Materials-related maintenance terms and their role in the planning of pipeline maintenance

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Recently published standards and regulations frequently display considerable terminological confusion, notably where maintenance planning for pipeline networks is concerned. This creates considerable problems both for the manufacturer and the user and may sometimes even render questionable the very point of the procedures described. The purpose of this article is to draw attention to such discrepancies and offer assistance to future revisions of such publications.

1. Introduction

The shift from failure-based or corrective maintenance to a preventive or even condition-based maintenance strategy represents a considerable challenge for operators of pipelines or pipeline networks. For cathodically protected pipelines, a maintenance plan can be realized on the basis of measurement data. For pipelines without cathodic corrosion protection in place, meaningful data of indicative strength are required on their condition and damage so that a statistically based maintenance plan can be drawn up. In the context of maintenance planning for pipeline networks, the service behavior of components and materials is dealt with in DVGW Code of Practice G 403 and/or DVGW Worksheet W 403 as well as in the associated regulations for data capture, DVGW Worksheets G 402 and W 402 [1][2][3][4]. With cathodically protected pipelines, the need for action in the maintenance area can largely be derived directly from the measurement findings, while maintenance planning for pipelines without cathodic corrosion protection is currently still dependent on the evaluation of damage statistics. Also, to describe the service behavior of these pipelines or components along the lines of Worksheets G 402 and W 402, it is not sufficient to refer solely to the design of the components in question, for the damage statistics must also establish a relationship between component failure and actual operating time. The damage rate over operating time then yields an empirical function that describes a component's service behavior. In connection with maintenance planning, it is necessary to demarcate such concepts as serviceability, lifetime and operating time as well as such terms as imperfection, damage or failure of a component.

***Figures 1** and **2**: Damage caused by a digger tooth to a polyethylene-coated steel pipeline and a polyethylene pipeline*

2. Maintenance planning terminology

2.1 Serviceability

Serviceability is the time span during which a component or a material maintains the required performance features and can be operated under the service conditions for which it has been designed. Inorganic materials such as cast iron, steel, concrete, asbestos cement or stoneware possess infinite serviceability under the predominantly static loads acting on a buried pipeline. For this reason, no creep rupture tests are specified in the technical delivery conditions for this application area. The mechanical properties of these pipes remain constant. The serviceability of pipes of organic materials, such as polyethylene, is ascertained in accordance with DIN 8075 [5]. Here, it must be considered that, unlike with inorganic materials, serviceability does not refer to the mechanical properties in their entirety but is confined solely to strength (see explanations [5]).

It therefore follows that data on the serviceability of such components can be obtained from the manufacturer or a testing institute. For water supply pipelines, DIN EN 805 specifies a minimum serviceability period of 50 years – a requirement that ultimately can only be fulfilled by components with a serviceability period that is at least equal to this time span [6].

2.2 Lifetime

In contrast to component serviceability, lifetime is limited by factors such as production-related differences between materials, the care taken during pipe-laying, service and/or environmental conditions and, in the case of pipelines, external loads and third-party interference (***Figure 1***, ***Figure 2***). It is certainly not isolated events, such as damage caused by an excavator, that is decisive here, but ultimately the frequency of damage that can be derived from damage statistics.

Irrespective of the material, damage to pipeline components is invariably caused by a combination of corrosion and/or aging and external influences. With some materials, however, a reversal of causality merely has to be considered. While, for instance, corrosion damage to a steel pipe protected by an anti-corrosion coating is usually the result of external influences and thus damage to the coating, the sensitivity to external effects of pipes made of such materials as polyethylene or PVC, which is higher in any case due to their low strength, will be even further increased in the event of embrittlement. Embrittlement of these materials occurs over time as a result of corrosion and aging (***Figure 3***). The period until a material becomes brittle must not be confused with its strength-related serviceability (see above). A review of the internal pressure creep curves of the first generation of plastic pipes shows that they are obviously calculated into the brittle fracture range, in view of a 50-year serviceability arrived at by extrapolation, cf. Figure 1 in [7] vs. Figure 4 in [8]. The same applies in principle to gray cast iron, whose susceptibility to fracture may increase over time as a result of graphite corrosion (***Figure 4***). Graphite corrosion is a damage type which releases iron from the microstructure. Due to the high carbon content of gray cast iron, what remains is a graphite microstructure of the same shape, but without the necessary strength properties. In subsidence areas or under point or dynamic loads, this mostly trough-shaped material damage acts as a notch and thus promotes fracture of the material.

