BACKGROUNDS OF CRITERIA FOR FITNESS FOR PURPOSE IN IN-SERVICE GAS TRANSMISSION PIPELINES

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The basis and backgrounds for guidelines concerning defect criteria in in-service gas transmission pipelines are described and illustrated with examples of assessment diagrams.
Two main defect types are distinguished.
a. Pressure controlled defects like axial notches, dents and most of the corrosion defects.
b. Strain controlled defects like circumferential notches and weld defects in girth welds.

INTRODUCTION

Defects may be discovered during the construction of a pipeline detour, modification, repairs or in relation to cathodic protection monitoring, pigging inspection or other inspections such as periodic excavations.
Defects may also occur as a consequence of work being carried out, e.g. digging operations.

Acceptance criteria of defects in in-service pipelines will be less conservative than defect criteria in pipelines under construction.
That is because criteria for in-service pipelines are based on "strength" and "safety", while the criteria for pipelines under construction are based on "good workmanship".
The latter represents mainly what can be achieved by proper workmanship, which is a good basis for construction.

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STARTING POINTS

A defect is either acceptable or not. However, under service conditions some defects may be accepted temporarily while safety of somewhat larger defects may be quaranteed by pressure reduction.
Correct measurement or a conservative estimate of defect dimensions is a first requirement for the assessment.

Starting points of the criteria of any defect are:

a. No leakage is allowed.
b. Under service conditions the pipe should have enough strength against internal pressure and external forces, with a certain safety margin.
c. The pipeline should survive a hydrostatic test at the highest test pressure.
d. Static load conditions.
e. No stress type corrosion, H_2S or CO_2-problematics.

The material properties to be used for the derivation of the criteria are obtained from the companies material specifications and of material data bank. The data bank stores material properties of materials that came available from reroutings etc. and which have been tested.

NOTCHES

For derivation of the criteria for notches the depth of a notch is conservatively assumed to be equal to twice the measured depth, because:

- deformation of material around the notched zone will cause an embrittled zone near the notch tip;
- possible formation of microcracks under the notch tip (formation of microcracks is very likely in cracks exceeding 10% of the wall thickness);
- inaccuracies in measuring notch depth.

Notches in longitudinal direction

An axial notch is a pressure controlled type of defect.
Because the pipeline steels are tough the so called "Battelle formulas" for "flow stress"-dependent materials (Maxey (2) and Mayfield et al (4)) can be used as a basis for the assessment diagrams.

For each pipe class (design stress level determined by p_d en F_o) and pipe material (Re) the criterium for "plastic collapse" can now be expressed in a/d and l/d.
The effect of a wall-breaking defect can be expressed in l/d.

A graph can be made where the line for plastic collapse and the line for propagation (= bursting line) are plotted, see figure 1.

For fitness for purpose (category A) for long defects a safety factor 4, on the collapse line for measured depth (= ½ real depth), is applied on notch depth.
For short notches the safety factor was relaxed to 1,33 (3/8 bursting line) as such defects will lead to leakage only.

Because the depth of a notch in circumferential direction is restricted to 0,35 d* (see figure 3) for axial notches the limit for the depth was set at 0,35 d (instead of 0,375 d).
For the allowable length of a short notch a safety factor 4 was used with regard to the bursting line.
For the fitness for purpose criteria, sometimes a small correction can be necessary in the collapse line for hydrostatic testing at 1,05 Re (if that is the lower boundary).
However, in general, for the applied safety factors the defect will survive the hydrostatic test.

Notches in category C are temporarily allowed, but should be repaired, as these defects will not sustain a hydrostatic test.
In damage category D, where only leakage can occur (escape still possible), the working pressure should be reduced by 10% to avoid that a possible subcritical defect becomes critical (Eiber (3)).
In category E, pressure should be reduced to such a level that no fracture propagation is possible.
No fracture propagation will occur if the hoop stress has been reduced to 0,3 Re (Maxey (2), Fearnehough (6)).

For "new" defects, for example a defect caused by excavating, pressure should be reduced at once (blow off) for damage categories D, E and F.
For "old" defects found during inspection, for categories D and E, pressure reduction may be effected by equalizing pressure differences.
Defects in category F may then be recategorized as category E.
This is because such defects have survived a longer time, hence material properties must be more favourable than assumed in the assessment diagram, e.g. increased yield stress.
Figure 2 gives an example of an assessment diagram.

