NRC PUBLIC MEETING SUMMARY REPORT

Date: March 31, 2011

Meeting Contact: Gary L. Stevens
RES/DE/CIB
301-251-7569
Gary.Stevens@nrc.gov

Subject: CATEGORY 2 PUBLIC MEETING - SIMPLIFIED ENVIRONMENTALLY-ASSISTED FATIGUE ANALYSIS FOR OPERATING NUCLEAR POWER PLANTS

Meeting Date/Time: Tuesday, March 22, 2011

Location: U.S. Nuclear Regulatory Commission
One White Flint North, 9th Floor, Room B02
11555 Rockville Pike
Rockville, MD 20852-2738

Purpose: The NRC staff is performing research on environmentally-assisted fatigue, and is soliciting relevant input from interested technical parties on this subject. The purpose of this meeting was to have technical discussions related to the evaluation of environmentally-assisted fatigue (EAF) for operating plants, with a focus on boiling water reactors (BWRs).

The American Society of Mechanical Engineers (ASME) Boiler & Pressure Vessel (B&PV) Code, Section III has detailed procedures for the fatigue analysis of nuclear facility components. The environmental fatigue criteria (in particular, the environmental fatigue multiplier, F_{en}, factors) recommended in NUREG-1801, Revision 2, "Generic Aging Lessons Learned (GALL) Report," (as defined in NUREG/CR-6583, NUREG/CR-5704, and Regulatory Guide 1.207 and associated NUREG/CR-6909) involve time-rate effects not typically considered in ASME fatigue analyses. Also, the F_{en} factors are based on tests at constant temperature, whereas much of the fatigue stress cycles in nuclear facility components are due to temperature transients. Finally, the environmental fatigue rules require determination of the component strain rate, but the information necessary for calculating strain rate is not always available, especially for actual operating transients.

A method was presented by the industry to apply the environmental fatigue rules in ASME fatigue analysis based on information that is readily available in the design thermal cycle diagrams and associated stress reports. The objective of the method is to develop a simplified, bounding approach that does not require detailed knowledge of the actual operating transients.

Summary: The announcement for this meeting was posted on March 7, 2011 on the NRC web site. It is available via ADAMS at Accession No. ML110620614.

The meeting agenda is provided in Attachment 1.

Meeting attendance is provided in Attachment 2.

Gary Stevens (NRC) opened the meeting and summarized that the NRC Office of Nuclear Regulatory Research is performing research on environmental fatigue. Argonne National Laboratory (ANL) is performing technical consulting on proposed ASME Code Section III Code Cases, reviewing additional available laboratory collected over the past 10 years or so, and reviewing aspects of the F_{en} methodology that have led to practical application issues. The intent will be to revise Regulatory guide 1.207 appropriately, if warranted, based on the results of these efforts.

The industry's presentation, as given by Bob Carter (EPRI) and Sam Ranganath (XGEN Engineering) is provided in Attachment 3. (Note that the presentation provided in Attachment 3 has been revised to correct several typographical errors that were identified during the meeting.) Bob stated that the industry's objectives in presenting this material were three-fold, as follows:

1. For locations where is can be demonstrated that design transient severity overwhelm environmental effects, can F_{en} effects be ignored?
2. What is the best way to submit such work to the NRC? Via a Topical Report, a Lead Plant Study, or both?
3. Could the proposed methodology be used for other locations? i.e., besides the feedwater nozzle location discussed in the presentation?

There were several questions asked during the presentation to clarify the content, and discussion ensued afterward.

There were no other presentations offered, nor were there any comments from any members of the public.

The meeting was adjourned at 3:40 pm.

Attachments: The following attachments are included with this report:

Attachment 1

AGENDA
SIMPLIFIED ENVIRONMENTALLY-ASSISTED FATIGUE ANALYSIS FOR OPERATING NUCLEAR POWER PLANTS

March 22, 2011

1:00 p.m. – 4:00 p.m.

Location:

U.S. Nuclear Regulatory Commission
One White Flint North, 9th Floor, Room B02
11555 Rockville Pike
Rockville, MD 20852-2738

Purpose of Meeting:

The purpose of this meeting is to have technical discussions related to evaluation of environmentally-assisted fatigue (EAF) for operating plants, with a focus on boiling water reactors (BWRs).

Agenda:

Time	Topic	Led By
1:00 p.m. - 1:05 p.m.	Attendance	NRC
1:05 p.m. - 1:15 p.m.	Opening Remarks and Background	NRC
1:15 p.m. - 1:30 p.m.	Description of Planned NRC Research Activities	NRC
1:30 p.m. – 3:00 p.m.	Technical Presentations by Interested Parties*	Miscellaneous
3:00 p.m. – 3:30 p.m.	Discussion	NRC
3:30 p.m. – 3:45 p.m.	Public Comments	Miscellaneous
3:45 p.m. – 4:00 p.m.	Conclusion/Document Actions	NRC
4:00 p.m.	Adjourn	

* Interested parties should pre-arrange relevant technical presentations by contacting the designated NRC meeting contact.

Attachment 2

Attendance List

The following individuals participated via telephone:

Name	Organization	E-mail
Dave Bremer	NPPD – Cooper Nuclear Station	dwbreme@nppd.com
Russ Cipolla	Intertek - APTECH	russel.cipolla@intertek.com
Steve Gosselin	Scandpower Inc.	srg@scandpower.com
Jack Cole	Vice Chair, ASME Section III	jrcole07@charter.net
Chris McGaughy	AREVA	chris.mcgaughy@areva.com
Dave Gerber	Structural Integrity Associates	dgerber@structint.com
Tim Gilman	Structural Integrity Associates	tgilman@structint.com
Bill Weitze	Structural Integrity Associates	wweitze@structint.com
Paul Hirschberg	Structural Integrity Associates	phirschb@structint.com
Jon Hornbuckle	Southern Nuclear Operating Co.	jehornbu@southernco.com
Ken Wolfe	EPRI	kwolfe@epri.com
Paul Donavin	Nextera Energy	paul.donavin@nexteraenergy.com
Robert Gurdal	AREVA	robert.gurdal@areva.com
Tom Quintenz	Exelon Nuclear	tom.quintenz@exeloncorp.com
Nancy Chapman	Bechtel	ngchapma@bechtel.com
Har Mehta	GE-Hitachi Nuclear Energy	hardayal.mehta@gene.ge.com
Shannon Chu	EPRI	schu@epri.com
Rob Tregoning	NRC	robert.tregoning@nrc.gov
Terry Herrmann	Structural Integrity Associates	thermann@structint.com
Yogen Garud	Consultant, Argonne	yogengarud@gmail.com
Lora Drenth	XE Nuclear	lora.drenth@xenuclear.com

The following page provides a list of participants that attended in person.

ATTENDANCE LIST
for
Public Meeting

SIMPLIFIED ENVIRONMENTALLY-ASSISTED FATIGUE ANALYSIS FOR OPERATING NUCLEAR POWER PLANTS

March 22, 2011
1:00 p.m. – 4:00 p.m.

Location: U.S. Nuclear Regulatory Commission
One White Flint North, 9th Floor, Room B02
11555 Rockville Pike
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Name	Organization	E-mail
Gary L. Stevens	U.S. NRC-RES	gary.stevens@nrc.gov
On Yee	NRC-NRR	on.yee@nrc.gov
Robert Carter	EPRI	bcarter@epri.com
Sam Ranganath	XGEN	sranganath@sbcglobal.net
Randal Schmidt	PSEG	Randal.Schmidt@pseg.com
Letitia Midmore	EPRI	lmidmore@epri.com
Allen Hiser	NRC/NRR	Allen.Hiser@nrc.gov
Randy Stark	EPRI	rstark@epri.com
Chuck Wirtz	FirstEnergy	cjwirtz@firstenergycorp.com
Robin Dyle	EPRI	RDYLE@EPRI.COM
Mark Gray	Westinghouse	GRAYMA@WESTINGHOUSE.COM
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John Tsao	NRC-NRR	John.Tsao@NRC.gov
K.R. Hsu	NRC-NRO/DE	Kaihwa.hsu@nrc.gov
Antonio Dias	NRC/DLR	Antonio.Dias@nrc.gov

<u>Attachment 3</u>
Presentation Material

(33 pages follow)

Simplified Methods for Including Environmental Effects in ASME Code Fatigue Analysis for BWRs

Sam Ranganath
XGEN Engineering

Bob Carter
EPRI

March 22, 2010
U.S. NRC Office
Washington, DC

Outline

- Objectives
- Background
- BWR Design Transients vs. Actual Transients
- Analysis of Stresses due to Step Change vs. Ramp
- Effect of Stress Over-Estimate vs. Fen on Fatigue Usage
- Summary and Conclusions
- Potential Next Steps

