Industry Risk-Informed Appendix G Program: Approach Summary and Results Status

NRC/EPRI MRP/BWRVIP Meeting
Rockville, Md.
August 21, 2008

Agenda

1. *ASME Code Guidelines & Regulatory Requirements*
   - ASME Section XI, Appendix G
   - 10CFR 50, Appendix G
   - Regulatory Guide 1.99, Rev. 2
   - Branch Technical Position 5.2
2. *Limiting Service Level A & B Events*
   - PWRs – Low temperature overpressure protection (LTOP)
   - BWRs – System leak test
3. *Approach*
4. *Status*
   - *Computational Results*

ASME Code Guidelines & Regulatory Requirements

1. *ASME Section XI, Appendix G*

- Provides guidelines to prevent brittle fracture of ferritic components in the reactor coolant pressure boundary.
- Applicable for Service Level A & B events.
- Is a non-mandatory ASME Code appendix.
- Defines pressure temperature limits (for the RPV shell region) using

$$2.0 \times K_{Im} + K_{It} < K_{Ic} \quad \text{normal operation}$$

$$1.5 \times K_{Im} < K_{Ic} \quad \text{leak testing}$$

- Specifies that LTOP system must be enabled at temperatures up to the greater of 200F or RT_{NDT} + 50F.

ASME Code Guidelines & Regulatory Requirements

2. *10CFR50, Appendix G*

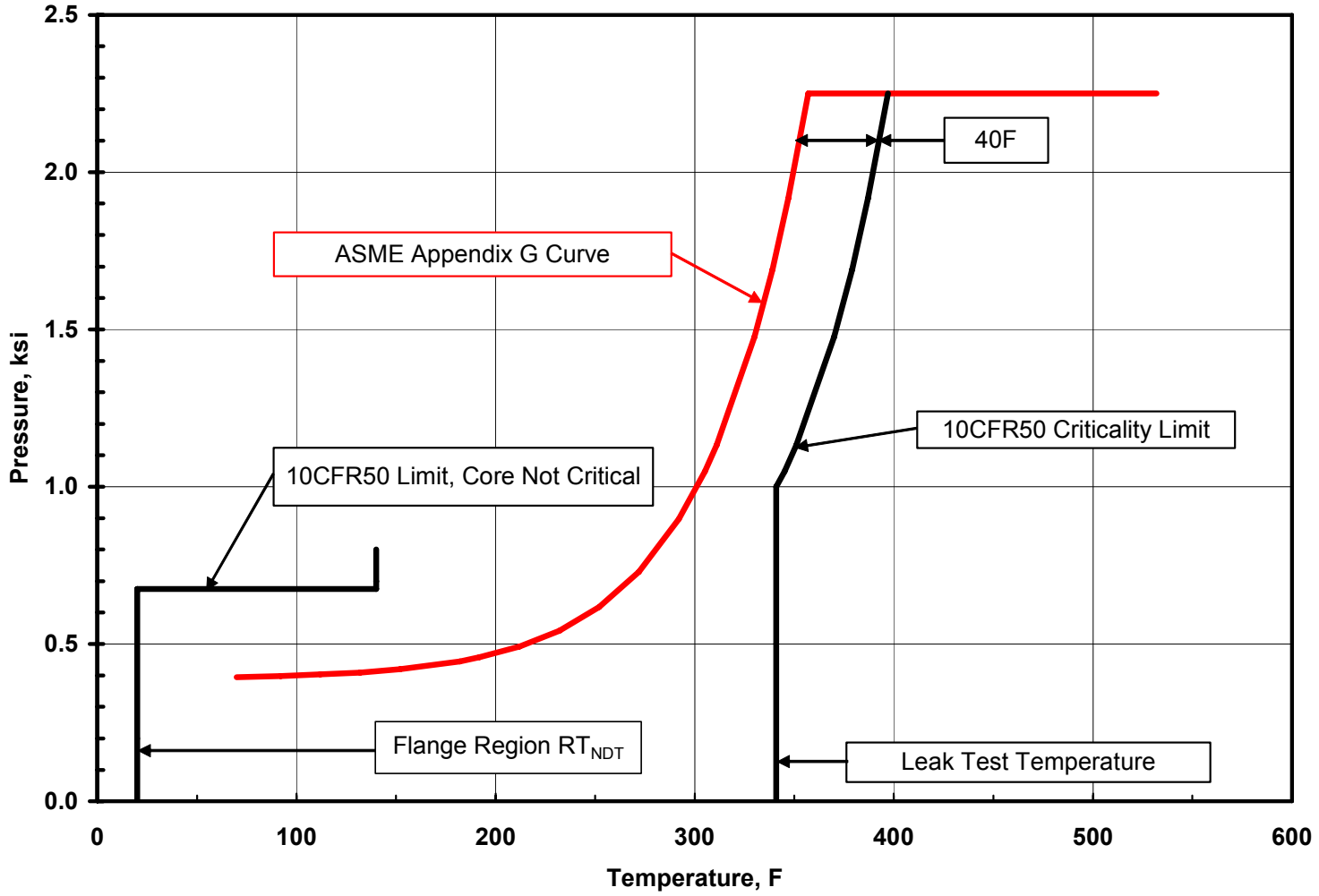
- *10CFR50, Appendix G requires implementation* of ASME Section XI, Appendix G and *adds additional requirements for fracture prevention of the reactor pressure vessel.*

