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Exact Assessment with Technical Condition Analysis (TCA) and Corrosion Assessment Programm "KaRo"

High bearing Capacity of high-pressure Steel Pipes subjected to Corrosion

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Exact Assessment with Technical Condition Analysis (TCA) and Corrosion Assessment Programm "KaRo"

High bearing Capacity of high-pressure Steel Pipes subjected to Corrosion

Over the last few years, VNG developed an integrated system for the Technical Condition Analysis (TCA) of high-pressure gas pipelines which represents a major step toward the predictive maintenance. Specific evaluation tools incorporate the latest scientific advances. TCA uses probabilistic evaluation principles for assessing rehabilitation requirements in VNG's old lines.

The approach has fundamentally changed VNG's strategies for maintaining high-pressure gas lines, meaning that

- *costs are reduced to the level required for reliable operation and supply,*
- *planning confidence exists in the preparation/implementation of proposed steps, and*
- *the reliability and technical integrity of VNG's network can be verified.*

An important part of this TCA is the assessment program for corrosion "KaRo".

Introduction

Verbundnetz Gas Aktiengesellschaft is a wholesale gas merchant and a service provider for the energy sector in eastern Germany. Its customers include regional and local distribution companies, power plants and large industrial users.

The company operates a close-meshed system of modern pipelines with integrated underground storages. These high-pressure lines with a total length of approx. 7,500 km in pressure ranges from 20 to 83 bar have nominal diameters from 50 to 1,100 mm. The oldest line dates are from the year 1930, and the average age for the entire system is about 26 years (**Figure 1**). Technical standards differ widely due to changes in construction codes since 1930.

Germany's regulations for high-pressure gas lines of public utilities make it mandatory on operators to keep systems in an orderly condition, monitor them continuously, carry out necessary maintenance and repair work immediately, and to take safety measures as required by circumstances [1]. These regulations apply to lines of all ages, which thus have to meet present standards of health, safety and environmental protection.

Apart from safety, the reliability of a network is vital for its availability and the security of supply. An efficient system is a major competitive advantage, making high-quality predictive maintenance a strategic factor for retaining, or restoring, excellent standards in the operation of high-pressure lines. Other important criteria include the optimal use of resources and finance, and routine servicing and monitoring.

The minimum technical requirements (codes of practice) for monitoring, inspection and maintenance are not always sufficient to prevent damage to lines. To reduce the risk of damage, and to optimize monitoring intervals and minimize repair costs at the same time, an operator needs detailed information on the condition of a line and the effect of operating and ambient conditions, i.e. of loading in general. Condition monitoring and effective intervention based on limiting values which are technically and economically plausible can ensure better predictive maintenance and lower costs.

Service life

A high-pressure gas transmission line reaches a limiting state if its reliable operation can no longer be guaranteed, meaning that it constitutes a danger to life and limb, and to the environment. While in commercial terms, a line has been written off after 25 to 50 years, it may be operated safely for 100 years or more from a technical point of view.

High-pressure lines built in Germany and complying with present engineering codes are of a quality which ensures a sufficient potential service life and adherence to minimum technical standards over a foreseeable period, provided the line is used and monitored as intended (**Figure 2**).

Conversely, service life will be shortened by loads resulting from operation (i.e.

