STP-PT-028

IMPACT TESTING EXEMPTION CURVES

FOR LOW TEMPERATURE OPERATION OF PRESSURE PIPING

ASME STANDARDS TECHNOLOGY, LLC

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ASME STANDARDS TECHNOLOGY, LLC

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FOREWORD

This document was developed under a research and development project which resulted from ASME Pressure Technology Codes & Standards (PTCS) committee requests to identify, prioritize and address technology gaps in current or new PTCS Codes, Standards and Guidelines. This project is one of several included for ASME fiscal year 2008 sponsorship which are intended to establish and maintain the technical relevance of ASME codes & standards products. The specific project related to this document is project 07-04 (B31#2), entitled, "Impact Testing Exemption Curves For Low Temperature Operation Of Pressure Piping."

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ABSTRACT

Extension of ASME exemption curves has been accomplished by consistent application of old and new ASME fracture mechanics concepts originally intended for pressure vessels. It is recognized that materials produced by modern means may be deserving of greater credit for toughness and reassignment to different traditional curves or even new curves may be in order. Where there is impact toughness data, the mean temperature in the transition region may be estimated and new exemption curves developed. Procedures described were used to adjust exemption curves for thickness where pipe wall is less than the normal Charpy specimen width.

1 INTRODUCTION

This study investigated the impact test exemption curves of ASME Section VIII, UCS-66, with the objective of extending them to thicknesses representative of piping components. Specifically, the purposes of the investigation included:

- Extension of the curves (particularly Curves for material groups A and B) to lower temperatures and to thicknesses less than 0.394 inches
- To understand the technical and historical origin of these curves
- To expand in a more systematic and complete way the several exceptions to these curves, namely UCS-66(d) and UG-20(f)
- Evaluation of data and history in light of modern steel production methods, which produce materials that are less prone to low temperature failures.

2 BACKGROUND

ASME Section VIII, UCS-66 requires impact testing of materials classified in groups according to curves shown in Figure UCS-66. For MDMT above the curves, materials in each group are exempt from impact testing. For MDMT below the curves, materials must be tested unless lower than normal allowable stresses or other specified conditions are met. Curves for various material types (classifications) are shown in Figure 1 in which temperature of exemption decreases with decreasing thickness. Impact testing is required for the specific combinations of design temperature, material classification and thickness below the respective curves. Thin materials have lower allowable design exemption temperatures and the curves become quite steep as the thickness decreases as shown Figure 1. The curves are truncated at the thickness of a full size Charpy impact specimen.

Recently, B31.5 has adopted some of the provisions of UCS-66 for determining when impact testing is required. However, UCS-66 Curves A and B are truncated at 18˚F and -20˚F, respectively, and below 0.394 inch thickness. It is this region (e.g., < –20˚F and < 0.394 inch thick) that is pertinent to most industrial refrigeration piping.

The desired result of this project was to be new, extended curves or an entirely new format for impact testing exemption and testing. The extension of these curves down to lower temperatures and thicknesses will be a great benefit to the industrial refrigeration industry. For example, a simple blanket extension of Curve B materials down to –55˚F would relieve piping contractors and engineers of the burden of extra calculations, oversized pipe schedules, purchasing and tracking multiple grades of pipe and fittings on the same job site as well as extra testing and inspections. This interest comes at a time when customers of steel makers are being told that today's continuous casting methods are "cleaner," have better control of carbon content and are much more resistant to brittle fracture. Therefore, a supplement of this project is to verify (and quantify) such claims. The result of this project could then be new and more applicable curves, or an entirely new format applied to impact testing criteria.

ASME B31.5, Pressure Piping Code for Refrigeration Piping, also includes provisions to derate the allowable stress of carbon steel materials when used at low temperatures. This possibility is discussed herein.

3 APPROACH

In developing the ASME Section VIII, Division 2 Rewrite under PVRC, the entire technical and historical basis for the current UCS-66 exemption curves was examined, understood, checked, corrected and upgraded to modern fracture mechanics standards. The relevant equations were established and applied to understand the old exemption curves and then modified as needed to develop exemption curves applicable to the higher design allowable stresses and demands of Section VIII, Division 2. The result of that effort was a completely systematic approach that can be applied to all code sections and criteria and even modified for particular geometries and default flaws if desired. Specifically, the method was updated to use the most modern stress intensity solutions for the crack driving force and appropriate Failure Assessment Diagram (FAD) based computations and families of toughness curves to set exemption temperatures. The computations also were improved to systematically treat residual stresses and the implications of reducing stresses below allowable values in order to enable operation at lower temperatures than permitted by the exemption curves. The results were approved for the Section VIII, Division 2 Code.

Another element worth noting is the importance of a systematic and reasonable scheme for correlating fracture toughness with Charpy energy. PVRC has fashioned an approach to smoothly correlate values from the lower shelf to the upper shelf. It is an improvement on the work of Barsom and Rolfe, yet is derived from, and is not inconsistent with, their work. As a result of the comprehensive work and approach, it would be possible to create new exemption curves (e.g. E, F, G, etc.) based on the performance of new materials (that have been improved due to their composition, melting practice, etc.) or to justify moving a material from one curve to an existing curve if its classification is now deemed to be incorrect.

3.1 History and Concepts

The technical basis for the exemption curves was well documented in by Professor H. Corten and Alan Selz over 20 years ago in separate ASME conference papers that are summarized here. Professor Corten's paper details use of early fracture mechanics approaches to assure adequate plasticity of material in the presence of sharp, crack-like assumed flaws. These flaws were stipulated to be ¼-thickness deep, semi-elliptical surface flaws with 6:1 aspect ratios. However, no flaw would be assumed more severe than the one found in a 4-inch section. The logic was that more severe flaws would most certainly be identified using ASME mandated inspections and testing and therefore would be excluded from the component under consideration. Several clever engineering assumptions were invoked at the time which enabled the exemption curves developed to be independent of yield strength or design allowable stress. Additionally, because of the mathematical relations used the shapes of the exemption curves could be essentially independent of material type (the assumed category into which the covered steel specifications were arranged).

1) All toughness curves (all materials and fracture toughness as well as Charpy) were assumed to be of a single shape and transition temperature width, i.e., hyperbolic tangent, centered about a characteristic temperature (Figure 2). The same reference temperature was assumed applicable for Charpy and fracture toughness.

2) Four characteristic temperatures were assumed to be adequate to cover the materials of interest 114˚F, 76˚F, 38˚F and 12˚F. The materials were termed A, B, C and D, respectively.

3) The half-width of the transition temperature (C_R in Figure 2) from lower shelf to upper shelf was independent of material or strength and set as 66˚F.

4) The fracture toughness curve (actually a curve of required toughness) was set to be proportional to the specified minimum yield strength of the material.

5) The upper and lower shelf energies were also set as functions of the yield strengths.

6) Standard semi-elliptical cracks of dimensions dependent on thickness were assumed to be present.

7) The required crack tip plasticity was proportional to the square of the ratio of the crack driving force to the yield strength and inversely proportional to the thickness.

8) The material fracture toughness required was essentially the dynamic or high rate fracture toughness which was assumed to vary with the square root of the Charpy energy in U.S. customary units as conservatively proposed at that time by Barsom as:

$$CVN = \left(\frac{K_{1d}}{12}\right)^2 \tag{1}$$

9) The maximum design stress that a material might see was assumed to be 2/3 the specified minimum yield strength.

10) The coefficients A and B defined in Figure 2 were set as 1.7 and 1.37 for all materials as shown in the equation below.

$$K_{1d} = \sigma_{ys}\left\{1.7 + 1.37 \cdot \tanh\left[\frac{T - T_0}{C_R}\right]\right\} \tag{2}$$

where: T_0 = mid temperature of transition change.

11) The upper shelf toughness values were assumed to be related as correlated by Barsom and Rolfe without specific regard to dynamic or static values of fracture toughness

$$CVN_{us} = \frac{K_{us}^2}{5 \cdot \sigma_{ys}} + \frac{\sigma_{ys}}{20} \tag{3}$$

The resulting relation between yield strength and toughness is illustrated in Figure 3.

The above described assumptions, simplifications and approximations set the stage for greatly simplified mathematical solutions for what became the exemption curve equations and only 4 curves were established. They were obtained by simply shifting the characteristic temperature T_0.