Objectives

- To demonstrate generically that there is sufficient conservatism in current ASME code analysis to offset any environmental effects; i.e. no plant-specific Fen analysis is needed
- To obtain feedback from the NRC staff

Background

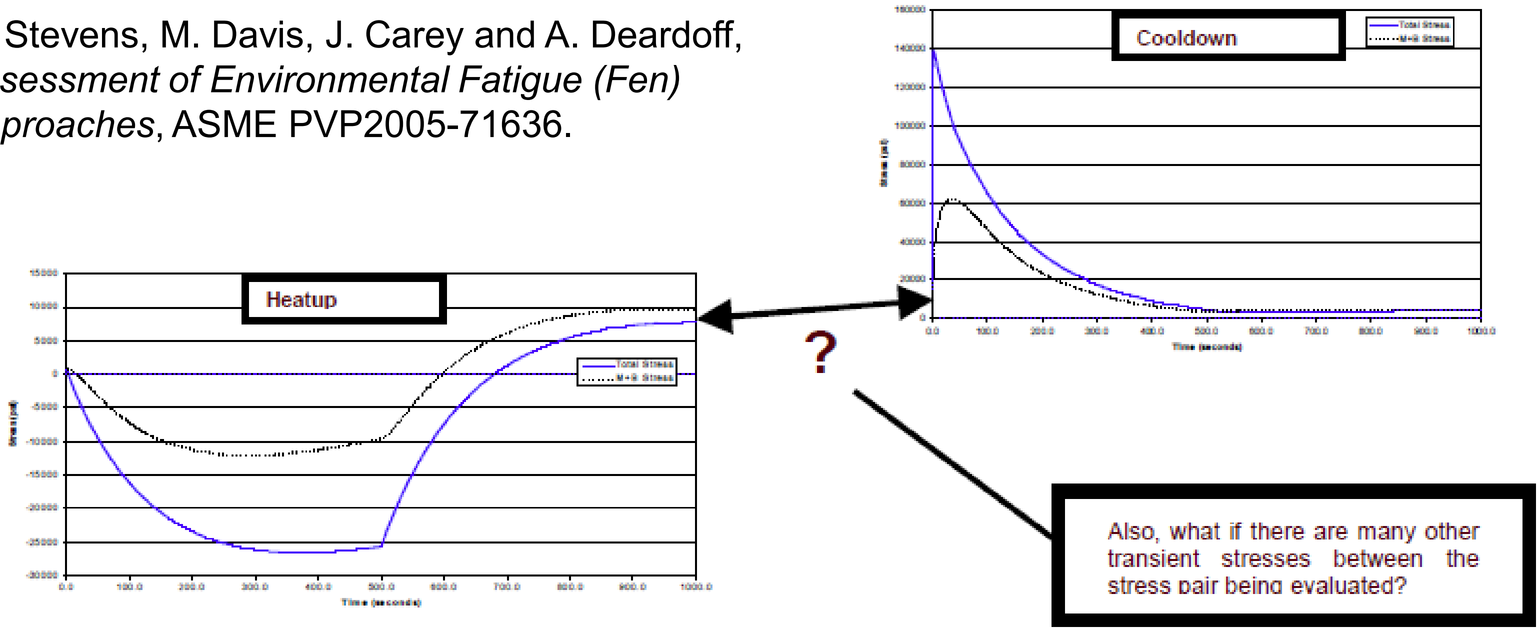
- Fatigue tests in the environment have clearly shown that there is a significant reduction in fatigue life due to EAC
  - Tests done at constant temperature
  - Plant conditions involve temperature and thermal stress cycling
- The Fen rules in RG 1.207 consider factors such as strain rate ($\dot{\varepsilon}$), temperature (T) and dissolved oxygen (O)
- Difficult to define these parameters for plant conditions
  - In actual plant cycling, the strain rates are not known a priori
  - Analysis done using idealized transients often with step changes in temperature (conservative for current ASME Code analysis)
  - Temperature and oxygen content change through the transient
  - Difficult to consider stress range pairs that occur over months and years (e.g. scram-earthquake, cooldown-hydro test)
- Need to reconcile design transients and plant cycles

Comparison of Reactor vs. Test Cycling

Actual Plant Fatigue Cycling	Cycling as Analyzed in ASME Code analyses	Fatigue Cycling in Most EAC Test Programs
Combined pressure and temperature transients	Analyzed based on elastic behavior	All the tests are based on mechanical load cycling alone
Temperature varies during much of the stress cycling	Temperature effects are included in the analysis	Almost all the tests are done at constant temperature
During a cool-down highest stresses occur at lower temperatures	The concurrence of low temperatures and high thermal stresses is not addressed	Effect of lower temperatures during tensile stress is not addressed (isothermal tests)
The ramp times for the different transients are not known	Most thermal transients are analyzed as step changes	Ramp time (proportional to 1 / frequency) is an important variable
Weld residual stresses exist but are not quantified	Weld residual stresses are considered in ASME code fatigue analysis, but are eliminated because of shakedown in many cases	Residual stresses affect fatigue initiation, but most specimens do not include welds
Peak to peak cycling ranges come from transients that could be separated by months	Fatigue usage is computed by combining the extreme cases	Cycling in the test is well defined (not separated by months), uniform, in sequence
Water chemistry (conductivity, sulfate and chloride, oxygen) varies during plant operation	Water chemistry is not a consideration in ASME Code fatigue analysis	Autoclave water chemistry is an important factor in fatigue initiation and crack growth

Linking of Transients

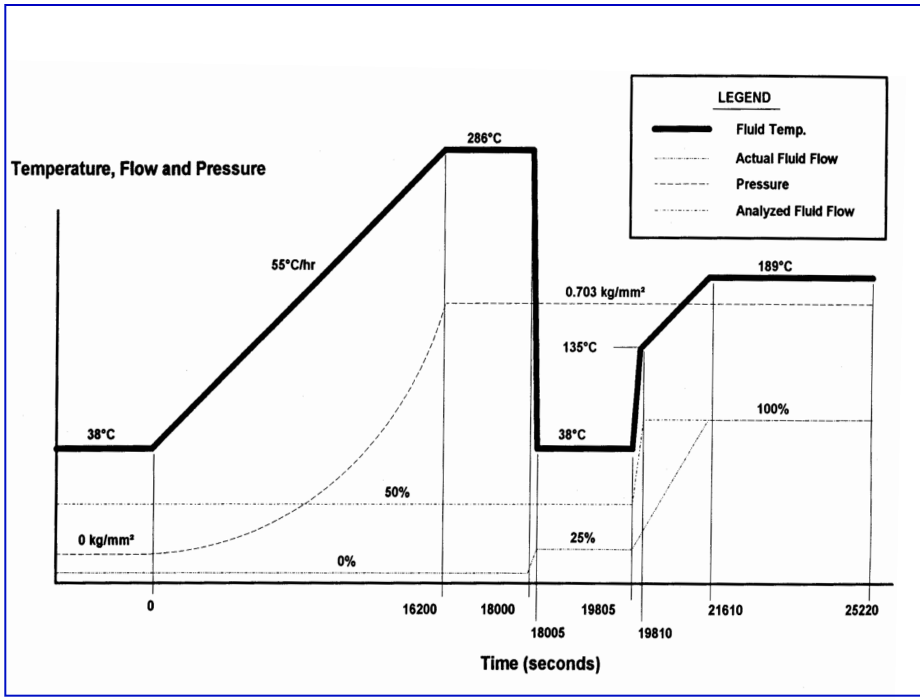
G. Stevens, M. Davis, J. Carey and A. Deardoff, *Assessment of Environmental Fatigue (Fen) Approaches*, ASME PVP2005-71636.

