The EPRG Recommendations for Crack Arrest Toughness for Line Pipe Steel (Third Edition)

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The third edition of the EPRG recommendations for crack arrest toughness for line pipe steels is presented. The third edition extends the applicability of the recommendations to pipelines transporting lean natural gas at pressures up to 100 barg (1450 psig), in diameters up to 1422.4 mm (56 inch), in grades up to Grade L555 (API 5L X80), and design factors up to 0.8.

A quantitative definition of a lean gas is included in the third edition.

The recommendations are intended to be applied to new pipelines. The recommendations are not intended to be applied retrospectively to existing pipelines.

INTRODUCTION

The European Pipeline Research Group (EPRG) first published recommendations for the toughness required to arrest a long running ductile (shear) fracture in a buried onshore pipeline transporting lean natural gas in 1983 [1]. The toughness was measured by the full-size equivalent, upper shelf Charpy V-notch impact energy. The EPRG then revised and re-published the recommendations in 1995 [2]. The first edition was applicable to line pipe steel grades up to API 5L X70. The second edition was extended to include recommendations for API 5L X80. The 1995 edition of the *EPRG recommendation for crack arrest toughness for high strength line pipe steels* is applicable to pipelines transporting lean gas at pressures up to 80 barg, in diameters up to 1422.4 mm (56 inch), in grades up to Grade L555 (API 5L X80), and design factors up to 0.72.

The second edition is included, with minor modifications, as one of five approaches in Annex G PSL 2 [product specification level] pipe with resistance to ductile fracture propagation, as G.7 EPRG Guidelines – Approach 1, in ANSI/API Spec 5L / ISO 3183:2012 [3,4]. A third table was included for pipelines designed to operate at 80% SMYS (a design factor equal to 0.8), and the minimum toughness for L555 (X80) was increased to 80 J, to be consistent with the minimum requirements in API Spec 5L for line pipe supplied to PSL 2.

The first and second editions of the recommendations were based on the AISI (American Iron and Steel Institute) Formula and the Battelle Short Formula[1], and were validated against a data set of full-scale fracture propagation tests conducted using air or lean natural gas. The third edition is based on the Two Curve Model [5-7]. An empirical correction factor, the Leis, 1997 & Eiber, 2008a,b correction factor [8-11], is applied to account for the limitations of the Charpy V-notch impact energy that become increasingly evident as the impact energy increases.

A lean gas contains a low concentration of the so called heavier hydrocarbons, such as ethane, propane, butane and higher. A rich gas contains a higher concentration of these heavier hydrocarbons. It typically exhibits a phase transition during decompression. A higher toughness is required to arrest a running ductile fracture in a pipeline transporting a rich gas. A descriptive definition of a lean gas is potentially ambiguous. Consequently, a quantitative definition of a lean gas is included in the third

[1] The AISI and the Battelle Short Formulae are empirical and semi-empirical models, respectively, for calculating the Charpy V-notch impact energy required to arrest a running ductile fracture.

edition. The recommendations are only applicable to pipelines transporting lean gas, as defined using this definition of a lean gas.

The intent of the first and second editions was that at least half of the pipes in an order would have a toughness that is higher than the minimum toughness predicted to arrest a running ductile fracture, i.e. at least half of the pipe in the order is nominally predicted to be 'arrest' pipe, and at most half of the pipe in the order is nominally predicted to be 'propagate' pipe. Vogt et al., 1983 [1] state that: "*… in order to take account of the statistical distribution of the Charpy toughness in an actual pipe supply, these requirements have been multiplied by a factor of 0.75. This ensures as can be shown by statistical analysis* [Gaessler and Sawitzki, 1981 [12]] *… that 50% of the pipes of an order meet the predicted requirements.*" Similarly, Re et al., 1995 [2] state that: "*It has been shown by statistical analysis that 50% of the pipes in an order exceed 1.3 times the minimum specified [average] value …*" The specified values in the second edition are 0.75xAISI for Grades L245 to L450 (Grade B to X65), 0.9xAISI for Grade L485 (X70) and 1.0xSF for Grade L555 (X80). The full-scale test data notionally showed that the toughness needed to be approximately 1.0xAISI to conservatively predict most of the test data for Grades L245 to L450 and approximately 1.3xSF to conservatively predict most of the test data for Grade L555. So, it followed from the statistical analysis that, if the specified value is 0.75xAISI (or 1.0xSF), then the all-heat average is 1.0xAISI (or 1.3xSF) and then at least half of the pipe in the order is predicted to be arrest pipe, and at most half of the pipe in the order is predicted to be propagate pipe.