Additional Requirements in 10CFR50, Appendix G

Operating condition	Vessel pressure[1]	Requirements for pressure-temperature limits	Minimum temperature requirements
1. Hydrostatic pressure and leak tests (core is not critical):			
1.a Fuel in the vessel	≤20%	ASME Appendix G Limits	([2])
1.b Fuel in the vessel	>20%	ASME Appendix G Limits	([2]) +90 ° F([6])
1.c No fuel in the vessel (Preservice Hydrotest Only)	ALL	(Not Applicable)	([3]) +60 ° F
2. Normal operation (incl. heat-up and cool-down), including anticipated operational occurrences:			
2.a Core not critical	≤20%	ASME Appendix G Limits	([2])
2.b Core not critical	>20%	ASME Appendix G Limits	([2]) + 120 ° F.
2.c Core critical	≤20%	ASME Appendix G Limits + 40 ° F.	Larger of [([4])] or [([2]) + 40° F.]
2.d Core critical	>20%	ASME Appendix G Limits + 40 ° F.	Larger of [([4])] or [([2])+160°F]
2.e Core critical for BWR ([5])	≤20%	ASME Appendix G Limits + 40 ° F.	([2])+60°F

[1] Percent of the preservice system hydrostatic test pressure.
[2] The highest reference temperature of the material in the closure flange region that is highly stressed by the bolt preload.
[3] The highest reference temperature of the vessel.
[4] The minimum permissible temperature for the inservice system hydrostatic pressure test.
[5] For boiling water reactors (BWR) with water level within the normal range for power operation.
[6] Lower temperatures are permissible if they can be justified by showing that the margins of safety of the controlling region are equivalent to those required for the beltline when it is controlling.

Illustration of Limits in Appendices G of the ASME Code & 10CFR50 for a PWR



ASME Code Guidelines & Regulatory Requirements

3. *Regulatory Guide 1.99, Rev. 2*

- Provides guidelines for assessing the effect of neutron irradiation on the fracture toughness of ferritic steels. The irradiation effect is described by an adjustment to RT_{NDT}.
- Provides guidelines for assessing the effect of uncertainty for the irradiation damage model. This uncertainty is described by an added margin to the adjusted RT_{NDT},
- Adjusted $RT_{NDT} = RT_{NDT(u)} + \Delta RT_{NDT} + \text{Margin}$

4. *Branch Technical Position 5.2*

- Specifies that the LTOP system must be enabled at temperatures up to RT_{NDT} + 90F.

Illustration of Limiting Service Level A PWR Condition (LTOP)

