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COMPARISON OF FATIGUE MODELS IN API 1183 FOR PREDICTING FATIGUE LIFE OF PIPELINE DENTS

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ABSTRACT

Pipeline dents are mechanical damage caused by a third party on buried pipelines during construction or maintenance repair. Since 2008, the Pipeline Research Council International (PRCI) has sponsored a large pipeline dent program on experimental tests, integrity assessment, and inline inspection of pipeline dents with and without interfacing other anomalies. For more than ten years, many experimental data, numerical results and assessment models have been developed. On this basis, American Institute of Petroleum (API) recently published a recommended practice (RP) 1183 – Assessment and Management of Pipeline Dents. This API code provides the pipeline industry "standard methods" for evaluating severity and predicting fatigue life of pipeline dents with a single peak.

This paper discusses fatigue methods prescribed in API RP 1183 for predicting fatigue life of pipeline dents. This API standard provides two types of dent fatigue criteria. One is screening methods based on dent fatigue life in Sections 7.4.1, 7.4.2, and 7.4.3 of API 1183. The other is assessment methods for predicting fatigue life of dents in Section 8.3.4. Because of complexity of fatigue methods and math equations given in the content, Annexes A.1 to A.5 in API 1183 provide a set of standard examples for calculating fatigue life, determining restraint condition, and evaluating the screening and assessment methods for plain dents. However, after careful examination, it was found that many issues and errors exist in this new API standard. In particular, comparisons using these Annex examples in API 1183 showed self-inconsistence between the screening methods and the assessment method. This paper presents the detailed fatigue life calculations, comparisons, and self-inconsistent results of the dent screening and assessment methods given in API 1183. On this basis, recommendations are made on how operators should use API RP 1183, and what actions API should take to improve this code.

KEYWORDS: API 1183, mechanical damage, pipeline dent, fatigue life, screening model, assessment model

1. INTRODUCTION

Pipeline dents are mechanical damage (MD) caused by a third party on buried pipelines, such as backfilling rocks during pipeline construction, or rocks setting underneath a pipeline, or excavator backhoes during maintenance repair. Dents are associated with a significant local plastic deformation and can cause pipeline failures. It has been recognized that dent is one leading cause of failures in both liquid and gas transmission pipelines. Therefore, fitness-for-service (FFS) or integrity management requires understanding of dent severity or possible local crack growth in service. In practice, MD covers a broad range of potential features, and varies from simple smooth features (e.g., rounded dents) that do not pose a threat to pipeline integrity, through more complex features that are not an immediate concern, into more severe events that cause immediate failure either by puncture during contact on pipeline or by cracking or collapse during re-rounding of the dents. Because of the significant importance, pipeline dents have been paid high attention to since the late 1950s [1-3], and many investigations have been performed worldwide to address the critical issues associated with dent integrity using both experimental and analytical efforts [4].

In 1997, American Petroleum Institute (API) developed a dent assessment standard, API 1156 [5] for smooth dents in liquid pipelines. In 2007, API developed a more general FFS code, API 579 [6] for assessing different flaws existing in pressure vessels. For pipelines, however, dent assessment remains a great challenge due to complexity of its geometry, shape, size, location, orientation, and influence of residual stresses. To meet practical needs of pipeline operators, Pipeline Research Council International (PRCI) sought research proposals in 2006 to address urgent MD concerns, and initiated four separate large MD programs in 2008 to address different technical needs within the areas of MD inspection, characterization, assessment, and repair. Four dent programs [7] were designated: MD-1 of tools to detect and discriminate mechanical damage, MD-2 of ranking and screening mechanical damage defects, MD-4 of structural significance of

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mechanical damage, and MD-5 of guidelines for inspection and repair of mechanical damage defects.

Among these four MD programs, the MD-4 program was designed particularly to investigate the structural significance of MD, including severe combined dent and gouge defects. In 2008, five projects were initiated for the MD-4 program to cover full-scale tests and model improvements for actual MD defects found in the field, including MD interfered with welds, corrosion defects, or gouges. In particular, Project MD-4-1 [8] was assigned to conduct full-scale tests on dents and gouges for experimental validation of MD assessment models for modern pipeline steels X52 and X70. Project MD-4-2 [9] was assigned to perform full-scale tests for experimental demonstration of interaction of dents with localized corrosion and welds. Project MD-4-3 [10] was designed to develop an improved assessment model for predicting immediate burst failure of dent and gouge defects. Project MD-4-4 [11] was assigned to develop an improved assessment model for predicting time-delayed fatigue failure of combined dent and gouge defects. Project MD-4-6 [12] was assigned to perform full-scale tests for experimental validation of MD assessment models for vintage pipeline steels.

At the IPC2012 conference, Zarea et al. [13] summarized the experimental and analytical results for dents and gouges obtained by those MD-4 projects over the four years from 2008 to 2012. Since then, both PRCI and U.S. Department of Transportation (USDOT) Pipeline and Hazardous Materials Safety Administration (PHMSA) have continued to sponsor the MD programs, and numerous results have been obtained over the 10 years through great efforts by many researchers from different organizations using experimental, numerical, and analytical methods [14-26]. Recently, these results were incorporated with the pipeline dent management practice from operators, and a recommended practice (RP) code was developed by API and designated as API RP 1183 [27] with an objective for assessment and management of pipeline dents. API RP 1183 was published in November 2020. More recently, Zhao et al. [28] presented a detailed review on different standards and methods developed for dent assessment and failure prediction of pipelines.