Dawson and Pistone, 1998 [13] revisited this statistical analysis and concluded that the average toughness of pipe (albeit mostly large diameter pipe) manufactured in the mid-1990s by pipe mills in western Europe was at least twice the specified toughness. Dawson and Pistone, 1998 also compared the recommended values against the full-scale test data, noting that both the AISI and Short Formulae gave conservative and non-conservative, incorrect predictions. It was shown that the all-heat average would need to be greater than 1.0xAISI in order for at least half of the pipe in an order to be predicted to be arrest pipe. It was also shown that the proportion of propagate pipes in an order depends upon both the mean and standard deviation of the distribution of the toughness, and on the accuracy of the model that has been used to predict the toughness required to arrest a running ductile fracture. The assumption that the median toughness of the pipe in an order is equal to approximately 1.3 times the specified toughness is not, in of itself, sufficient to ensure that at least half of the pipe in an order is predicted to be arrest pipe, although, from Dawson and Pistone, 1998, it is clear that it was a reasonable assumption for line pipe manufactured in western Europe up to and including the late 1990s.

The first edition of the recommendations was written at a time when it might have been difficult for pipe mills to consistently produce line pipe in some geometries and grades with a specified minimum upper shelf Charpy V-notch impact energy equal to 1.0xAISI. The first and second editions specified a toughness less than that required to arrest a fracture (as in 0.75xAISI) and then assumed that the distribution of the toughness of the pipe in an order would ensure that at least half of the pipe in an order would be predicted to be arrest pipe.

The third edition of the recommendations specifies the toughness required to arrest a fracture. It is a simpler, slightly more conservative approach, that does not depend upon any assumptions regarding the distribution of the toughness of the pipe in an order.

THE EPRG RECOMMENDATIONS FOR CRACK ARREST TOUGHNESS FOR LINE PIPE STEEL

The *EPRG recommendations for crack arrest toughness for line pipe steels* is applicable to pipelines transporting lean gas at pressures up to 100 barg (1450 psig), in diameters up to 1422.4 mm (56 inch), grades up to Grade L555 (API 5L X80), and design factors up to 0.8. The recommendations are applicable to welded and seamless pipe.

The requirements for the application of the recommendations are given in Table 1. A lean gas is defined in Table 2. A gas is defined as lean if all of the conditions in Table 2 are satisfied. It is defined as rich if any of the conditions in Table 2 are not satisfied.

The toughness recommendations are presented in Tables 3, 4 and 5, for design factors of 0.625, 0.72 and 0.8, respectively. The recommendations refer to the upper shelf, full size equivalent Charpy-V impact energy of the pipe body in Joules. Tables 3, 4 and 5 do not give a value when the calculated value is greater than 200 J (148 ft.lbf). The Two Curve Model with the Leis, 1997 & Eiber, 2008a,b correction factor should be used in these cases. A full-scale fracture propagation test is recommended if the calculated Charpy V-notch impact energy is greater than 200 J. A full-scale test might not be required if there exists a test or tests in a similar geometry, grade and toughness, or some other appropriate testing or analysis, to demonstrate that the calculated toughness is sufficient to arrest a running ductile fracture.

The toughness may be specified as either the minimum average of a set of three individual test specimens (per test unit) or as the minimum average of the order item (the all-heat average).

- If the toughness is specified as the minimum average of a set of three, then the specified minimum individual value is 0.75 times the specified minimum average value of a set.
- If the toughness is specified as the minimum average of the order item, then the specified minimum average value of a set of three is 0.75 times the specified minimum average value of the order item, and the specified minimum individual value is 0.5625 times the specified minimum average value of the order item (i.e. 0.75 times the specified minimum average value of a set).