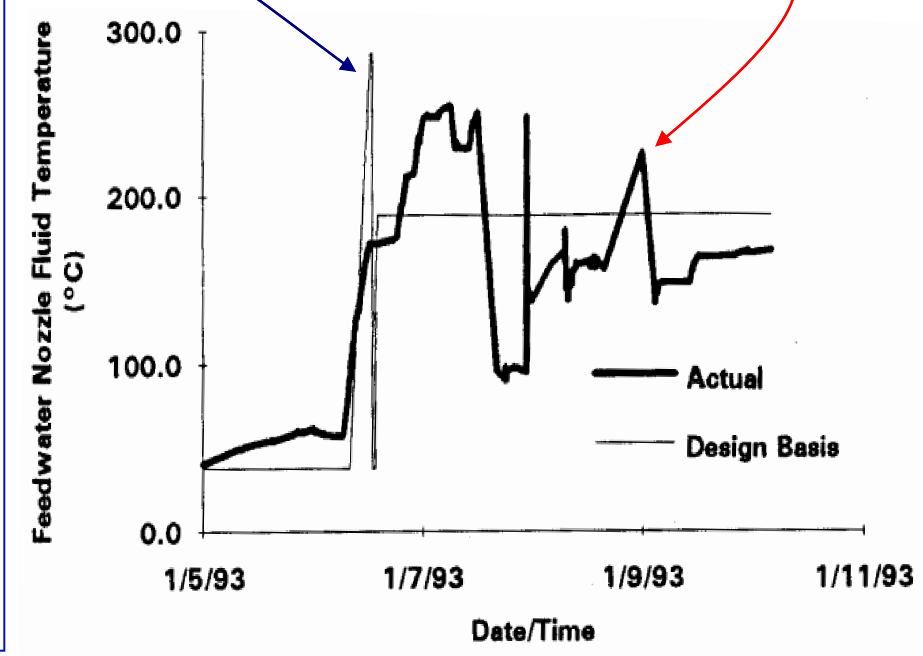


- How to treat cases where the starting and ending stress points are not equal?
- What rate of change is assumed for the discontinuity between transients?
- What is strain rate?
- The “real world” is different than laboratory tests, i.e., loading rates are random as opposed to carefully controlled (“ramped” or “saw-toothed”) loads applied in the laboratory.

BWR Startup-Turbine Roll Transient

Design Basis Transient — Compared with — **Actual Transient**

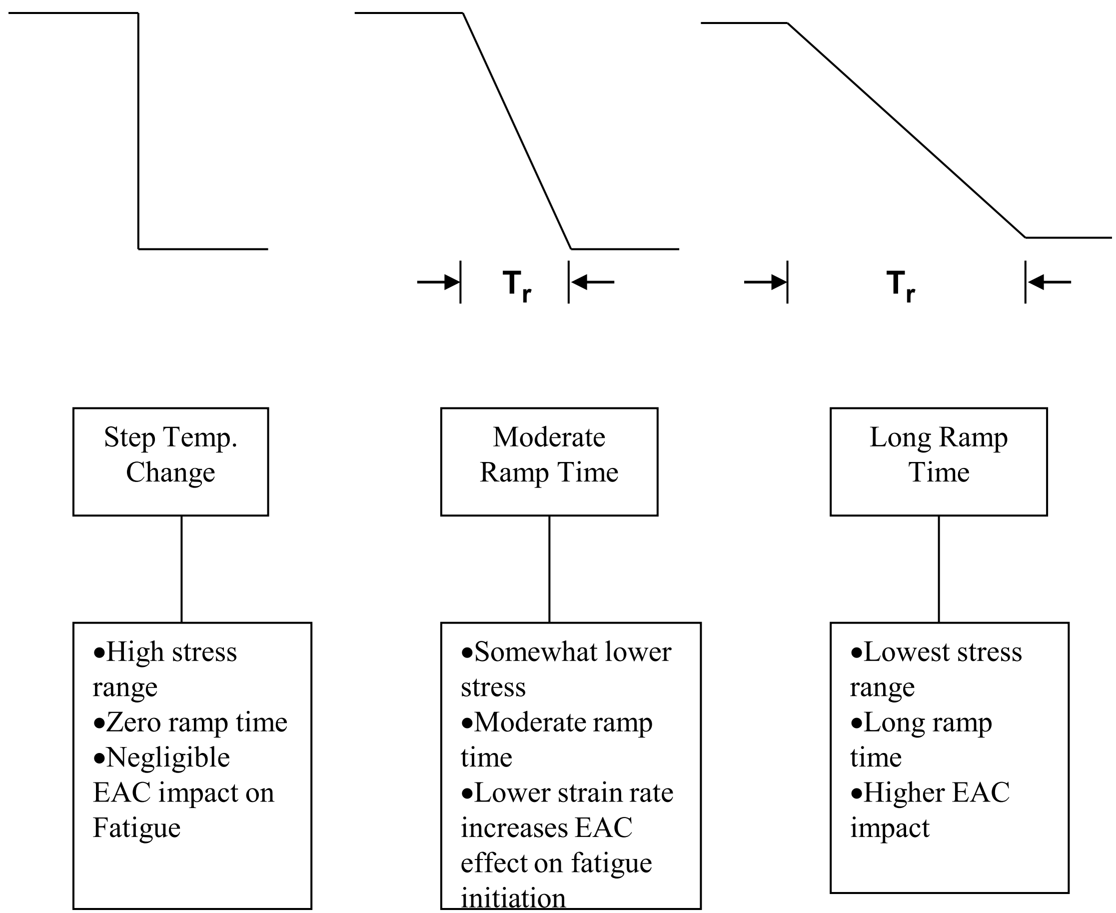




- Design basis transient occurs over ~7 hours
- Actual transient occurs over several days
- Ramp effects and associated stresses are significantly different

Effect of Ramp Time on EAC Fatigue

Temperature
vs.
Time



Design Thermal Cycles vs. Actual Transients

- Design thermal transients tend to be mostly step changes or rapid transients
  - Step changes overestimate the stresses and are conservative for fatigue analysis
  - Slow transients result in lower stress, but have greater environmental effect
- Plant operation experience show much slower transients
  - Trade off between higher design stress estimate (conservative) and higher Fen effect during operation (non-conservative)

If the conservatism in stress is sufficient to account for the Fen factor, then the current cumulative usage factor (CUF) will still be bounding with environmental effects

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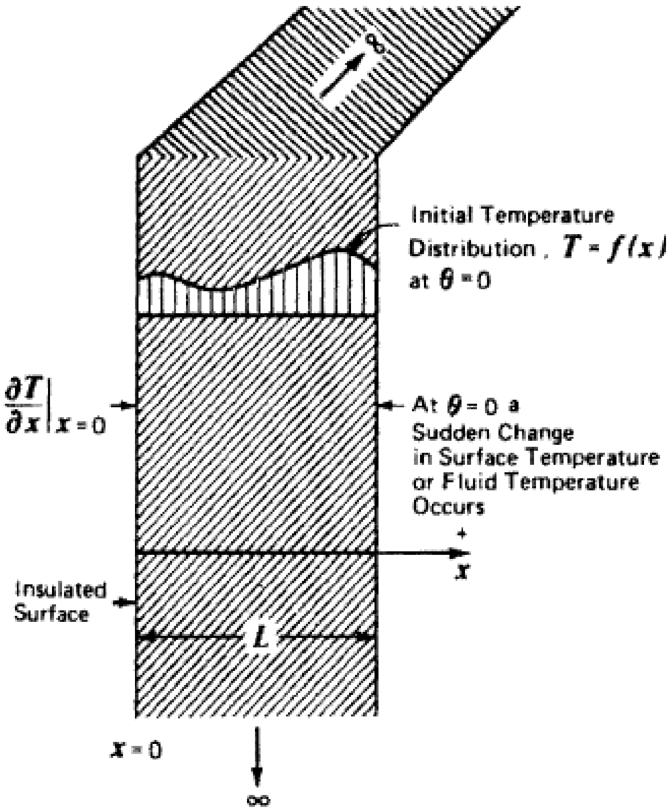
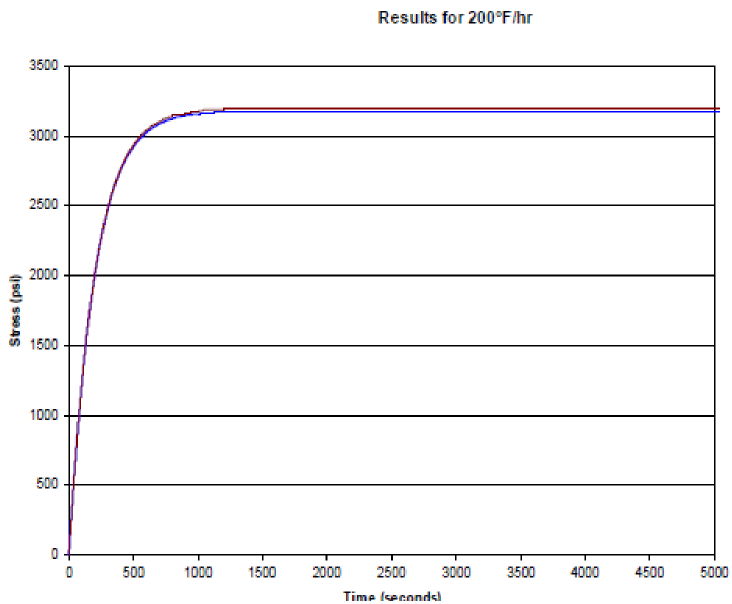
Thermal Stress Analysis for Ramp and Step Change