Development background of API 1183 [27] was reviewed by Tiku et al. [20] at IPC2016 on an improved pipeline dent integrity management that was developed by BMT [25] based on the finite element analysis (FEA) simulation, including the FEA process and novel engineering tool for pipeline integrity management with consideration of dent formation, re-rounding and through life response to pressure fluctuations to evaluate the figure life of dent features. The FEA results were used to develop dent severity and fatigue life models based on In-Line Inspection (ILI) dent shape data, restraint condition and operating pressure for single peak dents. Dotson et al. [24] compared fatigue lives calculated from the PRCI MD-4-9 (i.e., API 1183) model, four existing fatigue assessment models, and Stress Concentration Factor (SCF) method for 220 actual dents from a 24-inch pipeline with depths ranging from 0.6% to 4.5% outside diameter (OD) of the pipe, and 32 dents from a 30-inch pipeline with depths ranging from 1% to 2.5% OD. Their assessment included both top-line and bottom-line dents, and studied the influence of restraint condition on dent remaining life. Their comparisons showed that the MD-4-9 model and the SCF approach have a good correlation for the top-line dents, but no correlation for bottom-line dents. These authors pointed out that complex dent shapes, including multiple peaks, make the application of the MD-4-19 (or API 1183) method in a great challenge. Even so, the pipeline industry has started to implement API RP 1183 in the pipeline dent management. For example, Explorer Pipeline Company [29] recently reviewed API 1183 methods for implementation in their technical practices (TPs) that provide guidelines for consistently performing integrity assessments of their pipelines. Their review identified some inconsistences between Explorer TPs and API RP 1183. Moreover, Polasik et al. [30] recently discussed discrepancies between the screening methods and the shape-based assessment method prescribed in API 1183 [27]. It was found that a dent "passes" the screening process, indicating the dent is non-injurious, but the shape-based assessment dictates the dent is injurious, and a response should be taken.

To the best of the author's knowledge, API RP 1183 was developed primarily based on the results [31] over the past ten years from the research sponsored by PRCI, USDOT, INGAA, pipeline companies, and other organizations. Prior to publication of this RP, however, API did not initiate a round-robin program to evaluate or validate the methods included in API RP 1183. As a result, some discrepancies [30] exist in API RP 1183. To ensure this API code valid and effective for pipeline operators to use in practice, this paper further evaluates the pipeline dent screening and assessment methods prescribed in API RP 1183 using the examples provided in its Annex A. Some major errors and self-inconsistences are identified and discussed in this paper.

2. BRIEF REVIEW OF SCREENING AND ASSESSMENT METHODS PRESCRIBED IN API RP 1183

API RP 1183 provides basic information for identifying, characterizing, screening, assessing, and considering remedial actions for pipeline dents with or without coincident features. The objective is to assemble existing methods and guidance for the pipeline industry to assess and manage pipelines containing plain dents in a comprehensive and self-consistent guidance document [31]. The primary methods and guidance prescribed in API 1183 include 1) Guidance for identifying which features are dents, 2) Standardized terminology to apply to dent features, 3) Recommended techniques for characterizing dents, 4) Techniques for considering coincident feature interactions, 5) Screening tool for identifying non-injurious dent features, 6) Assessment tools for consider dent formation potential for cracking, failure pressure and fatigue life assessment, 7) Guidance on available remedial actions including reassessment, operational changes and repair, and 8) Guidance on field data collections and reporting procedures. This paper focuses on the fatigue life screening methods outlined in Section 7.4, and the shape-based fatigue life assessment method specified in Section 8.3 of API 1183, as briefly reviewed next.

2.1 Dent Screening Methods

Two key elements included in the pipeline dent integrity management are screening and assessment. Of which, the screening element acts a filter prior to the assessment element by applying conservative and simplified screening tools to identify non-injurious dents that do not require further detailed FFS assessments or any response action to be taken by the operator. In other words, *API 1183 [27] specifies that dents identified as non-injurious by all screening tools do not need to undergo further detailed FFS fatigue life assessment*. Thus, all screening techniques are conservative dent assessment tools for quickly identifying non-injurious dents. Three screening tools introduced in Section 7.4 of API 1183 are presented in order of increasing complexity or data requirements and decreasing levels of conservatism for single peak dents, and the most conservative tool is presented first in this API code. As such, if one of the screening approaches presented in Section 7.4 demonstrates that the dent has a longer fatigue life than the desired pipeline operational life, the dent is not susceptible to fatigue failure over the defined operational period. Because the screening tools are conservative, additional safety factors on fatigue life are not required by the API code.

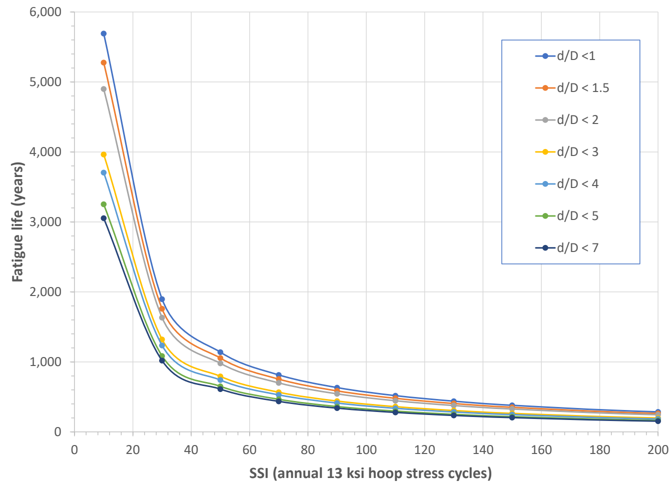
2.1.1 Screening Method 1 in Subsection 7.4.1

The first screening method that is considered as the most conservative (i.e., provides a lower bound estimate of fatigue life) is called Spectrum Severity Indicator (SSI) fatigue life screening method. This SSI screening method was initially developed for the project sponsored by the Interstate Natural Gas Association of American (INGAA) [22], and thus is referred to as INGAA approach in this paper. This approach is expected to provide the minimum fatigue life of a plain dent.

By studying a range of dent shapes and pipe geometries, this screening approach was developed for evaluation of cyclic loading severity for both restrained and unrestrained dents. The spectrum severity of a pipeline operational pressure time history is defined using SSI on an annual basis, where the SSI is the number of cycles of a reference stress range (i.e., $\Delta\sigma_{SSI}$ = 90 MPa or 13 ksi) for one year that results in the same fatigue damage as for the actual pressure time history. Mathematically, SSI = $D_T N_{eq}$, where D_T is the annual accumulated damage from the actual pressure time history, and N_{eq} is the calculated fatigue life for the equivalent SSI stress range of 13 ksi [22].

The minimum expected fatigue life of a dent defined by the INGAA screening approach is listed in Table 6 of API 1183 with use of total deformation dent depth that is normalized by pipe diameter (d/OD). The results presented in Table 6 are the lower bound fatigue lives for a range of shapes formed in a range of pipe geometries grouped by the maximum dent depth. Thus, Table 6 provides a conservative estimate of the fatigue life for both restrained and unrestrained dents based on ILI reported total dent depths. Figure 1 plots the results in Table 6, and shows the fatigue life is a function of SSI on an annual basis associated with the stress range of 13 ksi. It demonstrates that the fatigue life decreases with increasing SSI and d/D ratio for both restrained and unrestrained plain dents.