The plasticity relation between thickness and the square of toughness in assumption 7 above leads to the relation below where the proportionality constant ∞ is assumed to be close to 1.

$$\sqrt{thickness} \propto \left\{1.7 + 1.37 \cdot \tanh\left[\frac{T - T_0}{C}\right]\right\} \tag{4}$$

This equation in turn can be rearranged to give

$$T = T_0 + C * [\text{Arc}\tanh\{\sqrt{thickness} - 1.7\} / 1.37] \tag{5}$$

The above is the exact equation used by Corten as the basis for the exemption curves. The exemption temperature increased gradually and systematically with the square root of thickness as shown in Figure 4 which compares the ASME exemption curves with the calculated curves published by Corten (as recently verified when PVRC computed the curves using his equations). The Corten calculated curves were modified by the ASME committee members of the time to allow design conditions reportedly used for existing equipment, conditions which were therefore justified by past experience. The maximum differences between calculated and published curves are at the extremes of thickness. At thicknesses greater than 4 inches, the simple Corten equation shown did not account for the cap on the size of the reference flaw. Included in Figure 4 are the curves calculated for the new ASME Section VIII, Division 2. The effect on the curve flattening due to the flaw size cap can be seen in the lines at high thickness values. Thus, the relation between the new calculations and the published curves is unmistakable and validated, especially for B, C and D materials.

It should be noted at this time that a very significant element of conservatism was used introduced for pressure vessel applications by ignoring the shift in the fracture toughness transition temperature due to loading rate. This is illustrated in Figure 5 for which Barsom's yield strength dependent fracture toughness rate shift equation was used to calculate the A material Charpy toughness requirement. Corten made the same calculation in highlighting this point. While some doubt has recently been expressed about the yield strength dependence of the shift as calculated by Barsom, there is no doubt that a significant rate dependence exists and introduces a great deal of conservatism into the calculation of fracture toughness requirements.

4 NEW FRACTURE MECHANICS APPROACH TO REQUIRED TOUGHNESS

4.1 Description of FAD-Based Fracture Mechanics

To develop the toughness rules for the new ASME Section VIII, Division 2, the above approach was modernized and upgraded. An applied stress equal to the allowable design stress and residual stress for both the as-welded and heat treated condition were considered in conjunction with a surface breaking reference flaw. The driving force for brittle fracture (applied stress intensity) is computed using the applied stress, residual stress and reference flaw size. The resistance to brittle fracture or required material fracture toughness is set equal to this computed stress intensity. The required Charpy V-Notch impact energy (CVN), the minimum design metal temperature (MDMT) using the familiar exemption curve designations (i.e., A, B, C and D) and the reduction in the MDMT permitted based on reduced design stress were determined using a new MPC fracture toughness model described in API 579-1/ASME FFS-1, Appendix F, paragraph F.4.5.3. The required Charpy V-Notch impact energy (CVN) was then determined from the fracture toughness using a correlation/interpolation scheme described in this section.

As in API 579-1/ASME FFS-1, the Failure Assessment Diagram (FAD) approach is used for the evaluation of crack-like flaws in components. The FAD approach was adopted because it provides a convenient, technically based method to provide a criterion for the acceptability of a component with a crack-like flaw when the failure mechanism is measured by two distinct criteria: unstable fracture and limit load. Unstable fracture usually controls failure for flaws in components fabricated from a brittle material and plastic collapse typically controls failure for large flaws if the component is fabricated from a material with high toughness. Mixed mode fracture occurs between these extremes. In the analysis of crack-like flaws, the results from stress analysis, stress intensity factor and limit load solutions, the material strength and fracture toughness are combined to calculate a toughness ratio, K_r, and load ratio, L_r. These two quantities represent the coordinates of a point that is plotted on a two-dimensional FAD to determine acceptability. If the assessment point is on or below the FAD curve, the component is suitable for continued operation. A schematic that illustrates the procedure for evaluating a crack-like flaw using the Failure Assessment Diagram is shown in Figure 6.

4.2 Reference Flaw Size

To compute the crack driving force, a semielliptical surface flaw with the depth, a, and length, $2c$, is assumed. This flaw size was established based on early research work pertaining to the sensitivity and detection capability of radiographic examination (see WRC Bulletin 175).

$$a = \min\left[\frac{t}{4},\ 1.0\ in\right] \tag{6}$$

$2c = 6a$ or $c/a = 3$

To compute the crack driving force, a, the following membrane stresses were assumed for the applied primary stress, σ_m^P, and residual stress, σ_m^{SR}.

$$\sigma_m^P = \frac{2}{3}\sigma_{ys} \tag{7}$$

Component not subject to PWHT:

$$\sigma_m^{SR} = \frac{2}{3}\sigma_{ys} \tag{8}$$

Component subject to PWHT:

$$\sigma_m^{SR} = 0.20\sigma_{ys} \tag{9}$$

4.3 Required Material Fracture Toughness

The toughness ratio for the FAD-based fracture mechanics approach discussed above is:

$$K_r = \frac{K_I^{\,P} + \Phi K_I^{\,SR}}{K_{mat}} \tag{10}$$

For steels with a yield plateau (i.e., $L^P_{r(\max)}=1.0$), the following simplified FAD may be used, see API 579-1/ASME FFS-1, Part 9, Figure 9.20, Note 4.

$$K_r = \left(1.0 - (L_r^P)^{2.5}\right)^{0.2} \tag{11}$$

Combining the two equations above and solving for the required material toughness, $K_{mat,}$ the following expression is obtained. Note that the required material fracture toughness is a function of the wall thickness as is reflected by the exemption curve and due to the change that is attributable to the assumption of increasing flaw size with thickness.

$$K_{mat}(t) = \frac{K_1^P + \Phi K_1^{SR}}{\left(1.0 - \left(L_r^P\right)^{2.5}\right)^{0.2}} \tag{12}$$

The fracture toughness parameters, K_1^P and K_1^{SR}, are obtained as follows using geometrical curve fitting parameters for computed fracture mechanics quantities. In these equations, the parameter $K_{RF}^{Cylinder}$ was derived using API 579-1/ASME FFS-1, Annex C using the KCSCLE2 Solution with a 1 ksi membrane stress and the reference flaw. The membrane stresses are set in accordance with the assumption about residual stresses described above. The resulting equations for the fracture toughness parameters are functions of the cylinder wall thickness and radius to thickness ratio.

$$K_1^P = \sigma_m^P \cdot K_{RF}^{Cylinder} \tag{13}$$

$$K_1^{SR} = \sigma_m^{SR} \cdot K_{RF}^{Cylinder} \tag{14}$$

$$K_{RF}^{Cylinder} = \left(\begin{array}{l} 79.22136 + 30.478223 \cdot \sqrt{t} \cdot \ln\left[t\right] - 198.45648 \cdot \sqrt{t} + \\ 125.45723 \cdot \ln\left[t\right] + \dfrac{127.66614}{\sqrt{t}} - \dfrac{12.649681}{t} + \\ 13.817361 \cdot \exp\left[t\right] - \dfrac{0.071270789}{\sqrt{R/t}} - \dfrac{0.14373602 \cdot \ln\left[R/t\right]}{\left(R/t\right)^2} \end{array} \right) \tag{15}$$

$K_{RF}^{Cylinder}$ utilized in the development of the toughness rules herein was developed using the data in API 579, 2000 Edition, Appendix C and is valid for a thickness range of 0.25 inch $\le t \le$ 4 inches. The equation below is a new data fit developed for piping applications in this project using the data in API 579-1/ASME FFS-1, Annex C and is valid for a thickness range of 0.001 inch $\le t \le$ 4 inches. The difference between the data in API 579, 2000 Edition, Appendix C and API 579-1/ASME FFS-1, Annex C is that more accuracy in the data was provided for $a/t \le 0.2$. The difference in the toughness driving force data fits is typically less than 5% where there is overlap and the effect on the exemption curve temperatures is only a few degrees. All fracture mechanics based results used to develop the toughness rules will be updated in future editions of Section VIII, Division 2; however, it is anticipated that the results will show minor differences.

$$K_{RF}^{Cylinder} = \exp\left[-0.102270708 + 0.500090962 \cdot \ln[t] + \frac{0.043587868}{\ln\left[\frac{R}{t}\right]}\right] \tag{16}$$

The plasticity interaction, Φ, defined below, was derived by curve fitting the plots shown in Figure 9.19 of API 579-1/ASME FFS-1.

$$\Phi = \begin{pmatrix} 0.99402985 - 0.34259558 \cdot L_r^P + 0.07849594 \cdot L_r^{SR} + \\ 1.3153525 \cdot \left(L_r^P\right)^2 - 0.035075224 \cdot \left(L_r^{SR}\right)^2 + 0.2222982\left(L_r^P\right)\left(L_r^{SR}\right) - \\ 0.97610564 \cdot \left(L_r^P\right)^3 + 0.0041367592 \cdot \left(L_r^{SR}\right)^3 - \\ 0.0062624497 \cdot \left(L_r^P\right)\left(L_r^{SR}\right)^2 - 0.16970127 \cdot \left(L_r^P\right)^2\left(L_r^{SR}\right) \end{pmatrix} \tag{17}$$