Defects in category F (F from Fout, the Dutch word for wrong) are not acceptable and pressure should be reduced to atmospheric pressure in that category.

If the wall thickness is larger than the minimum wall thickness required for internal pressure the allowable notch depth from the assessment diagram for minimum wall thickness may be increased by half the extra thickness d*-d (a factor half, because the real notch depth is assumed to be twice the measured notch depth).

Notches in circumferential direction

A circumferential notch is a strain controlled type of defect.
In a straight pipeline section the longitudinal tensile stress from internal pressure only is 0,3 times the circumferential stress from internal pressure.
Near bends where displacement in axial direction is possible the longitudinal stress from internal pressure can be 0,5 times the circumferential stress.
Because of settling, manner of construction, landslide, crossing of faults, areas with mining subsidence etc., bending forces may also be found (and sometimes axial forces as well).
In general, the stresses near the notch are not known and cannot be calculated in a simple manner, since immediate action may be necessary.
Even if stresses would be known they may change because of continued settling, embankment, drainage etc. in the future.

Stresses of the loads under consideration are in fact often partly displacement-controlled and partly load-controlled.
The latter is the case, like in settling, because of the stored elastic energy in the connecting parts and the nature of loads and reaction forces that cannot simply be calculated from equilibrium.

Basis for the acceptance of circumferential defects is that possible concentration of deformations in the small zone of the defect is avoided. Hence, the surrounding material must yield before the defect itself leads to failure (see also Spiekhout (12)).

Since the pipeline materials are ductile, failure of such defects can be predicted by the plastic collapse criterion (Garwood et al (13)) and can be expressed in a/d* and l/D (see the assessment diagram in figure 3).

Like for axial notches, the real depth is assumed to be equal to twice the measured depth and for circumferential defects a starting point is the real wall thickness, because of unknown external forces.

For strain controlled defects, because external forces cannot be reduced, the assessment represents a yes/no situation (A or F). The defect is either acceptable or it is not.

However, "old" defects in category F, if repair is going to be carried out urgently, may be recategorized to D and the 10% pressure reduction may be effected by equalizing pressure differences (if this type of defect fails, only leakage is possible).

For "old" defects which have survived in category F the applied stress will be lower than the yield stress.
Pressure reduction will hardly contribute to the reduction of stresses in the defect zone, but it is assumed that 10% pressure reduction of the working pressure will, for the greater part, avoid failure of a possible subcritical defect.

A circumferential defect is termed "old" if the defect is found during an inspection and if the stresses from external forces did not change in the period before inspection or will change in the period after inspection (strain gauge measurements may be required).
For example if a defect in category F is found straight away, say within 1 week after excavation (the defect did not arise from the excavation), because stress level changes during excavation, the defect is categorized F.
If the defect in category F would be found a certain period after the excavation, it may be recategorized as D.

Notches in oblique direction

The length of an oblique notch is projected in longitudinal and circumferential direction.
For the projected length in longitudinal direction assessment is made according to criteria for longitudinal notches.
This is in accordance with results of burst tests reported by Maxey (5).
For the projected length in circumferential direction, assessment is made according to criteria for circumferential notches.
From both assessments the most severe category is decisive.

Interaction rules

In the case of more adjacent notches, defect dimensioning is done according to ASME (16), figure IWA-3400-1 "Linear Surface Indications, Illustrative Flaw Configurations and Determination of Length l".

CORROSION

In this chapter only criteria for general corrosion and local corrosion, e.g. caused by bad paint maintenance or cathodic protection problems, will be discussed.
Pitting is considered to be a type of local corrosion.

If the corrosion is acceptable (category A) further corrosion should always be excluded by means of proper protection of the affected zone.

General corrosion

If the decrease in wall thickness by corrosion will be more or less equal over a large area the corrosion is termed "general". General corrosion is pressure controlled and is an "old" type of damage. For the minimum wall thickness d (calculated from internal pressure) the allowable decrease in wall thickness after cleaning (blasting or brushing) is set as for a defect with $l/d = \infty$ for longitudinal notches.
It could be argued that for general corrosion the factor 2 on measured depth does not need to be taken into account.
On the other hand for a subcritical situation a circumferential stress at "flow" stress level is not desirable (there will be a difference between "flow" stress locally at a notch and a circumferential "flow" stress).

To account for extra wall thickness d^*-d the allowable decrease of minimum wall thickness may be increased by the extra thickness d^*-d.

