PRESSURE-TEMPERATURE LIMIT CURVES

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Introduction

- A primary goal in the design, fabrication and operation of nuclear power plants is to ensure that the likelihood of fracture of pressure-retaining components in the reactor coolant boundary is acceptably low
- Regulations and Codes and Standards (C&S) contain requirements to achieve such a goal:
  - Requirements for materials
  - Rules for design
    - Including also analytical procedures based for on fracture mechanics for the prevention of brittle fracture
  - Welding and NDE
  - …

Introduction (cont.)

- During operation, the reactor is operated within explicit pressure-temperature (P-T) limits to ensure that acceptable margins against failure are maintained during normal reactor heat-up and cooldown, and pressure tests
- This presentations cover the US requirements for the development of P-T limits
- These requirements are applied for the Spanish NPPs of US design

Fracture toughness requirements of 10 CFR 50, Appendix G

- "The pressure-retaining components of the reactor coolant pressure boundary that are made of ferritic materials must meet the requirements of the ASME Code, *supplemented by the additional requirements set forth below*, for fracture toughness…. For the reactor vessel beltline materials, including welds, plates and forgings, the values of RT_{NDT} and Charpy Upper-Shelf Energy must account for the effects of neutron radiation…."
- The "*additional requirements*" referred to above are the following ones:

Fracture toughness requirements of 10 CFR 50, Appendix G (cont.)

- Minimum Charpy Upper-Shelf Energy (USE) requirements
- P-T limits for heat-up, cooldown, and test conditions must be at least as conservative as those obtained by following Appendix G of ASME Code Section XI
- Additional safety margins (beyond ASME) when the reactor core is critical
- Minimum temperature requirements determined by the RT_{NDT} of the RPV closure flange materials

Fracture toughness requirements of 10 CFR 50 Appendix G (cont.)

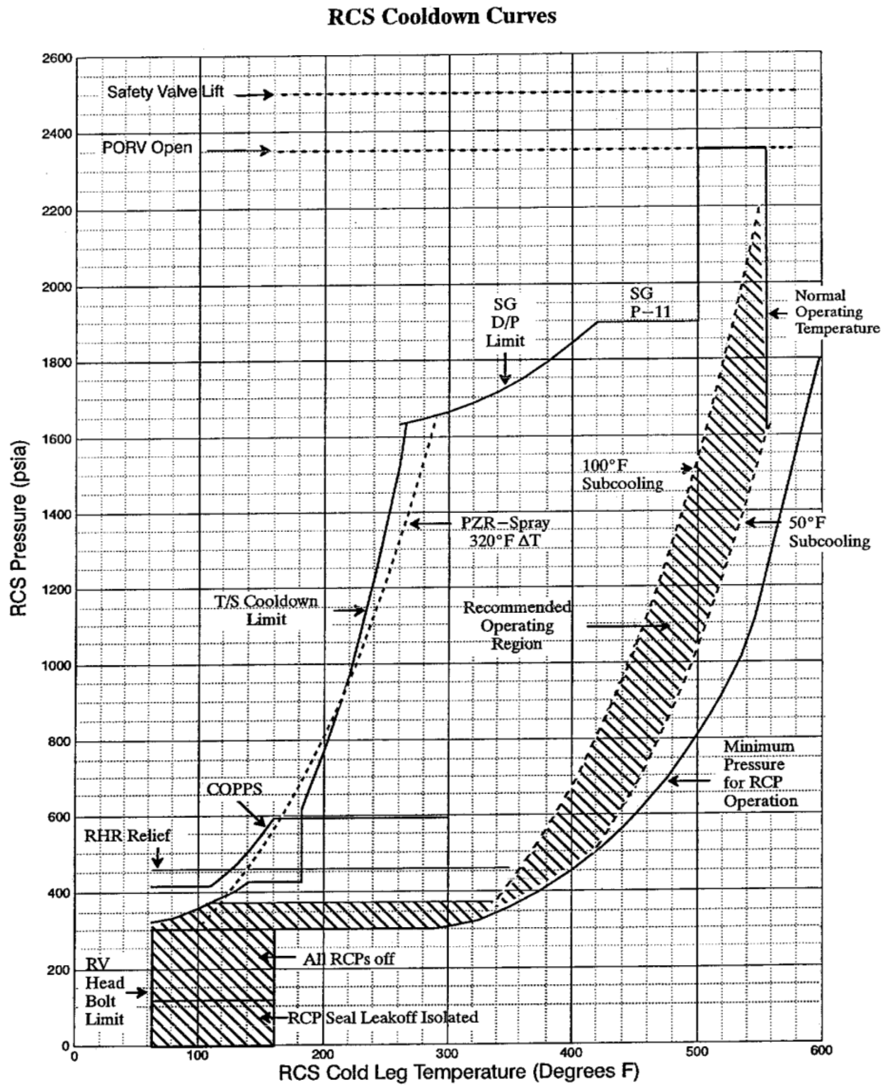
Operating condition	Vessel pressure[1]	Requirements for pressure-temperature limits	Minimum temperature requirements
1. Hydrostatic pressure and leak tests (core is not critical):			
1.a Fuel in the vessel	≤20%	ASME Appendix G Limits	([2])
1.b Fuel in the vessel	>20%	ASME Appendix G Limits	([2]) + 90 °F(6)
1.c No fuel in the vessel (Preservice Hydrotest Only)	ALL	(Not Applicable)	([3]) + 60 °F
2. Normal operation (incl. 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([6])
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.