The minimum average of a set of three shall not be less than 40 J, to be consistent with the general fracture initiation toughness requirements for PSL 2 pipe in ANSI/API Spec 5L / ISO 3183:2012.

The predicted length of a running fracture is longer if the toughness is specified as the minimum average of the order item than if it is specified as the minimum average of a set of three, because the probability that a pipe in an order item is a propagate pipe is higher. If the toughness is specified as the minimum average of the order item, then the predicted length of a fracture (with a probability of 95%) is less than or equal to approximately eight (8) pipe lengths. If the toughness is specified as the minimum average of a set of three, then the predicted length of a fracture (with a probability of 95%) is nominally less than or equal to approximately five (5) pipe lengths, although it does depend on the distribution of the toughness of the pipe in the order (the predicted length might be higher or lower than five).

The toughness recommendations in Tables 3, 4 and 5 are based on the following considerations:

(1) Pipelines constructed from welded or seamless line pipe transporting lean natural gas, as defined in Table 2. Pipelines transporting rich gas and those designed without backfill or with frozen backfill are not included.

(2) The maximum design pressure of the pipeline is not greater than 100 barg (1450 psi).

(3) The minimum design temperature of the pipeline is not less than 0 ºC (32 ºF).

(4) The recommended minimum toughness requirements are based on calculations conducted using a set of bounding decompression curves for a lean gas, and the Two Curve Model (TCM) [5-7] with the Leis, 1997 & Eiber, 2008a,b correction factor [8-11] (the decompression calculations were

conducted using GASDECOM [14]). The minimum value is 40 J (consistent with the second edition)[2]. Calculated values greater than 200 J are not tabulated, because, above 200 J, the likelihood of Charpy V-notch test specimens not breaking significantly increases and the Charpy V-notch impact energy is increasingly less representative of the fracture resistance of the line pipe steel.

(5) The recommended minimum toughness requirements are intended to ensure that at least half of the pipe in a pipeline is predicted to be arrest pipe and that at most half is predicted to be propagate pipe (consistent with the intent of the first and second editions). The recommended minimum toughness is equal to 1.0xTCM with the correction factor for values not exceeding 94 J and 1.06xTCM with the correction factor for values exceeding 94 J. The factors of 1.0 and 1.06 are based upon a statistical analysis of a dataset of full-scale fracture propagation tests [16]. The distribution of propagate pipes and arrest pipes in the pipeline is assumed to be random.

(6) The recommended minimum toughness requirements apply to the pipe body. The requirements do not apply to the seam weld or the heat affected zone.

(7) The recommendations are not intended to be applied retrospectively to existing pipelines.

The recommended minimum toughness values in the third edition are higher than in the first or second editions, because: i) the bounding decompression curves for a lean gas are more severe than that for the ideal gas representative of methane that was used in the development of the Short Formula, and are more severe than that for air, as was used in the full-scale tests conducted by the American Iron and Steel Institute; ii) the toughness specified is the predicted value, not a lower value; and iii) the Leis, 1997 & Eiber, 2008a,b correction factor is applied.

IMPACT TESTING

Drop weight tear and Charpy V-notch tests of the pipe body should be conducted at a test temperature equal to 0 ºC.

Drop weight tear testing on pipe with a nominal diameter less than 508 mm (20 inches) or on pipe with a small diameter to wall thickness ratio might present practical difficulties. An alternative test is acceptable provided that the alternative is shown to be sufficient to ensure that a running fracture will be ductile.

Drop weight tear tests should be conducted in accordance with API Recommended Practice 5L3 [17].

Charpy V-notch tests should be conducted in accordance with ASTM A370-17 [18] or ISO 148-1:2016 [19]. A striker with a radius of 2 or 8 mm may be used, subject to the requirements specified in ISO 3183[3].

[2] A minimum value of 40 J was specified in the second edition in order to be consistent with (the now withdrawn) EN 10208-2:1997 Steel pipes for pipelines for combustible fluids. Technical delivery conditions. Pipes of requirement class B [2,15]. It is based on consideration of the toughness requirements for fracture initiation.