If the corroded zone is too small the corrosion should be termed local corrosion, because when decrease in wall thickness is too large there, deformations may concentrate in the corroded zone.

Local corrosion

Mostly, also if a relative large area has been corroded, the type of corrosion has to be termed "local".
Sometimes, the term general corrosion may be justified for above-ground small diameter pipelines with an even corrosion over a large distance.

The criteria for local corrosion are more stringent than for general corrosion, because of possible concentration of deformations in the corroded area, in the same way as for circumferential notches.
Hence local corrosion can be both a pressure controlled and a strain controlled defect.
The assessment is like that for oblique notches.
Local corrosion, if it is strain controlled, is termed "new" if stresses changed in the period just before inspection, e.g. excavation, or stresses are going to be changed after inspection.
The extra thickness d^*-d may be fully taken into account for the pressure controlled assessment.

DENTS

Two main types of dents can be distinguished: "plain" dents and "sharp" dents.
A "sharp" dent is a dent or buckle with sharp contours and is a severe type of defect.
In the sharp contours cracks can be present caused by bending, damage, or caused by external forces or fatique.
Cracks caused by damage may also grow by fatique.
Therefore "sharp" dents are classified in category F.
If it is an "old" defect it may be reclassified in E.
A dent may be termed "old" if it has been found during inspection and the stress level e.g. from excavation did not change in the period before inspection and will not change in the period after inspection.
A dent will mainly be a pressure controlled type of defect.
However, as in the case of excavation where supporting soil is removed, the dent is also partly strain controlled.
Because of "rerounding" cracks may grow and result in failure.

A dent is termed a "plain" dent if the bending radii of the contours are larger than 5 d* and if the dent is free of micro cracks.
The minimum 5 d* bending radius of the contour is related to the minimum guaranteed strain at failure for the pipeline steels.

In a dent locally large strains can be present (Spiekhout et al (15)).
For plain dents, if no other defects which can cause stress concentrations are present, burst strength will hardly be influenced.
Results from burst tests (Jones (8)) also indicate that for plain dents with dent depths until 24% of the pipe diameter burst strength is hardly influenced.
If a safety factor 2 on dent depth is applied then no pressure reduction has to be effected until dent depths of 12%.
For pigging the maximum allowable decrease in diameter is 4% (category A).
Hence for larger dent depths the pipe section should be replaced before a pigging operation.
Therefore, dent depths between 4-12% are categorized B.
Category E_2 is between 12% and 24% dent depth.
Over 24% dent depth the dent is categorized F_2.

Welds or other defects in dents, such as notches and pitting corrosion, are referred to in the following paragraph.

NOTCHED DENTS

A notched (plain) dent is a very severe type of defect, because under internal pressure the dent tends to move outward (rerounding) and because of that the depth of the notch may increase.
Locally in the deepest part of the dent where the notch is, large strains will be present and material toughness will have decreased there.

The criteria for notched dents have been derived by means of a relationship from elastic fracture mechanics, assuming a long notch, with geometry factors for bending and normal stresses (Rook and Cartwright (14)). K_c was fitted by means of a relationship with C_v to experimental results of burst tests (Spiekhout et al (15)). The criteria can be expressed in H/D and a/d as shown in the assessment diagrams in figures 4a and 4b.

WELD DEFECTS IN GIRTH WELDS

If the "Workmanship" criteria for weld defects are not met, a further, less conservative, appraisal based on fracture mechanics may be made.
A parallel defect in a girth weld is a strain controlled defect. In contradiction to longitudinal and spiral welds a girth weld has not been fully tested hydrostatically. The stresses in longitudinal direction are mainly caused by external loads.

In the case of critical defect sizes, the weld will fail either in a brittle way or a plastic collapse type of failure, depending on weld toughness, wall thickness, defect sizes and applied stress.
The plastic type of failure can be predicted by the plastic collapse criterion as for notches in circumferential direction. For brittle fracture the COD-approach acc. PD 6493 (7) is used.

For the company pipeline steels the weld is "overmatched", which means that the maximum stress to be considered $\sigma_{app} = \sigma_y$, see Spiekhout (12).
σ_r is assumed equal to 0,5 σ_y and M is assumed equal to 1,5.
δ_m the lower boundary, with regard to the companies material data bank is taken as 0,075 mm.