Operating window

- 10 CFR 50 Appendix G P-T limits are just one of many P-T limits constraining plant operations
  - Reactor coolant pump net positive suction head (NPSH)
  - Margin for saturation
  - Steam generator operating limits
  - RCP seal differential pressure
  - RHR Relief valve
  - Low Temperature Overpressurization Protection (LTOP) Systems
  - …

Operating window

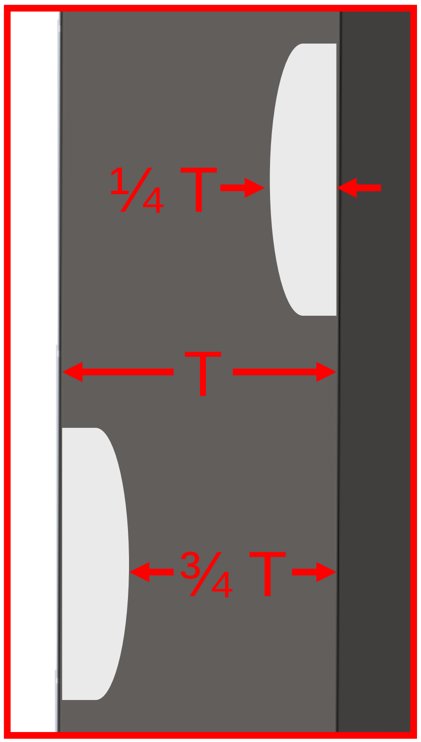


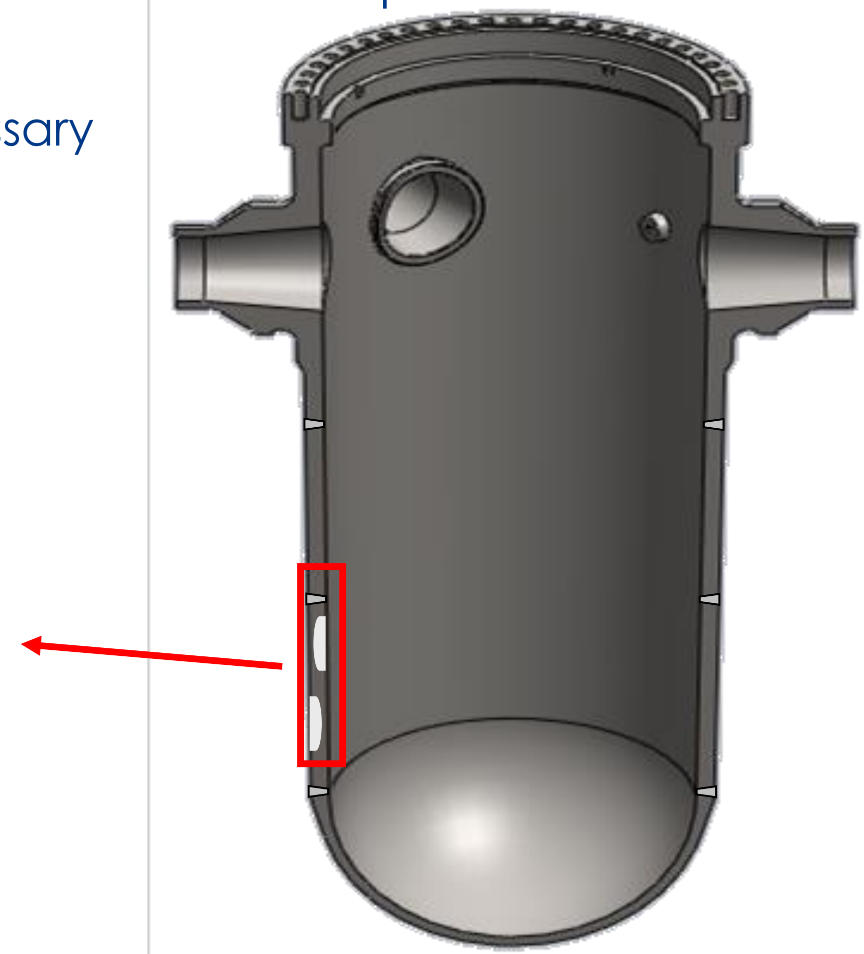
ASME Appendix G

- ASME Code Section III, Appendix G fracture mechanics method was introduced in 1972 for preventing brittle fracture in design and for initial plant operating P-T Limit Curves
  - Large (1/4-thickness depth) assumed reference flaw
  - Lower bound fracture toughness (K_{IR})
  - Safety Factor of 2 on primary stresses (e.g., those due to pressure)
  - Safety Factor of 1 for thermal stresses (due to their self-relieving nature)
  - Predicted irradiation embrittlement during the design life must be also taken into account

Reference flaw

- It is an axial (¼-thickness depth) sharp surface defect
  - Semi-elliptical: length equal to 6 times the depth
  - Final defect
    - No fatigue crack growth necessary

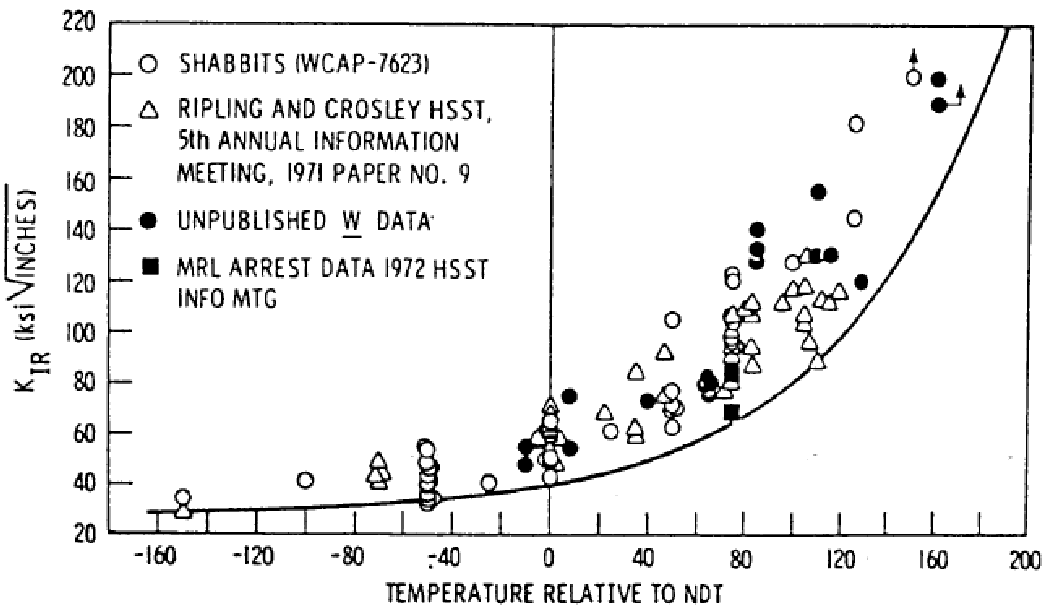




Fracture toughness K_{IR}

- In ASME Section III Appendix G the reference fracture toughness K_{IR} has been used
  - K_{IR} is the critical, or reference, stress intensity factor as a function of temperature, relative to the RT_{NDT} of the material
  - It was defined as a lower bound of dynamic and crack arrest toughness

