History of P-T Limits for Heatup, Cooldown, and Leak Test

The origin of current rules on reactor vessel integrity began in the late 1960s. This topic was of interest for both the Atomic Energy Commission (AEC) and the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code). Eventually, the results of these deliberations became what is currently 10 CFR 50 Appendix G and ASME Code Section XI Nonmandatory Appendix G, with the ASME Code appendix being incorporated by reference into the regulations. The following discussion summarizes the historical development of the regulations and the ASME Code.

10 CFR 50 Appendix G

A starting point for AEC consideration of vessel integrity regulations seems to be a document entitled, "Supplementary Regulatory Criteria for ASME Code Constructed Nuclear Pressure Vessels" [1]. This document references the General Design Criteria (GDC), which state, "...components must be designed and fabricated to quality standards reflecting the importance of the safety function which they perform" [1]. In this early document, it was recognized that ferritic vessels must be designed against brittle fracture for transients expected in the course of normal operation, including heatup, cooldown, and leak testing. Furthermore, a vessel surveillance program was already under consideration to take into account irradiation embrittlement through Charpy impact (or drop weight) testing.

Resistance to fracture was quantified in terms of Charpy impact energy for the purposes of these early rules, recognizing that ferritic steels exhibit a ductile-to-brittle transition temperature (called the nill ductility transition temperature or NDT). Examples of specific requirements found in early documents are summarized in the following bullets.

- For the closure flange and the shell and head materials connected thereto, the absorbed impact energy, CVN, should be no less than 30 ft-lbs average and 25 ft-lbs minimum at a temperature of 10°F [2].
- For shell materials surrounding the reactor core, NDT < 10°F.
- For shell materials surrounding the reactor core, CVN > 60 ft-lbs at a test temperature of 160°F.

The specimens for these tests were to be oriented such that the long axis of the specimen was parallel to the major working direction of the bulk material. The temperature for hydrostatic testing was required to be at least 60°F above the test temperature required to meet the CVN specifications.

The release of [1] was followed by an Advisory Committee on Reactor Safeguards (ACRS) Subcommittee meeting on the subject of vessel integrity [3]. Even at this early stage, the Subcommittee debated the possibility of quantifying probability of vessel failure. Recognized uncertainties at this time included neutron flux and temperature at the vessel inside surface. Some discussion centered on appropriate risk metrics for determining adequate protection of the public health and safety.

The first indication that vessel integrity regulations would be promulgated came with a draft version of 10 CFR 50.55a, which was attached to ACRS meeting minutes [4]. This draft version of the rule adopted the concept of "minimum service temperature," which is the temperature above which 25% of the operating pressure may be imposed on the system. Minimum beginning-of-life CVN values were specified for different ranges of section thickness.

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Adjustments were to be applied to the listed CVN requirements to account for radiation embrittlement of components whose "properties may be subject to significant degradation in service..." [3]. The CVN requirements in this early version of the regulations were in terms of "adjusted fracture energy," which accounted for differences in testing methods (i.e., drop weight vs. Charpy impact) and specimen size effects.

In 1971, a draft rule was release for public comment in the Federal Register Notice [5]. It was here that 10 CFR 50 Appendix G was first introduced. In 1973, the draft rule was brought before the Commission for a vote [6]. In response to public comments, this document included the following new features.

- Fracture resistance was characterized by the nil ductility reference temperature, RT_{NDT}. "This temperature is the higher value of the NDT from the drop weight test or the temperature that is 60°F below the temperature at which Charpy test data meet...50 ft-lbs and 35 mils lateral expansion" [6].
- The "minimum service temperature" or "lowest pressurization temperature" concept, along with the minimum CVN requirements, was replaced by a fracture mechanics based approach that allows for continuous buildup of pressure as a function of temperature. This change was the first step toward was the first step towards the current practice of calculating pressure-temperature limit curves.
- Analysis of "nozzles, flanges, and shell regions near geometric discontinuities" was required [6].
- A requirement was added to specify that the vessel temperature shall not "be less than the minimum permissible temperature for the inservice system hydrostatic pressure test nor less than 40°F above" the temperature required by the fracture mechanics analysis [6].
- Requirements for preoperational leak tests, with no fuel in the vessel, were added.