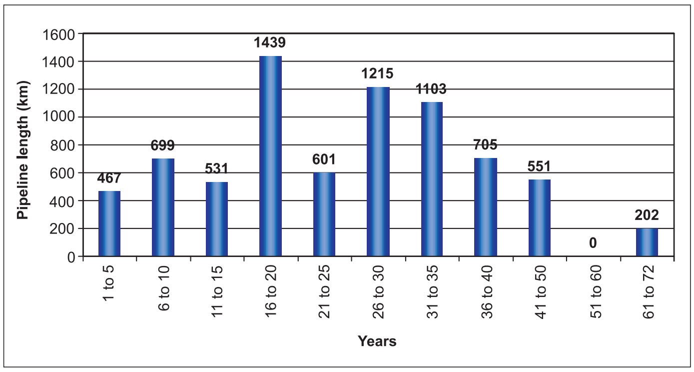

Fig. 1: Age structure of VNG network in 2003

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pressure changes), ambient conditions (third-party impact), and quality defects during construction. Some of the latter such as welding/coating defects, dents, mechanical damage to steel surfaces, and faulty material reduce the stability of a line but are now mostly detected and prevented by tests (100 % non-destructive testing, close potential survey, yield tests, etc.). However, such standards are not always observed and, in particular, did not apply to old networks where most repairs are now caused by third-party impact, corrosion, wear in valves, and welding defects. These faults indicate that, from an engineering viewpoint, damage to lines may occur despite conventional maintenance and inspection on a large scale. The simple conclusion is that the actual condition (wear) of a line can not be known in detail in each case.

Predictive maintenance, on the other hand, is based on such knowledge and requires examination and analysis beyond the scope of conventional regulations. Rehabilitation in this context is not aimed at achieving the best possible standard but a minimum quality which makes engineering sense and meets requirements made on system integrity under applicable legal and technical regulations.

Probabilistic method of analysis

These requirements make it imperative to define the assessment procedures to be used in condition monitoring. While it would be feasible to accurately calculate local and temporary loads acting on a high-pressure line, and thus to specify the overall loading, such a complex procedure would be extremely costly. Deterministic stress analysis, on the other hand, can not make allowance for factors such as insufficient cover. Under the applicable European standard, EN 1594 [2], high-pressure lines are exclusively designed for loads resulting from internal pressure. In keeping with the deterministic concept, any loading, which is not foreseen at the time of construction, would reduce safety factors if additional load bearing reserves were to be utilized.

Assigning points or marks to individual and compound loads, as generally practiced in assessment programs, do not give satisfactory results. These procedures often reflect a subjective judgment on the part of the person making the assessment. In addition, this approach will not give the kind of conclusive assessment needed to include such different factors as corrosion, dynamic stress and insufficient cover equally and in a comprehensible manner.

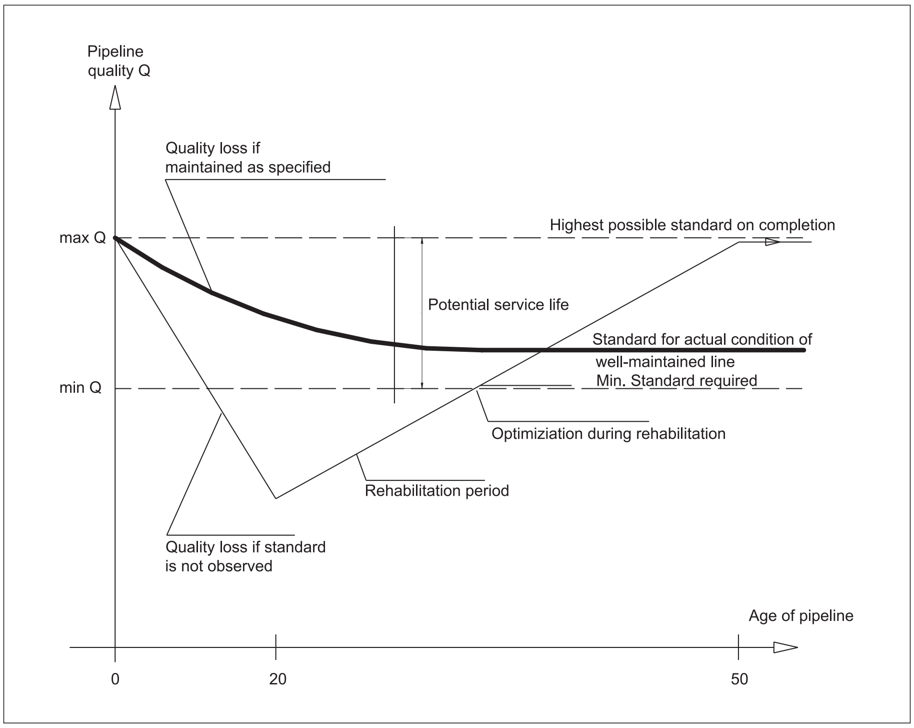

Fig. 2: Potential service life of a high-pressure line

Extensive condition monitoring calls for a probabilistic concept (using risk-based methods) where the required failure probabilities can be determined for all stress factors acting on a system or reducing its load bearing capacity. If these ratings are summarized, all load factors can be assessed according to a uniform concept [3].