$$K_{IR} = 26{,}8 + 12{,}445 \cdot \exp[0{,}0145 \cdot (T - RT_{NDT})]$$

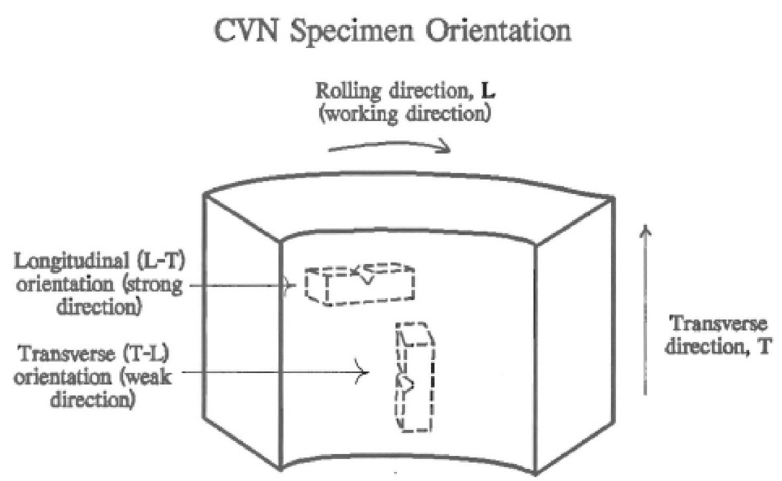


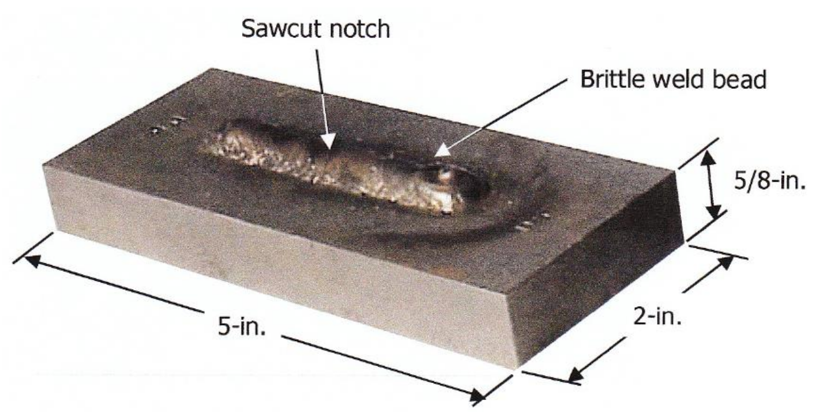
Welding Research Council Bulletin, WRC-175, 1972

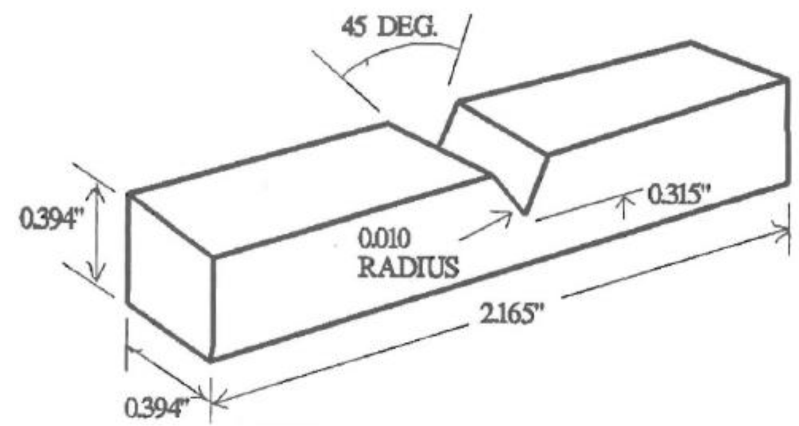
RT_{NDT} definition

- The Nil Ductility Reference Temperature RT_{NDT} is determined according to the ASME Code Section III, NB-2331 as follows:
  - Determine a temperature T_{NDT} by Drop Weight Tests
  - Test three Charpy V-notch (CVN) specimens in the T-L (i.e., weak) orientation at T_{NDT} + 60 °F (T_{NDT} + 33 °C);
    - Each specimen must exhibit a minimum of 50 ft-lb (68 J) energy and 35-mil (0.89 mm) lateral expansion
    - If so, then T_{NDT} is the reference temperature RT_{NDT}
  - If one or all specimens fail to meet the acceptance criteria, test groups of three Charpy specimens at progressively higher temperatures till criteria are met
    - The temperature at which the 35-mil and 50 ft-lb criteria are met is defined as the T_{Cv}
  - The RT_{NDT} is the higher of T_{Cv} – 60 °F (T_{Cv} – 33 °C) and T_{NDT}