As the ASME Code requirements for vessels became more mature, technical details were removed from the regulations in favor of incorporating the Code by reference. By 1980, the following supplemental requirements to the Code were found in a draft version 10 CFR 50 Appendix G issued for public comment [7].

- When the core is not critical, the pressure-temperature limits shall be as least as conservative as the Code requirements.
- When pressure is greater than 20 percent of the preservice hydrostatic test pressure, the temperature of nozzles, flanges, and other structural discontinuities shall be at least 150°F above RT_{NDT} of the material in those regions.
- When the core is critical, the vessel temperature shall not be lower than 40°F above the calculated pressure-temperature limits or lower than the minimum temperature for the inservice hydrostatic test.
- For boiling water reactors with pressure less than 20 percent of the preservice hydrostatic test pressure, the minimum temperature is 60°F above the RT_{NDT} of the closure flange.

Later, due to public comments, the Nuclear Regulatory Commission changed the RT_{NDT}+150°F requirement for structural discontinuities to RT_{NDT}+120°F for the cases of normal heatup and cooldown.

The current form of 10 CFR 50 Appendix G (as of the creation of this document) includes a Table describing the requirements, as in Table 1.

Table 1: Table from 10 CFR 50 Appendix G describing the pressure-temperature limits for the vessel.

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 (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.

ASME Code

This section describes a summary of Welding Research Council (WRC) Bulletin 175, which forms the technical basis of the current ASME Code rules on pressure-temperature limits [8]. In the early 1970s, ASME commissioned the Pressure Vessel Research Committee in order to further develop ASME Code requirements for pressure vessel fracture control. Their recommendations were published in WRC-175. Two approaches were discussed in this document. In the "transition temperature procedure," loading of the vessel is permitted only at temperatures higher than RT_{NDT}. This approach was similar to the "minimum service temperature" rules included in early versions of the AEC regulations [1]-[4]. WRC-175 also discussed the linear elastic fracture mechanics (LEFM) approach, where load carrying capacity of the flawed structure is quantified.

The LEFM and transition temperature approaches were combined in order to account for the temperature dependence (and radiation exposure dependence) of fracture resistance observed in ferritic steels. To describe the material resistance to fracture, the reference critical stress intensity factor, K_{IR}, curve was introduced, as in Equation 1.

$$K_{IR} = 1.223exp\{0.0145[T - (RT_{NDT} - 160)]\} + 26.777 \qquad \text{Equation 1}$$

This curve was based upon a lower bound statistical fit to measured dynamic and crack arrest toughness values. Using the empirical K_{IR} curve, a fracture mechanics parameter is estimated from the reference temperature determined by Charpy impact testing. Equation 1 is not appropriate for a material with yield strength greater than 50 ksi.

The governing equation for calculating a pressure-temperature limit curve, according to WRC-175, is equation 2.

$$K_{I\,pressure} + K_{I\,therm} \leq K_{IR} \qquad \text{Equation 2}$$

where $K_{Ipressure}$ is the stress intensity factor due to pressure loading, and K_{Itherm} describes the stress intensity factor due to thermal gradient loading. Recommendations on appropriate structural factors (or, safety factors) were also discussed. Equation 2 states that the driving force for crack growth may not exceed the material resistance to crack growth.

The next consideration in the LEFM approach is the postulated flaw size. Figure 1 shows example flaw geometries for internal axial and circumferential flaws in an infinite hollow cylinder.