Figure 3 shows an example of the failure probability p_f of a line as caused by internal pressure, compared with a deterministic approach.

The maximum operating pressure (MOP) is determined from the yield strength (R_e) of the material, the wall thickness and the outer diameter of a line, allowing for a safety factor which differentiates between national regulations. When the specified parameters are put into the design formula, the result is considered safe. The quotient of the operating load (B) and strength parameters (W) of a line is the utilization factor, the reciprocal value of which is its safety.

What, however, is the actual degree of safety for the admissible operating pressure? When it is assumed that the inlet parameters for the loading (internal

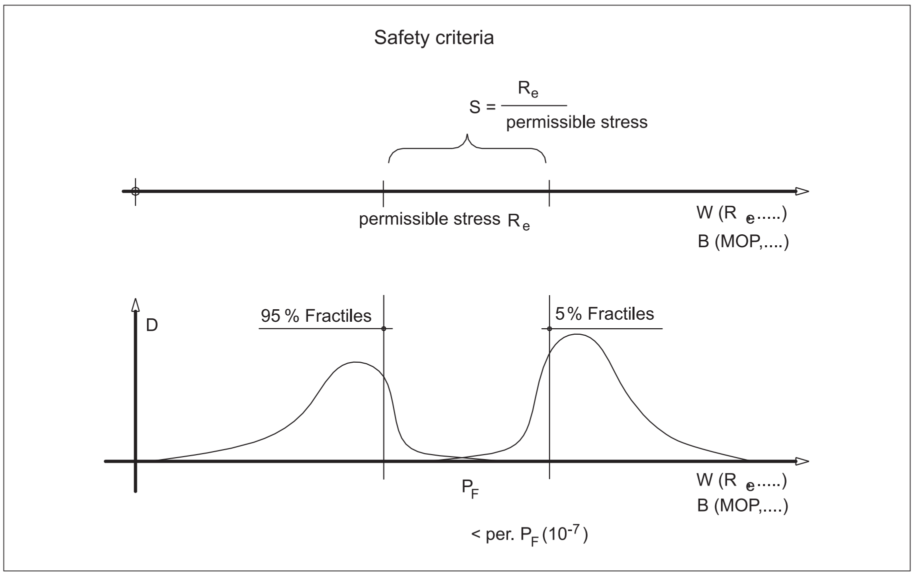

Fig. 3: Deterministic and probabilistic computation setup

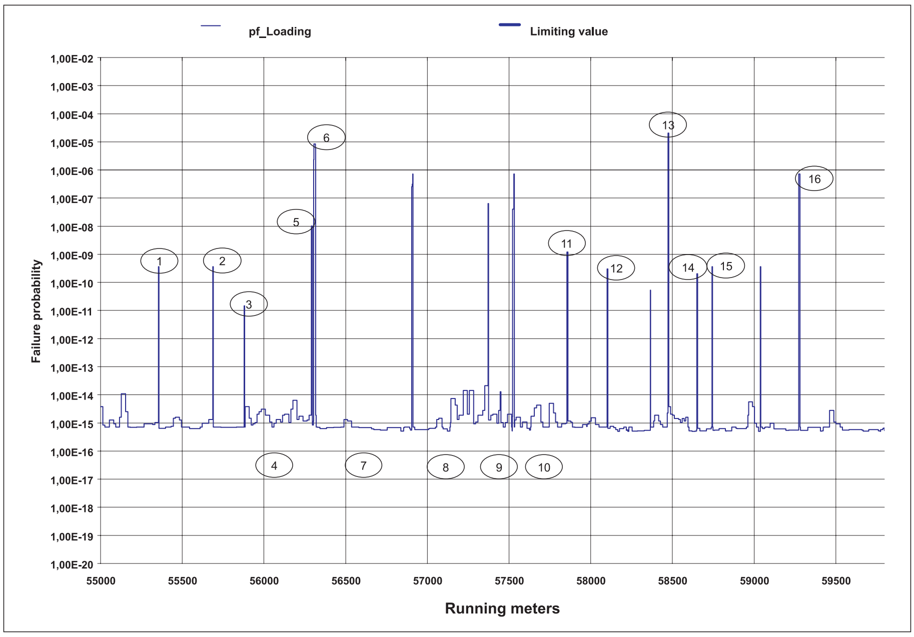

Fig. 4: Pipeline assessment for failure probability

Table 1: Explanations for marked locations

No.	Cause	Cover [m]
1	Crossing with traffic route, no sleeve pipe	0.80
2	Crossing with traffic route, no sleeve pipe	0.80
3	Crossing with traffic route, no sleeve pipe	1.01
4	Insufficient cover	0.70
5	Structure erected over pipe	0.64
6	Crossing with traffic route, sleeve pipe	0.63
7	Valve set	0.80
8	Insufficient cover	0.81
9	Structure erected over pipe	0.82
10	Insufficient distance from structure	0.80
11	Insufficient distance from parallel traffic route	0.70
12	Crossing with traffic route, no sleeve pipe	0.81
13	Crossing with traffic route, sleeve pipe	0.58
14	Structure erected over pipe	0.83
15	Insufficient distance from parallel traffic route	0.80
16	Crossing with traffic route, sleeve pipe	0.80

pressure) and strength of a line (yield strength, wall thickness, diameter) are subject to statistical distribution functions, two curves are obtained. The area below the intersection of the two curves represents the uncertainty of the deterministic calculation. Allowing for Germany's technical regulations applying, for instance, to material parameters, pipeline production, and to the construction, testing and operation of high-pressure gas lines, a failure probability of less than 10-7 is obtained, which is equal to one failure in more than ten million years.

Technical Condition Analysis (TCA) at VNG