RT_{NDT} definition





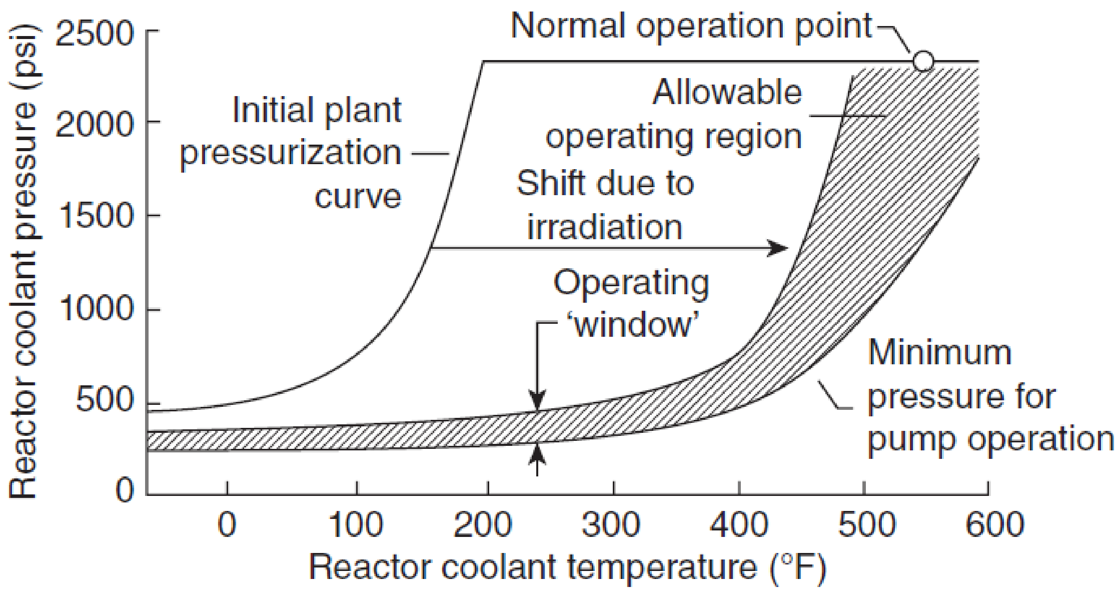


Drop Weight specimen (ASTM E 208)

Charpy V specimen (ASTM E 23)

Effect of neutron irradiation

- Neutron irradiation reduces the fracture toughness of the RPV materials
- This effect reduces the operating window



Effect of neutron irradiation

- Surveillance programs (Appendix H of 10 CFR 50) are implemented to monitor the radiation-induced embrittlement
- This ageing mechanism is cumulative;
  - P-T limit curves must be periodically updated
- US NRC Regulatory Guide 1.99, Revision 2 contains the methods for determining radiation embrittlement of reactor vessel materials
- The embrittlement effect is accounted for through an increase of RT_{NDT}

Effect of neutron irradiation

- The Adjusted RT_{NDT} (ART) is calculated by:

$$ART = \text{Initial } RT_{NDT} + \Delta RT_{NDT} + \text{MARGIN}$$

where,

- Initial RT_{NDT} is the RT_{NDT} of the unirradiated material
- ΔRT_{NDT} is the mean value of the adjustment of RT_{NDT} due to irradiation
  - Depends on the fluence and the material chemistry
- MARGIN is a term that accounts for uncertainties:

$$\text{MARGIN} = 2 \cdot \sqrt{\sigma_I^2 + \sigma_\Delta^2}$$

- where σ_I y σ_Δ are the deviations associated to the Initial RT_{NDT} and ΔRT_{NDT} respectively.

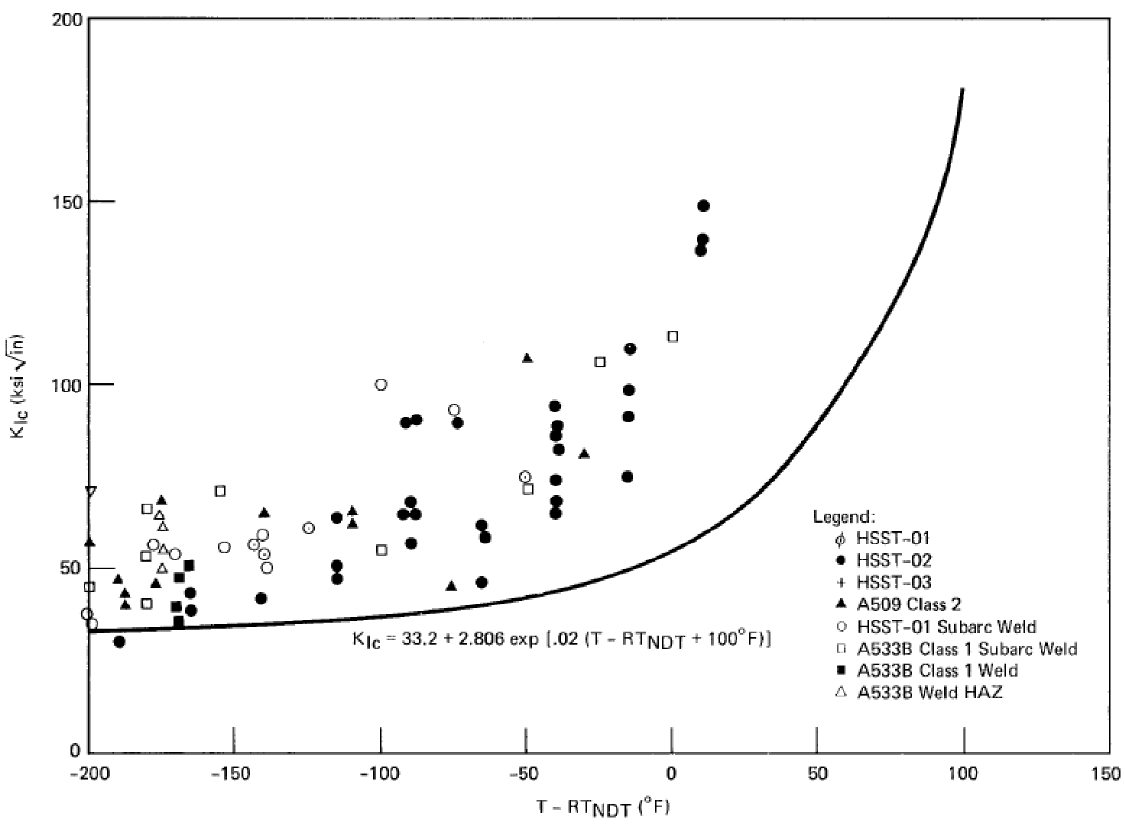
ASME Section XI, Appendix G

- In mid 1980's, an Appendix G (initially identical to that of ASME Section III) was incorporated into Section XI for obtaining allowable (P-T) limits curves for heat-up, cooldown and pressure test to prevent fracture of the RPV and other ferritic pressure retaining components
- Several updates were introduced in subsequent years
  - Use of circumferentially oriented ¼-thickness (and ¾-thickness) assumed reference flaw for vessel with only circumferential welds

