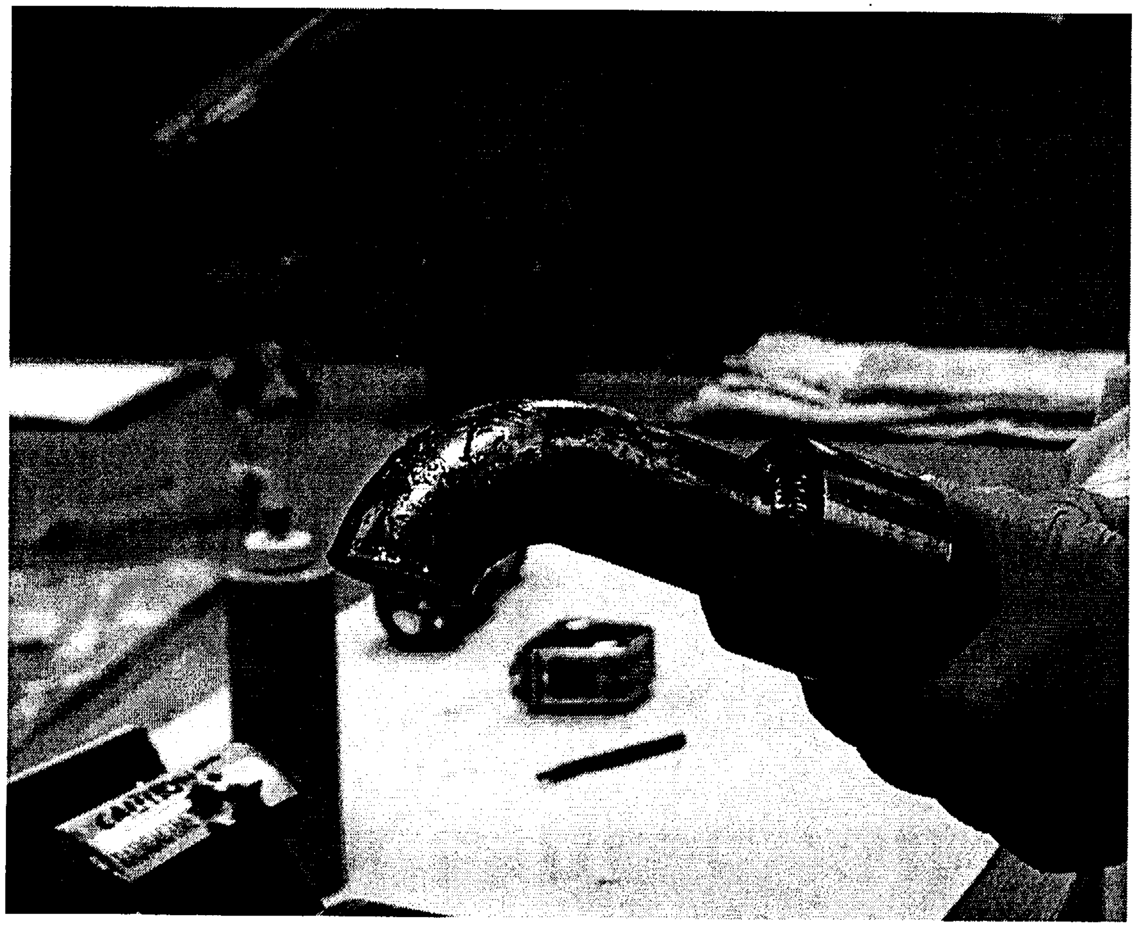
- Mockups Constructed
  - 3-Inch Diameter (6 Specimens)
    - 2 Pipes (No weld) w/ Axially Oriented Crazing and Straight & Skewed Cracks
    - Pipe w/ Circumferential Crack & Craze at Weld
    - Safe-End w/ Craze and Straight & Skewed Cracks at Counterbore
    - Elbow w/ Craze & Skewed Crack on Side
    - Elbow w/ Craze & Skewed Crack at Extrados
  - 1.5-Inch
    - 2 Pipes (No weld) w/ Axial & Skewed EDM Notches (To verify Proper Coupling and Wave Impingement)
- Technicians were allowed to calibrate on 1 mockup
- Required to examine other specimens as a blind test

Pulse Echo Ultrasonic Results

- Detected & Length-Sized Craze & Thermal Fatigue Cracks
  - Echo-Dynamic Technique
  - 2.25 or 5 MHz
  - Flat Wedge for Axial Scan (Circ. flaw)
  - Contoured (2x OD) for Circumferential Scan
- Generic Ultrasonic Examination Procedure Included as Appendix to Report
- Length-Sized Dominant Cracks in Oconee Drain Line at Field Trial Evaluation