VNG and Dr.-Ing. Veenker Ingenieurgesellschaft (Veenker) have developed a system for assessing failure probabilities and obtained authority certification for general use with pressurized lines. It uses a modular program which makes allowance for all factors acting on a network. A limiting value is compared with the total failure probability calculated in each case, and action need only be taken if the limiting value is exceeded (**Figure 4**, **Table 1**).

This limiting value should be in keeping with the risks generally accepted by society. Judging from the literature, a failure probability of 10^{-6} (unit: one failure per km/year) is a meaningful limiting value when assessing a high-pressure gas line. The failure probabilities calculated also make it possible to prioritize/schedule the necessary steps whenever the limiting value is exceeded. Where national regulations do not specify any set points, comparisons must be made with other countries and operators must act with responsibility. In addition, the limiting value for the failure probability of a gas line may be qualified in terms of the hazard created to human health in the event of failure. This risk is the product of the line's failure probability and the probability of an effect which line failure may have on humans. This effect is expressed mainly as the distance from built-up areas, i.e. settlement density and/or the probability of humans being present (for instance where a line crosses traffic routes, etc.). This means that the same failure probability would require an earlier response for a line laid in the vicinity of built-up areas than one leading through regions which have not been built up.

The integration of Technical Condition Analysis into a geographic information system (GIS) has provided VNG with a tool not only for documenting the current condition of a line in a central office but also for comparing lines, optimizing repair costs and prioritizing related jobs (**Figure 5**).

Parameters required in this connection may be called up for any point along the line as raw data vectors consisting of 44 pieces of data each. Of these, 32 are directly used in the assessment, the remainder providing extra input for more detailed evaluation and for information systems. Additional data is available in