The susceptibility to fracture also increases in fiber cement components when the mortar matrix degrades in acidic soil.

External influences as well as the physical environment and operating conditions are anything but homogeneous along a pipeline. Damage in a pipeline or a pipe network is necessarily a local phenomenon at first, whose frequency must be ultimately considered a major factor in the assessment of operating time. Here, significant variations may be encountered due to regional soil conditions, when

Figure 3*: Crack in an embrittled PE pipe on a point support*

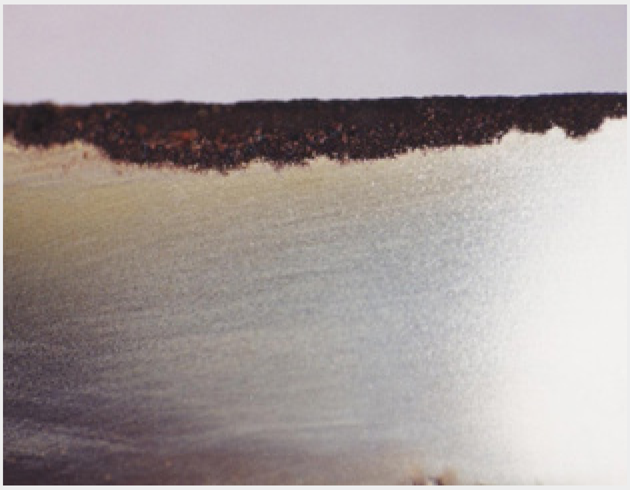

Figure 4*: Graphite corrosion in a gray cast iron pipe*

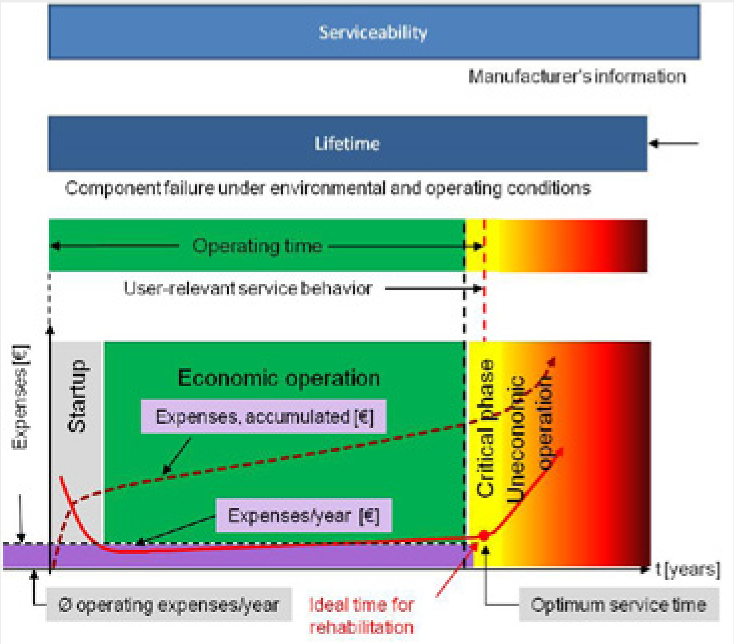

***Figure 5**: Interrelationships of operating behavior and maintenance strategy terminology*

brittle pipe materials are installed in sandy soil in the Lüneburg Heath or in the heterogeneous soils typical of Germany's medium-altitude mountains.

2.3 Operating time

It is important to demarcate operating time from lifetime, especially where pipeline operation is concerned. In the case of failure-based or corrective maintenance, the operating time corresponds to the useful life in the sense of DIN EN 13306 [9]. However, DVGW regulations advise against failure-based or corrective maintenance for pipeline networks [4] [10]. If corrective or failure-based maintenance is to be avoided, there has to be a residual useful time span left between lifetime and the operating time. Ideally, a pipeline's operating time is equal to the maximum time span until aging- or corrosion-induced changes in the material lead to an increase in damage frequency and the mean maintenance costs exceed the reinvestment costs. This target operating time should match up with the optimum date for replacement or rehabilitation, unless the actual operating time is reduced or extended due to other operational reasons. Other operational reasons can include the premature replacement of pipelines in connection with road improvement projects or high traffic volumes rendering replacement unacceptable and thus introducing a higher risk of failure and possibly higher maintenance costs.