The load ratio parameters, L_r^P and L_r^{SR}, are defined by the equations below. In these equations, the parameter $R_{RF}^{Cylinder}$ was derived using API 579-1/ASME FFS-1, Annex D using the RCSCLE2 Solution with a 1 ksi membrane stress and the reference flaw. The membrane stresses are set as noted above. The resulting equations for the load ratio parameters are a function of the cylinder wall thickness and radius to thickness ratio.

$$L_r^P = \frac{\sigma_m^P \cdot R_{RF}^{Cylinder}}{\sigma_{ys}} \tag{18}$$

$$L_r^{SR} = \frac{\sigma_m^{SR} \cdot R_{RF}^{Cylinder}}{\sigma_{ys}} \tag{19}$$

$$R_{RF}^{Cylinder} = \begin{pmatrix} 0.99829577 + 0.0071541778 \cdot t + 1.3018206\dfrac{c}{(R/t)} - 0.0019047184 \cdot t^2 - \\ \dfrac{4.3132859}{(R/t)^2} - \dfrac{0.042484369 \cdot t}{(R/t)} + 0.00011487158 \cdot (t)^3 + \dfrac{5.4284626}{(R/t)^3} + \\ \dfrac{0.12675001 \cdot t}{(R/t)^2} - \dfrac{0.0033013072 \cdot t^2}{(R/t)} \end{pmatrix} \tag{20}$$

The above equation was developed based on API 579, 2000 Edition, Appendix D and is valid for a thickness range of 0.25 inch $\le t \le$ 4 inches. Shown below is a new data fit developed for this project using the data in API 579-1/ASME FFS-1, Annex D and is valid for a thickness range of 0.001 inch $\le t \le$ 4inches. The difference in the data fits is typically less than 5% where they overlap. All fracture mechanics based results used to develop the toughness rules will be updated in future editions of VIII-2; however, it is anticipated that the results will show minor differences.

$$R_{RF}^{Cylinder} = 1.002550710 + \frac{0.3656047958}{\left(\frac{R}{t}\right)} - \frac{0.507558524}{\left(\frac{R}{t}\right)^2} + 0.2401731622 \cdot \exp\left[-\left(\frac{R}{t}\right)\right] \quad (21)$$

5 DERIVATION OF CHARPY V-NOTCH IMPACT TEST REQUIREMENTS

5.1 Required Fracture Toughness

The required material toughness, $K_{mat}(t)$, as a function of thickness is based on the reference flaw and applied stress. When $K_{mat}(t)$ was evaluated for ASME Section VIII, Division 2, the fracture toughness parameter and reference stress parameter given were evaluated at R = 100.

To derive the required CVN for a material as a function of thickness and yield strength, the CVN transition curve is divided into three regions.

5.2 Lower Shelf Vicinity CVN

In the vicinity of the lower shelf (near lower shelf, nls), the CVN requirement for the early part of the transition region is a function of thickness and is given, in U.S. customary units, by

$$CVN_{nls}(t) = \left(\frac{K_{mat}(t)}{15}\right)^2 \qquad for \qquad CVN_{nls}(t) \le 0.45\sigma_{ys} \tag{22}$$

An extensive review of fracture toughness data by MPC indicates that the above relation applies for the indicated limitation based on the yield strength of the material.

The fracture toughness for the near lower shelf region is then simply given by (also see API 579-1/ASME FFS-1, Annex F, paragraph F.4.5.2)

$$K_{nls}(t) = 15 \cdot \sqrt{CVN_{nls}(t)} \tag{23}$$

5.3 Upper Shelf Region CVN

The dynamic fracture toughness for an ASME exemption curve material (A, B, C or D) with a group temperature, T_0, for a specified yield strength, σ_{ys}, at a temperature, T, may be estimated as shown below, see API 579-1/ASME FFS-1, Annex F, paragraph F.4.5.3. This equation provides more reasonable values for the dynamic fracture toughness than the simple equation of Corten in the important region approaching the lower shelf where Corten's equation gives unrealistically low numbers for steels with ordinary, low yield strengths (Figure 7).

$$K_{1d} = \sigma_{ys}\left\{\sqrt{3} + \left(\sqrt{3} - \frac{27}{\sigma_{ys}}\right) \cdot \tanh\left[\frac{T - T_0}{C}\right]\right\} \tag{24}$$

T_0 = 114˚F for ASME Exemption Curve A

T_0 = 76˚F for ASME Exemption Curve B

T_0 = 38˚F for ASME Exemption Curve C

T_0 = 12˚F for ASME Exemption Curve D

C = 66˚F

For temperatures above the transition region, i.e., upper shelf behavior, the equation below provides estimated required fracture toughness:

$$K_{us} = K_{1d} = (2\sqrt{3} \cdot \sigma_{ys} - 27) \tag{25}$$

The Rolfe-Novak-Barsom correlation below, given in API 579-1/ASME FFS-1, Annex F, paragraph F.4.5.2, provides an estimate of the upper shelf CVN and the upper shelf fracture toughness and the yield strength.

$$CVN_{us} = \frac{K_{us}^2}{5 \cdot \sigma_{ys}} + \frac{\sigma_{ys}}{20} \tag{26}$$

5.4 Transition Region CVN

The equation given below can be used to model the transition region. This equation maintains proportionality between the CVN and fracture toughness in terms of the fracture toughness and $\sqrt{CVN}$. The parameters used are defined above.

$$CVN_{trans}(t) = \left(\left(\frac{K_{mat}(t) - K_{nls}(t)}{K_{us} - K_{nls}(t)} \right) \left(\sqrt{CVN_{us}} - \sqrt{CVN_{nls}(t)} \right) + \sqrt{CVN_{nls}(t)} \right)^2 \tag{27}$$

5.5 Final CVN Requirement

The required CVN for a material can be calculated as a function of the yield strength and nominal thickness as shown for the new ASME Section VIII, Division 2 in Figure 8 for components not subject to PWHT. The energy requirement was established as follows.

$$CVN(t) = \max\left[CVN_{min},\ CVN_{nls}(t),\ CVN_{trans}(t),\ CVN_{us}(t) \right] \tag{28}$$

5.6 Derivation of Impact Test Exemption Curves for Thin Piping

For pressure vessels, the impact test exemption curves in Figure 9 from ASME Section VIII, Division 2 gives exemption temperature based on a nominal component thickness for components not subject to PWHT. It is obtained by solving $K_{mat}(t)$ equation above for the temperature directly, again noting that the exemption temperature is a function of the thickness, or:

$$T(t) = \mathrm{Arc}\tanh\left[\frac{K_{mat}(t) - \sqrt{3} \cdot \sigma_{ys}}{\left(\sqrt{3} - \frac{27}{\sigma_{ys}} \right)} \right] \cdot C + T_0 \tag{29}$$

For all materials covered by the four exemption curves labeled A, B, C and D, the yield stress in the above equation was conservatively assumed to be 80 ksi, i.e., σ_{ys} = 80 ksi. In addition, the cut-off limit for the lower bound of the curve is taken as the temperature at which the thickness is equal to 0.4 inch as shown in Figure 9. This approach was modified for thin piping as described below.

For piping components of interest in this study the equations for a thickness range of 0.001 inch $\le t \le$ 4 inches cited above were used and evaluated at R=10 inches. A series of calculations showed that the effect of R on temperature was not strong. Exemption curves for various yield strengths are presented for piping in Figure 10 to Figure 13. The effect of yield strength is strong in thick sections. These plots allow the governing committees to make decisions regarding conservatism they wish to apply for piping applications based on relevant experience and operating practices with the materials in use.

The effect on PWHT, of course, is to lower the exemption temperature as shown by comparing Figure 12 and Figure 14 for Type C materials at thicknesses greater than that at which the lower shelf cut off (truncation) is reached for the heat treated material. For materials that are not post weld heat treated, for a given yield strength the cut off temperature for the heat treated material is acceptable but at a thinner wall and the corresponding assumed flaw size is proportionately smaller. The assumption of very small flaws permits achieving in principle the very low exemption temperatures indicated for material that is not post weld heat treated. For each yield strength, the truncation of the exemption curve occurs just above the lower shelf energy.

5.7 Derivation of Curves for Reduction in the MDMT Without Impact Testing

The permissible reduction in the MDMT without impact testing due to stress reduction is shown in Figure 15 for components not subject to PWHT. It is derived using the fracture mechanics concepts above with the important consideration regarding residual stresses. Residual stresses that comprise an important part of the crack driving force are not reduced when applied stresses are reduced. This was not properly accounted for in the calculations for stress reduction when done in the past for the ASME Code.