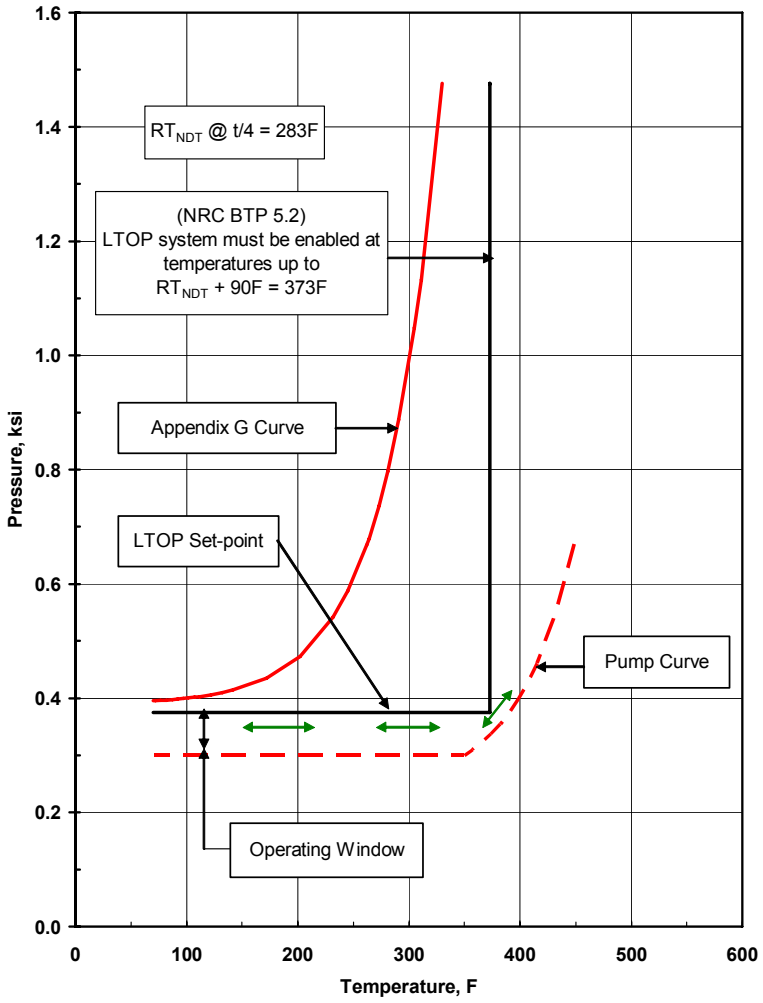
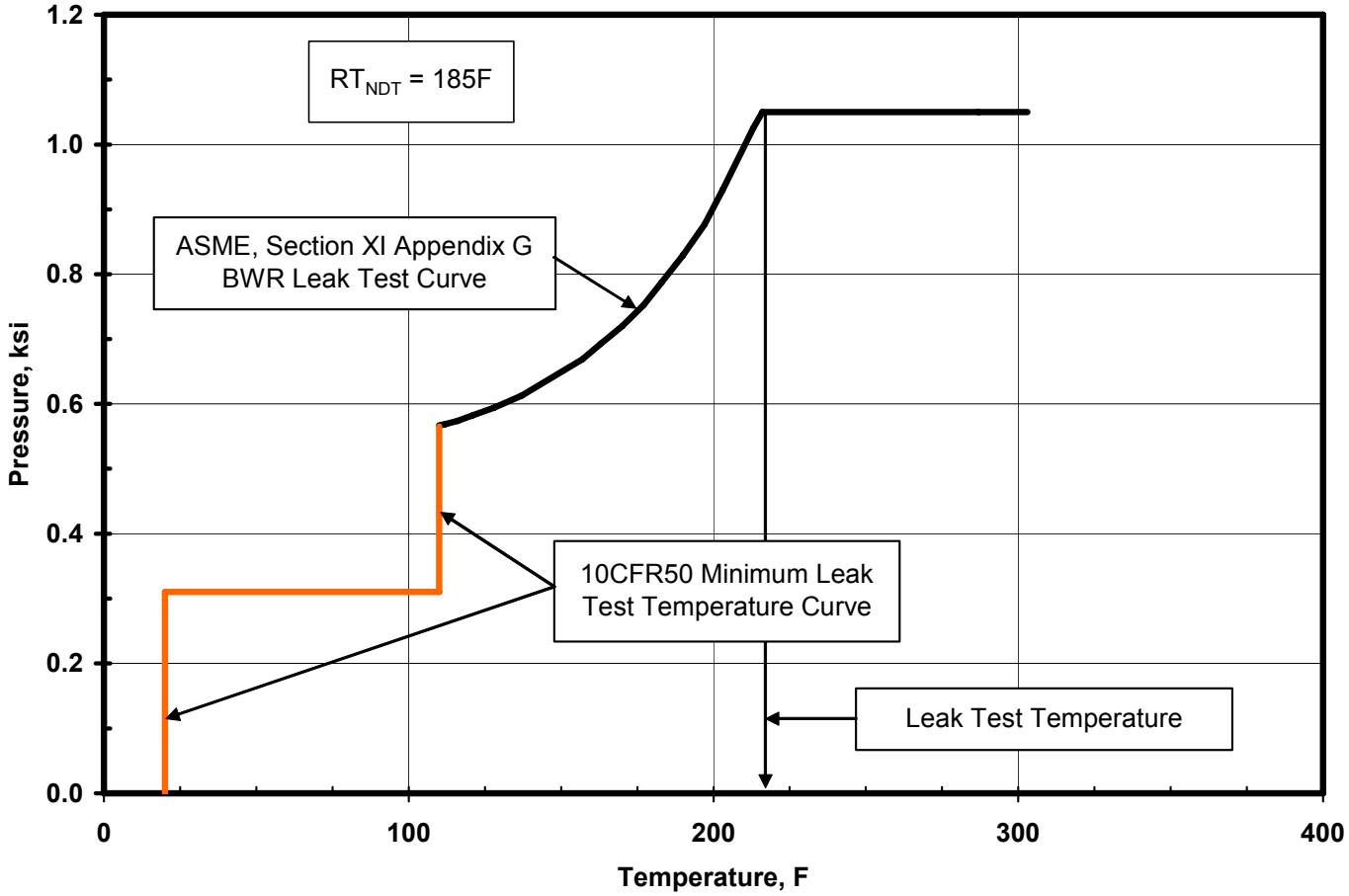


Illustration of Limiting Service Level A BWR Condition (Leak test)



Benefits for Developing a Risk-Informed Appendix G

- Fewer reportable events due to exceeding pressure temperature (P/T) limit curves.
- Increased LTOP pressure set-points with reduced likelihood of inadvertent LTOP events leads to fewer challenges and increased safety.
- Reduced temperature and reduced time to perform BWR leak test.

