VALIDITY OF STANDARD DEFECT ASSESSMENT METHODS FOR THE ALLIANCE PIPELINE OPERATING AT 80% OF SMYS

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INTRODUCTION

Alliance Pipeline (APL) applied for and received a waiver from Pipeline and Hazardous Materials Safety Administration (PHMSA) for relief from certain regulations limiting operation of the Alliance Pipeline to a maximum hoop stress of 72% of the specified minimum yield strength (SMYS). The waiver allows an increase of the currently established maximum allowable operating pressure (MAOP) such that the hoop stress may increase to a maximum level of 80% of SMYS in Class 1 areas. This represents an increase in MAOP and corresponding stress level of 11.1%. The stress levels in Class 2 and 3 areas contiguous with the Class 1 areas where pressure will be allowed to be increase will also increase 11.1% from their regulatory limits of 60% of SMYS and 50% of SMYS, respectively.

The waivers were requested and granted in consideration of extensive engineering analysis demonstrating that the pipeline system can be operated at the increased pressure and stress level without adversely affecting overall safety. PHMSA has specified a number of supplemental safety requirements as conditions to the waiver. These supplemental requirements address a wide range of matters encompassing pipe and materials used, SCADA systems, operations and maintenance procedures, and pipeline integrity management. One of the supplemental requirements in this last category is that APL must confirm that methods used to evaluate the remaining strength of pipe affected by corrosion are valid for the pipe characteristics and operating conditions. If such methods are not valid, a valid method must be submitted to PHMSA.

This document discusses whether the standard methods used to evaluate pipelines affected by corrosion are valid for application to the Alliance Pipeline operating at higher stress levels in accordance with the waiver.

SUMMARY AND CONCLUSIONS

A review of the history and technical basis for the most widely used assessment methods (ASME B31G, Modified B31G, and the Effective Area Method) indicate that there are no theoretical limitations the prevent the successful application of these methods to the Alliance Pipeline, and that the 345 full-scale validation tests substantially encompass the relevant dimensional, material, and operational parameters embodied in the pipe used in the Alliance Pipeline. Thus the use of any of the standard methods to evaluate metal loss due to corrosion affecting the Alliance Pipeline as uprated in accordance with the waiver is technically sound. Confidence in the ability to apply the standard methods is further provided by their many years of successful and reliable application to pipelines operating in Canada at hoop stress levels up to 80% of SMYS and having material and dimensional attributes that are not dissimilar to those of the Alliance Pipeline.

Two possible adjustments of the methods were considered. There is some technical justification for redefining the flow stress for X70 pipe as the average of SMYS and SMTS resulting in a slightly lower flow stress than the standard value taken as SMYS + 10 ksi. However, based on thousands of tensile tests the Alliance pipe is sufficiently over strength to offset the slightly less conservative value (SMYS + 10 ksi), so no adjustment appears to be necessary in order to perform standard assessments on the Alliance Pipeline and achieve the factor of safety implied by applying the same methods to more conventional pipelines. Secondly, the factor of safety of 1.39 implicit in ASME B31G and often applied with the other methods can be reduced to 1.25 in the uprated Class 1 pipe without encroaching on the factor implied by the design and construction of the pipeline. In accordance with terms of the waiver, the factors of safety in the uprated Class 2 and Class 3 segments of the line are 1.50 and 1.80, assuring that any anomalies remaining in any uprated pipeline segments will not fail at less than 100% of SMYS.

STANDARD CORROSION ASSESSMENT METHODS

Several assessment methods are in widespread usage in the pipeline industry for evaluating the remaining strength of line pipe affected by metal caused by external or internal corrosion. The principal methods are ASME B31G, the Modified B31G method, the Effective Area Method as embodied in software products such as RSTRENG or KAPA, and API 579 Levels 1 and 2. While this list is not comprehensive of all available methods for evaluating pipe affected by corrosion, it encompasses the techniques most often applied to evaluate corrosion affecting onshore pipelines in the US. These are referred to herein as the “standard assessment methods". Several other assessment methods have been successfully applied to pipelines in the US and elsewhere, including DNV RP-F101, PCORRC, and CORLAS. These techniques incorporate concepts similar to those embodied in several of the standard assessments listed earlier with modifications to certain assumptions or approximations. The purpose of this document is not to provide a comprehensive review and analysis of all available methods. For the most part, the assertions offered herein apply to most or all of the other methods currently in use.