(a)



(b)

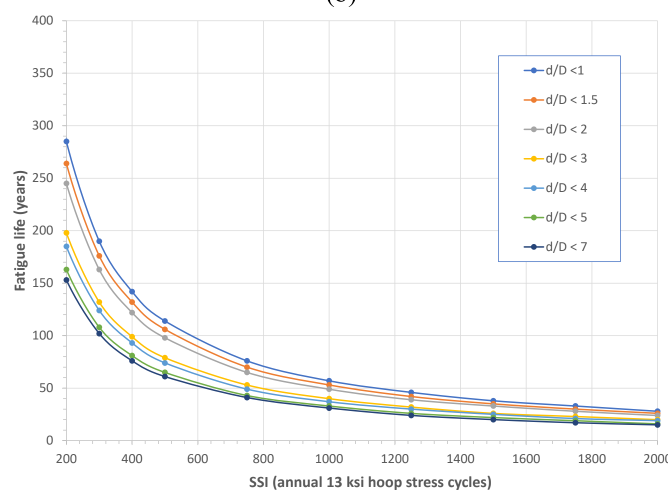


Figure 1. Fatigue life of a dent as a function of SSI for restrained and unrestrained dents: (a) SSI < 200, and (b) SSI ≥ 200

Due to simplification to use, the INGAA approach is very attractive to many operators who have a large number of dents from ILI runs, and need a quick screening to identify features that may be injurious [30]. This screening tool requires minimal input data and can be completed relatively quickly by operators or engineering consultants.

2.1.2 Screening Method 2 in Subsection 7.4.2

The second screening method has been developed to evaluate the dent cyclic loading severity in terms of the SSI for shallow restrained dents and all unrestrained dents. Since the dent maximum stress magnification factor K_{max} is used, this second screening method is referred to as the K_{max} approach in this work, where the fatigue life of a dent is defined as a function of SSI, K_{max} (or d/t, OD/t, level of pressure range), and restraint condition. Note that a stress magnification factor is the same as SCF by its definition [22]. A dent is defined as a shallow dent if the total dent depth d < 4% of OD for a smaller diameter pipe with OD ≤ 12.75 inches, or d < 2.5% of OD for a larger diameter pipe with OD > 12.75 inches.

For shallow restrained dents and all unrestrained dents, a lower bound fatigue life in years is calculated by [22]:

$$N \geq \frac{10^{log_{10}C - m log_{10}(\sigma_{ref} K_{max})}}{SSI} \tag{1}$$

where SSI is calculated for an actual pressure spectrum history time, the S-N curve is used is BS 7608 Class D mean -1sd [33], and thus $\log_{10}C = 12.6007$ for $\sigma_{ref} = 90$ MPa and m=3. K_{max} is defined in Eq. (2) based on the restraint condition and whether the dent has experienced a maximum pressure greater than or less than 20% of the specified minimum stress (SMYS):

$$K_{max} = \begin{cases} 7.5\left[1 - e^{\left(-0.065\frac{OD}{t}\right)}\right], unrestrained, P_{max} > 20\% \\ 9.4\left[1 - e^{\left(-0.045\frac{OD}{t}\right)}\right], unrestrained, P_{max} \leq 20\% \\ 0.1183\frac{OD}{t} - 1.146, \quad restrained\ dents \end{cases} \tag{2}$$

where restrained dents imply shallow restrained dents only. A similar approach is being developed for deep restrained dents, but was not available at the time of API 1183 publication.

If the calculated lower bound fatigue life from Eqs (1) is greater than the pipeline desired operational life, the dent is not susceptible to fatigue failure over the desired service life. Otherwise, more detailed FFS fatigue life assessment defined in Section 8 of API 1183 may be applied. In addition, it is expected that a dent may fail from the INGAA approach, but have an acceptable fatigue life if the K_{max} approach is used. In other word, a dent would not be expected to have a longer fatigue life when using the INGAA approach compared to that by using the K_{max} approach.

2.1.3 Screen Method 3 in Subsection 7.4.3

The third screen method was developed for estimating fatigue life of shallow restrained dents and all unrestrained dents for Operational Pressure Spectrum (OPS), where an OPS time history is defined using a histogram of pressure range magnitudes from the rainflow counting process [32]. This method is extended from the K_{max} approach by incorporating the rainflow cycle counted OPS instead of SSI. Thus, it is referred to as the K_{max}-OPS approach in this paper.

Determination of a lower fatigue life using this third screen method requires 1) performing an reainflow cycle counted analysis on the given OPS, 2) converting pressure range bin sizes in % SMYS pressure, 3) calculating K_{max} from Eq. (2) for each pressure range bin, 4) determining the critical stress range by multiplying K_{max} by the pressure range magnitude of the histogram for each pressure range bin, and finally 5) the Miner's Rule is utilized to estimate the damage per pressure range bin, the total fatigue damage, and the final estimated fatigue life. For the i-th pressure range bin, the fatigue damage is calculated by:

$$D_i = n_i \,/\, N_i \tag{3}$$

where $N_i = 10^{(log_{10}C - m log_{10}(K_{maxi}\Delta\sigma_i))}$ and n_i is the number of occurrences of the i-th stress range bin event. From Eq. (3), the total fatigue damage accumulated in all pressure range bins is added as D_T, and the final remaining fatigue life is estimated as $N = 1/D_T$ in years.

In comparison to the first two screening methods, it is expected that the K_{max}-OPS approach will determine a longer fatigue life, or should be less conservative than the INGAA approach or the K_{max} approach.

2.2. Dent Assessment methods

Dents that did not pass the screening criteria discussed above can be further evaluated using the FFS assessment approaches at three levels, with a higher level of assessment incorporating a lower level of conservatism. These FFS assessments of a dent include a potential for cracking initiated during dent formation, reaching the dent failure pressure, and fatigue damage accumulation. The three levels of dent fatigue assessment are defined as: Level 1 – Fatigue severity ranking, Level 2 – Closed-form fatigue life assessment, and Level 3 – FEA based detailed fatigue life assessment for any dents. This paper only discusses the PRCI developed Level 2 shape factor and shape parameter-based fatigue life assessment as detailed in Subsection 8.3.4 of API 579.