EPRI

Oconee 1 Elbow with Marked Ultrasonic Indications



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Time of Flight Diffraction

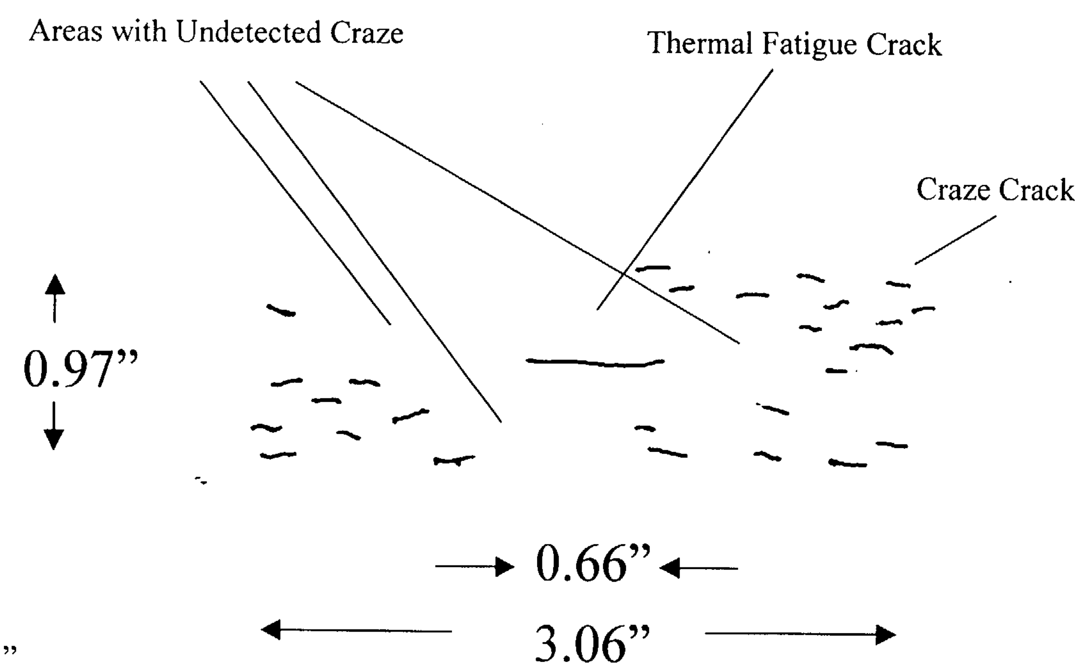
- TOFD Detected & Length-Sized Thermal Fatigue Cracks
- Showed Potential for Depth Sizing
- Scanners Need Improvement for Small Diameter Pipes
- Essential Variables Included in Report

Radiography Results

- Detected All Thermal Fatigue Cracks in Mockups. Requires
  - Fine Grain Film
  - Well Designed Shielding
- Detected Cracks with Depths >= 10%
- Length Sizing with Accuracy +/-25%
- Craze Detection Resulted in Accurate Identification & Size of Crazed Area
- Essential Variables Included in Report

Trace of the Radiographic Image for Mockup 9C-039

M Film, 10-mil Back/20-mil Front Screens, Crack 20% Deep/Craze 10% Deep



Actual craze length = 3”
Actual craze width = 1”
Actual thermal fatigue crack length = 1”

EPRI

Qualification of NDE Examiners

Examiner Qualification Necessary for Implementing NDE Methodology

UT

- Current Qualification Through Industry Standard for Piping, Plus
- Additional Indoctrination for Thermal Fatigue
  - Computer Based Training (CBT) Program Containing the Indoctrination has been Released for Beta Test

Conclusions

- Manual Pulse Echo Ultrasonics Performed Best.
  - Viable for Detection & Length-Sizing Thermal Fatigue Cracks When Applied in Accordance with EPRI Procedure
- Time-of-Flight Diffraction
  - Viable Detection Technique for Scanning Large Areas Semi-Automatically
  - Has Potential for Depth-Sizing
  - Scanners Require Modification for Small Diameter Piping

Conclusions (Continued)

- Conventional Radiography
  - Viable Technique for Detecting Cracks Deeper than 10% of Wall Thickness
  - Requires Fine Grain Film, and Well-Designed Shielding

- Ultrasonic Spectroscopy, Pulsed Eddy Current and Vibro-Modulation Require Further Development
- Report Provides Guidance for UT, TOFD, RT
- Computer Based Training Developed to Provide Recommended Indoctrination

MRP THERMAL FATIGUE PROJECT
Task 11
Interim Thermal Fatigue Management Guidelines
(MRP-24)

Art Deardorff
Structural Integrity Associates
November 29, 2000

BACKGROUND

- NRC Bulletin 88-08 Required Utility Actions Regarding Several Leakage Events
  - Farley - Tihange - Genkai
- HPI/MU Line Leakage at Oconee Raised Issue of Failures in Small (<4") Diameter SI Lines
- MRP Initiated Thermal Fatigue Program, Targeted for Completion in 2001
- In Mid-1999 Meeting with NRC, Commitment Made to Issue Interim Thermal Fatigue Management Guideline (ITFMG)

OBJECTIVE OF ITFMG

- **Provide Common Industry Approach to Reduce Probability of Leakage From Class 1 Piping Systems**

- **Applies to:**
  - **Non-isolable piping**
  - **Normally stagnant**
  - **Lines where thermal fatigue cracking has been observed**

- **Provides Guidelines for:**
  - **Identification of potentially susceptible locations**
  - **Evaluation criteria**
  - **Inspection/monitoring recommendations**

ITFMG OUTLINE

- Introduction/Background
- Recommendations
- Discussion of Basis of Choice of Locations
- Guidelines for Assessment, Inspection and Monitoring
- Feedback Request
- Appendices
  - MRP Thermal Fatigue Project Overview
  - Description of Significant Thermal Fatigue Cracking/ Leakage Events
  - Summary of EPRI UT Inspection Development Program