Using the plastic failure criterium and the brittle fracture criterium, assessment diagrams like the ones in figures 5 and 6 can be made.

SYMBOLS USED

D	–	diameter	(mm)
d^*	–	wall thickness (as measured)	(mm)
d	–	minimum wall thickness (from internal pressure calculation)	(mm)
a	–	defect depth	(mm)
l	–	defect length	(mm)
H	–	dent depth	(mm)
P_d	–	design pressure	(MPa)
F_o	–	design factor (the allowable hoop stress in the pipeline from design pressure is F_o. Re)	(--)
σ_{app}	–	applied stress	(N/mm^2)
σ_y	–	yield stress	(N/mm^2)
Re	–	minimum specified yield stress	(N/mm^2)
K_c	–	fracture toughness	(N/mm$^{-1,5}$)
C_v	–	Charpy-V impact value	(J)
δ	–	crack opening displacement (COD)	(mm)

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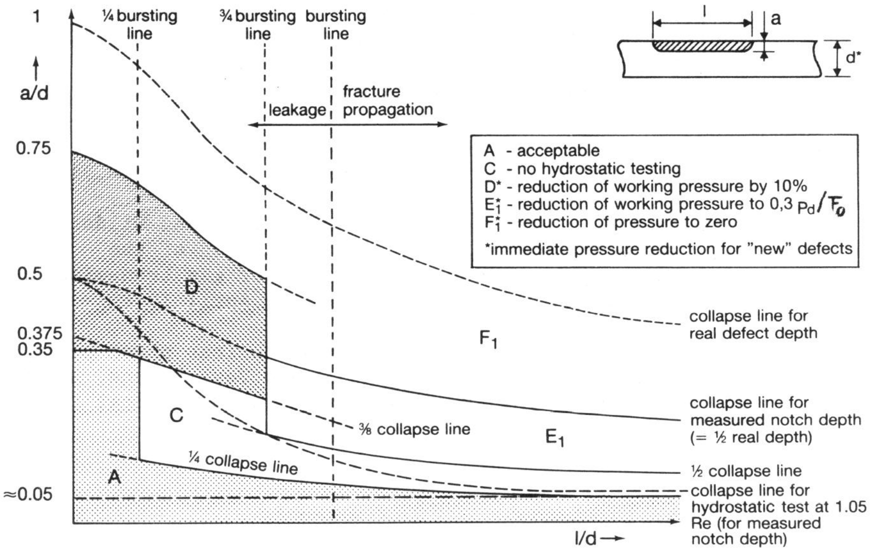

Figure 1. Design of assessment diagram for axial nothces

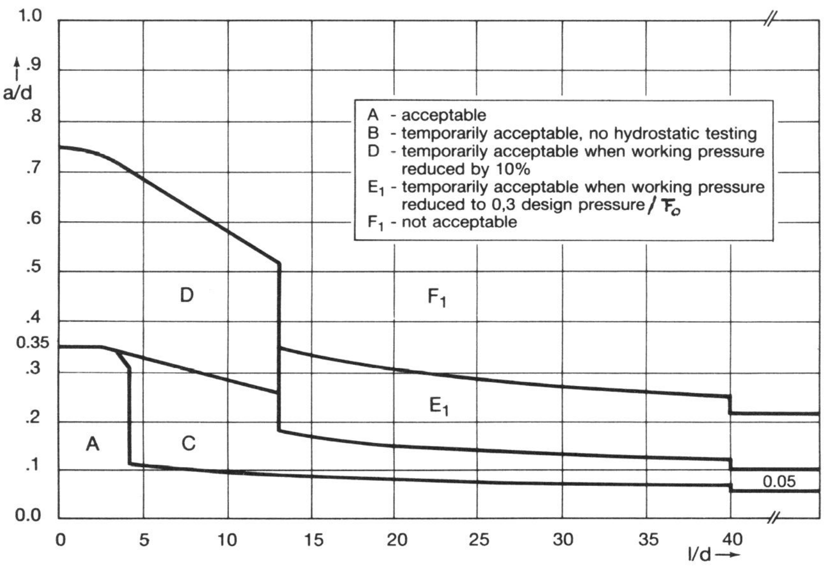

Figure 2. Assessment diagram for longitudinal notches (material X60-design pressure 6,62 MPa-design factor 0.65)