Given the many and varied factors affecting pipeline operation, the lifetime and particularly the service behavior of components can only be determined on the basis of systematic condition and damage assessment. Furthermore, neither manufacturers nor testing institutes can ever predict or even promise residual life- or operating time.

2.4 Damage vs. imperfection

When assessing the condition of pipelines in coated ferrous materials, the distinction between damage and imperfection merits special attention. DVGW Codes of Practice G 402 and W 402 define damage as a locally limited, impermissible impairment of a pipeline's functional integrity, usually associated with leakage [3] [4]. A void or crack in the coating and the associated corrosion attack does not, by definition, qualify as damage, as long as the actual wall thickness does not fall below the dimension required for pipeline operation (calculated wall thickness + safety coefficient). Such an imperfection does not impair a component's function. A repair can fully restore its integrity without any loss of function. This is particularly true of cathodically protected pipelines, as material removal from exposed steel surfaces in the area of voids or cracks in the coating is reduced to a minimum (≤10 µm/a) by the protective current.

2.5 Failure

Beyond damage, DIN EN ISO 8044 defines component failure as the complete functional loss of the technical system concerned [11]. This is where we come full circle to the initially highlighted terminology of service behavior (***Figure 5***). Failure of a component marks the end of its lifetime. In practice, however, this extreme form of component imperfection hardly figures at all, because its occurrence results in a reduction in operating time if only for economic and safety considerations. Thus, depending on soil conditions and environmental factors along the pipeline route, the time until corrosion failure of steel pipes without adequate corrosion protection will vary quite considerably. From an economic point of view, however, it makes little sense to repair a pipeline time and time again until the wall thickness in the most benign section of the pipeline route has reached a dimension deemed critical in the prevailing operating conditions.

Leaving aside operational requirements such as reroutings, for the maintenance engineer it is decisive to know whether and when the measures required to maintain a pipeline's integrity and the expenses involved in the repair of damage and consequential damage are no longer economically tenable compared to the cost of a new pipeline or rehabilitation of the existing pipeline. He also has to consider whether the construction of a new pipeline or rehabilitation of the existing one makes sense for safety considerations (cf. failure-based vs. preventive maintenance concept). These factors ultimately determine a system's operating time.

Figure 6: *Corrosion damage in steel pipe*

Figure 7: *Corrosion damage in a first-generation ductile iron pipe*

2.6 Damage cause and type

With a composite pipe system, such as coated steel pipe, corrosion as an electrochemical process allows the pipeline condition to be determined with the aid of measurements via the cathodic corrosion protection. Such a condition assessment relates primarily to the condition of the corrosion protection system. However, since damage to coated pipe of ferrous materials is invariably preceded by damage to the corrosion protection coating, the methods of measuring cathodic corrosion protection allow potential hazards to be assessed at an early stage. This condition-based maintenance and the associated targeted repair allow maintenance expenses to be reduced to a minimum. In addition, with such monitoring in place, it is also possible to fully exploit the operating reserves of a pipeline network. Outside of its use as a tool of condition-based maintenance, cathodic corrosion protection does not envisage damage, be it through tampering or material failure. Technical rules and, depending on the application, even ordinances (TRFL) therefore specify cathodic corrosion protection for gas pipelines operated at 5 bar and above [12]. The planning of maintenance measures for cathodically protected pipelines is not based on the evaluation of damage statistics, but on measurement results provided by the cathodic corrosion protection system. Such maintenance measures do not necessarily involve the replacement of a pipeline or pipeline sections and can consist of local repairs.

Only in the case of pipelines which are not cathodically protected, or have not been from the start, are damage data possibly available that permit statistically based maintenance planning. Here, maintenance expense depends on the evaluation of service behavior statistics and the associated assessment of damage causes and types. In the damage statistics, it is crucially important to differentiate between potential damage causes, so as to identify factors that are relevant for the pipeline's service behavior. Such evaluations yield pointers to action to be taken, for instance, if technical delivery conditions have to be adjusted due to product deficiencies, or construction site procedures have to be modified in the case of a distinct lack of care during pipe-laying.

Where pipes made of ferrous materials are concerned, two different design strategies have to be considered. For uncoated pipes or pipes with a thin coating, technical rules and standards require a corrosion allowance to be included in the design calculations. The resultant increased wall thickness necessarily results in a maximum design operating time, and damage is to be expected on expiry of this period. Still in use today in many water pipeline networks are pipes of ferrous materials that have no or inadequate corrosion protection (***Figure 6***). These also include, for instance, first-generation ductile iron pipelines (***Figure 7***). With these pipes, corrosion is both the type and cause of damage.