SELECTION OF SUSCEPTIBLE LOCATIONS

- Identify Locations Where Class 1 Thermal Fatigue Cracking had Occurred (Task 3)
- Excluded those that are
  - Unique in nature (e.g., non-US designs) and not related to turbulence penetration or in-leakage
    - Obrigheim 1986
    - Genkai 1988
    - Lovisa 1994
    - Biblis 1995
    - Loviisa 1997
  - Managed by other programs for lines with flow
    - Crystal River 1982
    - Oconee 1997

SELECTION OF SUSCEPTIBLE LOCATIONS

- **Remaining Events Include:**

  - Safety injection lines in-leakage events
    - Farley 1987
    - Tihange 1988
    - Dampierre 1992
    - Dampierre 1996

    All included possibility of leakage toward RCS

  - Drain/excess letdown lines (turbulence penetration)
    - Three Mile Island 1995
    - Mihama 1999
    - Oconee 2000

- **These Line Types Represent 50% of World Wide Leakage Experience and ALL of Related US Experience**

RECOMMENDATIONS

- **Multi-Step Approach Recommended**

- **Step 1: Perform an Evaluation per Guideline**
  - **Simple evaluation using guidelines can show lines not affected**

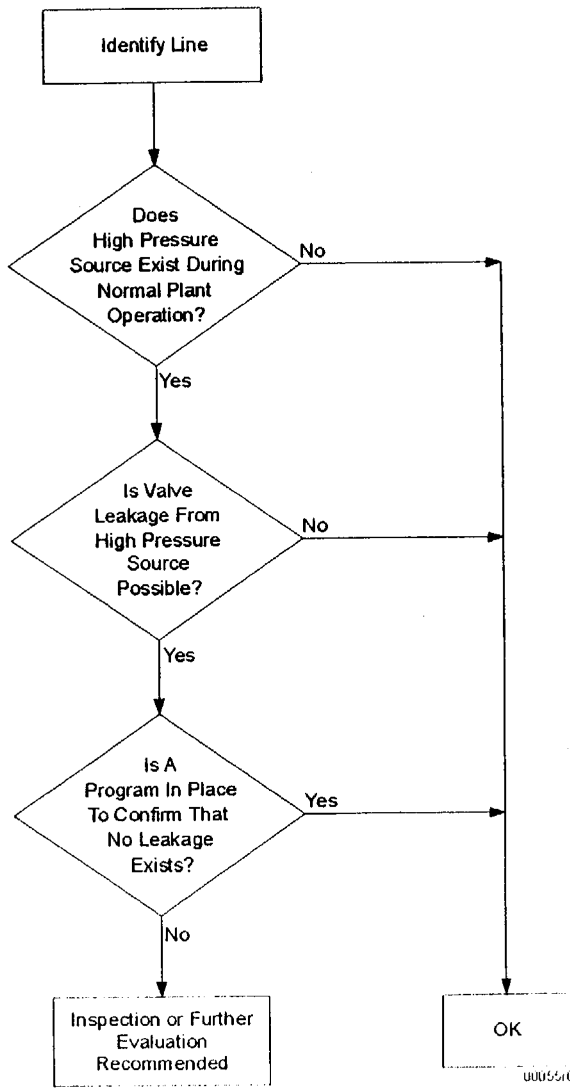
- **Then, if Required:**
  - **Step 2: Perform further evaluations; e.g., review plant specific monitoring data**
  - **Step 3: Perform Inspections**

LINES WITH POTENTIAL INLEAKAGE

- Susceptible Lines Are Those Stagnant Lines With High Pressure Source That Can Leak Toward RCS
  - B&W and CE plants probably not affected
  - W plants with 1½-inch SI lines included, although no pipe leakage ever observed

- Alternate Charging and Pressurizer Auxiliary Spray (W/CE Plants) Not Included Since Leakage Has Never Been Identified

INLEAKAGE EVALUATION CRITERIA



FACTORS SHOWING INLEAKAGE CANNOT OCCUR

- **System Configuration**
  (e.g., piping between charging pumps and RCS maintained at low pressure)