This dent FFS assessment requires the dent characteristic lengths and areas along with the material grade, pipe size, applied pressure range, and estimated S-N curve-based fatigue life to develop a so-called shape parameter (SP) equation that is related to dent shape with fatigue life. The SP regression equation is a single variable equation that relates the dent SP to the dent S-N fatigue life in the form:

$$N = A(SP)^B \tag{4}$$

where N is the estimated fatigue life for a given pressure range and mean pressure, SP is defined by Equations (30) and (31) in API 1183, respectively for restrained dents and unrestrained dents, and A and B are the SP-based fatigue life coefficient and exponent, respectively. Both A and B are functions of the applied pressure range that are listed in Annex F of API 1183 for all 28 pressure range combinations from 10% SMYS to 80% SMYS pressure. The S-N curve of BS 7608 Class D mean – 1sd [33] was used as a conservative fatigue model in the regression analysis of Eq. (4). A recent comparison [34] showed that this S-N curve of BS 7608 is more conservative than the S-N curve recommended by API 1156 [5].

This PRCI approach employs the three-dimensional (3D) shape of a dent that can be obtained by an ILI run or direct inspection to calculate the so-called characteristic dent lengths and areas that are extracted from both axial and transvers profiles through the deepest point of the dent, and then to determine restraint parameter (RP), restraint condition, and SP used to estimate fatigue life of the dent. If a dent is asymmetric, all four combinations of upstream / downstream (US / DS) axial profiles with clockwise / counterclockwise (CW / CCW) transvers profiles need to be evaluated with the dent RP and SP. The shape-based fatigue life is then calculated for all four combinations, separately. The lowest value of the SP fatigue lives shall be used as a conservative representative of the dent fatigue life. This approach will require a substantial amount of detailed dent profile calculations and operating pressure records, and depend on engineer's expertise to perform.

2.3. Restraint condition determination

Use of the screening and assessment methods discussed above needs to know the restraint condition of dents due to different performances of the two methods. Physically, a dent is restrained if an indenter remains in contact with the pipe while the pipeline is in service, and a dent is unrestrained if the indenter is removed from contact with the pipe after the dent is formed during the dent formation or when the pipe is put back in service. As discussed in Subsection 6.4.1 of API 1183, the clock position of a dent has been traditionally used to infer the restraint condition of a dent. The ILI systems can report the dent clock position to support determination of the dent restraint condition. Usually, top-line dents (above 4 o'clock and 8 o'clock positions) are likely unrestrained, and most of bottom-line dents (below 4 o'clock and 9 o'clock) are in the restrained condition. Apparently, this is an empirical judgment-based approach for determining the dent restraint condition that may not always be correct.

It was demonstrated that the shape of a dent from ILI data may be used to understand the dent restraint condition since the shape of the dent will change in response to the removal of the indenter [31]. Based on this understanding, a restraint parameter (RP or ρ) is defined below for estimating the dent restraint condition (see Subsection 6.4.2 of API 1183):

$$RP = max\left\{\frac{18\left|A_{15\%}^{AX}-A_{15\%}^{TR}\right|^{1/2}}{L_{70\%}^{TR}}, 8\left(\frac{L_{15\%}^{AX}}{L_{30\%}^{AX}}\right)^{1/4}\left(\frac{A_{30\%}^{AX}-A_{50\%}^{AX}}{L_{80\%}^{TR}}\right)^{1/2}\right\} \quad (5)$$

The RP parameter defined above is a dimensionless variable, where *RP > 20 indicates a restrained dent, and RP < 20 indicates an unrestrained dent*. When a calculated RP value is close to 20, the dent may be evaluated as both restrained and unrestrained. The shorter fatigue life derived from these evaluations would be conservatively applied to the dent. Note that the RP defined in Eq. (5) is applicable to both single-peak symmetric and asymmetric dents in various pipe geometries at pressures producing 10% to 100% SMYS hoop stresses. For an asymmetric dent, all four combinations or quadrants of US / DS axial profiles with CW / CCW transverse profiles need to be evaluated for determining restraint condition of the dent.

The restraint condition can be also estimated using the SCF, as discussed in Subsection 6.4.3 of API 1183. As suggested by Dotson et al. [24], a dent is possibly unrestrained if the product of the maximum operating pressure induced hoop stress as a fraction of SMYS (i.e., 0.6, 0.72, etc.) and the SCF is less than 2.5. A dent likely restrained if the product is between 2.5 and 3.5 or larger.

3. SELF-INCONSISTENCE OF SCREENING METHODS

Annex A of API 1183 provides a set of sample calculations to illustrate the application of dent restraint condition (Section 6), screening (Section 7), and FFS assessment (Section 8) methods prescribed in this API code. These samples given in Annex A of API 1183 are employed here to evaluate the screening methods first, and then PRCI Level 2 assessment. Last, the specified method is used to determine restrain condition of dents.

As described previously, the screening methods developed in API 1183 are conservative tools for quickly filtering non-injurious dents from a large number of ILI data. A screening "pass" indicates that a dent meets the integrity requirement, whereas a "fail" means a next-level dent assessment should be performed to determine if the dent is injurious.

3.1. Sample Calculation in Annex A.2

Example 2 given in Annex A.2 of API 1183 describes a shallow unrestrained dent for an X52 pipeline. Table 1 details the X52 pipe and dent parameters of grade, property, geometry, SSI, and target fatigue life expected for the pipeline.

Table 1. Dent Parameters for Example 2 in Annex A.2

Parameter	Value
Pipe outside diameter (OD)	24 in. (609.6 mm)
Pipe wall thickness (t)	0.281 in. (7.14 mm)
The OD/t ratio	85.41
Pipe grade	X52
SMYS of X52	52 ksi (358 MPa)
The maximum pressure range	> 20% SMYS
Total dent deformation depth (d)	0.36 in. (9.1 mm)
The d/OD ratio	1.5%
Annual SSI	100
Target life	100 years