Scope and Application of the Risk-informed Approach

- Scope of industry effort is to add an optional section to ASME Section XI, Appendix G for constructing risk-informed heat-up and cool-down curves.
- Maintain the current ASME Section XI Appendix G method.
  - It is anticipated that many operating plants may still use the conventional Appendix G method.
    - This will reduce the regulatory and licensee burden.
- Nozzles will be assessed using deterministic evaluation procedures and criteria being developed by the ASME WG OPC.

Risk-informed Approach

- The basic equation for determining the allowable pressure for normal operating heat-up and cool-down is:

$$2\,K_{Im} + K_{It} < K_{IC},$$

where

  - K_{Im} = stress intensity factor for membrane tension,
  - K_{It} = stress intensity factor for thermal stress,
  - K_{IC} = fracture toughness, and
  - 2 is the margin applied to the stress intensity factor for membrane tension, K_{Im}.

Risk-informed Approach

- The risk-informed margin is obtained based on the relationship
  - CPF x Event Frequency ≤ Acceptable Failure Frequency,

  where
    - CPF is conditional probability of vessel failure, and is determined from PFM analyses,
    - The event frequency is the frequency of normal operating startup or shutdown.
    - The acceptable failure frequency is 1E-6 per operating reactor year.

Risk-informed Approach

- The risk informed margin will be determined by finding the margin that will result in Failure Frequency ≤ 1E-6/yr when the reactor operates up to P/T limits determined from the equation

$$\text{Margin} \times K_{Im} + K_{It} < K_{IC}.$$

- Values of CPF were determined from the FAVOR software, version 06.1, Rev2. (cool-down) and FAVOR-HT (heat-up).

Why This Approach?

- Easy to understand and implement.
- Does not require changes to the current Code fracture mechanics equations.
- Does not require a change in the assumed reference flaw size.
- Maintains easy to use Code computational procedures.
- Risk informed margins have been used in other nuclear applications.

ASME Code, Section XI, Appendix G

1. *P/T limits for shell regions away from discontinuities*
   - $M_p \times K_{Ip} + K_{It} < K_{Ic}$
   - $K_{Ip} = M_m \times p \times R/t$
   - $K_{It} = 0.953 \times 10^{-3} \times CD \times t^{2.5}$; $0.953 \times 10^{-3} \times HU \times t^{2.5}$
   - $K_{Ic} = 33.2 + 20.734 \times EXP[0.02(T - RT_{NDT} - M_{RTNDT})]$,
   - *T = temperature at tip of the reference flaw (t/4 or 3t/4)*
   - *Irradiated* $RT_{NDT} = RT_{NDT(u)} + \Delta RT_{NDT}$ *at the tip of the reference flaw (t/4 or 3t/4)*
   - M_{RTNDT} *= margin added to* RT_{NDT}.

ASME Code, Section XI, Appendix G

2. Operation and Flaw Conditions
   - Steady State – Inside surface flaw with K_{It} =0
   - Heat-up – Outside surface flaw
   - Cool-down – Inside surface flaw
   - Axial and circumferential flaws

3. Equation for assessing risk-informed P/T limits
   - $p = \{33.2 + 20.734 \times EXP[0.02(T - RT_{NDT} - M_{RTNDT})] - K_{It}\} \times \{t/R\} \times \{1/M_p\} \times \{1/M_m\}$.