A chronology of the development of the more common assessment methods, and key technical differences, are summarized in Table 1.

Table 1. Chronology and Key Features of Standard Assessments

Fracture mechanics	**Metal loss evaluation**		
NG-18 Ln-sec Equation	ASME B31G	Modified B31G	Effective Area ("RSTRENG")
• CVN • Ductile or brittle • Exact bulging factor • $S_{Flow}=S_Y+10$ • Area = $(\pi/4)dL$	• No CVN • Ductile initiation • Simplified bulging factor • S_{Flow}=1.1xSMYS • Area = 2/3 dL	• No CVN • Ductile initiation • Exact bulging factor • $S_{Flow}=S_Y+10$ • Area = 0.85 dL	• No CVN • Ductile initiation • Exact bulging factor • $S_{Flow}=S_Y+10$ • Area=Exact profile
1973 →	*1984* →	*1989* →	*1990*

NG-18 Log-Secant Equation

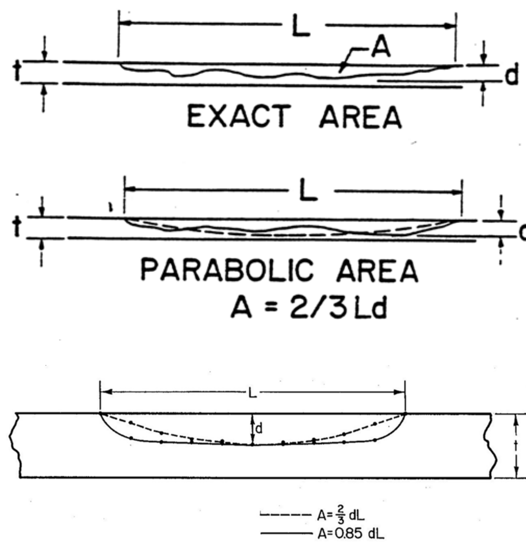
The corrosion assessment methods listed above were derived from the NG-18 "log-secant" equation which describes the relationship between the size of a longitudinally-oriented defect and the failure stress level in a pressurized cylinder. The NG-18 "log-secant" equation was the result of several years of research funded by the gas pipeline industry via the Pipeline Research Committee (now the Pipeline Research Council International, Inc., or PRCI). ("NG-18" refers to the designation of the committee task group assigned to administrate that particular research contract.) The equation was derived in several steps by various researchers starting from the Dugdale "strip-yield" model *[1]* for a through-wall crack in an elastic-plastic flat plate in tension. Steps that lead to the NG-18 equation included the modification by Folias for a factor accounting for the bulging that occurs around a crack in a pressurized cylinder *[2]*, expression by Hahn in terms of plane stress fracture toughness *[3]*, correlation of the strain energy release rate at fracture to the Charpy V-notch upper shelf impact energy *[4]*, the heuristic transformation to surface defects by Maxey, et al *[5]*, and expression in terms of flow stress and validation testing by Kiefner, et al *[4,5]*. The NG-18 equation was validated by 130 experiments consisting of burst tests performed on pipe specimens covering a wide range of dimensions and strength levels with through-wall slits or surface notches machined into them.

ASME B31G and Modified B31G

Although the validity of the NG-18 equation was thereby established, its complexity presented a barrier to usage in the field, particularly in an era when digital calculators were not necessarily widely available, let alone laptop computers. In 1984, the American Society of Mechanical Engineers (ASME) introduced the "B31G" Supplement *[6]* to the B31 Code for Pressure Piping of which B31.4 and B31.8 are sections. The B31G Method contains look-up tables of acceptable length dimensions of corroded areas depending on the maximum measured depth and the dimensions of the pipe, along with optional calculations for the "Safe Operating Pressure" considering the measured length and depth of the corroded area. Certain assumptions and simplifications were imposed in order to reduce the complexities of the NG-18 equation to this field-level assessment tool, including a simpler mathematical approximation for Folias' bulging factor valid over only a limited length, a requirement that pipe have sufficient ductility to initiate a fracture in a ductile manner, an assumption that the net area of metal loss in a longitudinal section is the same as if the corroded profile were parabolic with the same maximum length and depth dimensions as the actual defect, and approximation of the flow stress as SMYS multiplied by a factor of 1.1. (The flow stress is considered to be the stress at the root of a defect at the point of failure in a material capable of strain hardening. It is not a material property specified in pipe purchase specifications or product specifications.)