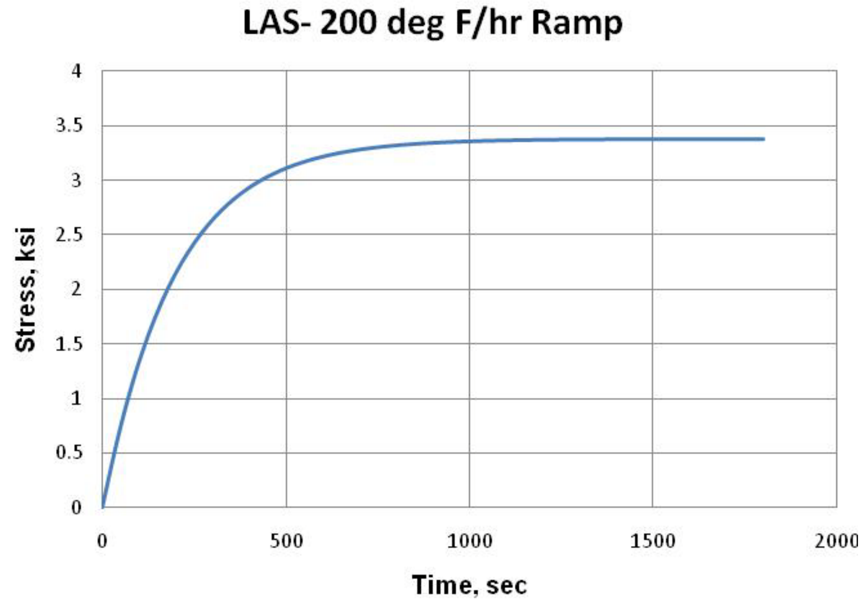
- Thermal analysis for a an infinite plate insulated on one side (x=0) and subjected to fluid temperature change on the other face
  - Assumed heat transfer coefficient on wetted surface
  - Initial temperature assumed to be constant prior to transient
  - Step change or ramp temperature change assumed
  - Through thickness variation in temperature and average temperature determined
  - Stress analysis for pipe configuration



Validation of the Solution

Present Analysis





Inputs:

Material properties from:	LOWALLOY.INP	
Slab thickness :	2.5	inches
	(0.21	feet)
Heat transfer coeff. :	2500	BTU/hr-ft^2-F
Material conductivity :	22.7	BTU/hr-ft-F
Material diffusivity :	0.35	ft^2/hr
Material coeff. of exp. :	7.34E-06	in/in-F
Material Youngs modulus :	2.67E+07	psi
Material Poissons ratio :	0.3	
Stress index, K3 :	1.5	
Transient Ti :	600	F
Transient Tf :	50	F
Transient delta-T :	550	F
Dissolved oxygen, DO :	55	ppb
Material sulfur content :	0.015	wt. %
Biot Number :	22.944	

Materials Reliability Program: Evaluation of Controlling Transient Ramp Times Using Piping Methodologies When Considering Environmental Fatigue (Fen) Effects (MRP-218). EPRI, Palo Alto, CA: 2007. 1015014. (G. Stevens)

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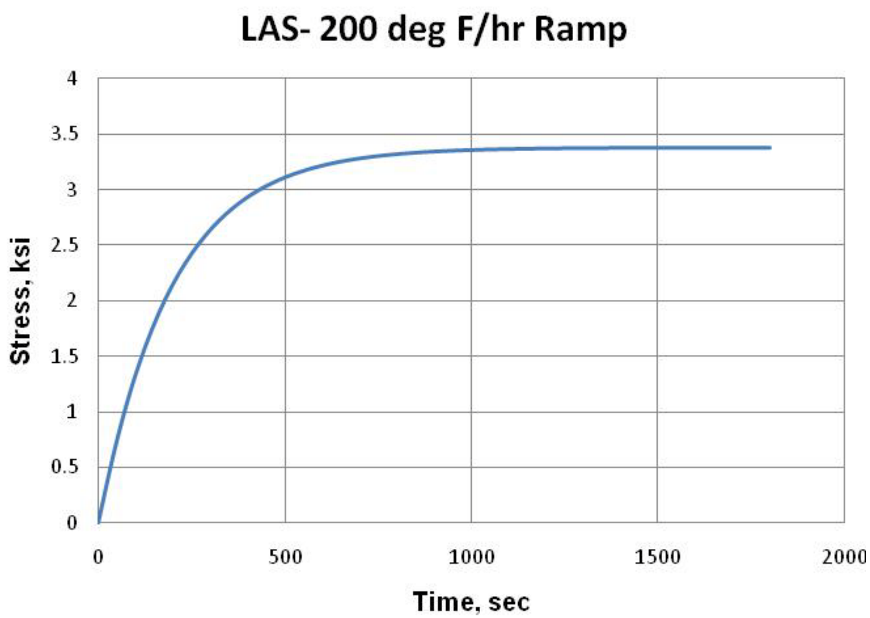
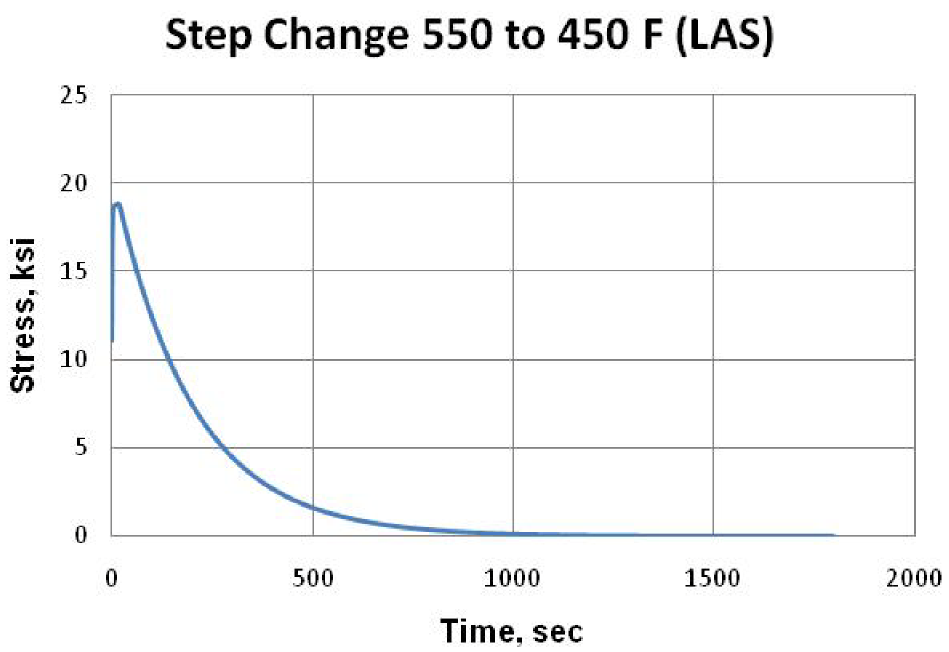
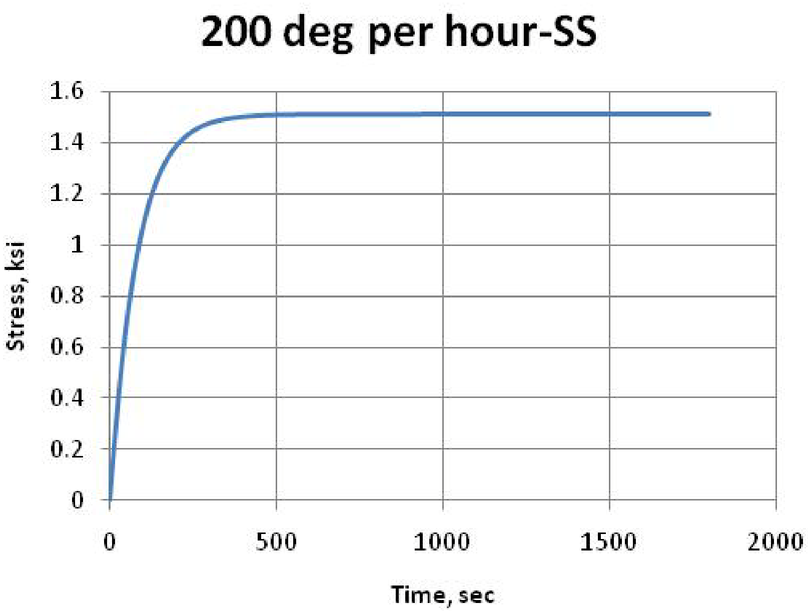
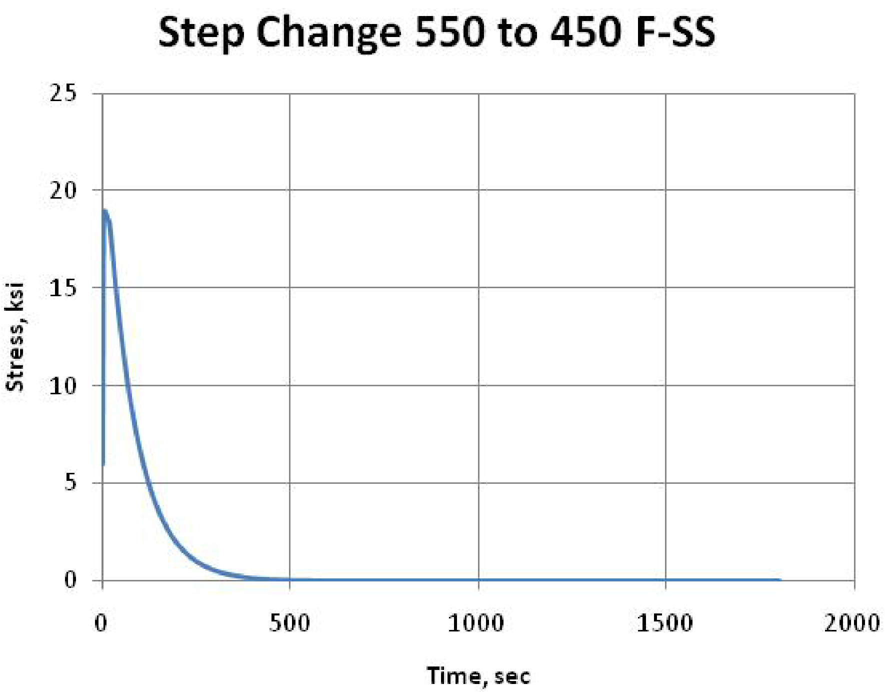
Ramp vs. Step Change Stress Comparison Low Alloy Steel (LAS)