Illustration of Risk-informed Margins for PWR Normal Operation

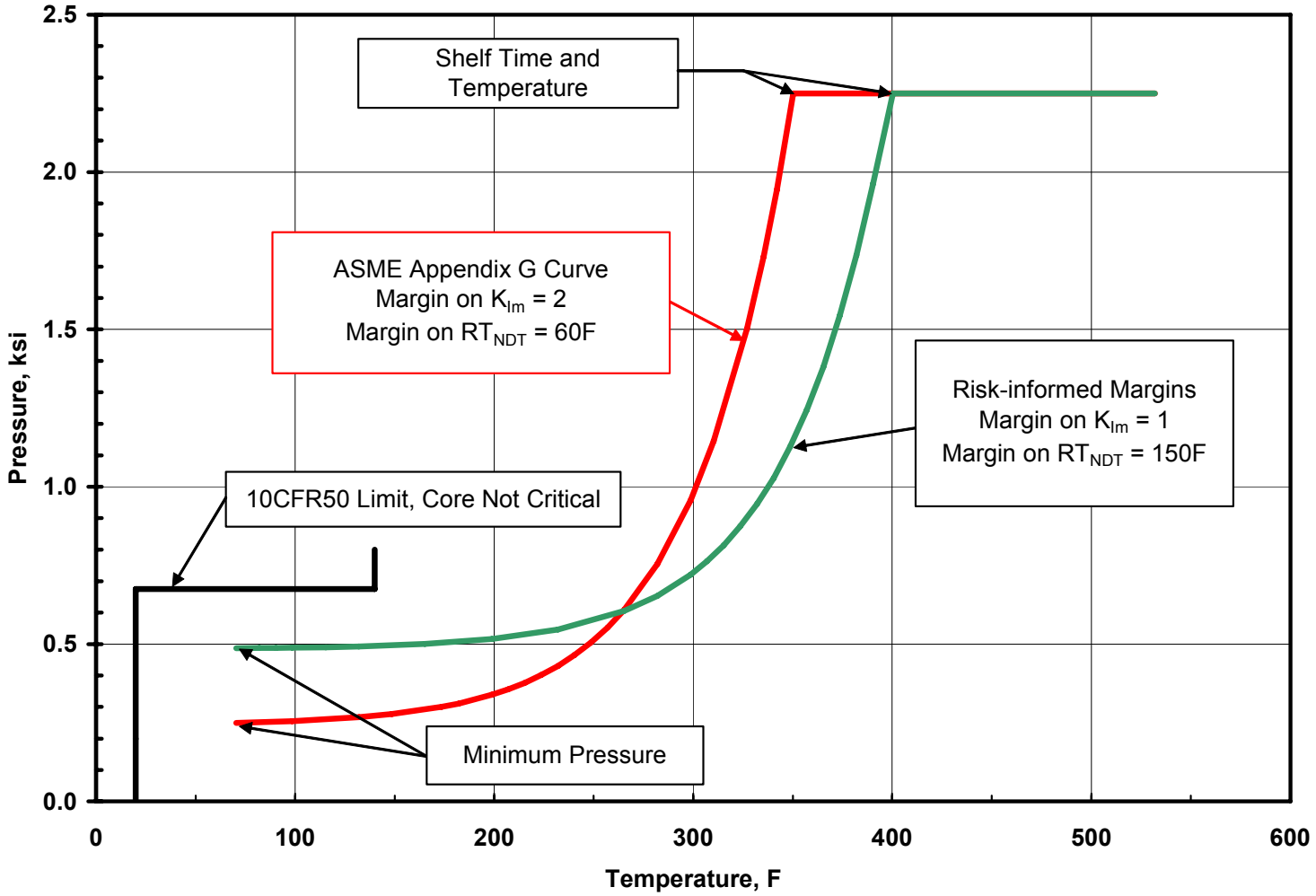
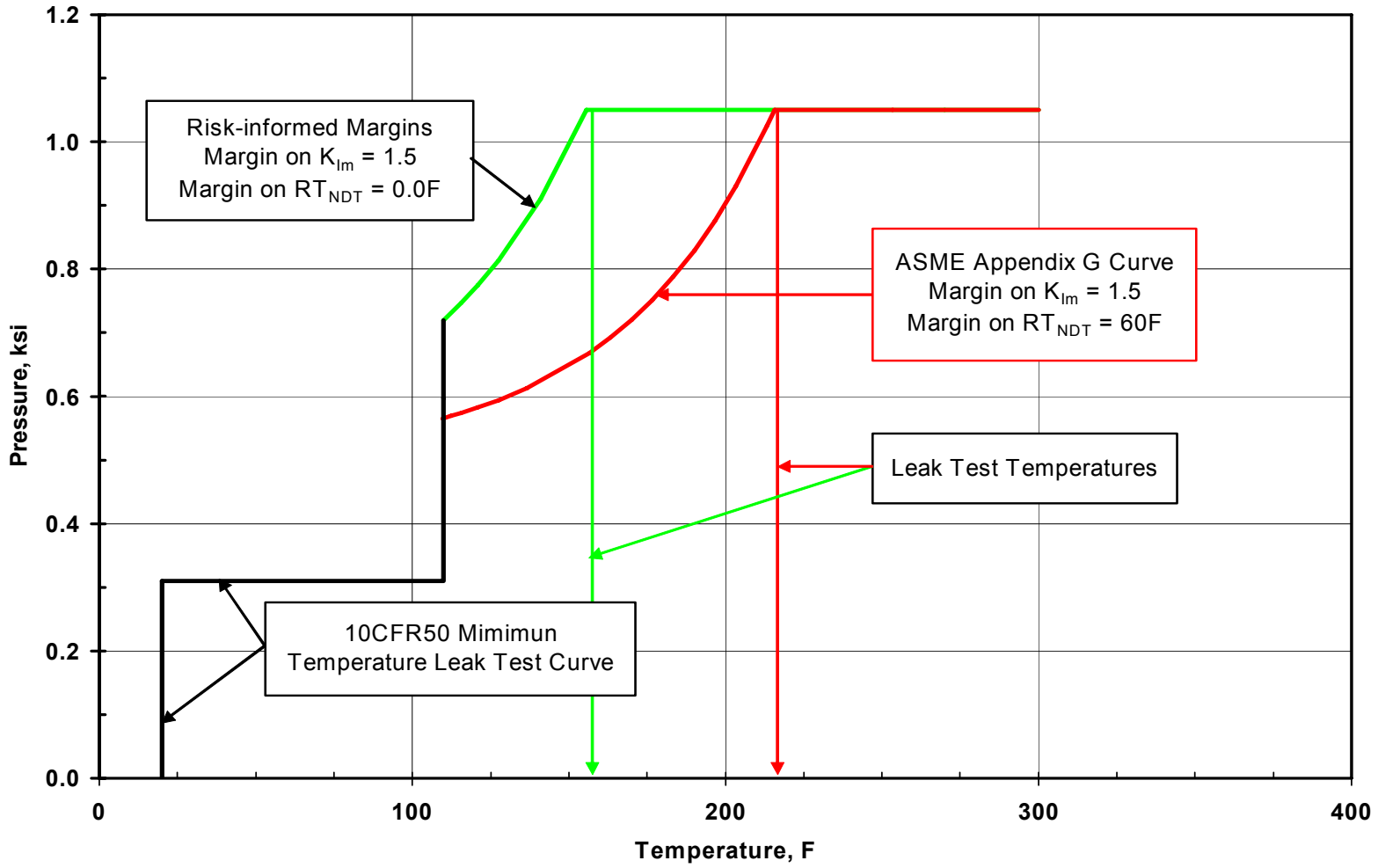