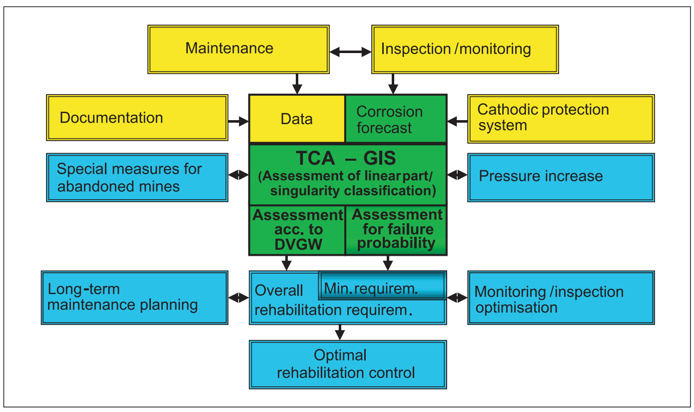

Fig. 5: Processing steps in Technical Condition Analysis

the form of singularities for major components, and specific points or sections of a line (valves, crossings, points where coverage is insufficient or lines run close to built-up areas, etc.). The number of singularities presently covered is 26, of which 16 may be accessed directly and checked for rehabilitation needs regardless of the overall assessment of a line.

Data acquisition starts from existing construction/operating files, the latest surveying documents being just as important as results from CP measuring tests. As the quality of input data is vital for the assessment result, a need for action signaled when a limiting value has been exceeded does not necessarily call for repair or replacement. Attention should instead be given to data quality and the origin of input data. The documentation available on old lines in particular is not nearly as extensive as the wealth of records stored for modern systems. On the other hand, full documentation is not required so that costly and comprehensive field tests (setting up line current test points, intensive troubleshooting, taking soil/material samples, excavation, etc.) can be limited to line sections with poor assessment data. As input data becomes more accurate, the safety status of a line can be better defined and conditions accepted which seemed more critical in earlier assessments.

VNG's Technical Condition Analysis is an assessment tool (**Figure 6**) for high-pressure gas lines which uses the latest scientific and technical advances to identify specific defects (by evaluating old welds/pigging results/corrosion forecasts) which are then integrated into a complex probabilistic assessment procedure. The aim is to optimize rehabilitation requirements for a line and respond quickly and accurately to particular requirements (for parameter studies, pressure increases, and specific ambient conditions such as abandoned mines).

Integration of advanced pigging procedures

Present state-of-the-art techniques include the internal inspection of high-pressure gas lines using intelligent pigs, a method that has been accepted worldwide as a means of identifying corrosion rates.

The preferred pigs for gas lines use a magnetic stray field.

VNG sees internal inspection not as a substitute for TCA but rather as an element of condition monitoring and as an excellent tool for obtaining more accurate results. Results obtained from intelligent pigs and input into complex TCAs are of such excellent quality that there is no need for costly repeat examinations and excavation. These measuring results are secured data indicating wall thickness reductions and corrosion sites that can be precisely located thus protecting entire sections of a line from deterioration.

Pigging normally provides a wealth of data. Integrating all of the data into the GIS-supported TCA system would make no sense both from a data processing and from a technical point of view. This is because not all of this information is related to reliability. In addition, not every loss of material, together with the geometric parameters, needs to be included separately in the TCA system, particularly in cases where the damage is trivial and does not affect line integrity. TCA thus relies on previously assessed data, which makes it all the more important to have suitable evaluation procedures.

With pigging equipment and evaluation software improving all the time, and an ever greater wealth of experience, the information contained in pigging results is becoming more valuable and more accurate. Even though metal loss can be reliably indicated by magnetic stray field pigs today, inspection firms fearing claims for damages are unwilling to guarantee 100 % reliability in the detection of what are known as features. Reliability normally ranges from 80 to 90 % and reaches 99 % when it comes to detecting metal losses from corrosion.

The authors are quite confident that most losses of material (from corrosion, missing weld passes) and circumferential cracks in welds are actually detected. It should, however, be noted that the admissible misalignment of edges in a weld may also be indicated as a feature, whereas inclusions (slag) or (clusters of) pores can not be recorded at all or with little reliability. This means that, however professional the inspection firm is, the operator's experience and know-how are quite important for interpreting pigging results and identifying necessary action.