[3] The data set of full-scale tests includes Charpy V-notch test data generated using a striker with a radius of 2 and 8 mm. An 8 mm striker was probably used in full-scale tests conducted on behalf of the American Gas Association, or the American Iron and Steel Institute, and a 2 mm striker was probably used in full-scale tests conducted on behalf of the British Gas Corporation, the European Pipeline Research Group, the Iron and Steel Institute of Japan, or Italsider. The different strikers probably contribute to some of the scatter that is evident in the full-scale test data.

The equivalent full-size impact energy of a sub-size Charpy V-notch test specimen should be calculated by multiplying the measured value by the ratio of the specified width of a full-size specimen to that of the sub-size specimen.

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REFERENCES

1. Vogt, G., Bramante, M., Jones, D.G., Koch, F.O., Kügler, J., Péro. H. and Re, G., 1983. EPRG Report on the toughness for crack arrest in gas transmission pipelines. In *3R International*, 3(1/2): 3-10.

2. Re. G., Pistone, V., Vogt, G., Demofonti, G. and Jones, D.G., 1995. EPRG recommendation for crack arrest toughness for high strength line pipe steels. In *3R International*, 34(10/11): 607-611.

3. American Petroleum Institute, 2012. *API Specification 5L Specification for Line Pipe*. Forty-Fifth Edition, December 2012. Washington, D.C., USA: API Publishing Services.

4. International Organization for Standardization, 2012. *ISO 3183:2012 Petroleum and natural gas industries – Steel pipe for pipeline transportation systems*. Geneva, Switzerland: International Organization for Standardization.

5. Maxey, W.A., Kiefner, J.F., Eiber, R.J. and Duffy, A.R., 1972. Ductile fracture initiation, propagation, and arrest in cylindrical vessels. In *Fracture Toughness. Proceedings of the 1971 National Symposium on Fracture Mechanics Part II*. ASTM STP 514. Urbana-Champaign, Illinois, 31 August-2 September 1971. Philadelphia, USA: American Society for Testing and Materials. 70-81.

6. Maxey, W.A., Kiefner, J.F., Eiber, R.J. and Duffy, A.R., 1973. Experimental investigation of ductile fractures in piping. Paper No. IGU/C 34-73, In *Proceedings of the 12th World Gas Conference*. Nice, France, 4-6 June 1973. London, UK: International Gas Union.

7. Maxey, W.A., 1974. Fracture initiation, propagation and arrest. Paper J. In *Fifth Symposium on Line Pipe Research*. Houston, Texas, USA, 20-22 November 1974. Falls Church, Virginia, USA: Pipeline Research Council International.

8. Leis, B.N., 1997. *Relationship between apparent (total) Charpy Vee-Notch toughness and the corresponding dynamic crack-propagation resistance*. Columbus, Ohio, USA: Battelle Memorial Institute. Available at: <https://docs.neb-one.gc.ca/ll-eng/llisapi.dll?func=llworkspace> 98-06-10 NEB - GH-3-97 Exhibit List (A13687). A0W3T3 - B - Alliance Pipeline Ltd. Exhibit No. B-82 & Exhibit No. B-114.

9. Leis, B.N., Eiber, R.J., Carlson, L. and Gilroy-Scott, A., 1998. Relationship Between Apparent (Total) Charpy Vee-Notch Toughness and the Corresponding Dynamic Crack-Propagation Resistance. In *Proceedings of the International Pipeline Conference 1998*. Calgary, Alberta, Canada, 7-11 June 1998. New York, NY, USA: American Society of Mechanical Engineers. Volume 2: 723-731.

10. Eiber, R.J., 2008. Fracture Propagation – 1: Fracture-arrest prediction requires correction factors. In *Oil & Gas Journal*, 106(39).

11. Eiber, R.J., 2008. Fracture Propagation – Conclusion: Prediction steel grade dependent. In *Oil & Gas Journal*, 106(40).

12. Gaessler, H. and Sawitzki, M., 1981. Auswirkung der statistischen Verteilung der Kerbschlagarbeitswerte auf das Rißverhalten von Rohrleltungen [Effect of the statistical

distribution of notched-bar impact values on the crack behaviour of pipelines]. In *3R Internationa*l, 20: 550-554.