The temperature reduction, $T_R(R_{ts})$, based on the stress reduction ratio, R_{ts} , is:

$$T_R(R_{ts}) = \mathrm{Arc}\tanh\left[\frac{K_{mat}(R_{ts}) - \sqrt{3}\cdot\sigma_{ys}}{\left(\sqrt{3} - \dfrac{27}{\sigma_{ys}}\right)}\right]\cdot C + T_0 \tag{30}$$

The reduced temperature, $T_R(R_{ts})$, is only a function of the stress reduction ratio, R_{ts}, yield strength but not the wall thickness. The final equation for the temperature reduction, $\Delta T(R_{ts})$, is simply given by:

$$\Delta T(R_{ts}) = T_R(1) - T_R(R_{ts}) \tag{31}$$

In ASME Section VIII, Division 2, if the computed value of the R_{ts} ratio is less than or equal to 0.24, then the MDMT may be set to −155˚F and impact testing is not required unless a lower MDMT is desired. This requirement roughly stipulates that if the operating stresses are equal to, or less than, 10% of the specified ultimate tensile strength, operation for ferritic materials is permitted on the lower shelf. This rule is consistent with old ASME Section VIII, Division 2 where the limit for the R_{ts} ratio is 0.3. The purported justification for low-stress, lower shelf operation is that the stress is low enough that brittle fracture is not possible. The curves given in Figure 10 through Figure 14 are all truncated just above the lower shelf due to the temperature sensitivity of the calculations. As the lower shelf is approached, the curves become nearly vertical and extremely low temperatures would be permitted.

6 CONCLUSION

Extension of exemption curves has been accomplished by consistent application of old and new ASME concepts intended for pressure vessel applications. It is recognized that modern materials may be deserving of greater credit for toughness and reassignment to different traditional curves or even new curves may be in order. Where there is assurance that the mean temperature in the transition region for Charpy tests (adjusted for thickness where pipe wall is less than the normal Charpy width) can be conservatively and confidently set, T_0 values might be assigned and the methods described herein applied to develop new exemption curves for new steels or for steels produced with controlled modern practices. For example, several of the steel grades covered by ASTM A333 for low temperature service are required to be impact tested; both full size and subsize requirements are provided. Following the procedures described in this paper, fracture toughness transition curves have been developed for each grade as shown in Figure 16. It is apparent that these steels exceed the performance expectations of A, B, C and D materials shown in the ASME exemption curves.

While the superior behavior of steels is easily achieved with modern steel making practices that result in high levels of microstructural cleanliness, low limits on sulfur, phosphorus, silicon, carbon (and other elements long known to be detrimental to toughness) and increased, but small beneficial additions of manganese and nickel contents, without toughness testing or enhanced controls on composition and processing there is no assurance that adherence only to the usual specified limits on composition will provide adequate toughness. The compositional limits in almost all modern materials specifications are too wide to exclude inadequate material. In addition, heat treatment has a significant effect as well and actual temperatures and cooling rates cannot be verified after the fact. In the era of global sources of supply there are no assurances that material purchased was produced to modern practices or even that composition and heat treatment are as stated. There are numerous instances of piping components of low alloy steel provided to the electric utility industry where heat treatment did not lead to the properties desired. Caution is therefore urged in taking steps to upgrade a material’s type. We have found no data to suggest that the A and B exemption curves should be treated generally as overly conservative. On the contrary, available data suggest they are reasonable. Where data can be obtained on specific materials, the approach described herein can be applied to set new reference temperatures. However, quality assurance needs to be in place.

Additionally, it must be recognized that, except where toughness testing is required, there has been little incentive to study the behavior of piping steels and so very little data exists. This is especially true of low temperature properties. Other complications are extrapolating subsize specimen data to full-size equivalency and anisotropy.

A point of caution for piping application is that in pressure vessel applications loading rates are usually low (slow) while dynamic behavior is used to set exemption curves. This is a key element in the highly successful application of code rules, even after materials have suffered toughness degradation due to service aging, damage or fabrication. In piping systems, loading rates may be much higher than in vessels. Code limitations such as in UG 20 seek to assure performance within certain bounds. Caution and great deliberation are urged therefore in applying the technology and the very low exemption curves shown here for thin sections. The calculated values are presented, but there must be confidence that assumptions regarding secondary stresses, loading rates, flaws and materials are appropriate. For example, system stresses in piping may prove to be less predictable and much higher than membrane stresses in vessels. It must be remembered that at very low thicknesses the materials would be operating very close to their respective nominal lower shelf temperatures.

In regard to a stated objective of the project —to expand in a more systematic and complete way the several exceptions to the (*exemption*) curves, namely UCS-66(d) and UG-20(f)—the foregoing explains why lower yield strength materials noted in UCD-66(d) should be permitted to be used at greater thicknesses than the higher strength grades. The combinations of yield strength and thickness identified in UCS-66(d) all were found to result in about the identical crack driving force. That driving force is just about the lower shelf energy assumed for this work. The limit of –155˚F is 269˚F and 231˚F below the reference temperatures for A and B class materials, respectively. As may be judged from Figure 7, such an operation would be well down on the lower shelf and uncontrolled increases in the crack driving force of a piping system due to excess residual stresses, material hardness, system loads or even dynamic loading could prove problematic.

In contrast, UG-20(f) is consistent with the curves shown here for Class D materials and with the provisions listed is reasonable for Class C materials and, perhaps, for lower strength Class B material. There should be some concern about stresses due to welding or system loads for higher strength grades or where materials far exceed specified minimum strengths, a frequent event. The same comments apply with regard to Class A material with the 0.5-inch restriction.

FIGURES

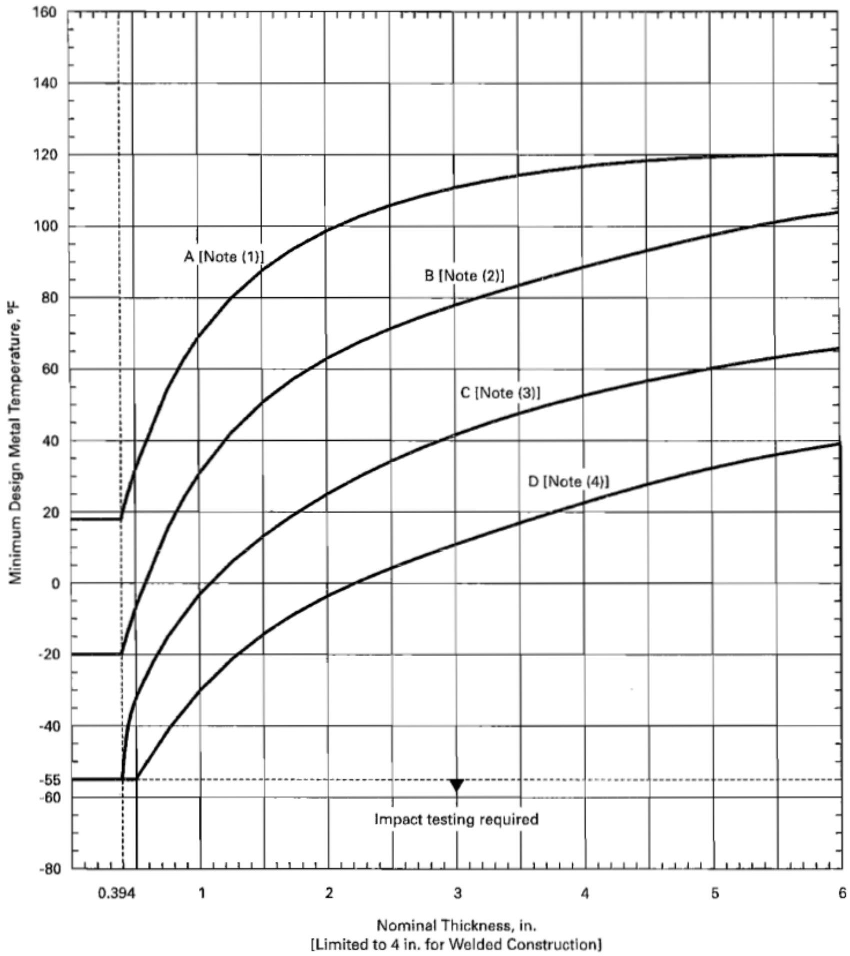

Figure 1 - UCS 66 Exemption Curves are Shown. Indicated Notes Define Covered Materials.