ASME XI Appendix G updates

- Use of K_{Ic} reference fracture toughness (instead of K_{IR}) for P-T limit curves
  - K_{Ic} is the lower bound, plane strain, crack initiation fracture toughness as a function of temperature, relative to the RT_{NDT} of the material
  - Use of K_{Ic} is justified by:
    - Use of historically large margins to cover uncertainties is no longer necessary
    - No evidence of critical flaw sizes in reactor vessels
    - No evidence of local brittle zones in vessel materials
    - Loading rates are slow (static); thus, no need to use a dynamic fracture toughness curve
    - Improvements in fracture mechanics analyses confirm large safety margins

ASME XI Appendix G updates



ASME XI Appendix G updates

- Improved formulas for the evaluation of stress intensity factors K_{Im} and K_{It} for the vessel shell
- Improved formulas for the evaluation of stress intensity factors at nozzle inner corner (ASME Section XI 2013 Edition)
- Method for determining Low Temperature Overpressurization Protection (LTOP) enable temperature

Basic equations

- For RPV shell cylindrical regions remote from discontinuities, the allowable pressure for each temperature of the coolant is determined by

$$(SF) \cdot K_{Im} + K_{It} < K_{Ic}$$

  - K_{Im} is the stress intensity factor (SIF) caused by membrane (pressure) stress
  - K_{It} is the SIF caused by thermal gradients through the vessel wall (wall thickness dependent);
  - $SF = 2$ for Level A and Level B Service Limits (Heat-up & Cooldown)
  - $SF = 1.5$ for hydrostatic and leak test conditions when the reactor core is not critical

Basic equations

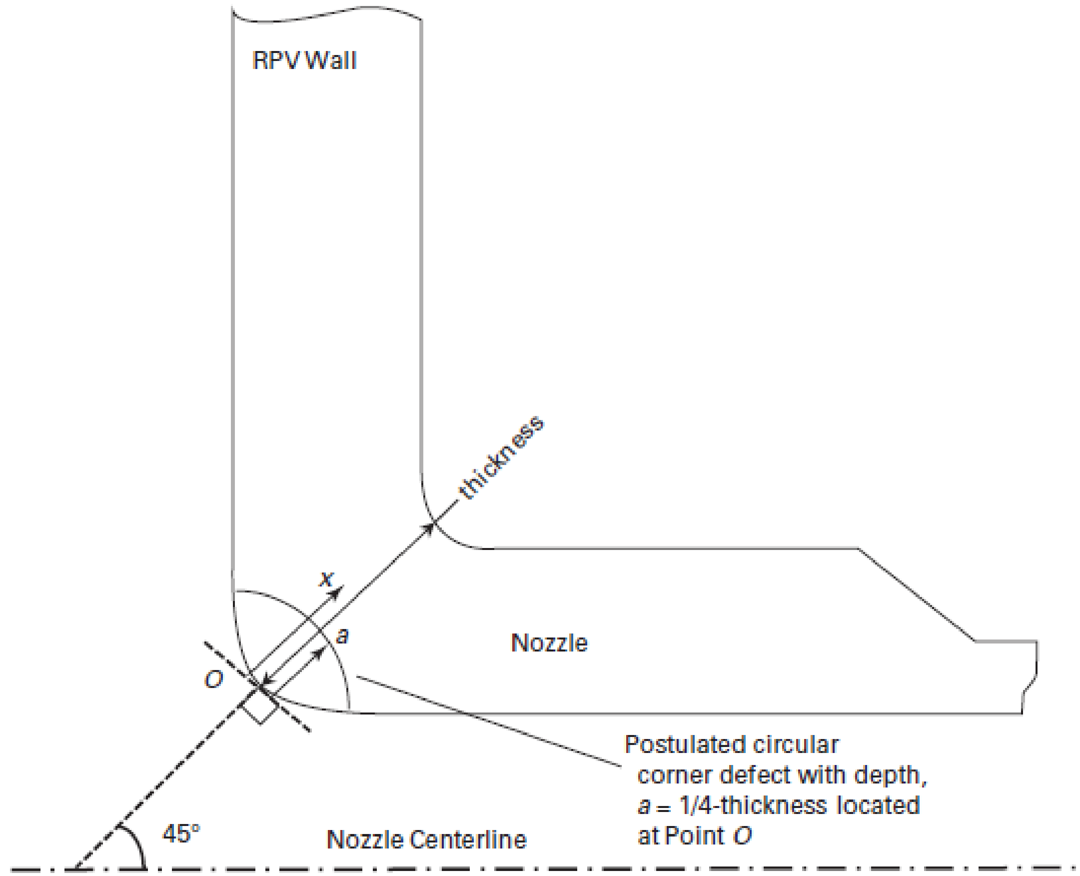
- For flanges and shell regions near geometric discon-tinuities, the allowable pressure for each temperature of the coolant is determined by:

$$(SF) \cdot \ (K_{Im} + K_{Ib})_p \ + (K_{Im} + K_{Ib})_s < K_{Ic}$$

  - K_{Im} is the SIF due to membrane stress
  - K_{Ib} is the SIF due to bending stress
  - Subindices p and s indicate primary and secondary stresses, respectively
    - For the purpose of this evaluation, stresses resulting from bolt preloading are considered primary
  - $SF = 2$ or $SF = 1.5$ as above

Analysis of nozzles

- The postulated defect is circum-ferential in shape, and shall be located at the corner of the nozzle and the cylindrical shell (RPV wall)



Analysis of nozzles

- The allowable pressure for each temperature of the coolant is determined by:

$$(SF) \cdot K_{Ip} + K_{It} < K_{Ic}$$

  - K_{Ip} is the SIF caused by pressure plus external loading on the nozzle end
  - K_{It} is the SIF caused by thermal gradients through the thickness (cross section)