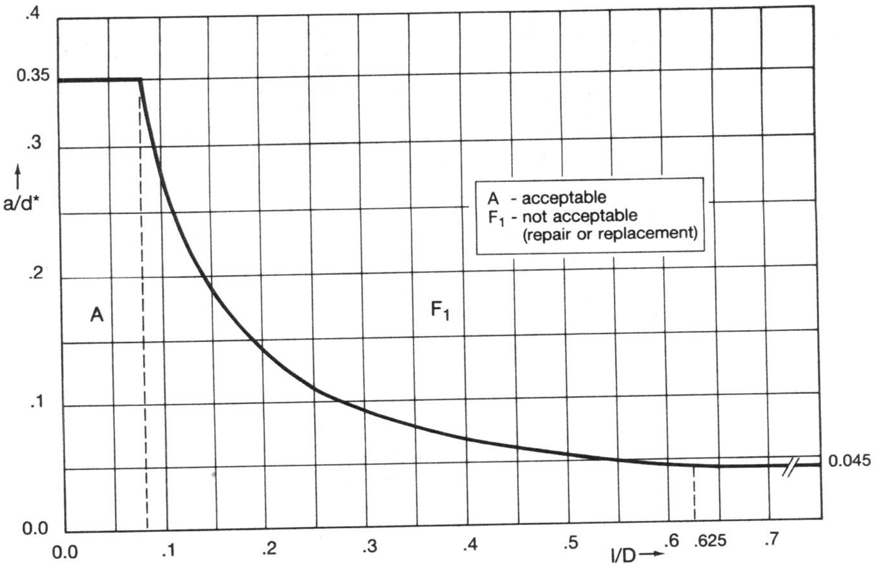

Figure 3. Assessment diagram for circumferential notches (all materials up to X65-all pipe classes)

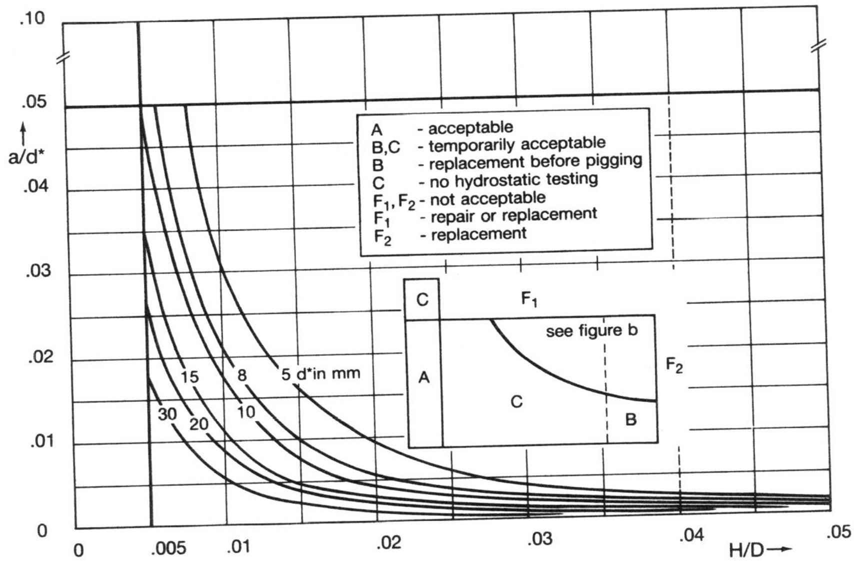

Figure 4a. Assessment diagram for notched dent damage (material X60-design pressure 6,62 MPa-design factor 0.65)