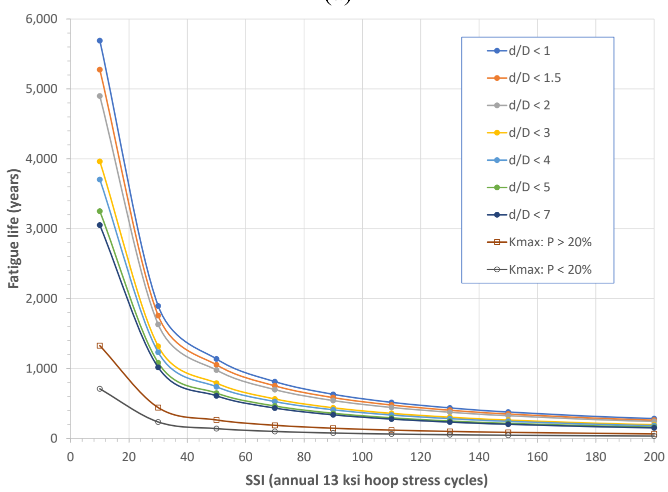
If the first screening method (i.e., the INGAA approach) is adopted, it determines from Fig. 1(a) that the fatigue life N_f = 586 years when SSI = 90, and N_f = 480 years when SSI = 90 for the shallow unrestrained dent of d/OD = 1.5%. Accordingly, the fatigue life of the dent is N_f = 533 years for SSI = 100. Because this estimated fatigue life N_f = 533 years is larger than the target life of 100 years, this unrestrained dent passes the first screening criterion, and thus is non-injurious.

If the second screening method (i.e., the K_{max} approach), it determines that K_{max} = 7.471 from Eq. (2) and N_f = 132 years from Eq. (1) for the unrestrained dent that has experienced a maximum pressure range > 20% SMYS. Again, because the estimated fatigue life N_f = 132 years is larger than the target life of 100 years, this unrestraint dent passes the second screening criterion, and thus is non-injurious.

However, the K_{max} screening approach determined fatigue life of N_f = 132 years is less than the INGAA screening approach determined fatigue life of N_f = 533 years. *This result is contradictory to API 1183 specification that the K_{max} approach is less conservative, and should determine longer fatigue life compared to the INGAA approach.*

To better understand this phenomena, the K_{max} value is determined from Eq. (2) for the unrestrained dent that the max pressure is larger or less than 20% SMYS, respectively for the X52 pipe with D/t = 85.41. And then from Eq. (1), the fatigue life N_f is a simple function of SSI for the X52 pipe. Figures 2(a) and 2(b) compare these two N_f – SSI curves obtained using the K_{max} approach with those determined using the INGAA approach, respectively for SSI < 200 and SSI ≥ 200.

(a)



(b)

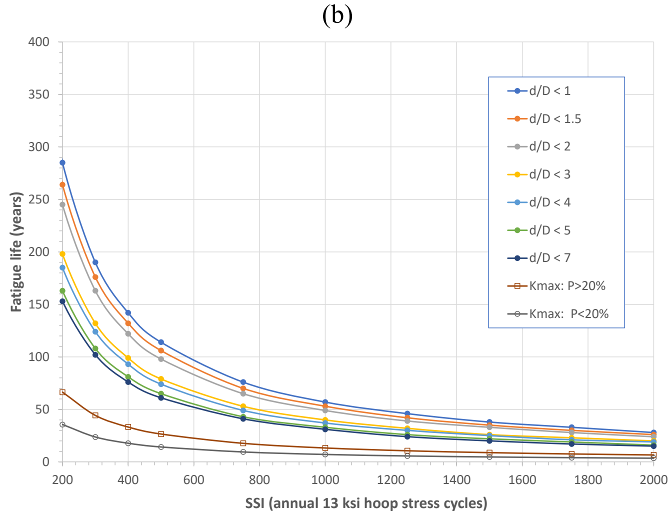


Figure 2. Comparison of fatigue life determined using the INGAA approach with those determined using the K_{max} approach: (a) SSI < 200, and (b) SSI ≥ 200

These two figures show that for the X52 pipe, the dent at any pressure level has a lower fatigue life obtained using the K_{max} approach compared to the INGAA approach for all dent sizes. Similar results are also obtained for other pipe sizes with a large or small D/t ratio. Thus, it is concluded *that the K_{max} approach always determines a shorter fatigue life compared to the INGAA approach for any pipe and dent sizes*. Again, this conclusion is contradictory to the specification of API 1183.

3.2. Sample Calculation in Annex A.3

Example 3 given in Annex A.3 of API 1183 describes another unrestrained dent in an X52 pipeline. Table 2 details the pipe and dent parameters of grade, property, geometry, SSI, and target fatigue life expected for the pipeline. Table 3 provides three assumed pressure cycles as the operational pressure spectrum for the dent defined in Table 2, where the annual SSI of the given pressure cycle is 100 that is equivalent to the annual cycles by the hoop stress of 13 ksi. Note that SSI = 100.3 is obtained using the procedure in Annex A5 of API 1183.

Table 2. Dent Parameters for Example 3 in Annex A.3

Parameter	Value
Pipe outside diameter (OD)	30 in. (762 mm)
Pipe wall thickness (t)	0.25 in. (6.35 mm)
The OD/t ratio	120
Pipe grade	X52
SMYS of X52	52 ksi (358 MPa)
The maximum pressure range	> 20% SMYS
Total dent deformation depth (d)	Not defined
Annual SSI	100
Target life	150 years

Table 3. Pressure Cycles for Example 3 in Annex A.3

Cycles #	P_{min} (psi)	P_{max} (psi)	P_{min} (%P_{SMYS})	P_{max} (%P_{SMYS})	ΔP (%P_{SMYS})
157	86.7	173	10	20	10
55	173	347	20	40	20
36	260	520	30	60	30

If the INGAA screening approach is used, a conservative fatigue life is estimated from Fig. 1(a) as 574 years if d/D < 1% and 308 years if d/D < 7% for SSI=100. Because the dent size is not specified for this example, the estimated fatigue life is N_f > 308 years that is larger than the target life of 150 years. Thus, this unrestrained dent is non-injurious.

If the K_{max} approach is used, K_{max} = 7.50 from Eq. (2), and the estimated fatigue life N_f = 130 years from Eq. (1) for the unrestrained dent. The estimated life of 130 years is less than the target life of 150 years, and thus this dent is injurious.

If the less conservative K_{max}-OPS approached is used, the procedures described previously in Section 2.1.3 determines the fatigue life for this unrestrained dent is 214 years, see details given in Annex A.3 of API 1183. The estimated fatigue life of

214 years is larger than the target life of 150 years, and thus this unrestrained dent is non-injurious.