- **Multiple Isolation Valves in Series**

- **Monitoring Programs**

- **Valve Leakage Trending Program**

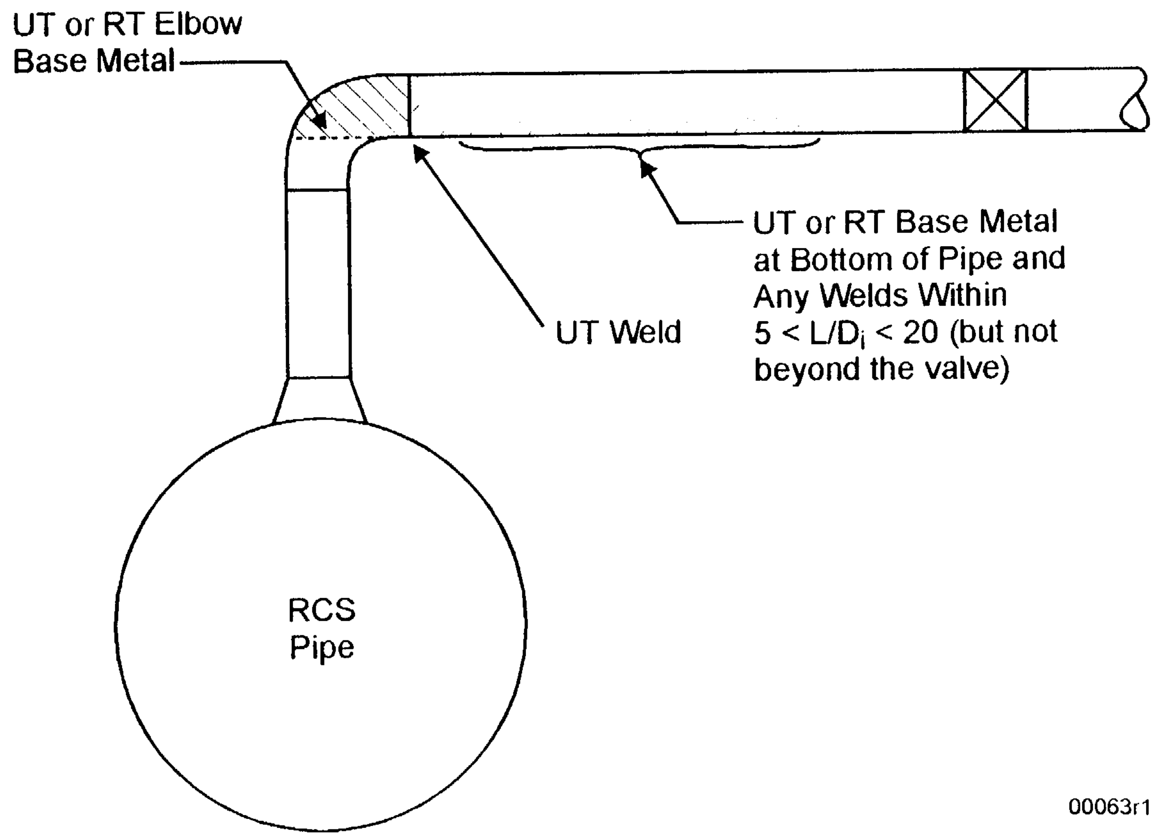
Note: If leakage is possible, assurance of negligible leakage must be provided throughout plant life

INLEAKAGE INSPECTION RECOMMENDATIONS

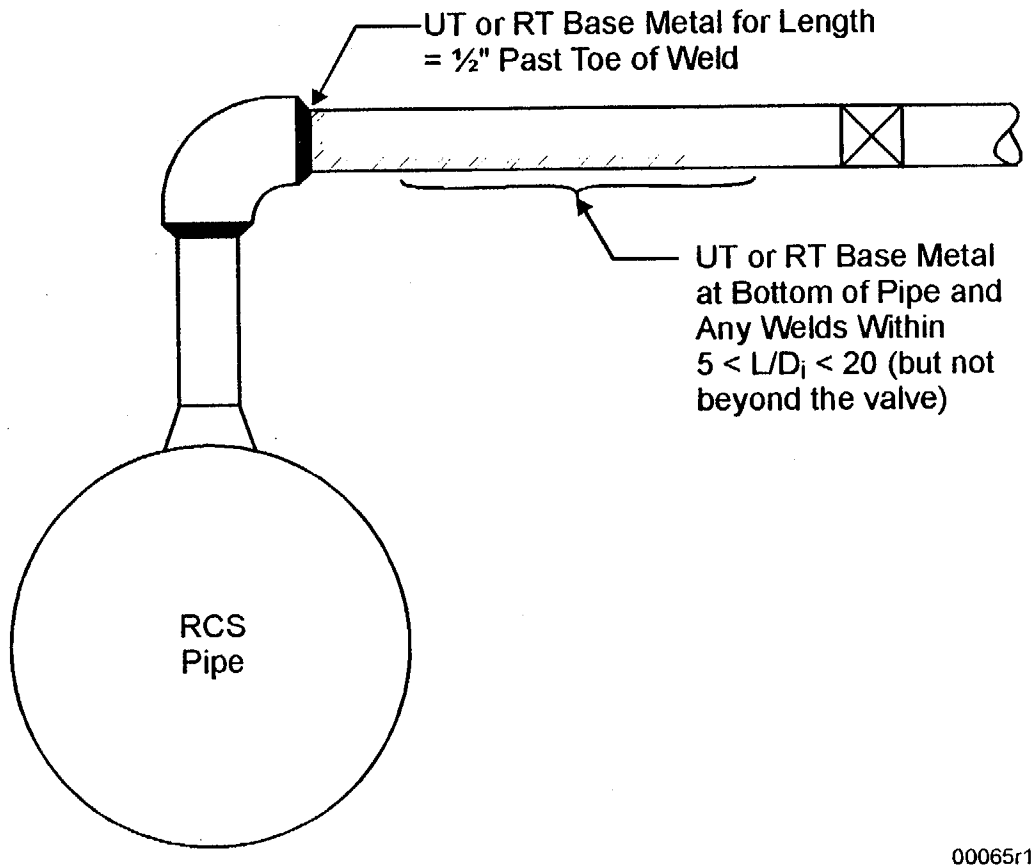
- Inspection is Concentrated on Four Regions
  - First horizontal weld
  - Butt-welded elbow base material
  - Scan along bottom of pipe (to $L/D_i = 20$)
  - Additional welds ($20\ L/D_i = 20$)