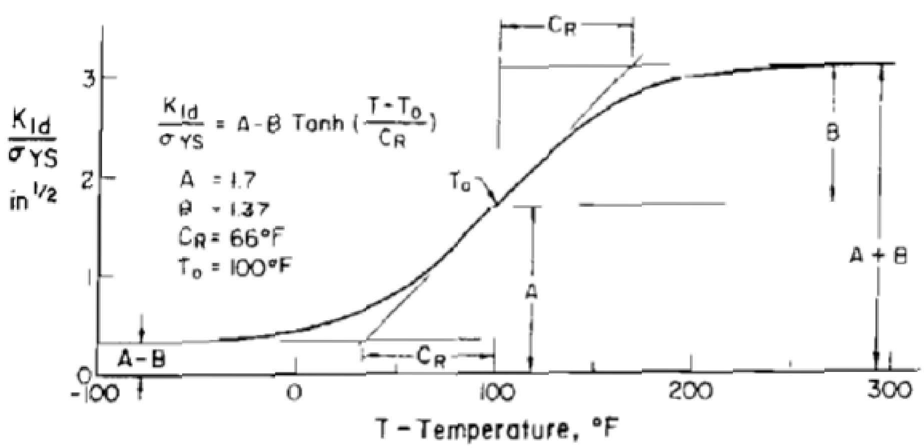

Figure 2 - Representative Hyperbolic Tangent Fracture Toughness Curve

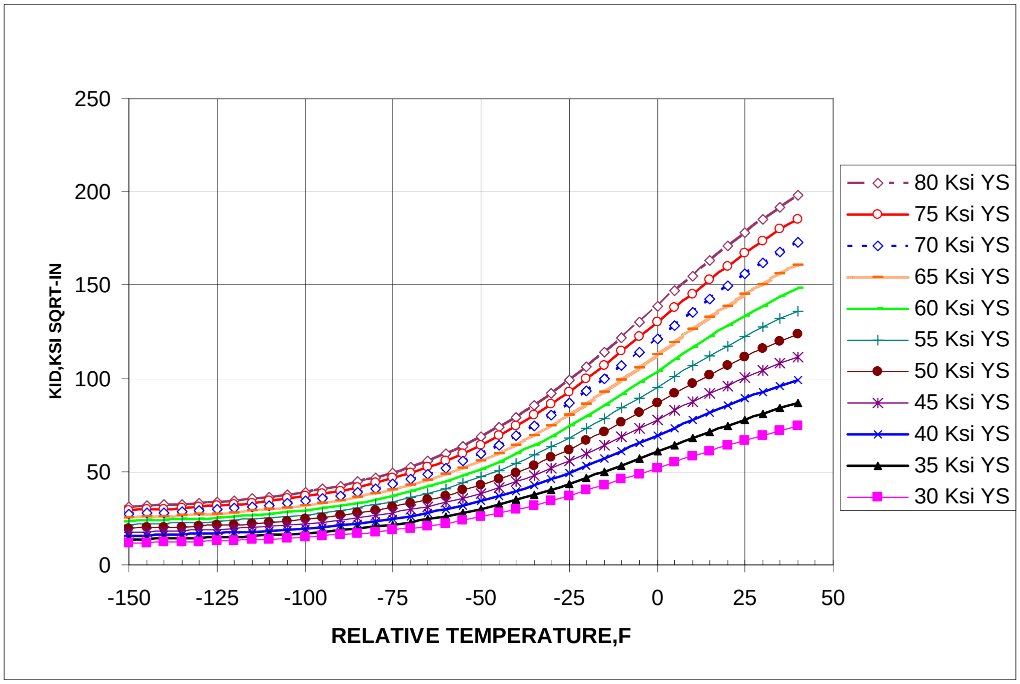

Figure 3 - Implied Dynamic Toughness Curves for Indicated Various Specified Minimum Yield Strength Values

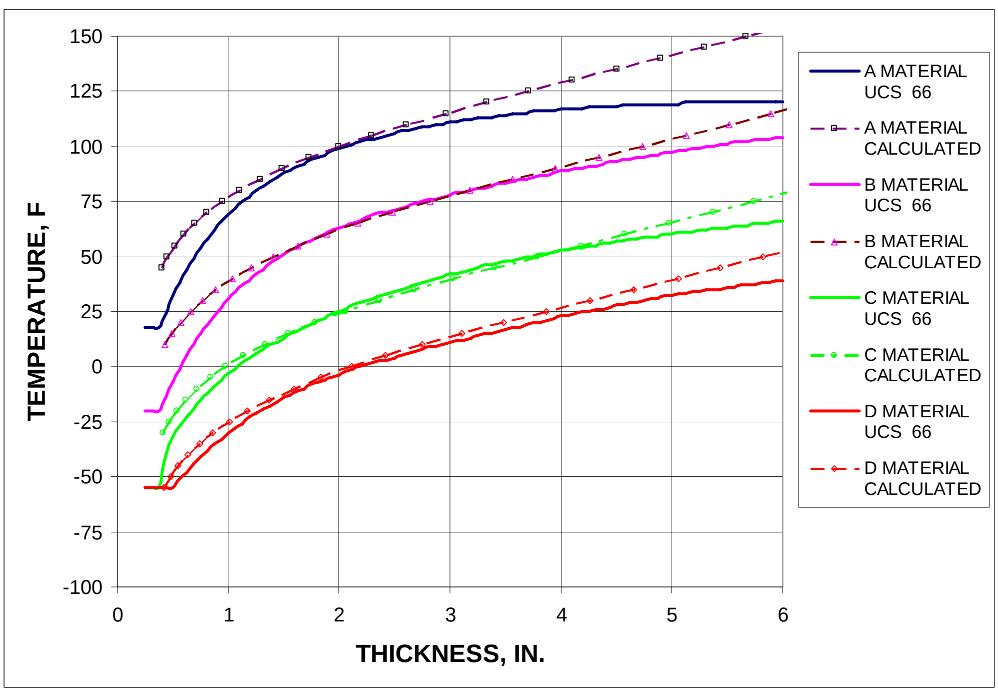

Figure 4 - Calculated Exemption Curves Based on Documented Initial Fracture Mechanics Assumptions as Compared with Published Curves

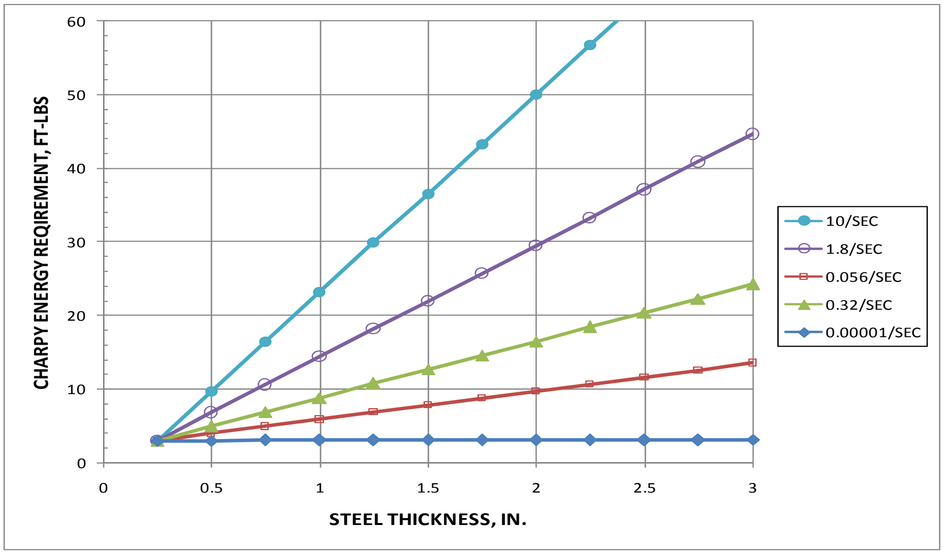

Figure 5 - Dependence of Charpy Energy Needed Meet the Toughness Requirement of the Exemption Curve for Indicated Thicknesses as a Function of Loading Rates (Per Second) Shown in the Legend, Ranging from Impact to Static (1E+01/Sec) to Static (1E-05/Sec), for a Material with 38 KSI Specified Minimum Yield Strength