- The stress distributions along the 45° path should be fitted by a 3rd degree polynomial:

$$\sigma(x) = A_0 + A_1 \cdot x + A_2 \cdot x^2 + A_3 \cdot x^3$$

  - x is the distance from the surface into the cross section

Analysis of nozzles

- The SIF must be calculated as follows (ORNL/TM-2010/246):

$$K_I = \sqrt{\pi \cdot a} \cdot \left[0.723\, A_0 + 0.551 \left(\frac{2a}{\pi} \right) A_1 + 0.462 \left(\frac{a^2}{2} \right) A_2 + 0.408 \left(\frac{4a^3}{3\pi} \right) A_3 \right]$$

- ¼ T depth flaw bounds flaw shape and crack front effects of smaller flaws
- Smaller flaw can be used if effects of flaw shape and variation of K_I along the crack front are considered

Steps in calculating P-T curves

- Perform thermal analysis of the vessel wall and calculate through-wall temperature distributions along heat-up and cooldown
- Perform stress analysis of the vessel and calculate thermal and pressure stresses
- Perform fracture mechanics analysis of the vessel beltline materials and calculate crack tip SIF (K_I) and determine irradiated material fracture toughness
- Determine allowable pressure vs. temperature for each beltline material and take worst case which may result in a composite curve

Heat-up

- Internal pressure produces tensile stresses on the assumed inside ¼ T flaw and outside ¾ T flaw that tend to open the flaw
- Heat-up process produces thermal stresses on the assumed inside surface ¼ T flaw that are compressive and tend to counteract the tensile stresses from internal pressure
- However, thermal stresses on the assumed outside surface ¾ T flaw are tensile and reinforce any pressure stresses, tending to open the flaw, and
- ¼ T location has a higher RT_{NDT} due to irradiation than ¾ T location

Heat-up

- Each data point on the heat-up curve for any heat-up rate must be the most limiting pressure between:
  - steady-state (¼ T flaw depth) and the finite heat-up rate (¼ T and ¾ T flaw depths)

Cooldown

- Internal pressure produces tensile stresses on the assumed inside surface ¼ T flaw that tend to open the flaw
- Cooldown process produces thermal stresses on the assumed inside surface ¼ T flaw that are tensile and tend to reinforce the tensile stresses from internal pressure
- ¼ T location has also a higher RT_{NDT} due to irradiation
- Each data point on the cooldown curve for any cooldown rate must be the most limiting pressure between steady-state and the finite cooldown rate

Hydrostatic and leak test

- Hydrostatic and leak test are calculated considering
  - ¼ T flaw due to higher irradiation
  - $SF = 1.5$ on primary stress
  - Isothermal conditions ($K_{It} = 0$)
- If fuel has not been loaded into the reactor vessel prior to performing the hydrostatic tests, the test must be performed at a temperature not lower than RT_{NDT} + 60 °F (RT_{NDT} + 33 °C)

Instrumentation uncertainties

- Administrative margins related to accuracy and uncertainty of instruments should be used (i.e., narrow range vs. wide range instruments); typically 410 kPa (60 psi) and 6 °C (10 °F)

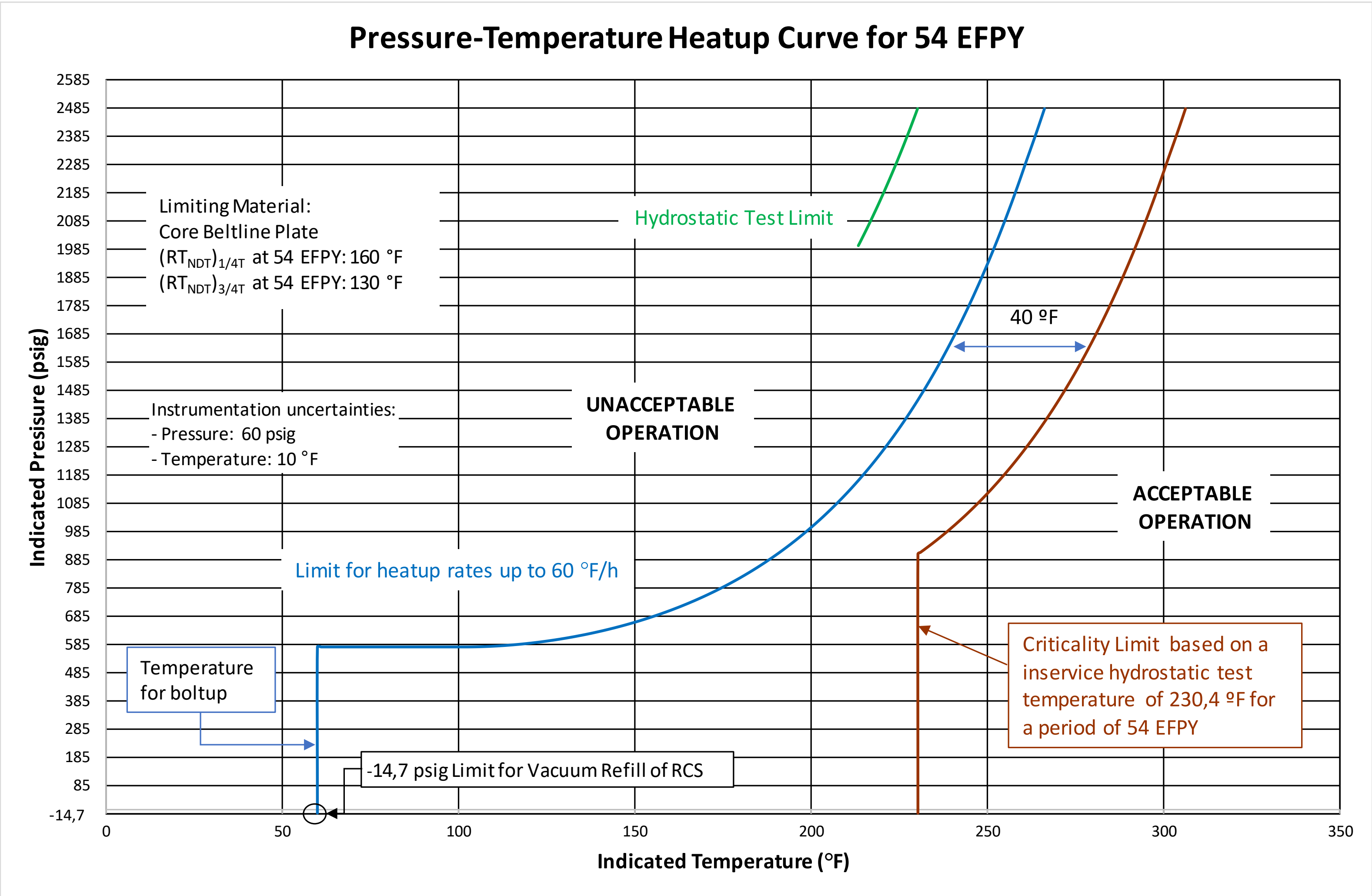
Additional requirements (10 CFR 50)