Ramp vs. Step Change Stress Comparison Stainless Steel (SS)





Observations from the Stress Analysis

- Actual temperature ramp rates are far lower than those used in the stress analysis
  - –Effect is two fold: stresses are much lower than the values in the stress report, but Fen factors are much higher
  - –The key question is: “Does the conservatism in the stress calculation make up for the environmental effect due to the low strain rates?”
  - –Stress might have been over-estimated by a factor of 10-50
  - –For a step change, stress is proportional to ΔT, but for a ramp the stress is proportional to ramp rate. Difference between step and ramp is significantly higher for higher ΔT

Ramp Rate	Calculated Stress (LAS)
Step Change (100° F)	**18.9 ksi**
Step Change (500° F)	**94.3 ksi**
200° F/hour	**3.4 ksi**
100° F/hour	**1.7 ksi**
50° F/hour	**0.85 ksi**
25° F/hour	**0.42 ksi**

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Fen Factors from RG 1.207

- Fen Factor for carbon steels is
  Fen,nom = exp(0.632 – 0.101 S* T* O* ε̇*)
- Fen Factor for low-alloy steels, is
  Fen,nom = exp(0.702 – 0.101 S* T* O* ε̇ *)

$S^* = 0.001$	$(S \leq 0.001 \text{ wt.\%})$
$S^* = S$	$(S \leq 0.015 \text{ wt.\%})$
$S^* = 0.015$	$(S > 0.015 \text{ wt.\%})$
$T^* = 0$	$(T < 150°C)$
$T^* = T - 150$	$(T = 150–350°C)$
$O^* = 0$	$(DO \leq 0.04 \text{ ppm})$
$O^* = \ln(DO/0.04)$	$(0.04 \text{ ppm} < DO \leq 0.5 \text{ ppm})$
$O^* = \ln(12.5)$	$(DO > 0.5 \text{ ppm})$
$\dot{\varepsilon}^* = 0$	$(\dot{\varepsilon} > 1\%/s)$
$\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$	$(0.001 \leq \dot{\varepsilon} \leq 1\%/s)$
$\dot{\varepsilon}^* = \ln(0.001)$	$(\dot{\varepsilon} < 0.001\%/s)$.

- For wrought and cast austenitic stainless steels, Fen,nom = exp(0.734 – T’ O’ ε̇ ’)

$T' = 0$	$(T < 150°C)$
$T' = (T - 150)/175$	$(150 \leq T < 325°C)$
$T' = 1$	$(T \geq 325°C)$
$\dot{\varepsilon}' = 0$	$(\dot{\varepsilon} > 0.4\%/s)$
$\dot{\varepsilon}' = \ln(\dot{\varepsilon}/0.4)$	$(0.0004 \leq \dot{\varepsilon} \leq 0.4\%/s)$
$\dot{\varepsilon}' = \ln(0.0004/0.4)$	$(\dot{\varepsilon} < 0.0004\%/s)$
$O' = 0.281$	(all DO levels).

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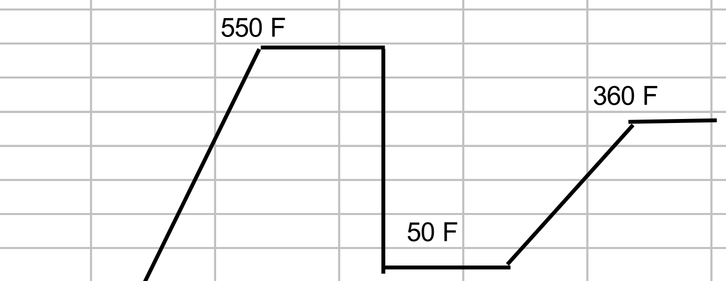
Fen Calculation

Fen Calculations



Tin	550			Typ Calcs	Sulfur %	0.01	DO, ppm	0.2
Tfi	50			Epsdot=0.001				
Tav	300							
Tavc	148.8889							
		LAS	CS	SS	Ni-Cr-Fe			
Typ Fen		**2.0178**	**1.8814**	**2.0834**	**1.4754**			

Equivalent Stress to Account for Fen

- One way is to use Markl's fatigue correlation
  - Stress proportional to $N^{-0.2}$
- Another way is to use the ASME Code fatigue curve
  - Equivalent stress depends on the location on the curve
- Determine the additional margin on stress needed to make up for the Fen effect