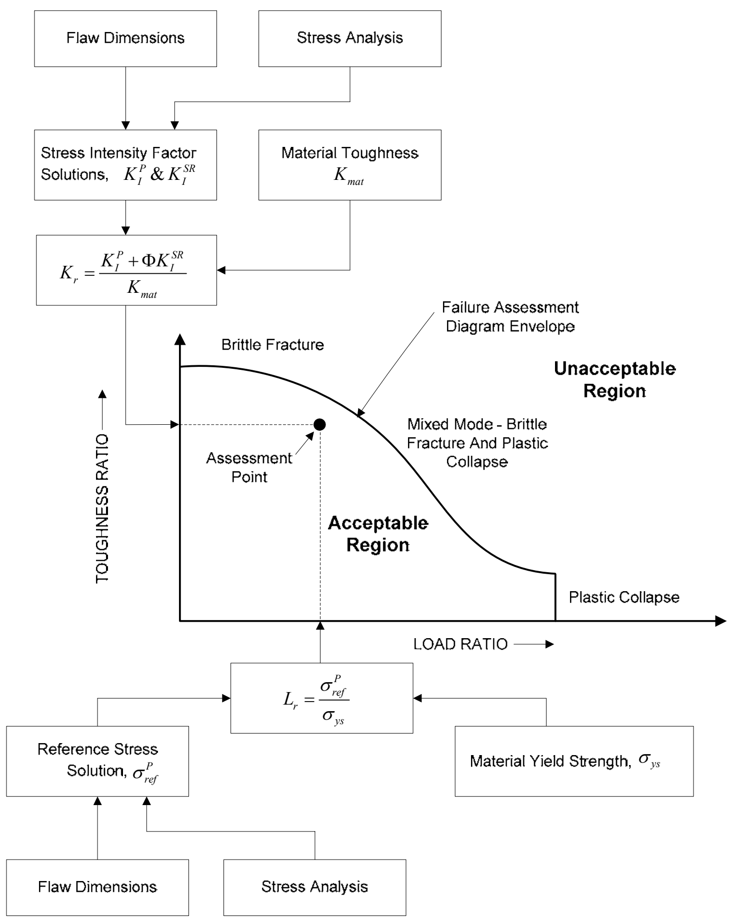

Figure 6 - The FAD Approach Schematic

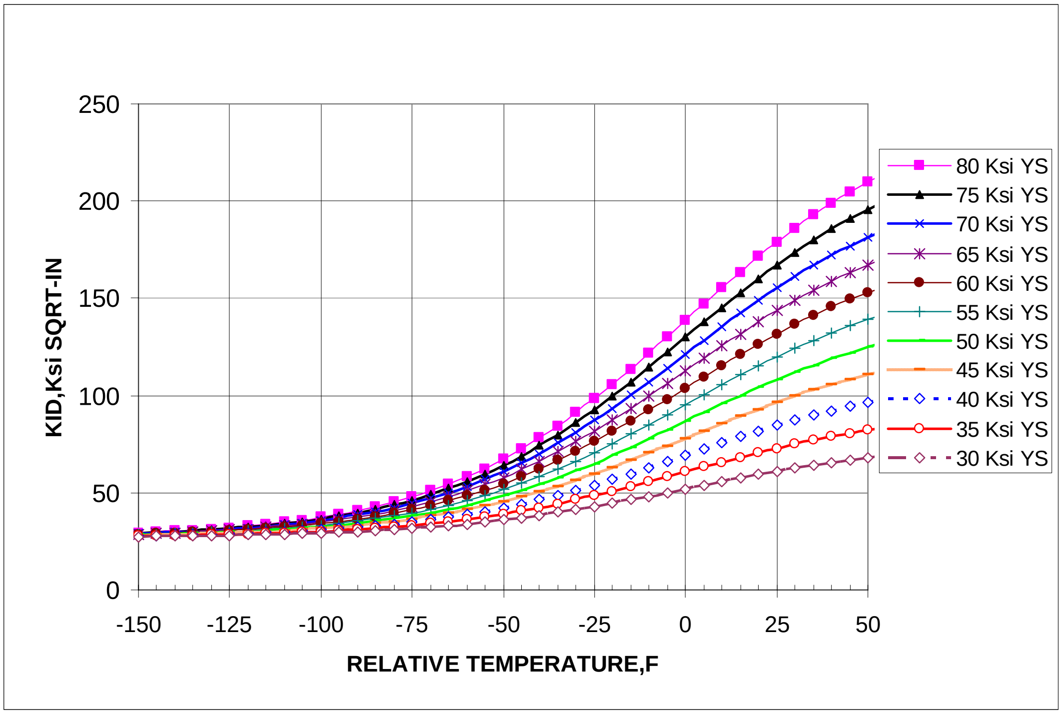

Figure 7 - Modified Hyperbolic Tangent Equation to Provide Uniform Lower Shelf Energy. The Relative Temperature is with Respect to T_o.

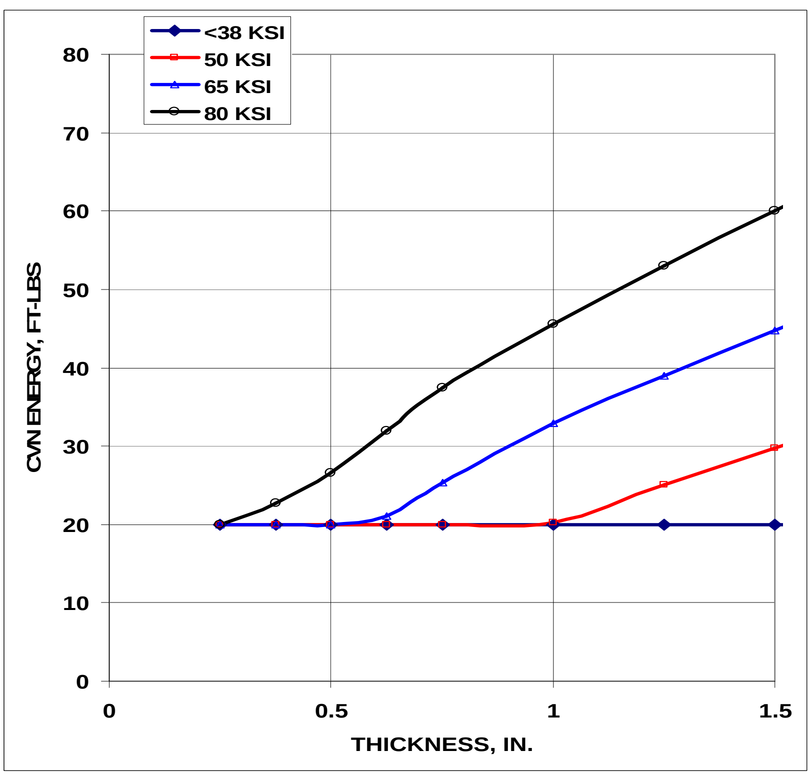

Figure 8 - Example of Charpy Toughness Requirement for As Welded Material for the Case that the Minimum is Set at 20 ft-lbs

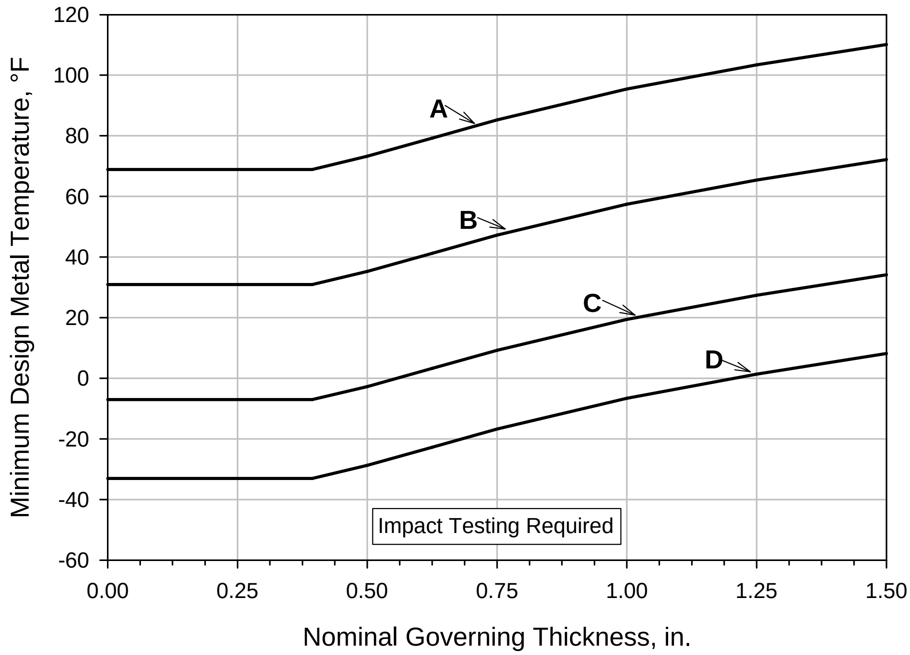

Figure 9 - Pressure Vessel Exemption Curves Calculated for Section VIII, Division 2 for Parts not Subject to PWHT