Today, pipes of ferrous materials have a composite design. The statistical requirements under service conditions determine the design of the core pipe of cast iron or steel. A corrosion allowance is omitted. Coatings of bitumen or polyolefins are used for external corrosion protection. In water line pipe, for reasons of hygiene, cement mortar is used for internal corrosion protection rather than plastics (***Figure 8***). Corrosion of the base material is no longer the cause of damage, but merely a damage type, because it is invariably the result of external factors, such as insufficient care in pipe-laying, soil movement, or failure of the coating material.

3. Terminology used in technical rules and standards

3.1 Lifetime – operating time – serviceability

The terminology used in technical rules and standards on the service behavior of materials is by no means consistent. This is true not only of the rules governing the application of components, but also of the technical delivery

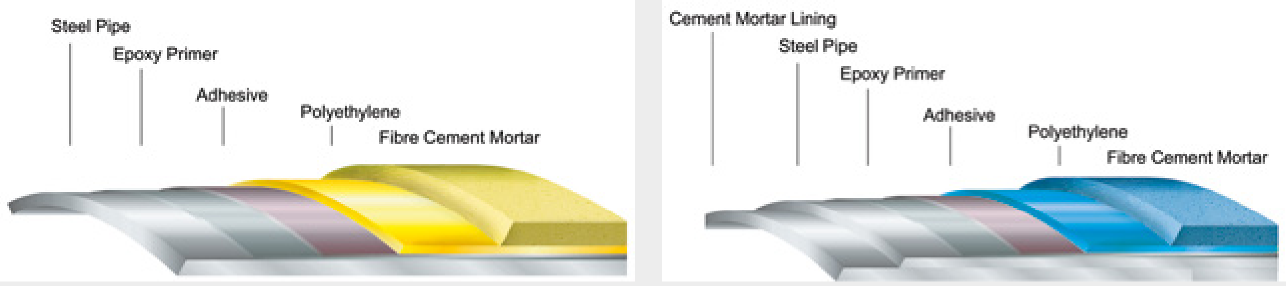

***Figure 8**: Composite pipe technology, taking steel pipe as an example*

conditions. For instance, in its early editions of 1976 and 1987, DIN 8075 for polyethylene (PE) pipes uses the term 'lifetime calculations' in the context of internal pressure creep tests, while the 1999 edition uses the correct term 'serviceability' [13] [14] [15]. It is probably because of this change in terminology that the plastic sector still mainly refers to the lifetime of its components, when what is actually meant is serviceability. The current edition of DIN 8075 (December 2011) still uses the term 'Betriebsfähigkeit' (serviceability) in its German version [5], although, in the English version published at the same time, 'Betriebsfähigkeit' is not translated as 'serviceability', but as 'minimum operating time'. DIN EN ISO 9080, on the other hand, uses the term 'lifetime', where DIN 8075 uses 'minimum operating time' [16]. Thoroughly misleadingly, the standards for plastic pipes thus use all these terms interchangeably at the same time.

Where steel pipes are concerned, the situation is in no way better. For instance, the European standard DIN EN 13480-3 and its national predecessor DIN 2413-1 also refer to lifetime calculations [17] [18]. In contrast to the standards relating to plastic pipes, these calculations are not part of the applicable technical delivery conditions.

Consequently, the term 'lifetime' may mean something completely different to a user or a maintenance specialist than to a pipe manufacturer. In discussions of material properties, these terms and concepts are also happily mixed up. Time and time again, the lifetime of plastic pipes is equated to the 50- or 100-year serviceability given in the standards. Also, this 'lifetime' of plastic pipes is very often compared to the actual operating time of pipes of ferrous materials that have corroded as a result of damage, soil movements, lack of care in pipe-laying, etc.

3.2 Damage cause and type

One shortcoming of damage statistics of pipes of ferrous materials is that they equate corrosion as a damage type to a cause of damage such as tampering, insufficient care in pipe-laying, soil movements, etc. In the questionnaire of DVGW Worksheet G 410, for instance, 'corrosion' as a type of damage can be entered with equal status alongside the actual causes of damage [19]. In the case of composite gas line pipe, this approach would render impossible any further differentiation of causes of damage, especially when one considers that no clear distinction is generally made between steel pipe and composite steel pipe. A statistical assessment based on such data is practically meaningless for maintenance planning, nor is it of any benefit for the user. In addition, if such data are used for the probabilistic design of pipes, the informative power of the resultant damage probabilities is negligible [20].