The B31G Method proved to be reliably conservative, and after tens of thousands of applications in the field and in-line inspection (ILI), we are aware of no failures of pipelines due to corrosion properly evaluated using the method. In fact, to the contrary, there was some evidence that the conservatism inherent to the simplifications embodied in B31G caused unnecessary pipe repairs. This led to the Modified B31G method *[7]*, which removed several conservative simplifications in an effort to be a bit more accurate. Specifically, the original but more complex calculation of Folias' bulging factor was restored, the flow stress was approximated as SMYS plus 10 ksi (based on a statistical fit to the NG-18 test database), and the net area of metal loss in a longitudinal cross section through the corroded area was approximated as 85% of a uniform-depth defect having the same maximum length and depth as the actual defect. Hence the Modified B31G Method is sometimes referred to as the “0.85dL Method”.

Figure 1(a) shows schematically how the 2/3 dL area approximation might compare to a realistic corrosion profile. Figure 1(b) compares the relative areas of the 2/3 dL approximation and the 0.85 dL approximation. The difference is small. The effect of this difference in the computed result compared to accounting for the area exactly as with the Effective Area Method depends on the actual profile, so is not consistent case to case.



(a)

(b)

Figure 2. Comparison of Area Approximations

The 85% area assumption is slightly more conservative than the parabolic profile assumption in B31G which assumes the metal loss area is only 67% of the area of a uniform-depth defect, but is more accurate for long-shallow corrosion. The aggregate result of the modifications of the area approximation, the flow stress approximation, and the bulging factor is that the Modified B31G Method usually, though not always, indicates a somewhat greater safe operating pressure than the original B31G method, meaning it is on average somewhat less conservative than the original B31G.

Effective Area Method (RSTRENG)

As a further enhancement, the Effective Area Method was developed to account as well as possible for the exact profile of a longitudinal section through the actual corroded area *[7]*. It examines all possible combinations along the profile of local metal loss as reinforced by the surrounding metal. The number of possible combinations depends on the profile discretization (there are N!/[2(N−2)!] combinations to check where N is the number of measurement points), so an algorithm in a computer program or spreadsheet is a practical necessity. The Effective Area Method and the Modified B31G Method were validated by 215 burst tests *[8]* performed on pipe containing actual corrosion defects, service failures, pipeline hydrostatic test failures, and artificial metal-loss defects. The first commercially available computer program making use of the Effective Area Method was RSTRENG (for "Remaining Strength") *[7,9]* and so is often referred to as "the RSTRENG Method". The method exists in the public domain *[9]*, hence it has been written into other calculation tools available to the pipeline industry (e.g., KAPA, CORLAS, and analyses offered by in-line inspection vendors). It is interesting to note that the original B31G document states that "the operator may make a more rigorous analysis of the corroded area … by performing a fracture mechanics analysis based upon established principles and practices using the actual profile of the corroded region." This allowance for a more advanced calculation appeared several years before the Effective Area Method was available.

Other Assessments

API RP 579 *[10]* presents three levels of assessment for metal loss due to corrosion. Level 1 is a formula that is essentially similar to the Modified B31G formula. It differs in the terms of the bulging factor rewritten to cover the full range with a single equation, and with the remaining strength factor operating on the yield strength instead of a flow stress.*[11]* Level 2 is essentially the Effective Area Method, also with the adjusted bulging factor. API 579 also recognizes a Level 3 analysis which relies on a finite element analysis. The Level 3 analysis is not related in any way to the methods discussed above.

The methods discussed above present trade-offs for the user between technical rigor and accuracy on the one hand, versus ease of use and reduced exactness on the other. In being modified from complex to simple, the exactness of the assessment decreases, but the simplifications were made so as to offset error with increased conservatism. So, one can say that more exact implies a less conservative computed result but not necessarily reduced safety because in using the more exact method the user is making a better quality estimate. The relative degrees to which the assessments differ in this regard are shown schematically in Figure 2.