Apart from various images and diagrams showing the overall condition of a line and emphasizing corrosion losses (number, depth, area or volume along the line), inspection reports usually contain a defect acceptance curve according to ASME B31G [4]. Calculations according to this standard are based on burst tests and apply to straight pipes only, with the exception of welds. In addition, the method may not be used for mechanical abrasion (drag lines), and no allowance is made for extra loads. Defect widths in a circumferential direction are neglected in the calculation. In practice, when dealing with older lines having bituminous coating, one often finds corrosion around assembly welds due to the inferior quality of field coating. There is also the question of the reliability of assessments according to ASME. In this connection, a few remarks on the determination of defect parameters seem in order.

The lengths, widths and maximum depths of individual corrosion sites ("boxes") are determined from the signals transmitted by sensors (measuring the magnetic flux between two permanent magnets). Boxes may overlap and, in order to allow for mutual interference, are combined into clusters following preset rules of interaction.

These clusters make up the features shown in the reports and provide the basis for calculations made according to ASME B31G. The resulting assessment may be regarded as quite conservative because the maximum depth of a box within a cluster is included in the

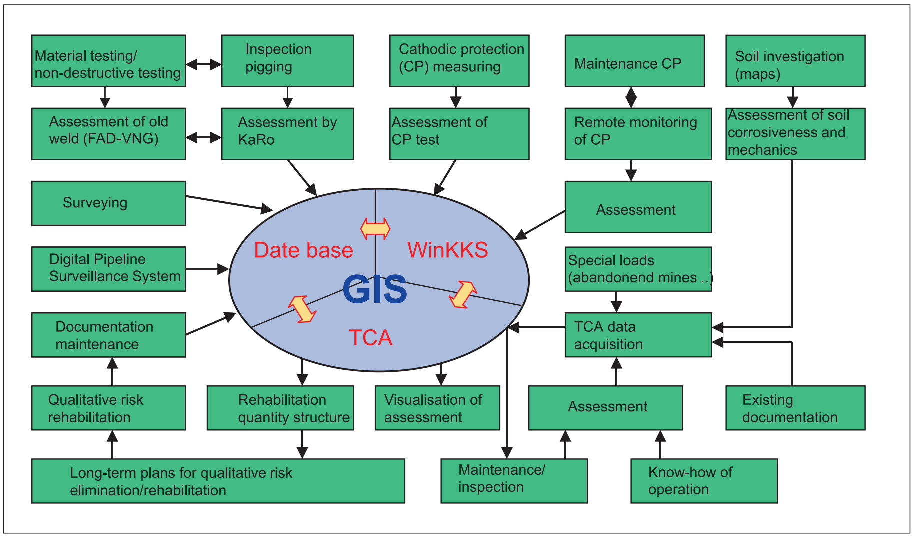

Fig. 6: Integrated Technical Condition Analysis (TCA) at VNG

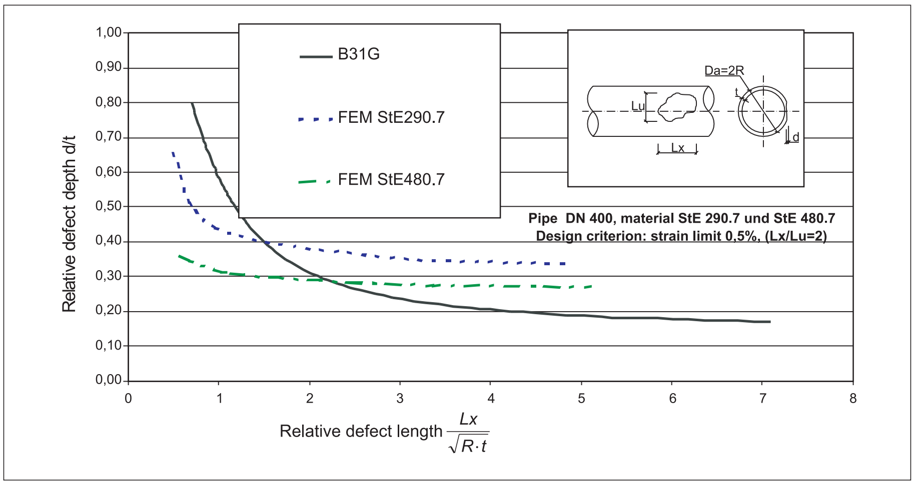

Fig. 7: Comparison of ASME B31G with FEM

computation, and regions having full or less reduced wall thickness are neglected (defect shape is a parabola across the length of the cluster).