- EPRI RI-ISI Criteria Recommended for Welds

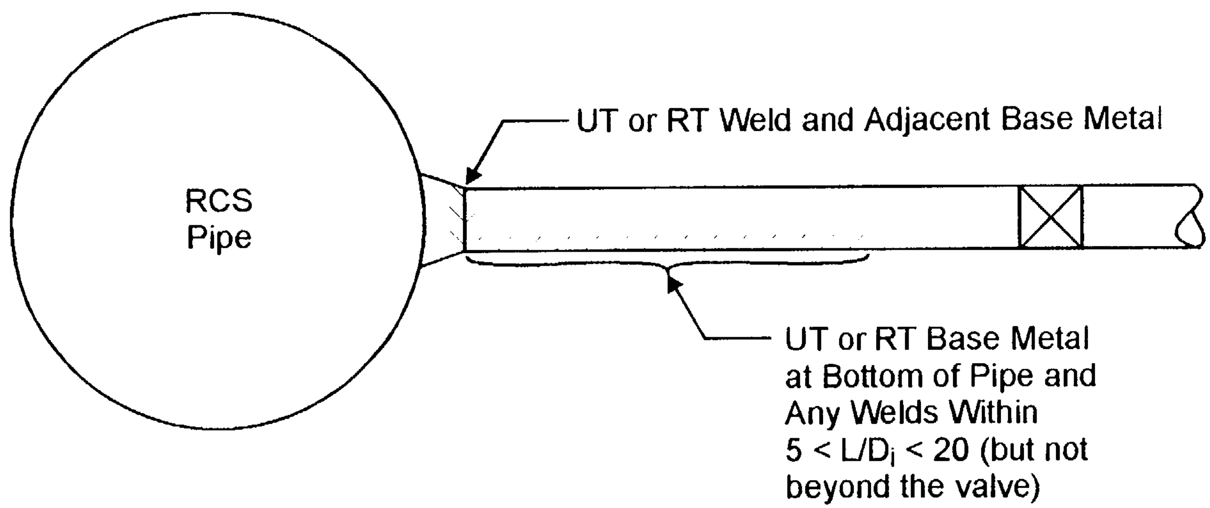
INLEAKAGE INSPECTION RECOMMENDATIONS



INLEAKAGE INSPECTION RECOMMENDATIONS

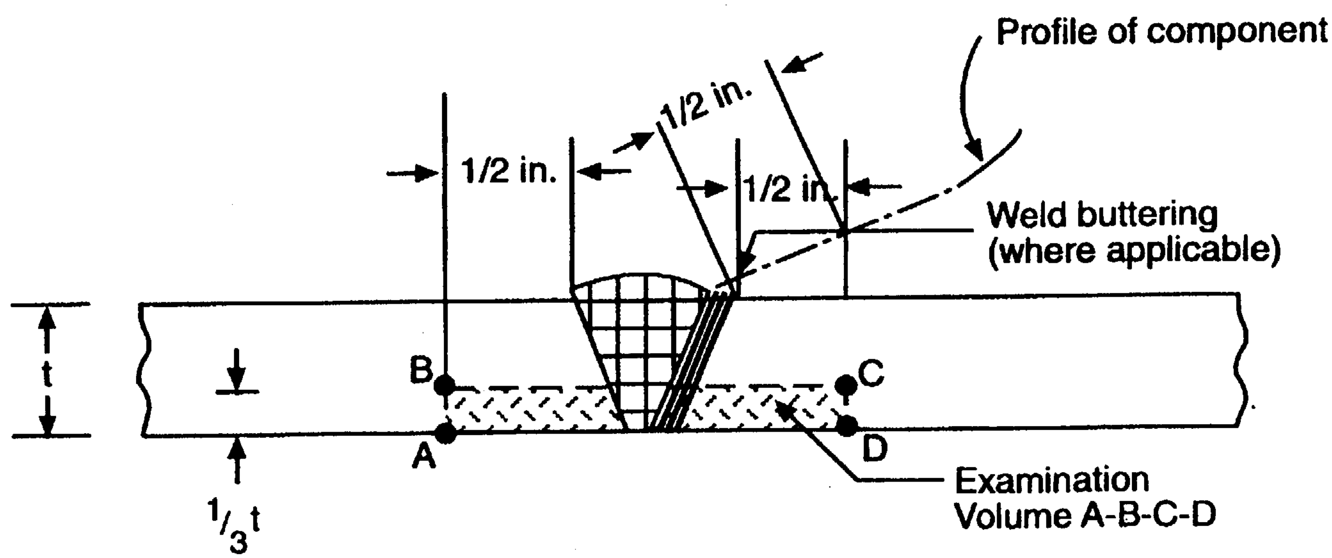


INLEAKAGE INSPECTION RECOMMENDATIONS



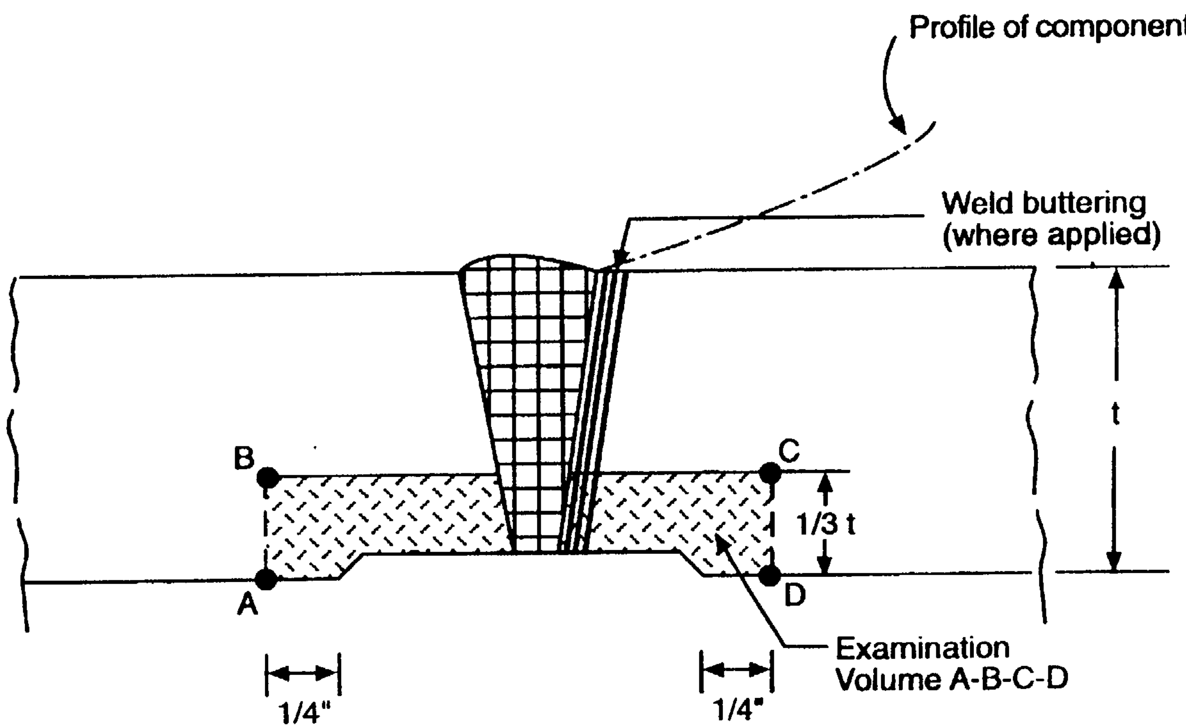
INLEAKAGE INSPECTION RECOMMENDATIONS

For welds <4" NPS



INLEAKAGE INSPECTION RECOMMENDATIONS

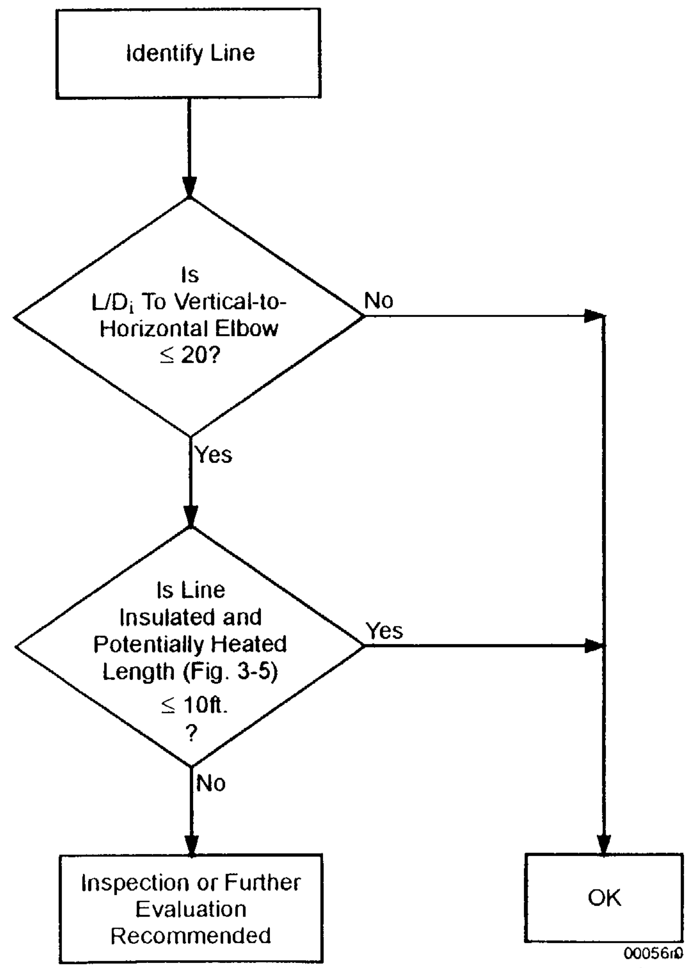
For welds 4" NPS and greater



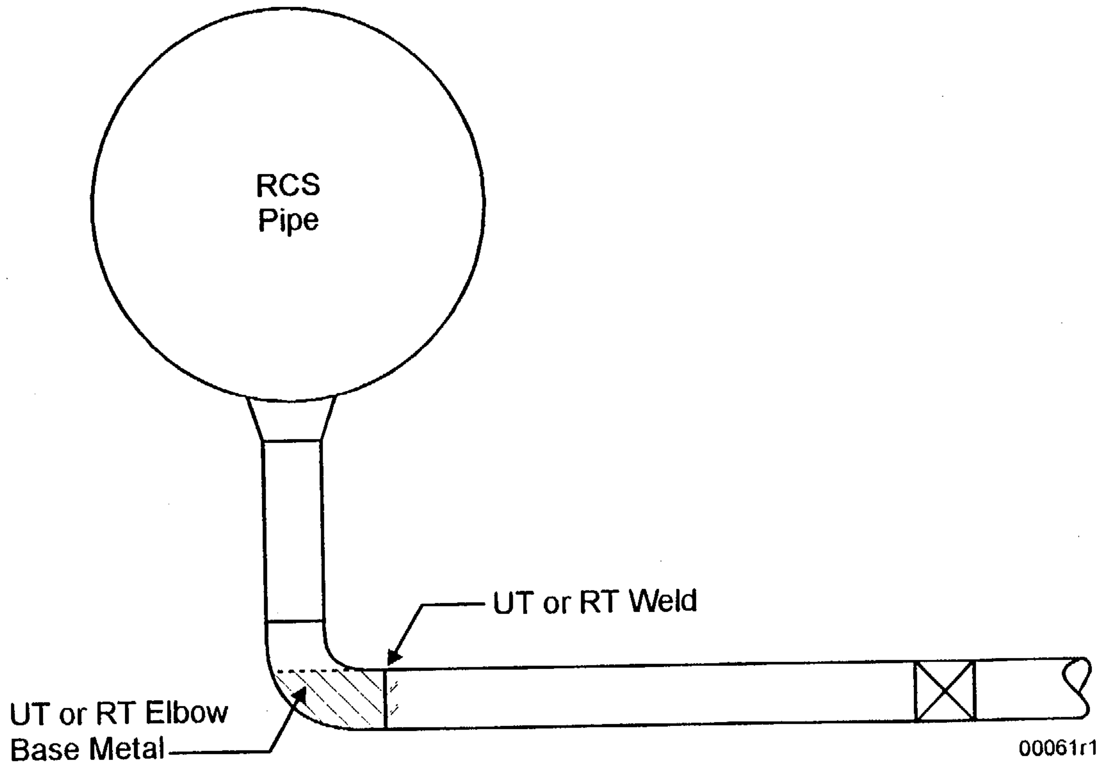
DRAIN-TYPE LINES

- Susceptible Lines are Those That