At present, DVGW Worksheets W 402 und G 402 are binding for maintenance planning. In these Worksheets, the differences between the terms are largely accounted for [3][4]. In the gas sector, composite pipe technology has become standard, where corrosion is generally treated as a type of damage [3]. Conversely, with water pipelines, which in many cases consist of bare or inadequately coated pipes made of ductile iron or steel, corrosion must additionally be considered as a damage cause with appropriate differentiation [4]. In principle, this also holds for materials such as gray cast iron, asbestos cement, PVC and PE, whose fracture mechanics changes due to aging or corrosion.

4. Maintenance and corrosion

Closer examination of the variables affecting a pipeline's lifetime or operating time reveals that, in practice, maintenance and the material's corrosion and/or aging behavior are almost inseparably linked to each other. According to DIN EN ISO 8044, corrosion is the interaction of a component with its environment which results in changes in mechanical properties and thus in failure of the component. This interaction can be of a physical, chemical or electrochemical nature. In the case of metals, it is predominantly, but not exclusively, an electrochemical process [11].

Every material is subject to corrosion. The term corrosion is well-known in connection with metallic materials such as steel and non-metallic materials such as concrete or glass. In the plastics sector it tends to be avoided. It can be assumed that the frequently stated claim that "plastic materials do not corrode" primarily refers to the material removal associated with corrosion in the sense of the Latin origin of the word (corrodere = gnaw away).

But according to the definition in ISO 8044, the effects caused by corrosion are not limited to material removal. Hydrogen-induced stress corrosion cracking, for instance, causes failure of steel components without the slightest trace of prior material removal. The same holds for stress corrosion cracking induced in polyethylene or polypropylene by chlorine or a wetting agent [21][22][23]. In the plastics sector, terms such as material aging or material degradation (impairment of the material's properties) are preferred [23]. Ultimately, however, material degradation just describes the effect of corrosion attack. The definition of the term 'corrosion' shows that a system's service behavior is decisively governed by environmental and service conditions. Besides wear, which mainly affects moving system components, the most important factors – especially in the case of pipelines – affecting the system's lifetime and operating time are corrosion and/or aging of the materials and the associated changes in their properties.

The exclusion of such causes of damage as external loads or tampering, as envisaged by DVGW Worksheets W 402 and G 402 for maintenance planning, must be viewed more than critically in this context – all the more so, since the question does indeed arise in practice as to how damage cases can be meaningfully differentiated according to their causes. These causes may relate to the material itself, to the operating time, or to insufficient care. It is indisputable that damage caused by an excavator says nothing at all about a material's service behavior and must be treated as an isolated incident. Such a type of external influence would be relatively unimportant in the context of damage statistics and would merely constitute 'background noise' in a statistical assessment. If we have pipe of a material that is brittle or has undergone embrittlement as a result of corrosion or aging under service conditions, or has been weakened by other corrosion processes, there is no need for an excavator to hit that pipe. All it takes is soil compaction in the vicinity of the pipeline to cause deformation of the pipe body and create a leak through which the pipeline medium can escape. The same applies in principle to non-conforming pipe-laying conditions or imperfections, such as subsidence areas, point loads or point supports along the pipeline route.

Asbestos cement pipes and PVC pipes have not been used for decades, although their relatively modest damage rates would seemingly justify their application [24]. In this context it must be noted that most of the damage cases caused by imperfections were repaired in the past. So the pipelines still in service now inevitably do not include such continually recurring and thus pipe-damaging imperfections along the route. If, in the case of brittle or embrittled material, external influences with immediate leakage are also eliminated from the damage statistics, then the damage rate necessarily drops to zero. There is practically no need for action, although – depending on the application – such materials represent a risk that should not be underestimated. According to Table 8 of DVGW Worksheet W 392-2, for instance, the abrupt water losses associated with gray cast iron as a result of pipe damage are to be expected in the case of pipes of asbestos cement and PVC as well [25]. If there were an increase in damage cases attributable to external influences, it would definitely be possible to identify corrosion processes such as embrittlement of PE and PVC, critically deep graphite corrosion in gray cast iron pipes, or a change in the properties of asbestos cement pipe laid in acidic soil.