- 10 CFR 50, Appendix G requirements for closure flange:
  - During heat-up, the closure flange region (stressed by the bolt preload) may become limiting for P-T limits
    - For boltup the minimum temperature is the RT_{NDT} of closure flange zone
    - However, higher values are usually adopted
  - For core non critical
    - The metal temperature of the closure flange zone must be greater than RT_{NDT} +120 °F (RT_{NDT} + 66 °C) for P > 20% of the preservice hydro test pressure (i.e., about 621.25 psi or 4285 kPa)
  - For core critical
    - The metal temperature of the closure flange zone must be greater than RT_{NDT} +160 °F (RT_{NDT} + 89 °C) when the pressure exceeds 20% of the preservice hydro test pressure

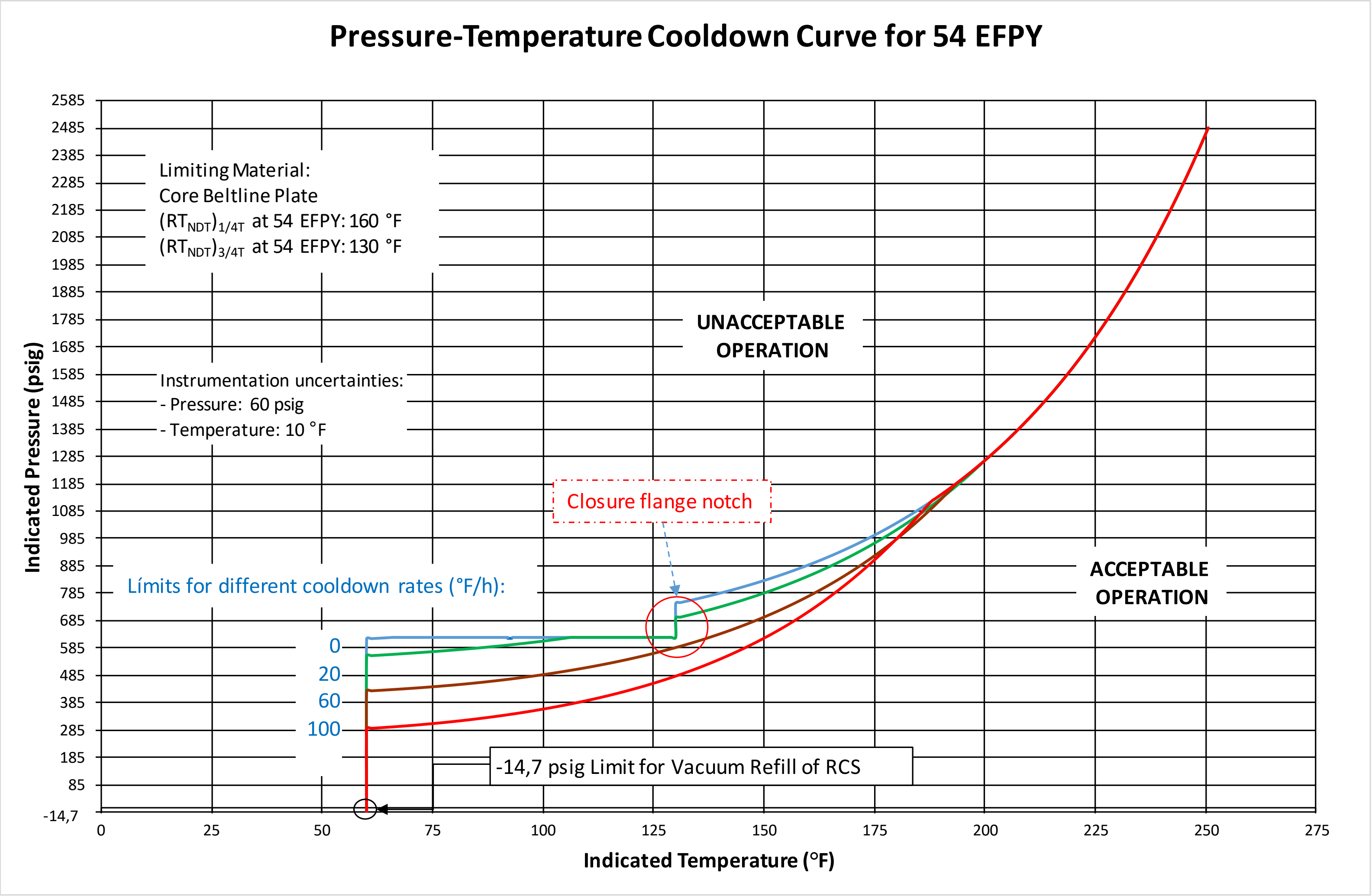
Additional requirements (10 CFR 50)

- 10 CFR 50, Appendix G requirements for core critical:
  - P-T limits must be 40 °F (22 °C) above any normal heat-up/cooldown (core not critical) limits
  - For any pressure, the core critical limit temperature must be at least that required for the pressure test limits

Sample curve



Sample cooldown curve



Extended beltline

- Historically, P-T limits only considered the region directly adjacent to the core (beltline)
- As neutron embrittlement levels increase in the existing reactor vessels, other materials outside of the traditional beltline are expected to be analyzed for reactor vessel integrity
- For plants of American design, changes in the fracture toughness properties of RPV materials have been demonstrated to occur at neutron fluence levels as low as $1x10^{17}$ n/cm^2 (E > 1 MeV)
- RPV materials whose predicted EOL fluence reaches that level constitute the "extended beltline"