  - Exit bottom of RCS piping
  - Turn horizontal at $L/D_i < 20$
  - Have potential to lose heat if turbulence penetration is occurring
  - > 1-inch nominal diameter
- Exclude Those That are Insulated with Length < 10 ft.
- Inspection Recommended at Elbows

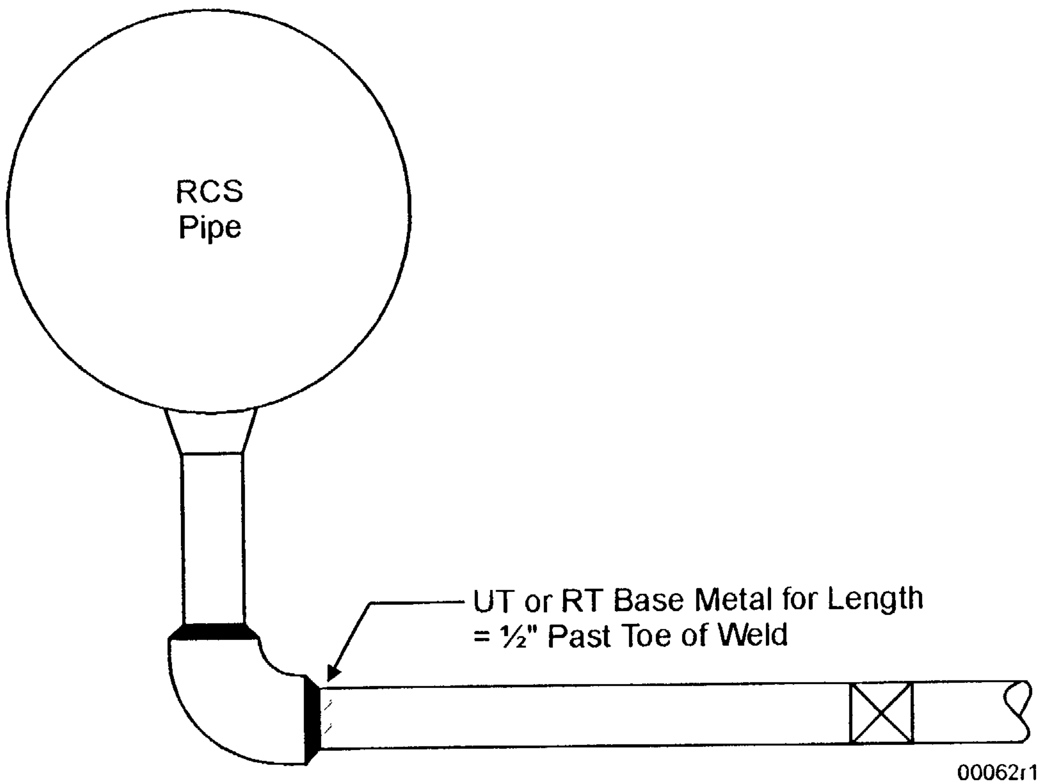
DRAIN-TYPE LINES



DRAIN-TYPE INSPECTION RECOMMENDATIONS



DRAIN-TYPE INSPECTION RECOMMENDATIONS



INSPECTION GUIDELINES

- Recommendations From Task 6 Included
- Training Should Include
  - Previous recognized program for piping ultrasonic inspection
  - Special indoctrination, referring to EPRI training material

MONITORING GUIDELINES

- General Guidance Provided On Monitoring
  - No specific recommendations provided for long-term monitoring
- Temporary vs. Permanent Monitoring
  - One-cycle monitoring of drain lines can show absence of thermal cycling
  - If monitoring is for in-leakage, data should be taken for each operating cycle
- Pressure and Valve Leakage Monitoring/Trending Discussed
- Baseline Inspections Recommended Prior to Monitoring