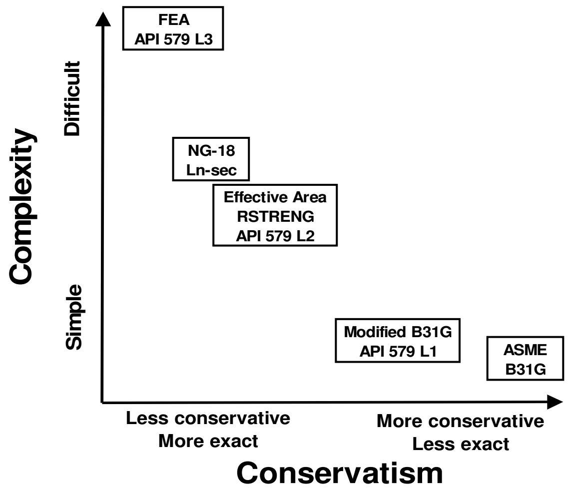


Figure 2. Spectrum of Assessment Complexity Versus Conservatism

APPLICATION TO THE ALLIANCE PIPELINE

The concern of interest is whether the methods discussed above can be safely and reliably used to evaluate the remaining strength of the Alliance Pipeline when it is operating at stress levels greater than 72% of SMYS. PHMSA seeks validation of the methods (or a method) for application to pipe of the similar dimensions, grade or strength, and operating stress level. The validity may be addressed in terms of whether the validating database encompassed pipe of like dimensions and strength levels, whether there are limitations inherent to the underlying theories or assumptions that would render them invalid, or whether there are special adjustments necessary to apply the methods in view of specific aspects of this pipeline's operation. Note that it is only necessary to validate the method for the Class 1 pipe, since the Class 2 and Class 3 pipe will operate at stress levels below 72% of SMYS even after the uprate is in effect.

NG-18 Log-Secant Equation

The NG-18 Equation, which is the theoretical fracture-mechanics basis for the corrosion assessment methods, was validated by 130 burst tests of pipe containing artificial through-wall slits and surface notches. The range of test parameters is listed in Table 2.

The pipe diameters tested ranged from 6-inch NPS to 48-inch OD, which encompasses the 36-inch OD of the line pipe used in APL. The wall thicknesses in the pipes tested ranged from 0.195 inch to 0.861 inch, which encompasses the wall thickness dimensions of the Class 1 line pipe used in APL. The reported yield strengths of the tested pipe ranged from 32.0 ksi to 106.6 ksi, and the reported ultimate tensile strengths of the tested pipe ranged from 53.4 ksi to

131.7 ksi. These ranges bracket the actual strength levels observed in the pipe mill test reports for APL pipe. The reported Charpy V-notch (CVN) absorbed impact energy in the NG-18 tests were generally less than the toughness of the APL line pipe. It is possible that this could cause the NG-18 equations to be more conservative when modeling the actual behavior of the APL pipe affected by a crack.

Table 2. Alliance Pipe Attributes and Validation Test Parameters

Parameter	Alliance Class 1 line pipe	Range of Attributes in Validation Tests	
		NG-18 log-sec Eq'n	Corrosion Methods
OD (inches)	36.0	6.625 to 48.0	10.75 to 48
Wall (inch)	0.622	0.195 to 0.861	0.197 to 0.500
D/t ratio	57.9	26.4 to 104.3	40.6 to 100.0
Actual YS (ksi)	70.0 to 87.5	32.0 to 106.6	28.4 to 74.8
Actual UTS (ksi)	84.7 to 103.6	53.4 to 131.7	40.2 to 85.5
CVN (ft-lb)*	94 to 371	15 to 100	n/a
No. of tests	n/a	130	215

*Standard full-size equivalent

<u>Metal Loss Area Methods</u>

The B31G, Modified B31G, and Effective Area Method were validated by 215 burst tests of natural corrosion and artificial metal loss defects in line pipe. The range of test parameters is listed in Table 2. The diameters of pipe used in these tests ranged from 10-inch NPS to 48-inch OD, which encompasses the 36-inch OD of the APL line pipe. The wall thickness of the pipes tested ranged from 0.197 inch to 0.500 inch, which is somewhat less than the 0.622-inch wall thickness of the APL Class 1 pipe. The only concern about pipe thicker than the tested range is that pipe that is substantially thicker and also of low toughness or having a high CVN transition temperature may violate the assumption of ductile fracture initiation. However, the actual wall dimension of the APL Class 1 pipe is not sufficiently thick to cause a shift in the transition temperature observed from standard full-size CVN test specimens, and it is highly improbable for pipe having the metallurgical specifications and fracture toughness properties of the APL pipe to exhibit non-ductile fracture initiation at anything but the most severe arctic temperatures (e.g., temperatures well below −50 F). Therefore the pipe wall dimension of the APL pipe is not a concern.