Clearly, the fatigue life of 214 years estimated by the K_{max}-OPS approach is larger than 130 years estimated by the K_{max} approach. Therefore, this example confirms that the K_{max} and K_{max}-OPS approaches perform as expected in the terms of relative conservatism as described in API 1183. However, both approaches show that the INGAA approach is not conservative. *This is contradictory to the API 1183 specification that the INGAA approach is the most conservative.*

4. SELF-INCONSISTENCE OF SCREENING VERSUS ASSESSMENT METHOD

4.1 Symmetrical dent calculation in Annex A.4

The previous examples examine the performance of three screening methods, and found self-inconsistence exists between the INGAA approach and the other two K_{max} approaches. This section examines the PRCI Level 2 shape-based assessment method as introduced in Section 2.2, and compares this assessment method with the three screening methods. By specification given in API 1183, the Level 2 assessment method is less conservative, and will predict a longer fatigue life than all three screening criteria.

The shallow dent of d/D = 1.5% in an X52 pipe with OD = 24 in. and t = 0.281 in. described in Table 1 for Example 2 in Annex A.2 of API 1183 is utilized here again to calculate the fatigue life using the Level 2 assessment method. The dent is assumed to be symmetric, and its dent characteristic lengths and areas are listed in Table 4 (i.e., Table A.7 in Annex A.4 of API 1183).

Table 4. Dent geometric lengths and areas for Example 2

Designed total deform dent depth (%d_{tot})	Axial Length (mm)	Axial Area (mm^2)	Transverse Length (mm)	Transverse Area (mm^2)
85	26.15	12.099	17.605	−
80	−	−	21.579	−
75	35.899	28.64	25.267	22.082
70	−	−	28.955	−
50	70.497	−	−	−
30	172.3	688.84	−	−
15	477.17	2725.8	82.992	308.37

A hypothetical annual pressure cycle loading for this dent in the X52 pipeline is listed in Table 3 (i.e., Table 4.8 in Annex A.4 of API 1183). The objective is to use the shape parameter equation (4) to calculate the total fatigue life of the dent for the given pressure cycle loading history.

Before performing fatigue assessment for this symmetric shallow dent, restraint parameter (RP) should be evaluated first. From Eq. (5), the RP for the symmetric dent is calculated as:

$$RP = max\left[\frac{18\times|2725.8-308.37|^{1/2}}{28.955},\ 8\times\left(\frac{477.17}{172.3}\right)^{1/4}\times\left(\frac{172.3-70.497}{21.579}\right)^{1/2}\right] = \max(30.57, 22.42) = 30.57 \quad (6)$$

Because the calculated RP = 30.57 > 20, the dent is a restrained dent. Also, because the total dent depth d = 1.5% OD is less than 2.5 % OD in the 24 in. pipe, *the dent is considered as a shallow restrained dent*. As such, the PRCI Level 2 shallow restrained dent shape parameter equation should be used for the fatigue life assessment of this dent.

From the annual pressure cycle loading history shown in Table 3 and following the procedure given in Annex A.5 of API 1183, annual SSI = 100.3 is obtained for the reference hoop stress range of 13 ksi (90 MPa).

If the INGAA approach is adopted, the fatigue life is estimated from Fig. 1(a) as N_f = 533 years for the shallow dent of d/D = 1.5% when SSI = 100.

If the K_{max} approached is adopted, K_{max} = 8.958 is obtained from Eq. (2) for the shallow restrained dent in the pipe of OD/t = 85.41. From Eq. (1), the fatigue life is obtained as N_f = 76 years for this restrained dent.

If the PRCI Level 2 shallow restrained dent shape parameter equation (4) is used, the annual cumulative damage D_T = 0.000575, as detailed in Tables A.9 and A.10 in API 1183. Thus, the fatigue life is estimated as $N_f = 1/D_T$ = 1,739 years.

This example demonstrates the PRCI Level 2 shape-based assessment method predicts a longer (or less conservative) life for the shallow restrained dent compared to the two screening methods. However, the INGAA approach predicted life of N_f = 533 years is significantly longer than the K_{max} approach predicted life of N_f = 76 years. Again, *this is contradictory to the specification of API 1183.*

4.2 Asymmetric dent calculation in Annex A.5

Example 1 in Annex A.1 of API 1183 provides the characteristic lengths and areas for a hypothetical asymmetric dent of d/D = 3.51% in the pipe with a diameter of 32 in. (812.8 mm) and a wall thickness of 0.312 (7.925 mm). It is assumed that the annual pressure cycle loading spectrum listed in Table 3 (i.e., Table 4.8 in Annex A.4 of API 1183) is applicable to this deep dent in the X52 pipeline. These given material and geometric conditions are found to meet the data requirements necessary to apply the PRCI Level 2 assessment method.

Again, from the annual pressure cycle loading spectrum given in Table 3 and following the procedure given in Annex A.5 of API 1183, annual SSI = 100.3 is obtained for the annual hoop stress range of 13 ksi (90 MPa). From the procedure specified in Annex A.5 of API 1153, the restraint parameter can be calculated for each quadrant of this asymmetric dent, and the restraint condition is determined, as detailed in next section.

If the INGAA approach is adopted, the fatigue life is estimated from Fig. 1(a) as N_f = 395 years for the deep dent of d/D = 3.51% when SSI = 100.

If the K_{max} approach is adopted, Kmax = 7.491 is obtained from Eq. (2) for the deep dent in the pipe of OD/t = 85.41 in the unrestrained condition. From Eq. (1), the fatigue life is obtained as Nf = 130 years for this deep unrestrained dent.

If the K_{max}-OPS described previously in Section 2.1.3 is adopted, using the annual pressure cycle loading spectrum in Table 3, the total damage $D_T = 0.004825$. Thus, the total fatigue life is obtained as $N_f = 1/D_T = 207$ years for this deep unrestrained dent.

If the PRCI Level 2 shape-based life assessment equation (4) for unrestrained and deep restrained dents is adopted, the annual cumulative damage for each quadrant is calculated and listed in Tables 1.1 to 1.4 in Appendix 1 of this paper for the asymmetric deep restrained dent.