This has led to the development of RSTRENG (Remaining STRENGth) [5], an assessment procedure where the limiting criterion (a strength value equal to what is known as flow stress) is fixed higher than ASME B31G both for the simplified and full/detailed versions. In the former version, the corrosion profile is defined as a rectangular area having 0.8 times the maximum defect depth and maximum defect length of a cluster across the pipe wall cross section. Full RSTRENG is more accurate in allowing for the defect contour so that the assessment is less conservative.

A comparison between ASME B31G and computations using the Finite Element Method (FEM) (as groups of curves corresponding to the length(Lx)-to-width(Lu) ratio of a wall thickness reduction versus the ASME limiting curve) shows that ASME B31G is very conservative regarding long defects (general corrosion) in the direction of the pipe axis and assessment in the case of short deep defects (pitting) becomes uncertain (**Figure 7**). Earlier publications have already referred to ASME B31G as being both very conservative and uncertain [6, 7, 8, 9].

KaRo - assessment program for corrosion

In view of what has been said above, VNG decided to base its evaluation of corrosion losses on FEM calculations, the requirement being to save time both in assessing a single defect in the field and in processing mass data from inspection pig runs. Conventional FEM calculations turned out to be unsuitable as they were very time-consuming (modeling and computation).

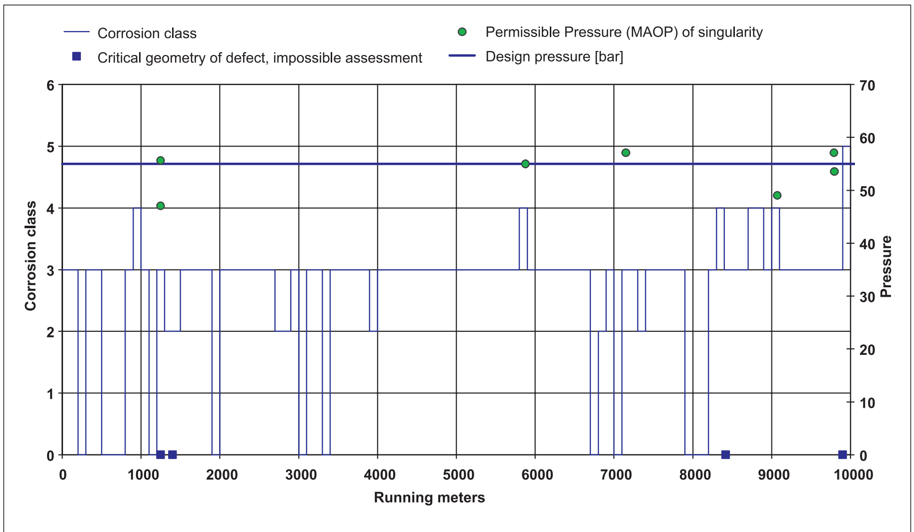

Fig. 8: KaRo assessment of inspection pig run

The company commissioned the development of KaRo [11], a program using the approach of neural networks on the basis of FEM analyses. The neural network was trained and verified by inputting a variety of FEM computations of concrete defects and parameter studies. In the meantime, this has enabled the safe assessment not only of the amount of metal wastage from corrosion in a straight pipe (condition for ASME B31G) but also of corrosion around welds, bends and on the inside of pipes.

KaRo requires no specific hardware or software. Individual defects can be calculated on site using a conventional laptop equipped with Windows 2000, and results are shown in a matter of seconds. Data from pigging runs is imported via an entry file that has been predefined for KaRo and is generated by inspection firms as part of their inspection reports, at no cost. Old inspection reports need to be adjusted to KaRo's data structure using software tools that generate the KaRo entry file from the usual databases of inspection reports at no extra cost.

Pigging runs are evaluated using the original box list. Boxes are taken into consideration and summarized for calculation on the basis of implemented interaction rules derived from FEM computations and parameter studies. The results of assessments for each material loss specified in terms of KaRo are stored in Access databases and visualized as Excel tables (**Figure 8**).