Illustration of Risk-informed Margins for BWR Leak Test



Results Summary for Palisades Cool-down at 100F/hr

WPS	Surface Flaws	Margin on K_{Im}	Margin on RT_{NDT} (°F)	Cool-down rate (°F/hr)	P min (psi)	CPI	CPF	Temp at Shelf (F)	Time to Shelf (min)	Time to 70F (min)	% CPF at Shelf Time	Time to 10% - 100% CPF (min)
Yes	No	1	0	100	533	4.1E-6	2.7E-6	250	169	277	100%	96 - 126
Yes	No	1	60	100	499	4.1E-6	2.6E-6	310	133	277	100%	96 - 128
Yes	No	2	60	100	250	1.4E-6	7.2E-7	350	109	277	100%	90 - 108
No	No	2	60	100	250	1.4 E-6	9.4E-7	350	109	277	99.5%	84 - 276
Yes	No	1	150	100	487	4.7E-8	1.5E-8	400	79	277	100%	65 - 76
No	No	1	150	100	487	1.5E-7	1.4E-7	400	79	277	45%	70 – 276

Results Summary for Palisades Cool-down at 60F/hr

WPS	Surface Flaws	Margin on K_{Im}	Margin on RT_{NDT} (°F)	Cool-down rate (°F/hr)	P min (psi)	CPI	CPF	Temp at Shelf (F)	Time to Shelf (min)	Time to 70F (min)	% CPF at Shelf Time	Time to 10% - 100% CPF (min)
Yes	No	1	0	60	818	2.9E-7	1.7E-7	251	281	462	100%	124 - 174
No	No	1	0	60	818	2.3E-5	2.1E-5	251	281	462	99%	216 - 456
Yes	No	1	0	60F/hr for 120 min then 100F/hr	533	5.4E-5	4.8E-5	250	221	329	100%	180 - 220
Yes	No	2	60	60	395	2.9E-7	1.6E-7	357	175	462	100%	125 - 174
No	No	2	60	60	395	2.9E-7	1.8E-7	357	175	462	99.9%	138 -180
Yes	No	1.5	80	60	524	2.1E-7	1.1E-7	359	173	462	100%	120 – 168
No	No	1.5	80	60	524	2.5E-7	2.0E-7	359	173	462	99.9%	134 - 438