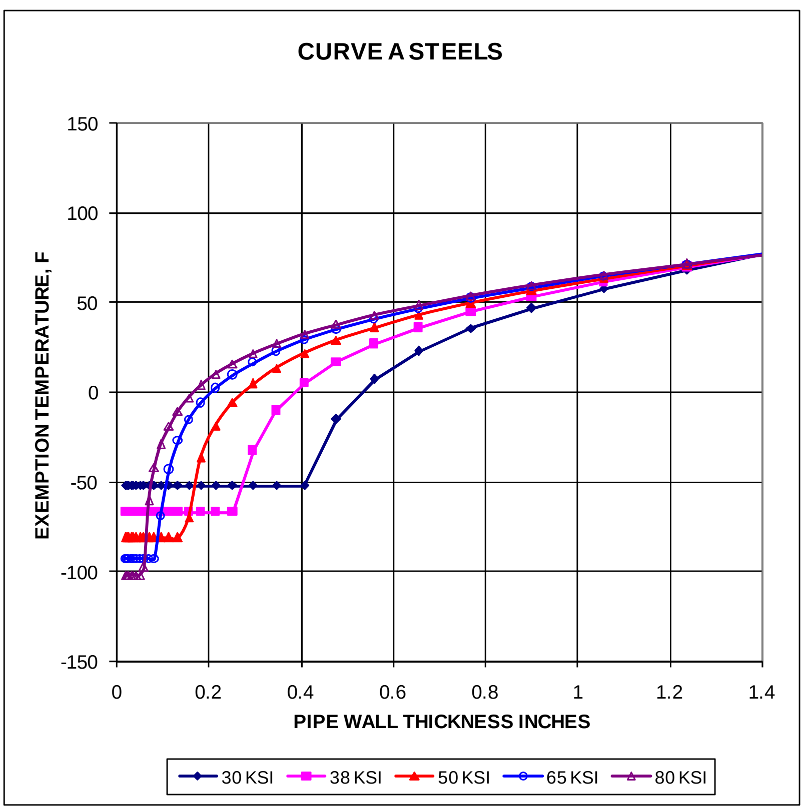

Figure 10 - Exemption Curves for Type A Assigned Materials of Various Possible Yield Strengths

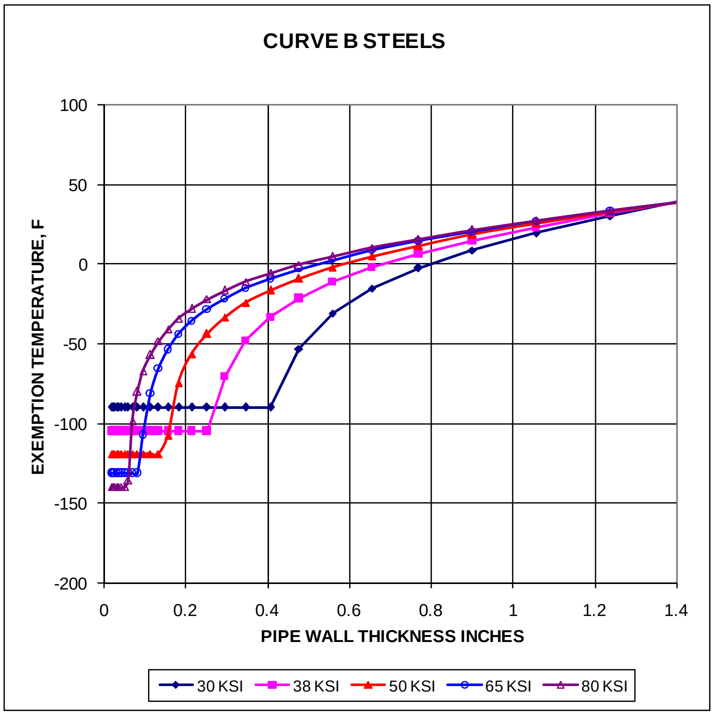

Figure 11 - Exemption Curves for Type B Assigned Materials of Various Possible Yield Strengths

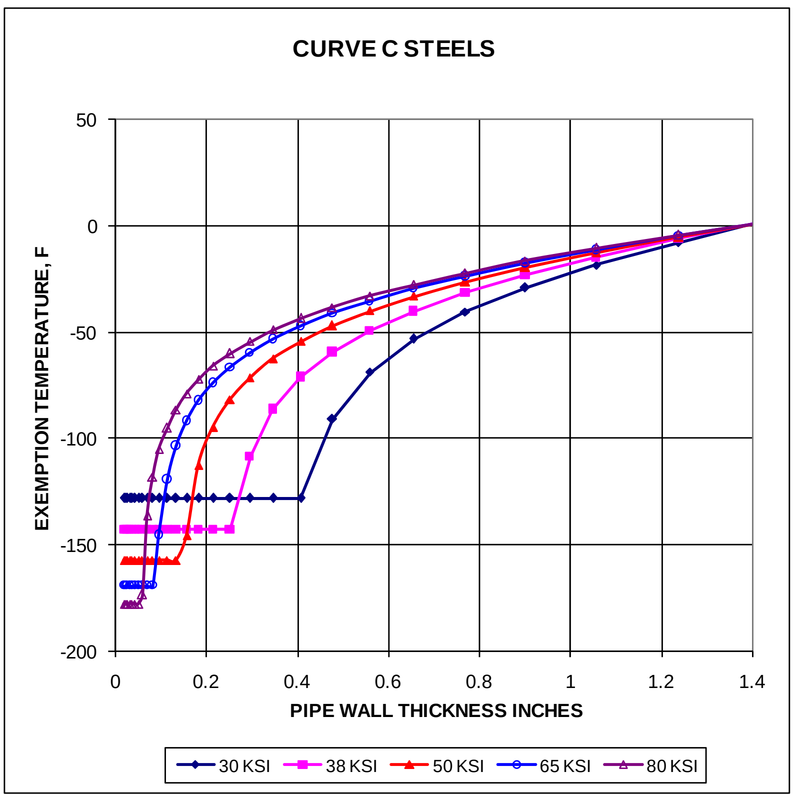

Figure 12 - Exemption Curves for Type C Assigned Materials of Various Possible Yield Strengths

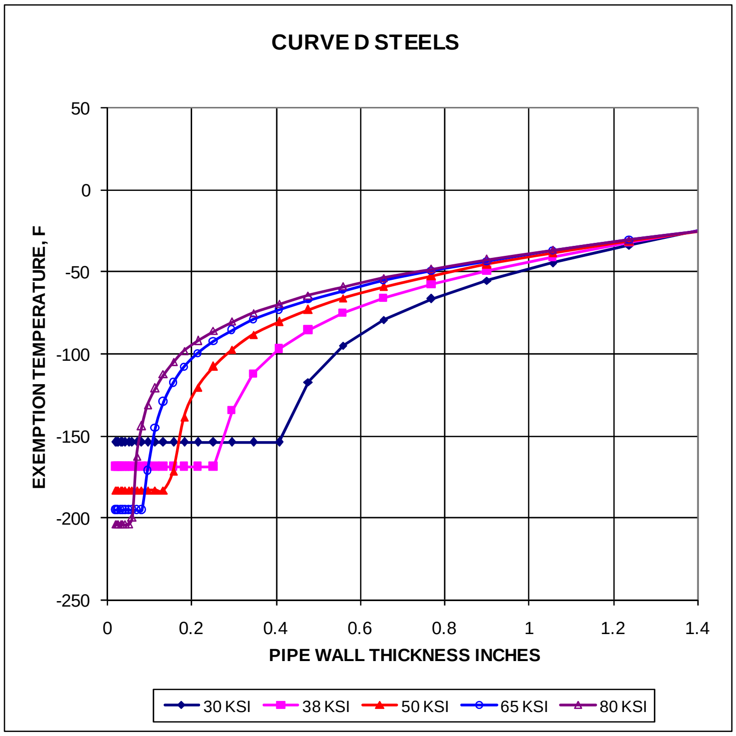

Figure 13 - Exemption Curves for Type D Assigned Materials of Various Possible Yield Strengths

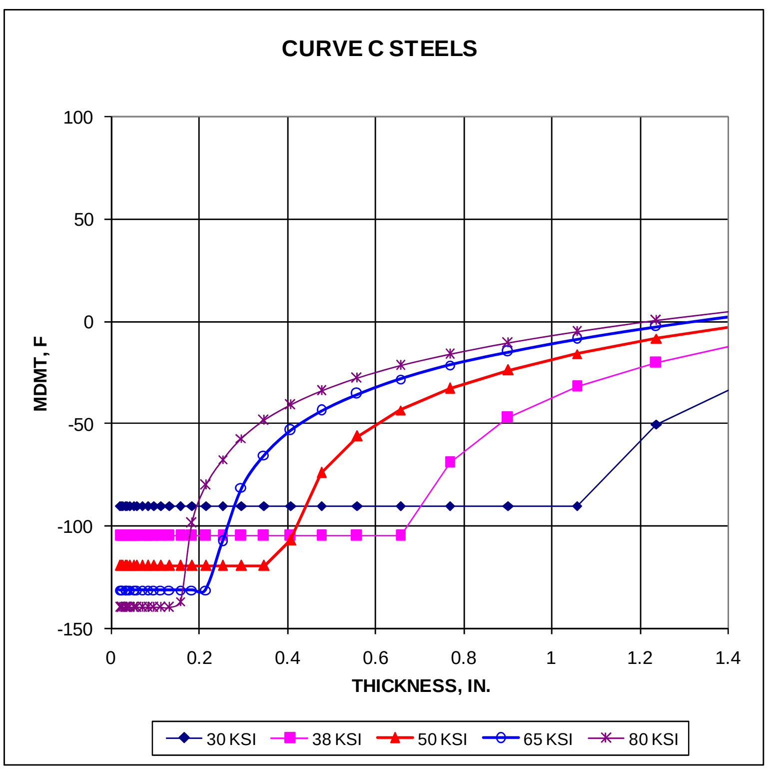

Figure 14 - Exemption Curves for Type C Assigned Materials of Various Possible Yield Strengths Where PWHT has been Performed