13. Dawson, J. and Pistone, V., 1998. Probabilistic evaluation of the safety embodied in the EPRG Recommendations for shear fracture arrest toughness. In *3R International*, 37(10/11): 728-733.
14. Eiber, R.J., Bubenik, T.A. and Maxey, W.A., 1993. *Fracture control technology for natural gas pipelines*. Project PR-3-9113 (NG-18 Report No. 208). Catalogue No. L51691. Falls Church, Virginia, USA: Pipeline Research Council International.
15. British Standards Institution, 1997. *BS EN 10208-2 : 1997 Steel pipes for pipelines for combustible fluids – Technical delivery conditions Part 2. Pipes of requirement class B*. London, UK: British Standards Institution.
16. Cosham, A., Koers, R., Andrews, R.M. and Schmidt, T., 2017. A statistical analysis of full-scale fracture propagation test data. In *Journal of Pipeline Engineering*, 16(4): 193-220.
17. American Petroleum Institute, 2014. *API Recommended Practice 5L3 Drop-Weight Tear Tests on line pipe*. Fourth Edition, August 2014. Washington, D.C., USA: API Publishing Services.
18. American Society for Testing and Materials, 2017. *ASTM A370-17 Standard test methods and definitions for mechanical testing of steel products*. West Conshohocken, Pennsylvania, USA: ASTM International.
19. International Organization for Standardization, 2016. *ISO 148-1:2016 Metallic materials – Charpy pendulum impact test – Part 1: Test method*. Geneva, Switzerland: International Organization for Standardization.

Table 1 Requirements for the EPRG recommendation for crack arrest toughness for line pipe steel

Type of requirement		**Requirement**
Geometry	Diameter	≤ 1422 mm (56 inch)
	Wall Thickness	≤ 31.8 mm (1.25 inch)
Grade		≤ L555 (X80)
Product Specification Level		PSL 2
DWTT	at the minimum design temperature	≥ 85 percent shear area
CVN	at the minimum design temperature	minimum average of a set of three (3) individual test specimens or minimum average per order item
Hoop Stress Design Factor		≤ 0.8
Design Pressure		≤ 100 barg (1450 psig)
Minimum Design Temperature		≥ 0 ºC (32 ºF)
Gas Composition		see Table 2
Backfill		buried

Table 2 The definition of a lean gas

Composition, mole%	
C1 ≥ 80.0	
$C1+N_2$ ≥ 88.0	
$C2+CO_2+C3+[C4+]$ ≤ 12.0	
C2 ≤ 10.0	
C3 ≤ 2.0	
[C4+] ≤ 1.0	
CO_2 ≤ 4.0	
N_2 ≤ 20.0	
C3+2[C4+] ≤ 3.0	
$C2+CO_2+10[C4+]$ ≤ 15	
$C2+CO_2+5C3$ ≤ 16.5 for	D ≤ 920
≤ 16.0	920 < D ≤ 1020
≤ 15.5	1020 < D ≤ 1120
≤ 15.0	1120 < D ≤ 1220
≤ 14.5	1220 < D ≤ 1325
≤ 14.0	1325 < D ≤ 1430

Notes:

1. The definition is only applicable to pipelines with a design pressure less than or equal to 100 barg (1450 psig) and a minimum design temperature not less than 0 °C (32 ºF).
2. [C4+] is the sum of i-C4, n-C4, i-C5, n-C5 and C6+.