- For Quadrant 1 (Q1 or US/CW), RP = 39.29, indicating a restraint condition, $D_T = 0.00290$, and $N_f = 345$ years.
- For Quadrant 2 (Q2 or US/CCW), RP = 18.29, indicating an unrestraint condition. For an unrestrained dent, the fatigue damage depends on the ILI pressure when the dent was created. Sine the assumed pressure varies from 10% to 60% of SMYS pressure, these two ultimate values are assumed to be the ILI pressures. If the ILI pressures are assumed to be 10% and 60% of SMYS, $D_T = 0.00323$ and 0.00370, and then $N_f = 309$ and 270 years, respectively.
- For Quadrant 3 (Q3 or DS/CW), RP = 36.56, indicating a restraint condition, $D_T = 0.00242$, and $N_f = 414$ years.
- For Quadrant 4 (Q4 or DS/CCW), RP = 17.82, indicating an unrestraint condition. If the ILI pressures are assumed to be 10% and 60% of SMYS, $D_T = 0.00373$ and 0.00427, and then $N_f = 268$ and 234 years, respectively.

If the restraint condition determination (in Section 6.4.2) is considered first, this asymmetric dent is a deep restrained dent, the lower fatigue life $N_f = 345$ years should be selected from Quadrant 1 and 3 as a conservative life of this deep dent. However, if the lowest fatigue life $N_f = 234$ years obtained using the PRCI Level 2 method (Section 8.3.4) is selected from all four quadrants, this deep dent is unrestrained. As a result, these two methods determine different restraint conditions or different fatigue lives. Apparently, this is another evidence that API RP 1183 determines self-inconsistent results. *This self-inconsistent results infer one of the two approaches for determining the restraint condition and for calculating fatigue life of the dent is inaccurate or incorrect*.

Table 5 compares the fatigue lives of this deep dent obtained from the three screening methods (i.e., INGAA, K_{max}, and K_{max}-OPS) and the PRCI Level 2 method. Except for the INGAA approach, the K_{max}, K_{max}-OPS, and PRCI Level 2 methods determines increasing fatigue life for this deep dent, which indicates the conservatism of these three methods decreases with increasing assessment level. This is consistent with the specification of API 1183. However, it is also found that the INGAA approach determines the longest fatigue life for this deep dent among the four methods. This means *the INGAA approach is not the most conservative tool, which is again contradictory to the specification of API 1183*.

Table 5. Comparison of fatigue lives (in years) for the asymmetric deep dent

ILI (%)	PRCI Level 2 Method				INGAA	Kmax (unrest.)	Kmax -OPS
	Q1	Q2	Q3	Q4			
10	345	309	414	268	395	130	207
60	345	270	414	234			

5. Restraint Condition Determination in Annex 5

The hypothetical dent given in Annex A.1 of API 1183 as Example 1 has been assessed in Section 4.2 above, where the total deformation of the dent d/D = 3.51% in a 32 in.-diameter pipe. The axial and transverse profiles of the dent are shown in Figures A.1 and A.2, respectively. The dent is an asymmetric feature, and its dent characteristic lengths and areas are listed in Table A.1 for the axial DS and US directions and for the transverse CW and CCW directions, respectively. With the data in Table A.1 and from Eq. (5), the values of RP for four quadrants are calculated as:

- Quadrant 1 (US + CW): RP=37.49, restrained dent
- Quadrant 2 (US + CCW): RP=18.28, unrestrained dent
- Quadrant 3 (DS + CW): RP=36.56, restrained dent
- Quadrant 4 (SC + CCW): RP=17.82, unrestrained dent

By the API 1183 specification as discussed in Section 2.3, the maximum value of the four RP given above, RP = 37.49, is the RP for the dent. As a result, per the API specification in Section 6.4.2, this hypothetical dent is a restraint dent due to RP > 20. Since the dent depth d/D = 3.51% > 2.5 %, this dent is deep restrained dent, as defined by the RP in Quadrant 1. The assessment in Section 4.2 shows that the fatigue life of this restrained dent is 345 years. On the other hand, the most conservative fatigue life of this dent is 234 years, as determined for Quadrant 4 and the dent is unrestrained. Thus, *these results are self-inconsistent*. Recently, Kainat et al. [35] also found that the restraint parameter equation determines incorrect restraint conditions for top-line and bottom-line dents from ILI data.

6. Discussions and Remarks

This paper briefly reviewed the screening and assessment methods prescribed in API RP 1183 for determining fatigue life of single peak plain dents. After that, four examples given in Annex A.1 to Annex A.5 of API 1183 were utilized in this paper to determine the restraint condition of a deep dent in an asymmetric condition and to calculate the fatigue life of an unrestrained shallow dent and a restrained shallow dent in the symmetric condition. For convenience of discussion, Table 6 compared the fatigue lives determined in the previous sections for all dent samples, including the Example source, d/D ratio, restraint condition, three screening approaches and the PRCI Level 2 assessment method.

Table 6. Fatigue lives (in years) of the dent samples using the screen and assessment methods

Example Source	d/D (%)	Restraint condition	INGAA	K_{max}	K_{max} -OPS	PRCI Level 2
Annex A.2	1.5	unrest.	533	132	/	/
Annex A.3	/	unrest.	>308	130	214	/
Annex A.4	1.5	restrain	533	76	/	1,739
Annex A.1	3.51	unrest.	395	130	270	262
Annex A.1	3.51	restrain	395	/	/	345

From Table 6, the following observations are made:

(1) Example 3 in Annex A.3 and Example 1 in Annex A.1 confirms that the K_{max} approach is conservative (i.e. predicts a shorter fatigue life) than the K_{max}-OPS approach.
(2) Example 4 in Annex A.4 and Example 1 in Annex A.1 confirms that the PRCI Level 2 method is less conservative (i.e., predicts a longer fatigue life) than the K_{max} screening method.
(3) All examples shows that the INGAA approach is the least conservative (i.e., predicts the longest fatigue life) for all unrestrained dents and shallow restrained dent. *This result is self-inconsistent and contradictory to the specification of API 1183 that the INGAA approach is the most conservative.*
(4) Moreover, Example 4 and Example 2 shows that the K_{max} approach determined fatigue life for a shallow restrained dent of d/D = 1.5% is shorter than that for the same dent in the unrestraint condition. Apparently, *this is different from the common experimental observation that a restrained dent has a longer fatigue life than the unrestrained dent* [16].
(5) For the asymmetric deep dent of d/D = 3.51% in Example 1, the restraint parameter equation determines this deep dent to be restrained, and the fatigue life is 345 years. However, the shape parameter life equation determines the shortest life to be 262 years, and this conservative life is associated with an unrestraint condition. *This self-inconsistency infers either the restraint condition equation or the shape parameter life equation is inaccurate or incorrect.*

In response to these observations, the present author recommends that the INGAA screening approach and the two K_{max} approaches for shallow restrained dents should not be used in the current forms. Instead, the two K_{max} approaches may be used when screening dents.