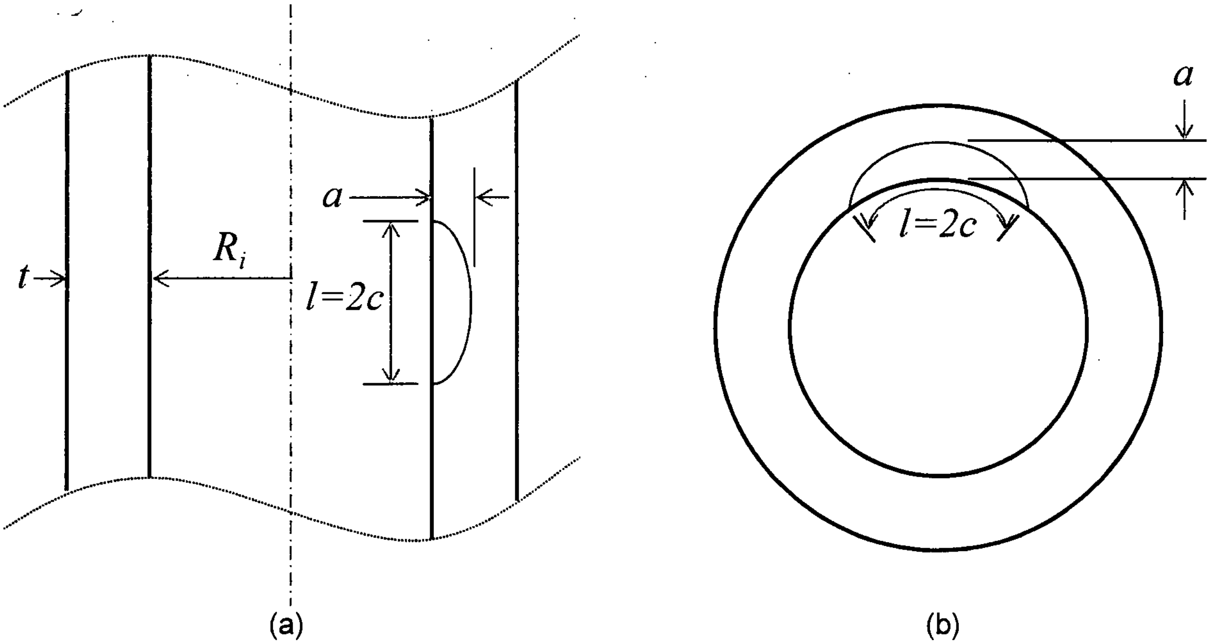

Figure 1: Example flaw geometries relevant to reactor vessel integrity: (a) internal, surface-breaking axial flaw and (b) internal, surface-breaking circumferential flaw. External surface-breaking flaws should be considered when tensile stresses develop at the outside surface (e.g., heat-up conditions).

Hoop and axial stress satisfy Mode I (i.e., crack opening mode) loading conditions for the axial and circumferential flaws, respectively. The recommended flaw dimensions in WRC-175 are: $a = 0.25t$ and $l = 6a$ for $4 \leq t \leq 12$. For $t < 4$ or $t > 12$, the analyst should use the $0.25t$ flaw for $t = 4$ or $t = 12$, respectively. The technical basis given for the $0.25t$ flaw was that a flaw of this size is unlikely to go undetected during required preservice and in-service nondestructive evaluation procedures. Embedded defects were excluded on the basis that stress intensity factors for these flaws are lower than for surface-breaking flaws. Flaws of larger length were considered excessively conservative, given other conservatisms present in the analysis.

The loading conditions for the analysis include primary membrane stress due to internal pressure and thermal stress due to through-wall thermal gradients that develop during normal heatup and cooldown operations. Residual stresses were neglected due to, among other considerations, post-weld heat treatment. WRC-175 discusses development of stress intensity factor equations for the internal pressure and thermal gradient loading cases. Modifications of the stress intensity factor equations are provided for the case of structural discontinuities, such as nozzles.

References

[1] Letter to Mr. John T. Conway from Harold L. Price with enclosures, August 16, 1967 (MLxxxxxxxxx).

[2] Electric Power Research Institute, "White Paper on Reactor Vessel Integrity Requirements for Level A and B Conditions," TR-100251, January 1993.

[3] Minutes of "NDT/Pressure Vessels/Containment Subcommittee Meeting," January 22, 1970 (MLxxxxxxxxx).

[4] Memo from J. E. Hard to H. Etherington, "Minutes of Meeting of April 2, 1970," April 7, 1970 (MLxxxxxxxxx).

[5] Federal Register, Vol. 36, No. 120, July 3, 1971, p. 5.

[6] Memo from Director of Regulation to The Commissioners, "Amendment to 10 CFR Part 50: Appendix G, 'Fracture Toughness Requirements,' and Appendix H, 'Reactor Vessel Material Surveillance Program Requirements,' " Secy-R 700, June 1, 1973 (MLxxxxxxxxx).

[7] Federal Register, Vol. 45, No. 222, November 14, 1980, p. 75536.

[8] Pressure Vessel Research Committee Ad Hoc Group on Toughness Requirements, "PVRC Recommendations on Toughness Requirements for Ferritic Materials," WRC-175, August 1972.