Markl's Fatigue Correlation

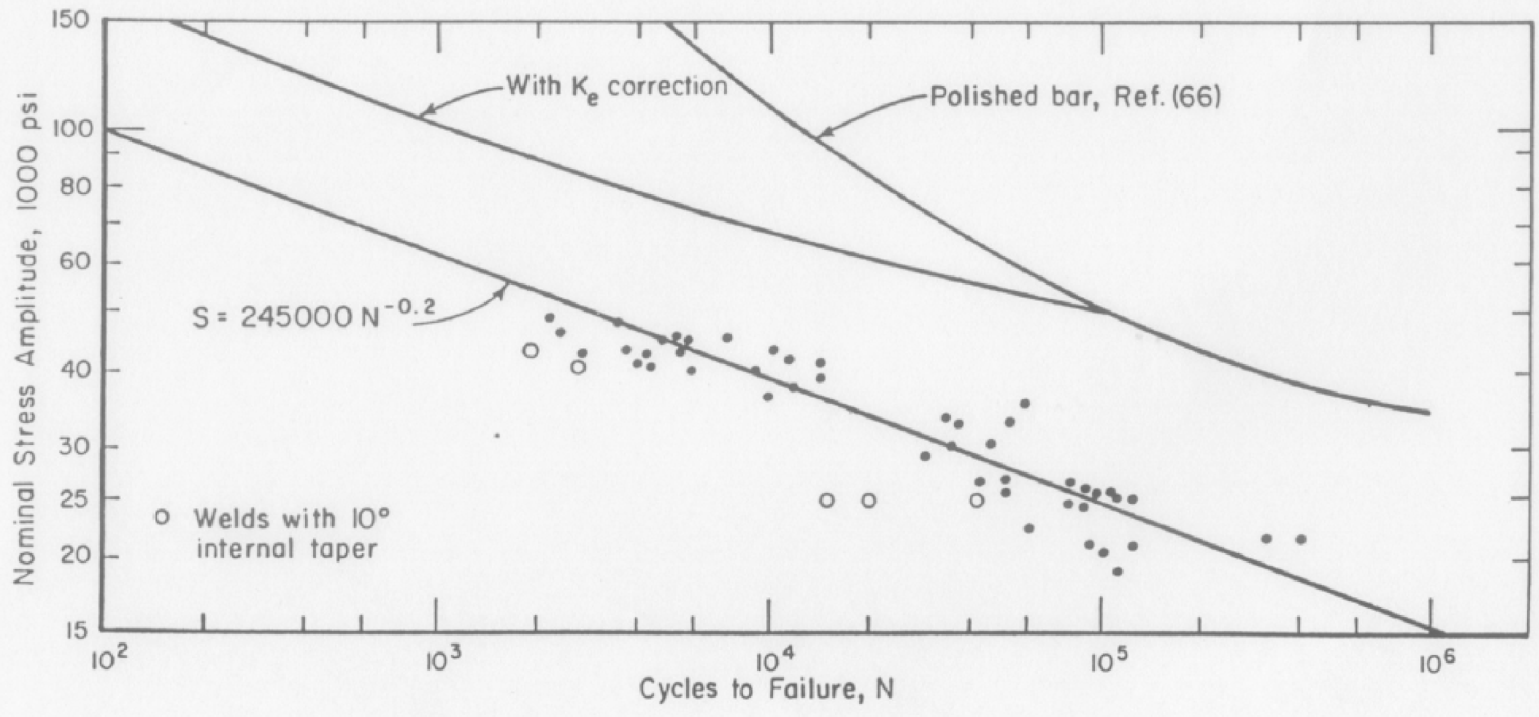


FIGURE 8. MARKL(65) FATIGUE TEST DATA ON GIRTH BUTT WELDS AND COMPARISONS WITH POLISHED BAR DATA AND CODE PLASTIC FATIGUE FACTOR, K_e

$iS = 245{,}000\ N^{-0.2}$

I = stress intensification factor = 1.0 for girth butt welds

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Equivalent Stress Based on the ASME Code Curve

TABULATED VALUES OF S_a, ksi, FROM FIGS. I-9.0

Figure	Curve	Number of Cycles [Note (1)] 1E1	2E1	5E1	1E2	2E2	5E2	8.5E2 [Note (2)]	1E3	2E3	5E3	1E4	1.2E4 [Note (2)]	2E4	5E4	1E5	2E5	5E5	1E6
I-9.1	UTS 115–130 ksi	420	320	230	175	135	100	...	78	62	49	44	43	36	29	26	24	22	20
I-9.1	UTS ≤80 ksi	580	410	275	205	155	105	...	83	64	48	38	...	31	23	20	16.5	13.5	12.5
I-9.2.1	...	708	512	345	261	201	148	...	119	97	76	64	...	55.5	46.3	40.8	35.9	31	28.2
I-9.2.2 (see Table I-9.2.2)																			
I-9.3	S_y = 18.0 ksi	260	190	125	95	73	52	...	44	36	28.5	24.5	...	21	17	15	13.5	12.5	12.0
I-9.3	S_y = 30.0 ksi	260	190	125	95	73	52	...	44	36	28.5	24.5	...	19.5	15	13	11.5	9.5	9.0
I-9.3	S_y = 45.0 ksi	260	190	125	95	73	52	46	39	24.5	15.5	12	...	9.6	7.7	6.7	6.0	5.2	5.0
I-9.4	MNS ≤$2.7S_m$ [Note (3)]	1150	760	450	320	225	143	...	100	71	45	34	...	27	22	19	17	15	13.5
I-9.4	MNS = $3S_m$ [Note (3)]	1150	760	450	300	205	122	...	81	55	33	22.5	...	15	10.5	8.4	7.1	6	5.3

- **In order to account for a Fen factor of 2, the conservatism in stress should be ~ 1.3**
- **The use of rapid ramp times in the design analysis more than assures a factor of 1.3**

Expected Value of Fen and Equivalent Stress Ratio (BWR-NWC)

Analysis for NWC (0.2 ppm Oxygen)

Determine stress factor to account for Fen

Material	Max Fen	Eq. Stress Ratio
Carbon steel	**1.88**	**1.3**
Low alloy steel	**2.02**	**1.3**
Stainless steel	**2.08**	**1.22**
Ni-Cr-Fe	**1.47**	**~1.1**

Conservatism in stress is more than enough to account for Fen effect

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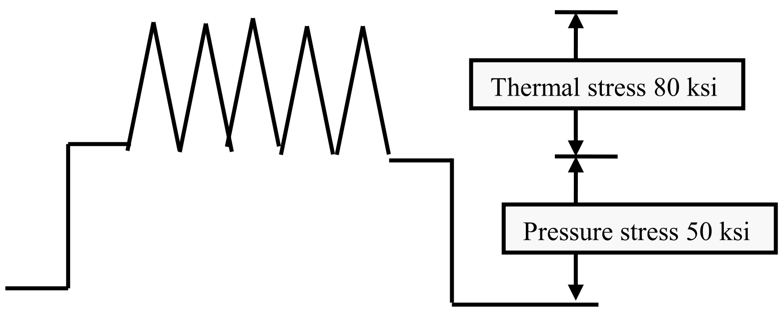
Pressure Cycling

- The previous analysis applies for the thermal transients which constitute much of the fatigue cycling
- Pressure stresses are unaffected by the ramp time issue
  - Fen factor must be applied to account for fatigue from pressure + thermal cycling
- In general, in the limiting BWR components (e.g. FW nozzle and piping) stresses from thermal cycling are higher than that from pressure
  - Conservatism from thermal stress calculation is still expected to cover environmental effects
- A generic review of these components is needed to confirm this

Example of BWR FW Nozzle

- Consider the example of the FW nozzle inner radius stress
  - Pressure stress ~ 50 ksi
  - Thermal stress with step change assumption ~80 ksi
  - Assume that with a slower ramp, thermal stress is 50% lower or 40 ksi
- Assume five thermal cycles for each pressure cycle (includes turbine trips and FW injection during cooldown)
- Fatigue analysis can be performed for this composite cycle with and without Fen effects
- For the composite cycle shown here the stress ranges are:
  - One cycle of pressure + thermal stress
  - Four cycles of thermal stress alone