Extended beltline

- US NRC issued a Regulatory Issue Summary RIS 2014-11[1]
  - Intent was to provide clarification on development of P-T limits
  - RPV nozzles, penetrations, and other discontinuities have complex geometries that may exhibit significantly higher stresses than those for the reactor vessel beltline shell region (cylindrical)
    - The higher stresses can potentially result in more restrictive P-T limits
  - All ferritic materials projected to experience fluence levels greater than 1×10^{17} n/cm^2 (E > 1 MeV) for the period of operation should be considered for P-T limit analysis

(1) "*Information on Licensing Applications For Fracture Toughness Requirements For Ferritic Reactor Coolant Pressure Boundary Components*"

Application of Master Curve

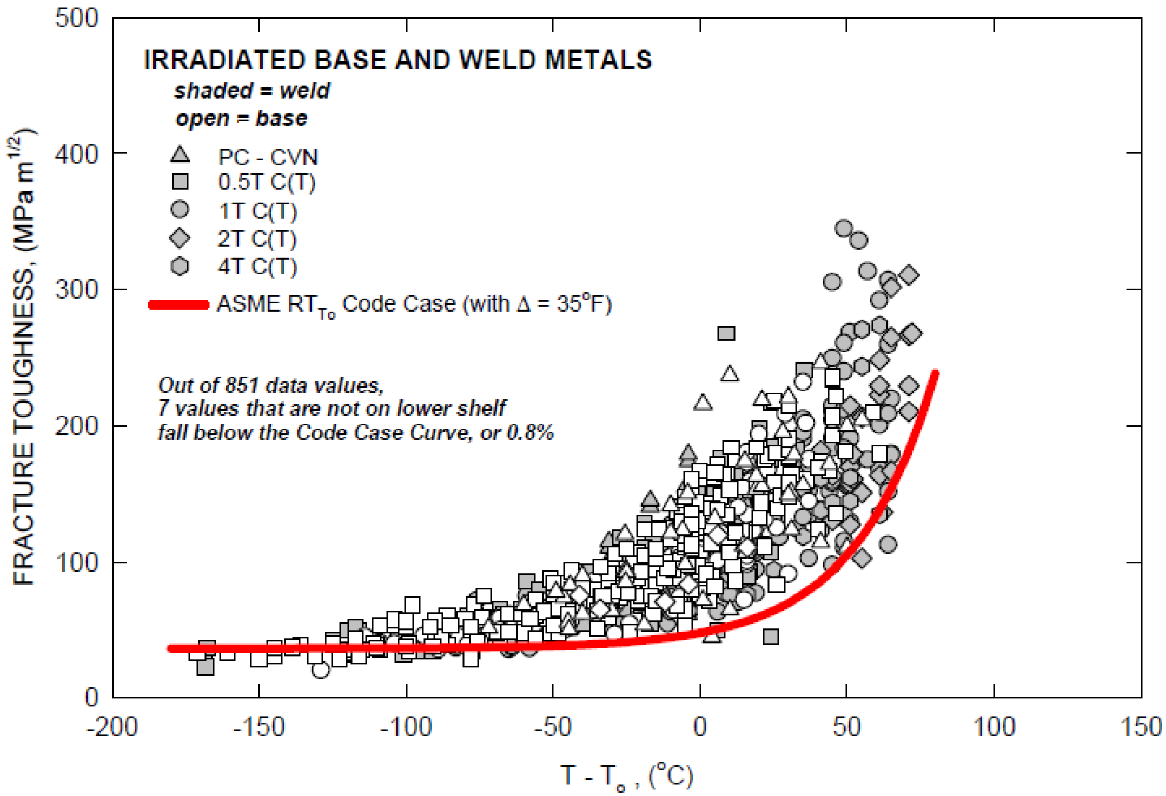
- The indexing parameter RT_{NDT} of ASME reference curves K_{IR} and K_{Ic} is, some cases, overly conservative in relation to the real toughness of RPV steels
- The Master Curve method can provide a directly measured fracture toughness temperature index, as well as statistically derived tolerance bounds for both unirradiated and irradiated steels
- ASME Code Case N-629 defines an alternative index RT_{T_0} for the reference toughness K_{IR} and K_{Ic}

$$RT_{T_0} = T_0 + 35\ °\mathrm{F} = T_0 + 19.4\ °\mathrm{C}$$

Where T_0 is obtained according to ASTM E 1921

Application of Master Curve

- This definition of RT_{T_0} appropriately bounds available data:



- ASME Code Case N-629 is now incorporated in Section XI Appendix G

Low Temperature Over-pressurization Protection (LTOP)

- By the late 1970s, 29 events occurred that produced pressure excursions above the P-T limits during PWR operation at lowtemperature
  - Service experience indicates most events are isothermal and occur between 100 – 200 °F (38 – 93 °C)
- Low Temperature Over-pressurization Protection (LTOP) systems must be in place to protect the vessel against brittle fracture due to high pressure (i.e., water solid) operation while at low temperature
  - Protects the low end of the Appendix G curves by implementing P-T setpoints in pressurizer relief valves

Low Temperature Over-pressurization Protection (LTOP)

- In Appendix G of Section XI the LTOP enable temperature is defined as the higher of
  - 200 °F (93 °C)
  - The coolant temperature corresponding to a metal temperature (1/4 T) of RT_{NDT} + 50 °F (RT_{NDT} + 33 °C)

Summary

- P-T limits operating curves are designed to ensure that there is an adequate margin against component failure from the combination of pressure, thermal stresses and flaws that may exist in the component
- Normally, are calculated for a given value of effective full power years (EFPY) which corresponds to a maximum fluence and limiting ART value for the specified EFPY
- If new surveillance data, fluence evaluations, or plant capacity factor causes this ART value to be exceeded, the curves may not be bounding for the EFPY
- Curves are updated periodically and as required to remain bounding

THANKS FOR YOUR ATTENTION

QUESTIONS?