5. Corrosion and/or aging in maintenance planning

Reducing maintenance and/or rehabilitation planning to the statistical analysis of damage cases is meaningless if material-specific changes and thus corrosion or aging are not considered. Maintenance or rehabilitation planning is thus not just a question of the statistical evaluation of damage data but, first and foremost, a question of the material used. Filling this gap is the primary objective of the currently updated DVGW Technical Rules GW 18 and GW 19 [26], at least for ferrous materials. DVGW Technical Rule GW 18 describes the recording of condition data and condition assessment based on measurement data obtained from a cathodic corrosion protection system, while data capture for the preparation of a condition register for pipelines without cathodic corrosion protection is the subject of DVGW Technical Rule GW 19. As in the case of condition-based maintenance with the aid of cathodic corrosion protection, such a condition register is intended to help define a decision period for the planned rehabilitation of a pipeline network without damage or failure determining the planning process.

Such an assessment basis is also required for other materials, such as asbestos cement, PE or PVC, especially since DVGW Worksheet W 402 now also requires an assessment of the degree of embrittlement [4], at least for plastic materials. However, the Worksheet does not describe how such an assessment is to be carried out and what the consequences are for the pipeline operator. While the correlation between acidic soils and the loss of strength is comparatively well-known in the case of asbestos cement pipes, the question arises whether the degree of embrittlement of PE or PVC pipes has ever been determined at all in the case of damage. This is all the more astonishing, given that on-site brittleness in components is relatively simple to verify [28].

Damage due to the embrittlement of polyethylene is generally less spectacular than that of pipelines made of gray cast iron, asbestos cement or PVC [25]. Nevertheless, the example of an envisaged use of PE pipes for the construction of pipeline networks operated at pressures >10 bar reveals that there are shortcomings not only in terms of reduced resistance to external influences (tampering) and lack of monitoring, but also due to the non-availability of a database on aging-related changes in the material's fracture mechanics, especially when one considers that the confirmation of serviceability in terms of strength alone is of little use here.

The fracture behavior of new materials is irrelevant with regard to the targeted operating time of pipelines. Similarly, the repeatedly discussed short-time tests in the presence of wetting agents yield no clue as to the change in fracture mechanics as a function of time (see the preface of [29]).

Given the lack of meaningful data on time-related changes in fracture mechanics, the verification of the suitability of alternative materials, as required, for example by an ordinance for transmission pipelines [12], is only possible by amassing and evaluating realistic damage statistics and condition data. The data required for this purpose are available to users as a result of decades of experience by means of systematic condition monitoring, which would have to be implemented. From today's point of view, extrapolating statements on a material's long-time behavior from short-time test results for a safety-critical application in a high-pressure gas pipeline would be more than questionable without such verification. The need for this kind of condition data acquisition must not be called into doubt by pointing out that the materials have undergone refinement in the meantime. Despite changes in the patterns of corrosion- or aging-induced changes over time in these further developed materials, the mechanisms as such remain the same.

6. Recommendations for further action

The present article shows that neither the technical rules and codes of practice nor the communication usual in this field of application show terminological consistency relating to operating time. Here, clear definitions would be desirable – in the form of a guideline, for instance. Such a guideline would be very helpful when revising the existing worksheets and technical rules on maintenance. The associated statistics can only provide a meaningful basis for skilled maintenance planning if the terminology is clear and consistent. This is particularly true when higher-level authorities compare or merge statistics.

Damage statistics require an unambiguous classification of damage causes and types. Factors of relevance in the field such as external influences must not be excluded. While damage statistics should be geared to the application area, independently of the material used, material-specific factors must be taken into account in condition assessments. It is not a question of checking the data in the technical delivery conditions, but the recording of mechanical properties and changes in materials applicable in practice. Maintenance planning is inconceivable without knowledge of the interrelationships between material changes and time. For ferrous materials, the relevant data to be recorded are currently being compiled in the DVGW Technical Rules GW 18 and GW 19 [26] [27]. The creation of a guideline for condition assessment is equally relevant for other materials as well. What makes pipelines and pipeline networks a special case and unlike other fields of application is that they have decades of operation behind them. Empirical values can therefore be provided neither by testing institutes nor by pipe manufacturers or starting material suppliers. Such data must necessarily be systematically gathered by the user if new ground is to be broken with a preventive or a condition-based method of pipeline or pipeline network maintenance. Among other things, this is also the justification of the brittleness testing of components made of plastic materials as envisaged by DVGW Worksheet W 402. Since, however, suitable procedures for an on-site assessment of such changes in materials are not covered by current technical rules for non-metallic materials, there is a need for appropriate action.

7. Literature

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