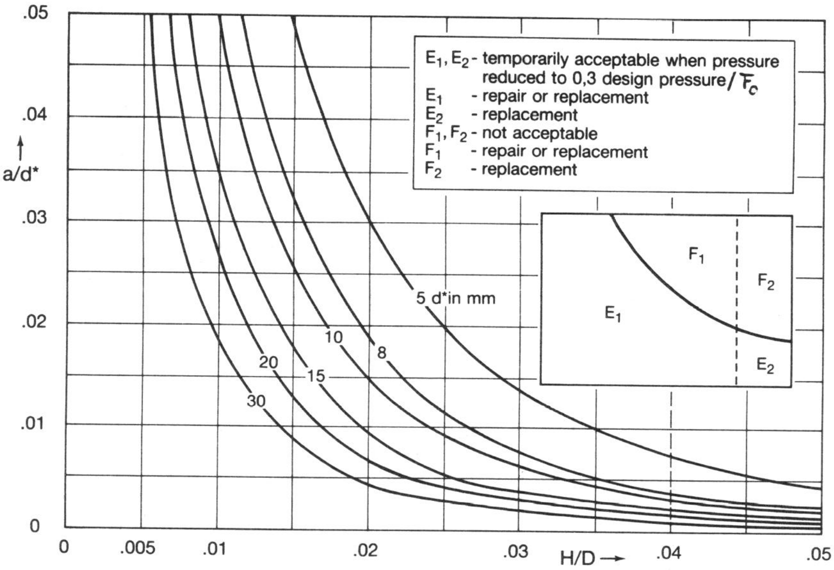

Figure 4b. Assessment diagram for notched dent damage (material X60-design pressure 6,62 MPa - design factor 0,65) - Continuation of figure 4a.

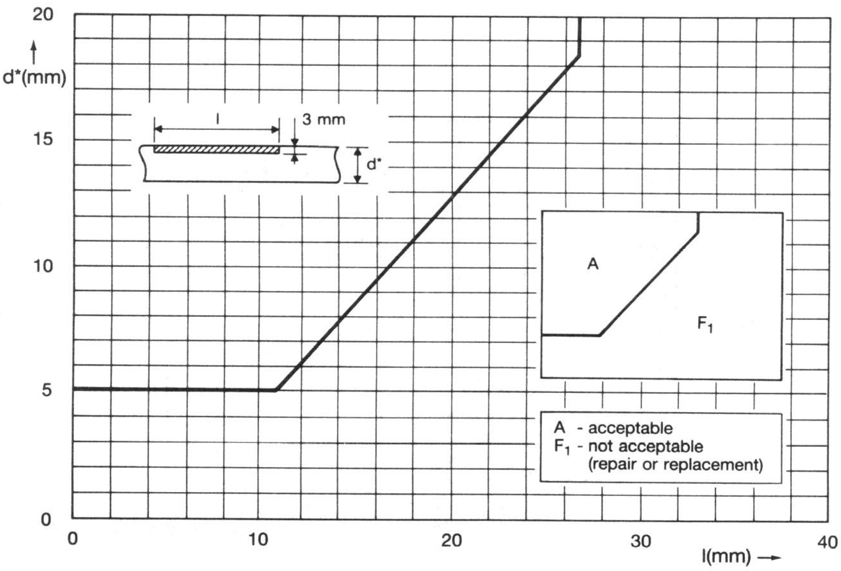

Figure 5. Assessment diagram for weld defects in girth welds (material X60-all pipe classes)

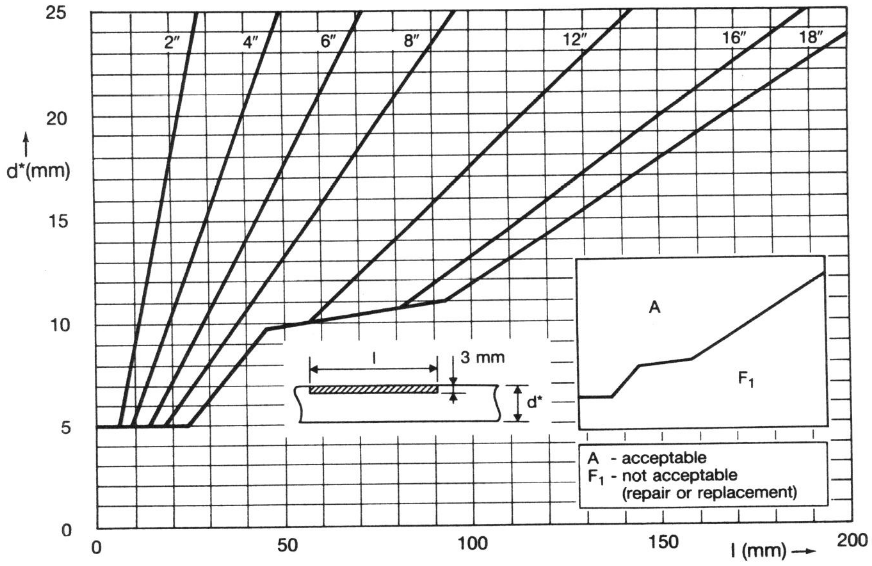

Figure 6. Assessment diagram for weld defects in girth welds (material Grade B-all pipe classes)