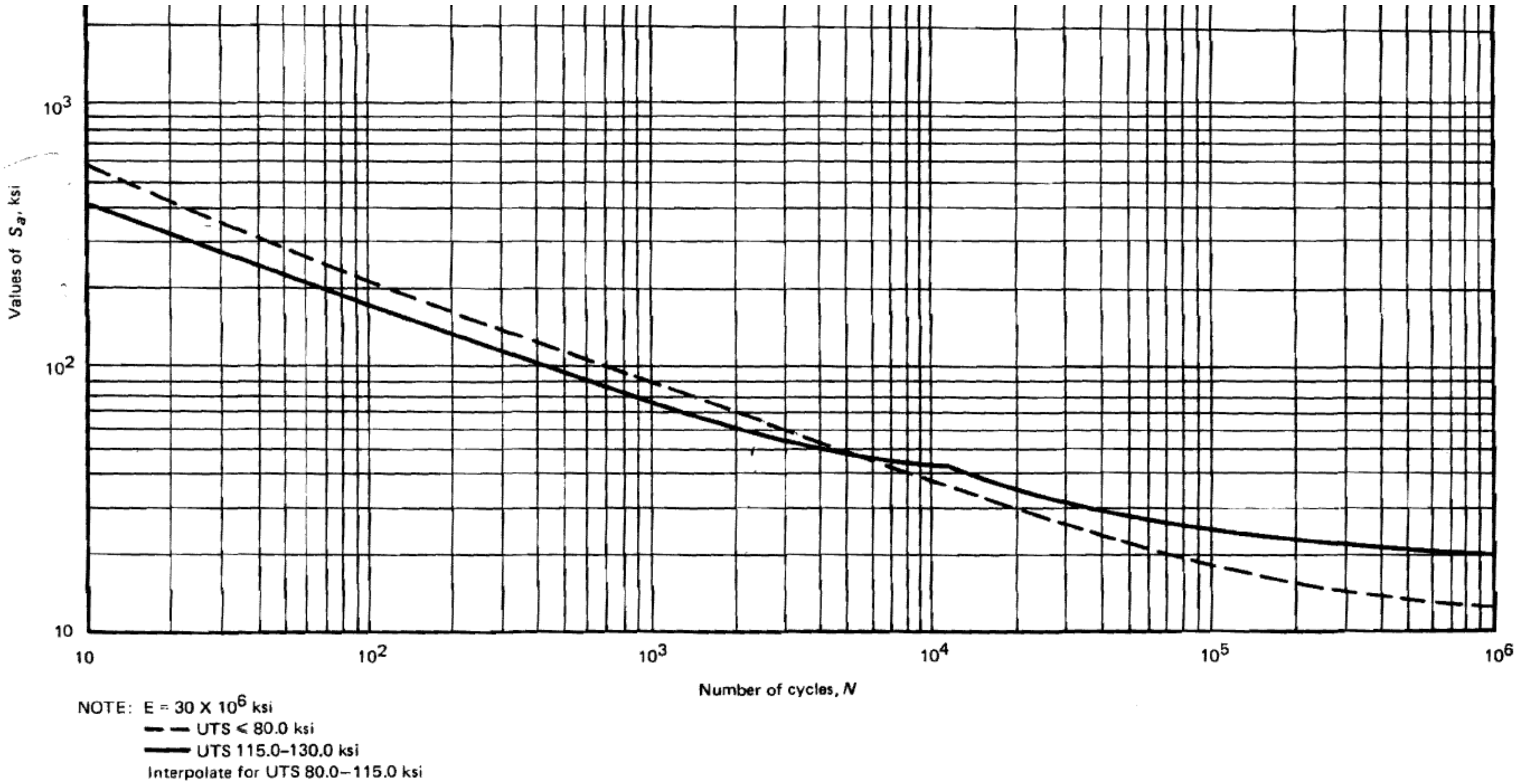


Amplitude = (pressure + thermal /2)
= (80 + 50) / 2 = 65 ksi

Sample Fatigue Usage Calculation

- Assume 240 composite cycles (pressure + 5 thermal cycles)
- Calculate current CUF (without Fen factors, but with design basis step change transients – 80 ksi range for thermal only)
  - 240 cycles - 65 ksi amplitude, usage = 240/2400 = 0.10
  - 240 x 4 = 960 cycles - 40 ksi amplitude, usage = 960/9000 = 0.107
  - CUF = 0.207
- Calculate new CUF including Fen (assumed to be 2.0) and ramp stress values (assumed to be factor of 2 lower or 40 ksi range for thermal only)
  - 240 cycles - 45 ksi amplitude, usage = 240/6000*2 = 0.08
  - 240 x 4 = 960 cycles - 20 ksi amplitude, usage = 960/(75000)*2 =0.026
  - CUF = 0.106
- This is just a sample calculation with an assumed stress reduction due to ramp assumption, but illustrates the process

ASME Code LAS Fatigue Curve



Other Observations

- If it can be shown that the ASME CUF remains bounding for environmental effects, it follows that the current pipe break analyses remain valid
  - No new pipe break analysis needed based on inclusion of environmental effects
- A plant using this method will still have to continue to monitor transient severity throughout the future operating life of the plant
- Since current CUF remains valid, the justification for license renewal is based on meeting 10 CFR54.21(c)1 part (i) ‘the analyses remain valid for the period of extended operation’

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Summary and Conclusions

- Comparison with plant data for BWRs suggests that the ramp rates for actual transients are well below that assumed in analysis
  - Design stresses are over-estimated but environmental effects are under-estimated. Trade-off between stress and Fen
- Analysis of step change vs. ramp temperature changes suggests that calculated design stresses are much higher than those for actual plant transients
  - Results presented here are based on typical BWR experience
- Stress conservatism of 30% (factor of 1.3) is more than sufficient to make up for the environmental effect

Summary and Conclusions (cont.)

- A case can be made that there is sufficient conservatism in current ASME code analysis to offset environmental effects; i.e. no separate Fen analysis is needed
  - Conclusion valid as long as the design thermal cycle diagram includes rapid rise time transients
  - Applicable to BWRs since comparison with plant data was limited to operating BWRs
- There have been no instances of environmental fatigue cracking in components with high fatigue usage
  - The conservatism in the calculated stresses may explain the apparent contradiction between operating plant experience and test data

Potential Next Steps

- Select specific BWR components for the initial analysis:
  - The FW nozzle/safe end has the highest fatigue usage
    - Significant number of thermal transients that are conservatively evaluated
  - Recirculation inlet nozzle (lower fatigue usage) but has more pressure cycles, less thermal transients
  - FW piping, the component with the highest CUF in piping
  - Other components may be added to this list later

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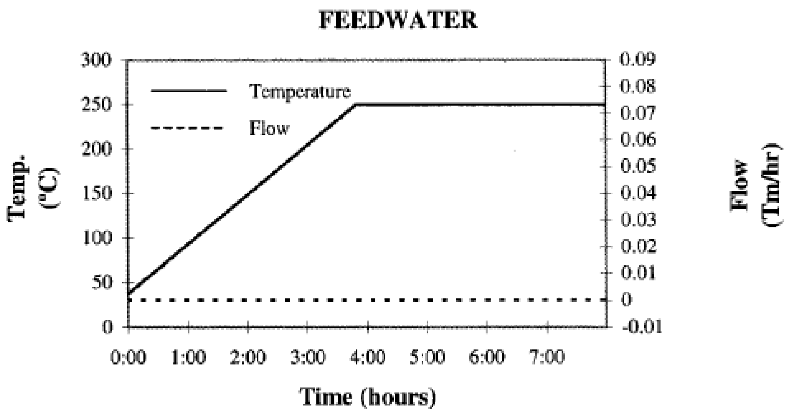
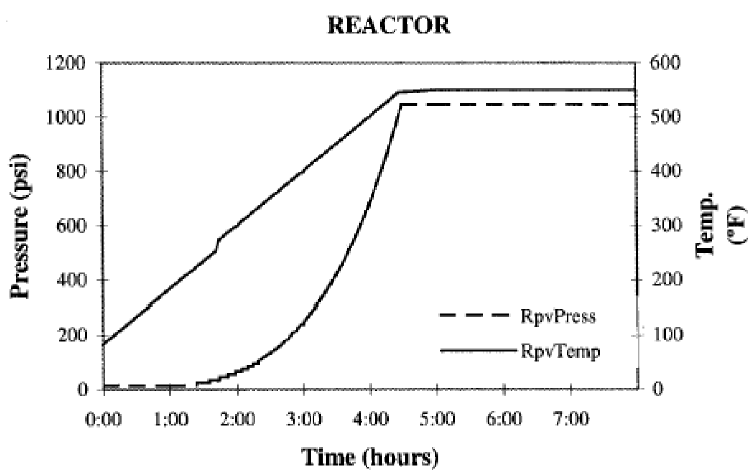
Backup Slides