CONCLUSIONS

- Interim Guidelines Address Locations Where Multiple Leakage Events Have Occurred
- Criteria Provided for Identification of Potentially Susceptible Safety Injection and Drain-Type Lines
- Inspection Recommendations Provided
- Monitoring Can be Used as Alternative Approach in Some Cases

MRP THERMAL FATIGUE PROJECT
TASKS 7 & 9

Operations, Maintenance, and Modifications to Eliminate Thermal Fatigue

Art Deardorff
Structural Integrity Associates

NRC / MRP / NEI Meeting
November 29, 2000

TASKS 7 & 9 – MITIGATION OF THERMAL FATIGUE PRIMARY SUBTASKS

- **Identify Operational Practices That Contribute to Thermal Fatigue, and Methods to Modify Them**
- **Identify Improvements to Valve Maintenance Practices to Prevent In-leakage**
- **Identify Potential Piping System Modification to Minimize Potential for Thermal Stratification / Cycling**

TASKS 7 & 9 – MITIGATION OF THERMAL FATIGUE METHODOLOGY

- Used Results of Task 3 (Operating Experience Review)
  - Identified events caused by operations or maintenance practices
  - Reviewed corrective actions to mitigate thermal fatigue
- Reviewed EPRI/Industry Reports on Valve Maintenance
- Evaluated Typical Piping System Geometries
  - Determined areas susceptible to thermal fatigue by plant system
- Held Plant Workshops to Collect Data/Obtain Feedback

PRS-00-087/3

TASKS 7 & 9- MITIGATION OF THERMAL FATIGUE POTENTIAL PLANT MODIFICATIONS

- Identified a Range of Possible Modifications:
  - Replace isolation valves with more leak resistant design
  - Add insulation on drain lines
  - Change piping geometry - insert / relocate vertical runs
  - Relocate valve – increase/decrease distance from RCL
  - Add pressure control system to prevent inleakage
  - Others

PRS-00-087/7

TASKS 7 & 9- MITIGATION OF THERMAL FATIGUE OPERATIONAL PRACTICES

- Little Can be Done Operationally That Affects Non-Isolable Stagnant Lines
- Some Changes Identified as Good Practice That Could Effect Other Systems
  - Charging / alternate charging - eliminate changeovers during operation
  - Manage surveillance tests of isolation valves to minimize thermal cycling
  - Reduce auxiliary spray cycling during heatup / cooldown
  - Reduce cycling of RC pumps to minimize potential cross leakage stratification
  - Etc.

PRS-00-087/8

TASKS 7 & 9- MITIGATION OF THERMAL FATIGUE MAINTENANCE PRACTICES

- Maintenance Practices Apply Mainly to Valve Leakage Reduction. A Number of EPRI Reports Available on Valve Maintenance
- Key Improvements to Maintenance Practices Identified
  - Proper valve selection, design, operator stem thrust and performance trending to reduce leakage
  - Implementation of program to prioritize and test safety injection system isolation valves
  - Monitor / measure / trend valve leakage
  - Maintain pipe support clearances to accommodate global stratification movements

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TASKS 7 & 9 – MITIGATION OF THERMAL FATIGUE GOALS OF THERMAL FATIGUE WORKSHOPS

- Review Plant Specific Piping Geometry to Identify Susceptible Locations
- Understand Preventative Actions That Have Been Taken
  - System modifications
  - Valve maintenance programs
  - Operating procedure considerations
  - Monitoring – temperature measurement, valve leakage
- Explain Thermal Stratification / Cycling Mechanisms and Causes of Cracking With Plant Staff
- Obtain Feedback and Suggestions

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TASKS 7 & 9- MITIGATION OF THERMAL FATIGUE WORKSHOPS

- Conducted Thermal Fatigue Workshops at Three PWR Plants
  - McGuire (W), Waterford (CE), Davis Besse (B&W)
  - Day 1: Reviewed plant unique P&ID's, piping isometrics, monitoring
  - Evaluated systems against Interim Thermal Fatigue Management Guidelines
  - Day 2: Workshop with plant staff from design/operations/systems/maintenance

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TASKS 7 & 9- MITIGATION OF THERMAL FATIGUE WORKSHOPS

- Plant Design Differences Affect Thermal Fatigue Susceptibility
  - Valve in-leakage not possible in some plants
  - Piping geometries/positions of isolation valves can eliminate potential for stratification
- The Three Plants Had Few Non-isolable Locations with any Potential for Thermal Stratification/Cycling
- Additional plant workshops planned for 2001 - 2002

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TASKS 7 & 9- MITIGATION OF THERMAL FATIGUE THERMAL FATIGUE MITIGATION REPORT

- Report Submitted for Publication by EPRI
  - Describes thermal fatigue mechanisms
  - Identifies systems and locations susceptible to thermal fatigue
  - Explains plant modifications, operating procedure changes, and maintenance actions that can be taken to mitigate thermal fatigue

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Conclusions

- TF ITG has made significant progress over the past year
- Guidance was assembled in a number of areas, e.g., the ITFMG, the NDE technology report, operating experience report, etc.
- The change of direction for the screening effort will provide insights into identifying where damaging TF may occur
- These products are being provided to utilities for implementation