Visualization distinguishes between what are known as corrosion classes and material losses that affect safety at the maximum operating pressure (MOP). For assessing corrosion classes a line is subdivided into equal lengths which may be selected as required but should not be less than the standard pipe length (10 to 20 m). In each of these sections the most critical but still admissible void at 105 % MOP is used to assign a corrosion class to the length of pipe. Inadmissible voids found at less than 105 % MOP and voids outside KaRo's application limits (MOP set to zero) are shown separately (singularity).

Allowance should be made for the fact that the failure parameters measured all carry tolerances (e.g. from pigging) and affect the result of the calculation. KaRo can make allowance for relevant failure tolerances. In this context, the experience gained by inspection firms and line operators, and findings from first test excavations are of great importance. Pigging results are generally much more accurate than specified and guaranteed by providers of these services, and more on the conservative side, i.e. failure tolerances are greater than those actually found. At any rate, the computation results need to be assessed by an experienced engineer.

The distinction made between corrosion classes and singularities makes integration into the TCA database possible.

Corrosion forecast

In most cases the only result available is from a single run using an intelligent pig. A comparison of voids found in two pigging runs shows that the findings are not always accurate enough and not easy to assign. Theoretical approaches must therefore be found.

The results of inspections in which pigs are used should generally be compared with those obtained from CP tests (e.g. close potential surveys). The available data (history) for a line often contains no details of where and when corrosion started, which means that a calculation of corrosion rates based on the age of the line and current material losses can only be correct by coincidence. For a corrosion forecast, however, corrosion rates can be derived as a function of ambient conditions (soil quality, foreign matter, local element formation, etc.), and the type and quality of coating.

In order to optimize the cost of repairing voids that previously had insufficient protection or whose protection status was unknown, KaRo was supplemented with a module that makes corrosion forecasts possible even without making reference to measuring results obtained from cathodic protection (worst case version). The module can also generate more detailed forecasts if factors involved in corrosion are known. The literature [11 – 14] describes corrosion rates for typical ambient conditions and coating materials, which have been verified in practice.

From these forecasts medium and long-term protection programs can be derived. In practice, the period after which a critical loss of material occurs can be calculated for each corrosion site separately or by processing mass data (from pigging reports). The integration of pigging data, CP data and corrosion-related ambient/material data in a GIS-supported TCA environment reduces time-consuming manual assignment to specific sites (locations) to a minimum.

Conclusions

The a.m. assessment methods indicate a thorough change of VNG's maintenance procedures for high-pressure gas lines. The company's current rehabilitation strategy based on Technical Condition Analyses for these systems means

- limiting repairs to accurately assessed and localized sites representing an acute quality risk,
- classifying other quality risks into a program of rehabilitation stages based on service life reserves,
- cutting costs to a level required to maintain operating reliability and the security of supply,
- planning confidence in the preparation and implementation of proposed measures, and
- a demonstration of the reliability and technical integrity of the gas network.

TCA makes it possible to collect the latest basic line data in a central office where it is available for users wishing to respond quickly to a change in requirements (parameter studies, pressure changes, etc.). Specific condition monitoring helps to further optimize current expenditure for maintenance and surveillance (maintenance intervals).

Approx. 80 % of VNG's network, which has a total length of about 7,500 km, was built before 1990, the year that brought Germany's political and economic unification. These lines conformed to codes of practice valid in the eastern part of the country, and not to the DVGW (Deutsche Vereinigung des Gas- und Wasserfaches) code now applicable throughout Germany. They are therefore described as VNG's old lines.

Pigging is possible in about 50 % of the VNG network and, until 2004, has been used on approx. 1,434 km of the system. Some 2,900 km of line have been assessed with TCA, and complete coverage is planned by the end of 2004. The efficiency of the approach taken is demonstrated by the fact that fewer failures and breakdowns are reported for the company's high-pressure network and costs for line rehabilitation have been reduced. VNG's experience with TCA has shown that even though information on specific lines may differ, assessment is possible, comparisons are meaningful and conclusions regarding repair requirements can be drawn to optimize costs.

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