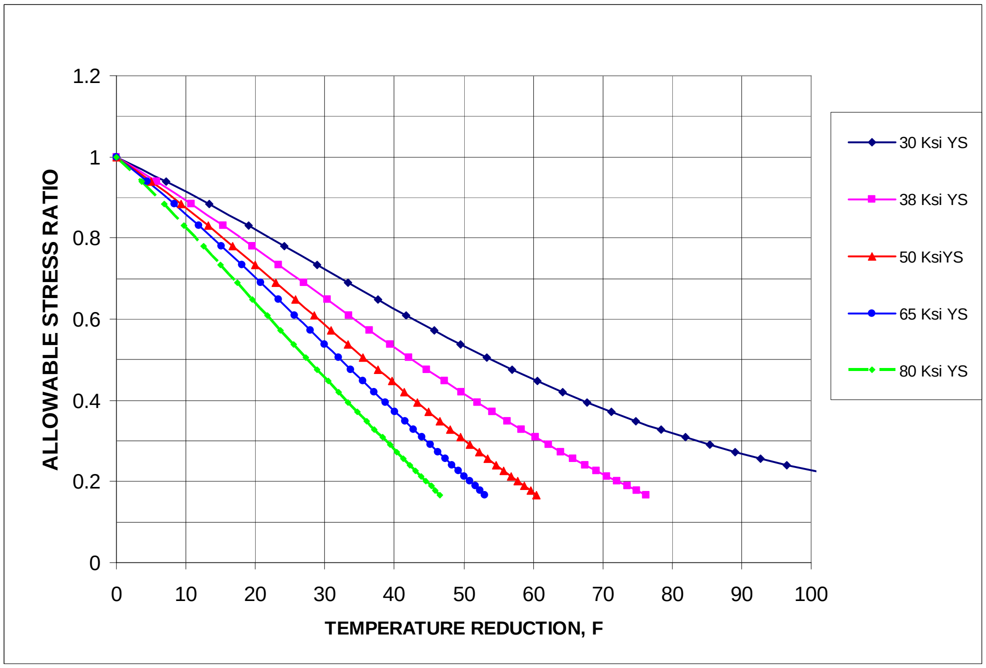

Figure 15 - Temperature Reduction Plots for Various Indicated Yield Strengths

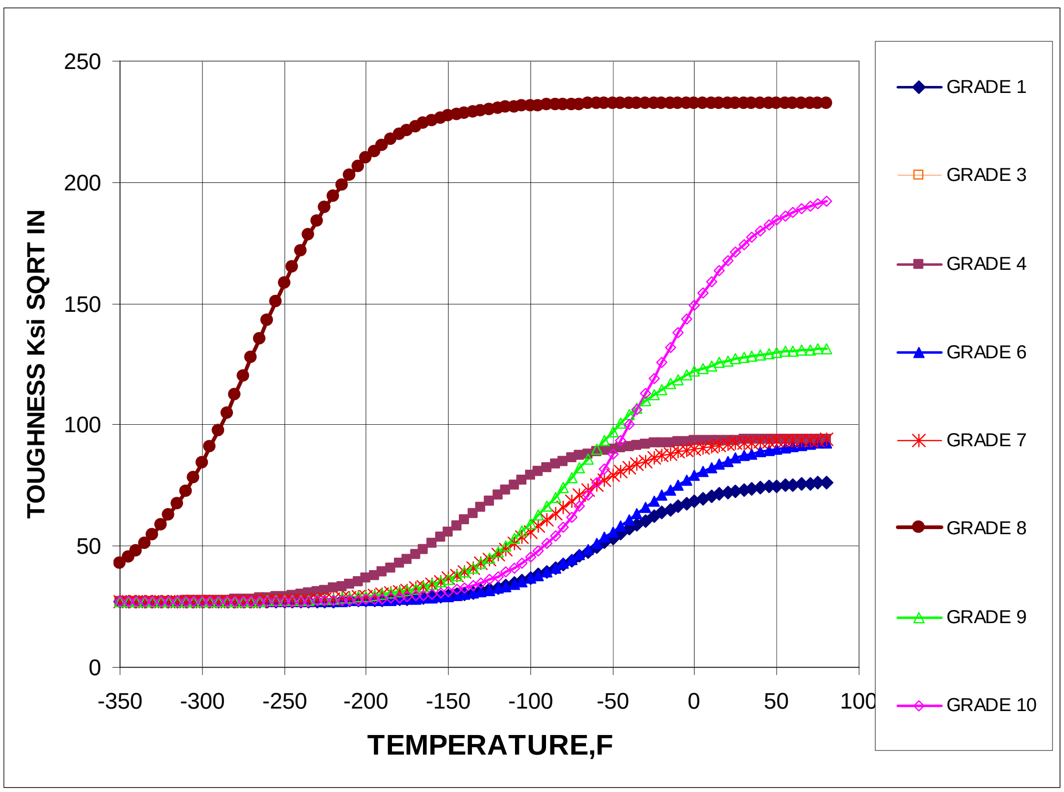

Figure 16 - Fracture Toughness Expectations Calculated from the Charpy Requirements in ASTM 333 for Steels for Low Temperature Service Using the Procedures Described Herein

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[1] J. Barsom and S. Rolfe, Fracture and Fatigue Control in Structures, Prentice Hall, 1987.

[2] H. Corten, Fracture Toughness Considerations Underpinning New Toughness Rules in Section VIII, Division 1 of the ASME Code also referred to as Fracture Toughness Considerations in a Proposed Modification to the ASME Code Section VIII, Division 1., unpublished

[3] Pressure Vessel Research Council, Recommendations on Toughness Requirements for Ferritic Steels, PVRC ad hoc group on toughness requirements, WRC Bulletin 175, Welding Research Council, New York, Aug. 1972.

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ABBREVIATIONS AND ACRONYMS

ASME	American Society of Mechanical Engineers
ASME ST-LLC	ASME Standards Technology, LLC
ASTM	ASTM International
CVN	Charpy V-Notch impact energy
FAD	Failure Assessment Diagram
MDMT	Minimum Design Metal Temperature
MPC	Materials Properties Council
PTCS	ASME Pressure Technology Codes & Standards
PVRC	Pressure Vessel Research Council
PWHT	Post-Weld Heat Treatment
WRC	Welding Research Council

NOMENCLATURE

a, c	Assumed semi-elliptical flaw depth and half width
C, C_R	Nominal half temperature range of transition region
CVN, $CVN(t)$	Charpy V-notch energy in U.S. customary units and where calculated for a thickness
CVN_{nls}	Charpy V-notch energy near lower shelf levels
$CVN_{trans}(t)$	Charpy V-notch energy in transition temperature range where calculated for a thickness
CVN_{us}, $CVN_{us}(t)$	Charpy V-notch energy on upper shelf and where calculated for a thickness
$K_{RF}^{Cylinder}$	Stress intensity calculated based on a flaw in a reference cylinder
K_{Id}	Dynamic fracture toughness
K_I^P	Stress intensity due to primary stresses
K_I^{SR}	Stress intensity due to secondary and residual stresses
K_{mat}, $K_{mat}(t)$	Required material toughness
$K_{mat}(R_{ts})$	Stress intensity calculated at reduced tensile stresses
$K_{nls}(t)$	Fracture toughness in near lower shelf region
K_r	Ratio of applied to material stress intensity
K_{us}	Upper shelf stress intensity
L_r^P	Load ratio based on primary stress.
L_r^{SR}	Load ratio based on secondary and residual stresses.
R/t	Radius and thickness of cylinder used for fracture mechanics calculations
$R_{RF}^{Cylinder}$	Calculated parameter for cylinder relating applied primary and secondary stresses to yield strength
T	Temperature, U.S. customary units
T_0	Material reference temperature taken as midpoint in transition region.
$T_R(R_{ts})$, $T_R(1)$	MDMT temperature calculated for reduced stresses and full stress, respectively
$\Delta T_R(R_{ts})$	Reduction in MDMT allowed for a reduced stress ratio
Φ	Plasticity correction factor
σ_{ys}	Specified minimum or actual material yield strength
σ_m^P	Primary applied membrane stress
σ_m^{SR}	Secondary applied membrane stress

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