As for the PRCI Level 2 shape-based assessment equation, it has a great change for users to calculate fatigue life for a plain dent because a set of extremely complicated curve fitting equations were given for determining the so-called shape parameter, shape factor, pressure factor, grade scale factor, scaling factor and others. It is very strange that all the curve fitting equations have either an integer or a common fraction as the exponent for an assumed power function. This arises a great question that if those shape-based fitting equations are correct.

In addition to the self-inconsistent issues and the challenging questions, there are many typos, or editorial or other errors in API RP 1183. For example, there are 95 references in total that are listed in Bibliography. Unfortunately, 19 references have been listed repeatedly from one to five times, resulting 34 repeats of the references. As a result, 53 references are related to repeating issues at a rate of 56%. It is surprising that so many simple errors exist in API RP 1183. For users, the current version of API 1183 looks like a draft edition.

Because so many issues or errors exit in the current version of API RP 1183, a special care should be taken by any user or operator if trying to implement the fatigue life screening and assessment methods into their pipeline dent management plan. The present author strongly suggests that API or PRCI should initiate a round-robin program to validate and verify all methods and equations given in API RP 1183 using both experimental tests and numerical simulations for ensuring accuracy and effectiveness of this API code so that this code can be a valuable tool for pipeline industry to use to improve their assessment and management of pipeline dents.

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Appendix 1. Dent Fatigue Damage Calculation Using PRCI Level 2 Shape-Based Assessment

From the characteristic lengths and areas given for Example 1 in Annex A.1 of API 1183 for a hypothetical asymmetric dent of d/D = 3.51% in the X52 pipe of a diameter of 32 in. (812.8 mm) and a wall thickness of 0.312 (7.925 mm) and from the annual pressure cycle loading spectrum listed in Table 3 (i.e., Table 4.8 in Annex A.4 of API 1183), all parameters required for calculating shape-based fatigue life using Eq. (4) can be calculated in this Appendix. This includes the calculations of pressure factor (PF), fitting parameter R to consider the pressure range and mean pressure, axial and hoop shape factors X_L and X_H, scaling factors λ_L and λ_H used for calculating X_L and X_H for unrestrained dents to consider the ILI pressure effect, and shape parameter (SP). The fitting parameters A and B are given in Tables F.1 to F.3 in Annex F of API 1183, and the scaling factors λ_L and λ_H are given in Tables G.1 to G.7 in Annex G of API 1183. For each pressure cycle bin, the fatigue life N_i is calculated from Eq. (4) or $Log(N_i) = Log(A) + Blog(SP)$, and the damage $D_i = n_i/N_i$. Then, the total cumulative damage for the pressure cycle loading spectrum is determined as $D_T = D_1 + D_2 + D_3$. Tables 1.1 to 1.4 give the values of those parameters and the cumulative fatigue damage for each quadrant of the asymmetric deep dent with an assumed ILI pressure of 10% of SMYS pressure.

Table 1.1 Dent fatigue damage calculation for Quadrant US – CW, RP =37.49

No.	Count #	P_{max} (%)	P_{min} (%)	ΔP (%)	PF	R	λ_L	λ_H	X_L	X_H	SP	LogA	B	N_i ($x10^4$)	D_i ($x10^{-4}$)
1	157	10	20	10	0.2466	1.0	/	/	3.399	0.085	10.817	6.087	-0.773	19.41	8.09
2	55	20	40	20	0.3915	0.666	/	/	3.399	0.085	7.294	5.357	-0.653	6.215	8.85
3	36	30	60	30	0.5130	0.386	/	/	3.399	0.085	4.340	4.859	-0.603	2.987	12.05

In the table, % means % of SMYS pressure $D_T = 0.00290$

Table 1.2 Dent fatigue damage calculation for Quadrant US – CCW, RP =18.29

No.	Count #	P_{max} (%)	P_{min} (%)	ΔP (%)	PF	R	λ_L	λ_H	X_L	X_H	SP	LogA	B	N_i ($x10^4$)	D_i ($x10^{-4}$)
1	157	10	20	10	0.2466	1.0	1.0	1.0	46.53	4.17	46.53	6.061	-0.423	22.65	6.93
2	55	20	40	20	0.3915	0.666	0.821	0.869	38.18	3.62	26.64	5.238	-0.358	5.346	10.29
3	36	30	60	30	0.5130	0.386	0.777	0.828	36.14	3.45	16.07	4.786	-0.339	2.382	15.11

In the table, % means % of SMYS pressure $D_T = 0.00323$

Table 1.3 Dent fatigue damage calculation for Quadrant DS – CW, RP =36.56

No.	Count #	P_{max} (%)	P_{min} (%)	ΔP (%)	PF	R	λ_L	λ_H	X_L	X_H	SP	LogA	B	N_i ($x10^4$)	D_i ($x10^{-4}$)
1	157	10	20	10	0.2466	1.0	/	/	2.594	0.054	8.255	6.087	-0.773	23.92	6.56
2	55	20	40	20	0.3915	0.666	/	/	2.594	0.054	7.294	5.555	-0.653	7.425	7.41
3	36	30	60	30	0.5130	0.386	/	/	2.594	0.054	4.340	3.291	-0.603	3.528	10.2

In the table, % means % of SMYS pressure $D_T = 0.00242$

Table 1.4 Dent fatigue damage calculation for Quadrant US – CCW, RP =17.82

No.	Count #	P_{max} (%)	P_{min} (%)	ΔP (%)	PF	R	λ_L	λ_H	X_L	X_H	SP	LogA	B	N_i ($x10^4$)	D_i ($x10^{-4}$)
1	157	10	20	10	0.2466	1.0	1	1	70.10	4.74	70.10	6.061	-0.423	19.05	8.24
2	55	20	40	20	0.3915	0.666	0.821	0.869	57.52	4.12	39.68	5.238	-0.358	4.636	11.86
3	36	30	60	30	0.5130	0.386	0.777	0.828	54.44	3.92	23.42	4.786	-0.339	2.097	17.17

In the table, % means % of SMYS pressure $D_T = 0.00373$