Results Summary for Palisades Cool-down at 40F/hr

WPS	Surface Flaws	Margin on K_{Im}	Margin on RT_{NDT} (°F)	Cool-down rate (°F/hr)	P min (psi)	CPI	CPF	Temp at Shelf (F)	Time to Shelf (min)	Time to 70F (min)	% CPF at Shelf Time	Time to 10% - 100% CPF (min)
Yes	No	1	0	40	961	0.0	0.0	251	422	693	na	na
No	No	1	0	40	961	1.1E-5	1.1E-5	251	422	693	97%	328 - 688
Yes	No	2	60	40	468	0.0	0.0	361	257	693	na	na
No	No	2	60	40	468	9.3E-8	5.4E-8	361	257	693	99.9	205 - 264
Yes	No	1.5	80	40	622	0.0	0.0	361	256	693	na	na
No	No	1.5	80	40	622	1E-7	7.9E-8	361	256	693	100%	204 - 256
Yes	No	1.5	70	40	622	0.0	0.0	351	271	693	na	na
No	No	1.5	70	40	622	1.7E-7	1.3E-7	351	271	693	99%	216 - 272

Results Summary for Palisades Heat-up

WPS	Surface Flaws	Margin on K_{Im}	Margin on RT_{NDT} (°F)	Heat-up rate (°F/hr)	P min (psi)	CPI	CPF	Time to Shelf (min)	% CPI at Shelf Time	Time to 10% - 100% CPI (min)
Yes	No	1	0	100	724	4.9E-8	na	124	100%	116 - 124
No	No	1	0	100	724	4.9E-8	na	124	100%	116 - 124
Yes	No	1	0	60	965	8.0E-9	na	181	99.7%	167 - 186
No	No	1	0	60	965	8.0E-9	na	181	99.7%	167 - 186

Results Summary for Palisades Low Temperature Pressurization

WPS	Surface Flaws	Margin on K_{Im}	Margin on RT_{NDT} (°F)	Cool-down or Heat-up rate (°F/hr)	P min (psi)	CPI	CPF	Time to Shelf (min)	% CPI at Shelf Time	Time to 10% - 100% CPI or CPF (min)
Yes	No	1	0	60F/hr cool-down to 70F, then ISO repressure to 1,250 psi @510m	818	2.9E-7	1.7E-7	281	100%	125 - 174
Yes	No	1	0	60F/hr cool-down to 70F, then ISO repressure to 2,500 psi @ 510m	818	6.0E-6	5.9E-6	281	3%	509-510
Yes	No	1	0	Isothermal pressure to 1,250 at 70F, 0.0m	na	2.7E-8	2.7E-8	na	na	na
Yes	No	1	0	Isothermal pressure to 2,500 at 70F, 0.0m	na	6.4E-4	6.4E-4	na	na	na
Yes	No	1	0	Heat-up from 70F at 60F/hr to 200F, then ISO pressure to 2,500 psi	965	1.7E-6	na	na	na	133-136
Yes	No	1	0	Heat-up from 70F at 60F/hr to 105F, then ISO pressure to 1,250 psi	965	0.0	na	na	na	na

Results Summary for Oconee 1 Cool-down at 100F/hr

WPS	Surface Flaws	Margin on K_{Im}	Margin on RT_{NDT} (°F)	Cool-down rate (°F/hr)	P min (psi)	CPI	CPF	Temp at Shelf (F)	Time to Shelf (min)	Time to 70F (min)	% CPF at Shelf Time	Time to 10% - 100% CPF (min)
Yes	Yes (OCsurf)	2	60	100	278	1.1E-5	1.2E-7	283	164	292	0.0	292
No	Yes (OCsurf)	2	60	100	278	1.2E-5	8.7E-8	283	164	292	0.0	272 - 292
Yes	Yes (OCsurf)	1	150	100	508	1.5-5	9.4E-7	331	135	292	0.0	272 - 292
No	Yes (OCsurf)	1	150	100	508	1.7E-5	1.1E-6	331	135	292	0.0	272 - 292
No	No (PLsurf)	1	150	100	508	1.7E-5	1.1E-6	331	135	292	0.0	272 - 292

Results Summary for Oconee 1 Cool-down at 60F/hr

WPS	Surface Flaws	Margin on K_{Im}	Margin on RT_{NDT} (°F)	Cool-down rate (°F/hr)	P min (psi)	CPI	CPF	Temp at Shelf (F)	Time to Shelf (min)	Time to 70F (min)	% CPF at Shelf Time	Time to 10% - 100% CPF (min)
Yes	Yes (OCsurf)	2	60	60	418	2.6E-6	1.3E-8	288	268	486	0.0	456 - 486
No	Yes (OCsurf)	2	60	60	418	2.8E-6	1.5E-8	288	268	486	0.0	456 - 486
No	No (PLsurf)	2	60	60	418	0.0	0.0	288	268	486	na	na
Yes	Yes (OCsurf)	1.5	80	60	546	3.4E-6	9.4E-8	290	266	486	0.0	456 - 486
No	Yes (OCsurf)	1.5	80	60	546	3.7E-6	8.7E-8	290	266	486	0.0	456 - 486
No	No (PLsurf)	1.5	80	60	546	0.0	0.0	290	266	486	na	na