The reported yield strengths of the tested pipe ranged from 28.4 ksi to 74.8 ksi, and the reported ultimate tensile strengths of the tested pipe ranged from 40.2 ksi to 85.5 ksi. These ranges do not bracket the actual strengths of pipe used in the Alliance Pipeline. CVN impact energy levels were not reported for the 215 metal-loss test pipes because the methods that were being evaluated do not require the use of CVN impact energy as input. The fact that the metal-loss tests do not fully encompass all strength levels possible in the APL line pipe should not pose a deterrent to the usage of the metal-loss assessment methods, for the following reasons. Firstly, the slit and notch tests clearly validate the NG-18 equation for the APL line pipe. The slit and notch tests represent more severe conditions in terms of notch acuity and sensitivity to fracture toughness levels than metal-loss. If a pipeline has optimal toughness, meaning it has sufficient toughness to fully develop flow-stress-dependent behavior, then the NG-18 equation simplifies to what is essentially the Modified B31G solution. The APL pipe has exceptionally high toughness and certainly would exhibit flow-stress-dependent behavior in the presence of a corrosion pit. Thus it can be concluded that the standard flow-stress-dependent, ductile-fracture-initiation metal-loss criteria are applicable to the APL pipe in principle.

Some practitioners have asserted that the Effective Area Method is not applicable to X70 pipe or stronger. Note that if the Effective Area Method is not applicable, then ASME B31G and Modified B31G are also not applicable. For the reasons explained above, it is our opinion that the standard assessments do apply and are valid in principle. The only possible basis for concern lies with the definition of flow stress, as will be discussed below.

Flow Stress Consideration

The issue concerning flow stress is that the definitions of flow stress used in ASME B31G (1.1 SMYS) and the Modified B31G (SMYS + 10 ksi) appear to be increasingly inconsistent with the actual property as strength levels and the corresponding ratios of yield/tensile strengths increase. The definition of flow stress as yield strength plus 10 ksi was based on a regression of the original 130 slit and notch tests, and for many samples of line pipe is numerically very close to the flow stress defined as the average of actual yield and ultimate strengths as used in some fracture mechanics relationships. Defining the flow stress for purposes of assessment as ½(SMYS+SMTS) would avoid the problem of a computed flow stress exceeding the SMTS for high yield/tensile ratio materials which could occur with the SMYS+10 ksi definition.

Redefining the flow stress as ½(SMYS+SMTS) results in a flow stress of 76 ksi for API 5L X70 line pipe. This is only 1 ksi (1.3%) less than the flow stress of 77 ksi obtained defining flow stress as 1.1xSMYS when applying ASME B31G, a negligible difference that is outweighed by scatter in the test data and the factors of safety applied to the results. On that basis no adjustment should be made when applying ASME B31G to the Alliance Pipeline. The redefined flow stress of 76 ksi is 5% less than the flow stress of 80 ksi obtained from SMYS+10 ksi, as is done when using the Modified B31G Method and the Effective Area Method. However, it is also just about equal to the 77-ksi actual average yield strength and is well below the average flow stress of 84 ksi calculated using actual yield and tensile strengths reported from the mill test reports for the APL pipe. In other words, the actual pipe on average is 10% stronger in terms of flow stress than the redefined flow stress based on specified minimum strength levels and 5% stronger than the original flow stress of SMYS+10 ksi. This factor of conservatism is additive to the factors of safety that would be used to define a "Safe Operating Pressure". On that basis no adjustment seems to be necessary when applying the Modified B31G or the Effective Area Method to the Alliance Pipeline. A comparison of flow stress terms is shown in Table 3.