BWR Startup – Design Basis vs. Actual Transient

Design Basis





Actual Transient

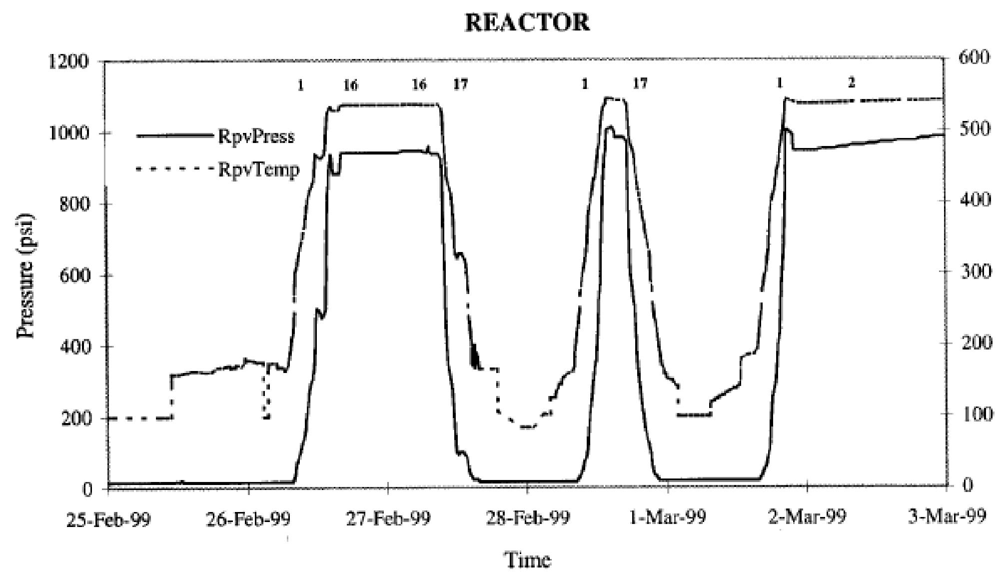
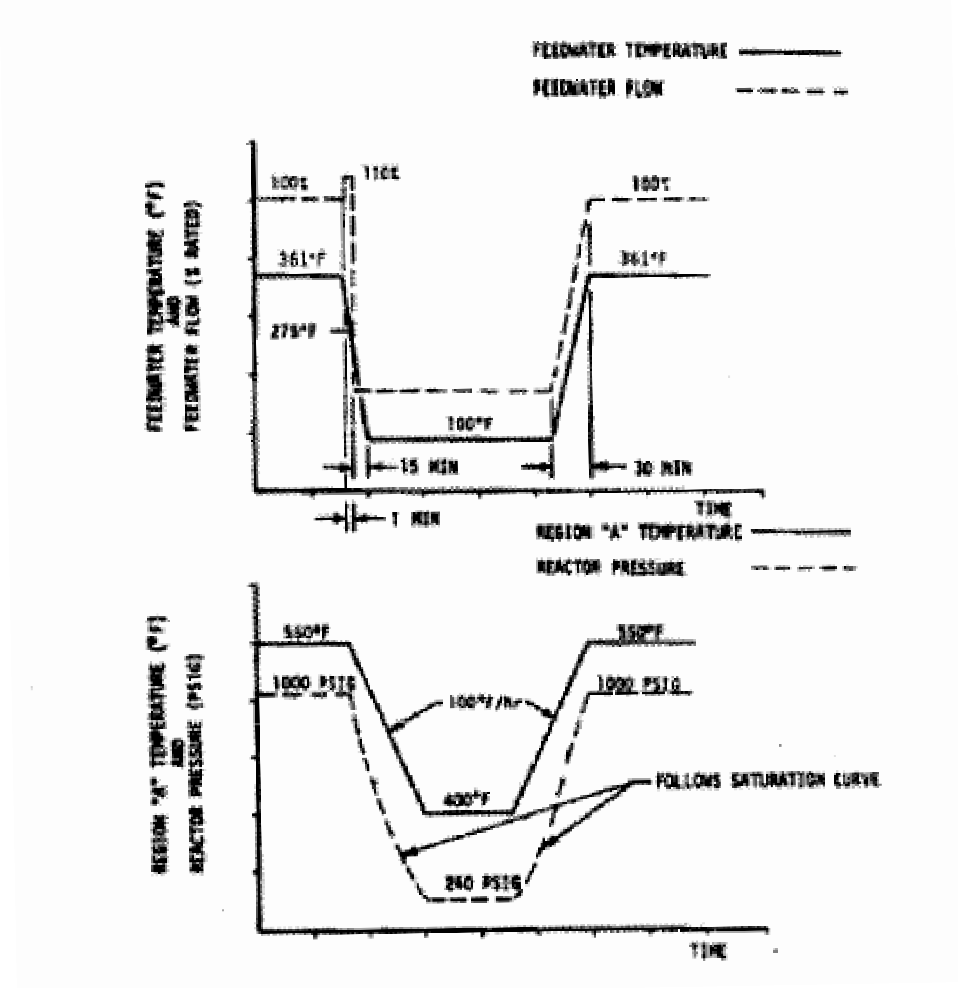


Figure 11. Actual Transient – Startup (1)

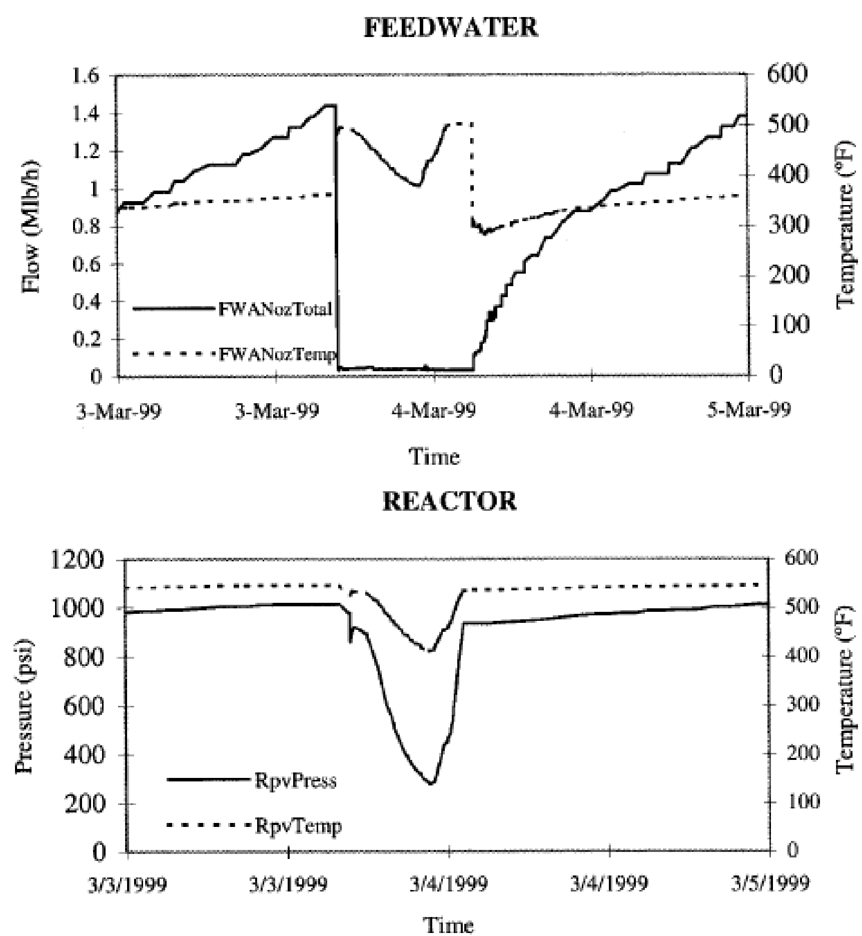
Note: No Feedwater during heatup

BWR Scram – Design Basis vs. Actual Transient

Design Basis



Actual Transient



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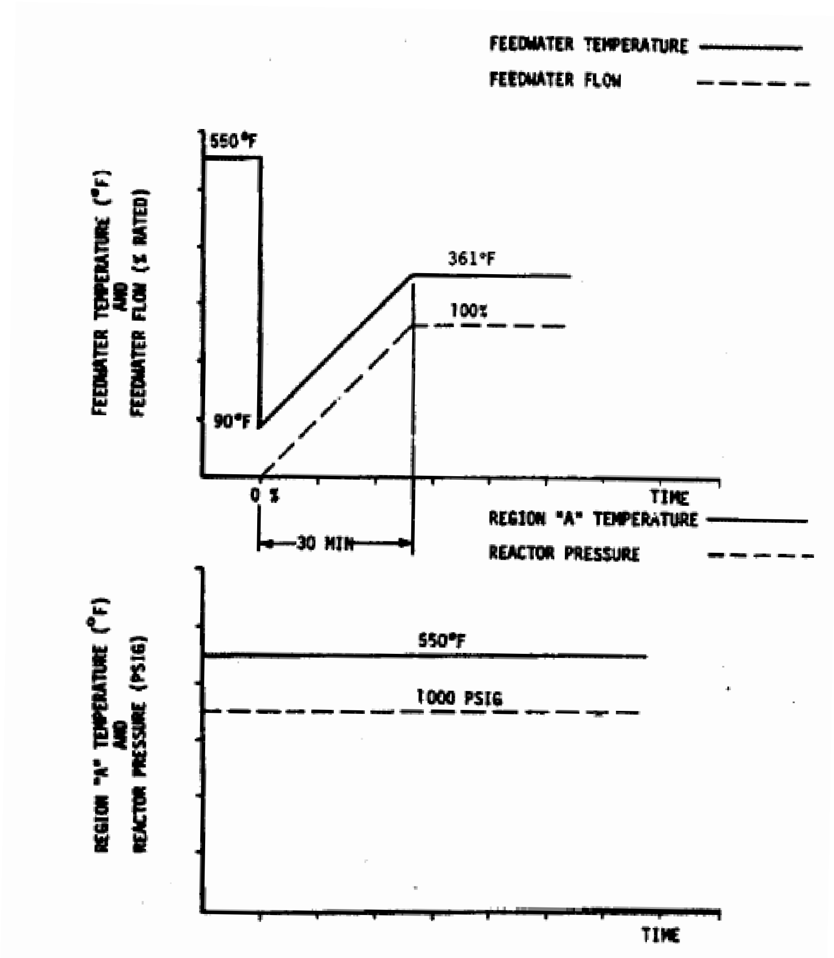
BWR Turbine Roll – Design Basis vs. Actual Transient

Design Basis



Actual Transient