Results Summary for Oconee 1 Cool-down at 40F/hr

WPS	Surface Flaws	Margin on K_{Im}	Margin on RT_{NDT} (°F)	Cool-down rate (°F/hr)	P min (psi)	CPI	CPF	Temp at Shelf (F)	Time to Shelf (min)	Time to 70F (min)	% CPF at Shelf Time	Time to 10% - 100% CPF (min)
Yes	Yes (OCsurf)	2	60	40	488	9.7E-7	4.6E-9	291	397	729	0.0	692 - 728
No	Yes (OCsurf)	2	60	40	488	1.0E-6	3.1E-9	291	397	729	0.0	688 - 728
No	No (PLsurf)	2	60	40	488	0.0	0.0	291	397	729	na	na
Yes	Yes (OCsurf)	1.5	70	40	645	1.5E-6	3.9E-8	283	410	729	0.0	684 - 728
No	Yes (OCsurf)	1.5	70	40	645	1.6E-6	4.2E-8	283	410	729	0.0	688 - 728
No	No (PLsurf)	1.5	70	40	645	0.0	0.0	283	410	729	na	na

Results Summary for Millstone 1 Cool-down at 100F/hr

WPS	Surface Flaws	Margin on K_{Im}	Margin on RT_{NDT} (°F)	Cool-down rate (°F/hr)	P min (psi)	CPI	CPF	Temp at Shelf (F)	Time to Shelf (min)	Time to 70F (min)	% CPF at Shelf Time	Time to 10% - 100% CPF (min)
Yes	No	2	60	100	308	0.0	0.0	284	148	277	na	Na
No	No	2	60	100	308	1E-8	7E-9	284	148	277	100	142 – 148
Yes	No	1	150	100	598	0.0	0.0	314	130	277	na	Na
No	No	1	150	100	598	2.5E-7	2.5E-7	314	130	277	0.0%	238 – 276

- Similar results obtained for 40F/hr and 60F/hr cool-down rates

Results Summary for Millstone 1 Heat-up & Leak Test

WPS	Surface Flaws	Margin on K_{Im}	Margin on RT_{NDT} (°F)	Heat-up rate (°F/hr)	P min (psi)	CPI	CPF	Temp at Shelf (F)	Time to Shelf (min)	Time to 70F (min)	% CPF at Shelf Time	Time to 10% - 100% CPF (min)
Yes	No	2	60	100	349	6E-8	0.0	260	114	0.0	99%	105 - 116
No	No	2	60	100	349	6E-8	0.0	260	114	0.0	99%	105 - 116
Yes	No	2	0	100	405	2.5E-6	0.0	200	78	0.0	99%	62 - 80
No	No	2	0	100	405	2.5E-6	0.0	200	78	0.0	99%	62 - 80
Yes	No	1.5	60	100	465	3.8E-7	0.0	237	100	0.0	100%	84 - 100
No	No	1.5	60	100	465	3.8E-7	0.0	237	100	0.0	100%	84 - 100
Yes	No	1.5	0	100	540	7.7E-6	0.0	177	64	0.0	100%	44 - 64
No	No	1.5	0	100	540	7.7E-6	0.0	177	64	0.0	100%	44 - 64
No	No	1	0	60	860	2.3E-5	0.0	121	51	0.0	100%	0 – 54
No	No	1	0	40	885	2.2E-5	0.0	113	65	0.0	100%	0 – 72

Results Summary for Brunswick 2 Cool-down at 100F/hr

WPS	Surface Flaws	Margin on K_{Im}	Margin on RT_{NDT} (°F)	Cool-down rate (°F/hr)	P min (psi)	CPI	CPF	Temp at Shelf (F)	Time to Shelf (min)	Time to 70F (min)	% CPF at Shelf Time	Time to 10% - 100% CPF (min)
Yes	No	2	60	100	361	0.0	0.0	200	198	276	na	na
No	No	2	60	100	361	0.0	0.0	200	198	276	na	na
Yes	No	1	150	100	629	0.0	0.0	230	180	276	na	na
No	No	1	150	100	629	3.5E-8	3.2E-8	230	180	276	0.0%	262 - 276

- Similar results obtained for 40F/hr and 60F/hr cool-down rates

Preliminary Conclusions

- It is feasible to increase allowable pressure by risk-informing ASME Section XI, Appendix G.
- It does not appear necessary to risk inform 10CFR50, Appendix G.
- It appears feasible to modify NRC BTP 5.2 to use the RT_{NDT} + 50F as the LTOP enable temperature.
- It appears feasible to use risk-informed margins to reduce the BWR leak test temperature.

Preliminary Risk-Informed Margins

Cool-down Rate F/hr	Margin on Pressure	Margin on RT_{NDT}
100	1	150
60	1.5	80
40	1.5	70
BWR Leak Test	1.5	0