Table 3. Flow Stress Summary

API 5L X70	**Alliance Pipe**	**ASME B31G**	**MB31G, RSTRENG**	**Fracture Mechanics**
SMYS = 70	Avg YS = 77.4	1.1 SMYS = 77	SMYS+10 = 80	½(SMYS+SMTS) = 76
SMTS = 82	Avg TS = 91.5			

Safety Factor Adjustment

The second area of adjustment involves the Factor of Safety to apply between the estimated failure pressure and the "Safe Operating Pressure". ASME B31G and the RSTRENG software package produce a computed "Safe Operating Pressure" equal to the computed failure pressure divided by a Factor of Safety equal to 1.39. The 1.39 factor is based on the assumption that the pipeline operates at 72% of SMYS and that it is desired to provide the equivalent Factor of Safety as is implied by a hydrostatic test of the line to 100% of SMYS. The appropriateness of this assumption can be debated for many common pipeline operating scenarios. It is proposed that an appropriate Factor of Safety is one that reflects the required ratio of test pressure to operating pressure necessary to achieve the uprate, namely 100%/80%=1.25 for the Class 1 sections operating at 80% of SMYS. When applying the Modified B31G or Effective Area Methods, the computed failure pressure should be divided by 1.25 to obtain a "Safe Operating Pressure" rather than 1.39. Note also that as a condition of granting the waiver, PHMSA stipulated a factor of safety of 1.50 in uprated Class 2 pipe (operating at 66.7% SMYS) and a factor of safety of 1.80 in uprated Class 3 pipe (operating at 55.6% SMYS). This assures that any anomaly remaining in any uprated section of the pipeline would not fail at less than 100% of SMYS.

When applying the original ASME B31G method in simplified form as presented in Appendix L of ASME B31.8, the "Safe Operating Pressure" given as P′ must first be calculated using the pressure corresponding to a hoop stress equal to 100% of SMYS for the "operating pressure" represented by "P" in the equations. The resulting P′ is the estimated failure pressure, which must then be divided by the desired Factor of Safety, in this case 1.25, to obtain the correct "Safe Operating Pressure".

The revised definitions for "Safe Operating Pressure" discussed above must be applied to assessments provided by in-line inspection (ILI) vendors, as well as assessments made in the field by coating inspectors or other technical personnel.

REFERENCES

1. Dugdale, D. S., "Yielding of Steel Sheets Containing Slits", *Journal of the Mechanics and Physics of Solids*, Vol. 8, 1960.
2. Folias, E. S., "The Stresses in a Cylindrical Shell Containing an Axial Crack", ARL 64-174, Aerospace Research Laboratories, October 1964.
3. Hahn, G. T., Sarrate, M., and Rosenfield, A. R., *International Journal of Fracture Mechanics*, Vol. 5, 1969.
4. Maxey, W. A., Kiefner, J. F., Eiber, R. J., and Duffy, A. R., "Ductile Fracture Initiation, Propagation, and Arrest in Cylindrical Vessels", ASTM STP 514, 1972.
5. Kiefner, J. F., Maxey, W. A., Eiber, R. J., and Duffy, A. R., "Failure Stress Levels of Flaws in Pressurized Cylinders, ASTM STP 536, 1973.
6. ASME B31G, "Manual for Determining the Remaining Strength of Corroded Pipe", 1984.
7. Kiefner, J. F., and Vieth, P. H., "A Modified Criterion for Evaluating the Remaining Strength of Corroded Pipe", Project PR 3-805, A. G. A. Catalog No. L 51609, December 22, 1989.

8. Kiefner, J. F., Vieth, P. H., and Roytman, I., "Continued Validation of RSTRENG", Project PR 218-9304, A. G. A., Catalog No. L51749, December 20, 1996.

9. Kiefner, J. F., and Vieth, P. H., "Evaluating Pipe – 1: New Method Corrects Criterion for Evaluating Corroded Pipe", Oil & Gas Journal, Aug. 6, 1990, and "Evaluating Pipe – Conclusion: "PC Program Speeds New Criterion for Evaluating Corroded Pipe", Oil & gas Journal, Aug. 20, 1990.

10. API Recommended Practice 579, "Fitness-for-Service", First Ed., January 2000.

11. Sims, J. R., Hantz, B. F., and Kuehn, K. E., "A Basis for the Fitness for Service Evaluation of Thin Areas in Pressure Vessels and Storage Tanks", ASME PVP-Vol. 233, 1992.