Table 3 Upper shelf, full-size equivalent (10x10 mm specimen) Charpy V-notch impact energy of the pipe body (in Joules) required to arrest a running ductile failure in gas transmission pipelines operating with a design factor of 0.625

a) a design pressure of 80 barg

Grade	Pipe outside diameter [mm]								
	≤ 510	> 510 ≤ 610	> 610 ≤ 720	> 720 ≤ 820	> 820 ≤ 920	> 920 ≤ 1020	> 1020 ≤ 1120	> 1120 ≤ 1220	> 1220 ≤ 1430
L245							40		40
L290		40			40				
L320									50
L360				50			60		
L390	40	50			60			70	
L415	50					70			80
L450		60		70			80		90
L485					80		90		110
L555	70	80	90		100	130	140	150	170

b) a design pressure of 100 barg

Grade	Pipe outside diameter [mm]								
	≤ 510	> 510 ≤ 610	> 610 ≤ 720	> 720 ≤ 820	> 820 ≤ 920	> 920 ≤ 1020	> 1020 ≤ 1120	> 1120 ≤ 1220	> 1220 ≤ 1430
L245					40			40	
L290		40					50		
L320								60	
L360	40		50		60			70	
L390	50		60			70		80	
L415		60		70					90
L450					80		90	100	110
L485	70		80		90	100	110	120	130
L555	80	90	100	120	140	150	160	180	200

Table 4 Upper shelf, full-size equivalent (10x10 mm specimen) Charpy V-notch impact energy of the pipe body (in Joules) required to arrest a running ductile failure in gas transmission pipelines operating with a design factor of 0.72

a) a design pressure of 80 barg

Grade	Pipe outside diameter [mm]								
	≤ 510	> 510 ≤ 610	> 610 ≤ 720	> 720 ≤ 820	> 820 ≤ 920	> 920 ≤ 1020	> 1020 ≤ 1120	> 1120 ≤ 1220	> 1220 ≤ 1430
L245	40	40	40	40	40	40	40	40	40
L290	40	40	40	40	40	50	50	50	60
L320	40	40	50	50	50	60	60	60	70
L360	50	50	50	60	60	70	70	70	80
L390	50	60	60	70	70	80	80	80	90
L415	60	60	70	70	80	80	90	90	110
L450	70	70	80	80	90	100	110	120	130
L485	80	80	90	100	110	120	130	140	160
L555	100	120	140	150	170	190	200		

b) a design pressure of 100 barg

Grade	Pipe outside diameter [mm]								
	≤ 510	> 510 ≤ 610	> 610 ≤ 720	> 720 ≤ 820	> 820 ≤ 920	> 920 ≤ 1020	> 1020 ≤ 1120	> 1120 ≤ 1220	> 1220 ≤ 1430
L245	40	40	40	40	40	40	40	50	50
L290	40	40	40	50	50	50	60	60	70
L320	40	50	50	60	60	60	70	70	80
L360	50	60	60	70	70	80	80	90	90
L390	60	60	70	80	80	90	90	100	110
L415	70	70	80	80	90	100	110	120	130
L450	80	80	90	100	110	120	130	140	160
L485	90	90	110	120	140	150	160	170	190
L555	130	150	170	190					

Table 5 Upper shelf, full-size equivalent (10x10 mm specimen) Charpy V-notch impact energy of the pipe body (in Joules) required to arrest a running ductile failure in gas transmission pipelines operating with a design factor of 0.8

a) a design pressure of 80 barg

Grade	Pipe outside diameter [mm]								
		> 510	> 610	> 720	> 820	> 920	> 1020	> 1120	> 1220
	≤ 510	≤ 610	≤ 720	≤ 820	≤ 920	≤ 1020	≤ 1120	≤ 1220	≤ 1430
L245	40		40				50		
L290			50		60				70
L320	50					70		80	
L360	60		70		80		90		110
L390	70		80	90		100	110	120	130
L415		80	90	100	110	120	130	140	150
L450	90	100	110	120	130	140	150	170	180
L485	110	120	130	150	160	180	190	200	
L555	170	200							

b) a design pressure of 100 barg

Grade	Pipe outside diameter [mm]								
		> 510	> 610	> 720	> 820	> 920	> 1020	> 1120	> 1220
	≤ 510	≤ 610	≤ 720	≤ 820	≤ 920	≤ 1020	≤ 1120	≤ 1220	≤ 1430
L245	40				50			60	
L290	50			60		70			90
L320		60		70		80		90	110
L360	70		80	90		100	110	120	150
L390	80		90	100	110	120	130	150	180
L415	90	100	110	120	130	150	160	170	
L450	110	120	140	150	170	180	190		
L485	140	150	170	190	200				
L555									

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