Sense and nonsense of service-life statistics

Condition-based maintenance of cathodically protected steel pipelines

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The technical service life of buried components remains restricted, irrespective of the material used, as a result of external mechanical influences and also due to chemical or electrochemical and physical interactions of the components with their surroundings. To assure the unimpaired functioning of such components, informationally valuable criteria are of great significance during operation for the assessment of the remaining service life and for planning rehabilitation projects. One possibility for this is provided by the evaluation of statistical data, which, however, inevitably involves uncertainties. Questions arise, in the case of steel components, as to the rationality or otherwise of such service-life statistics where additional provisions for the operation and maintenance of a piping system are implemented using the potentials of cathodic corrosion protection (CCP). The importance of cathodic corrosion protection in modern pipeline engineering practice, and the significance of this anti-corrosion system for the pipeline service life and rehabilitation planning are examined in this article using examples drawn from practice.

Introduction

Service-life statistics have taken on a significance which should not be underestimated. This was evident in the rehabilitation planning of recent years and, with the deregulation of the gas market, such statistics are currently very relevant to the depreciation methodology of gas supply systems. The problem with their use lies in determining a calculated average service life. In the past, pipe types which in fact fully exploited their potential technical service life were in practice very much the exception. These include, for instance, steel pipe with or without adequate corrosion protection such as was laid in the early 20th century and also later in the German Democratic Republic.

The first-generation of ductile iron pipes also belong in this category. The technical service life of these pipes is decisively determined in each case by the aggressiveness of the soil environment. With these types of pipe, it is quite possible in principle to establish the service life and implement statistical rehabilitation planning projects on that basis.

An assessment of more modern pipe types on the basis of existing damage analyses is difficult, because here accidental damage and/or imponderables relating to external interference. Ground subsidence, laying faults or defective materials are among the main causes [1]. The point in time at which failures occur in pipelines damaged in such a way cannot ultimately be related to their potential technical service life. Pipeline damage due to imponderable events occurs independently of the pipe material and age of the pipeline. Depending on the intensity and dynamic of the mechanical interference, damage caused by external factors manifests itself either directly through leakages or, in the longer term, in the area of scratches and scores, critical point loads or point supports. As long as real technical service life remains an unknown factor, it follows necessarily that its average value, as required for calculation purposes, cannot possibly be determined.

The evaluation of corrosion processes in pipeline networks calls for a very sophisticated approach depending on the materials and pipe construction. In the case of corrosion damage to ferrous materials, account must be taken, on the one hand, of the already mentioned pipe categories with no or inadequate corrosion protection but whose technical service life can be estimated on the basis of already known empirical values. In contrast, steel line pipe, for example, made in conformity with the relevant technical rules and, since the mid-1960s, protected by polyethylene coating, will be exposed to corrosion only in the event of external interference or pipe-laying faults provided the coating is otherwise intact. In such cases, corrosion damage is to be evaluated in the same way as impermissible third-party interference or

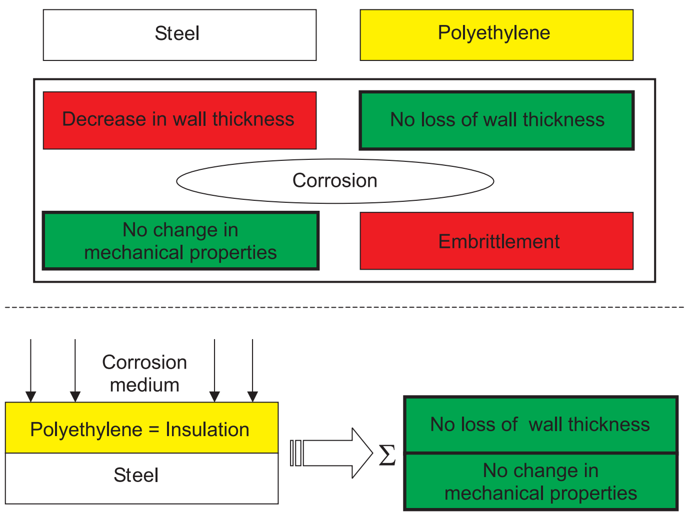

Fig. 1: Synergy between steel and plastic under buried pipeline conditions

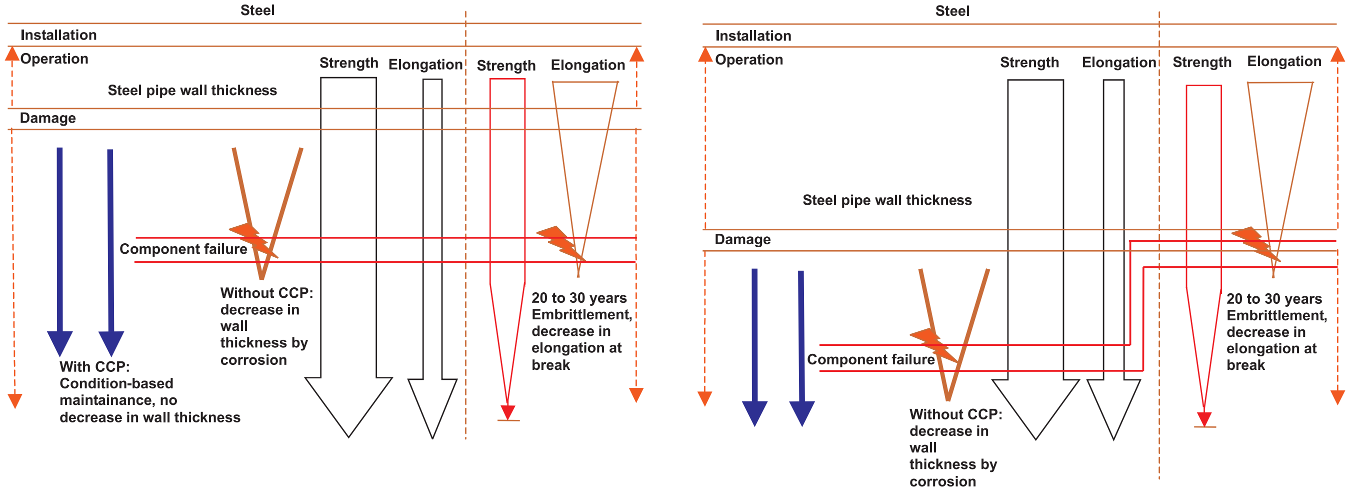

Fig. 2: The significance of cathodic corrosion protection

point loads, which restrict the service life of other products, too.

Recent studies have shown that in case of external interference corrosion processes in plastics should not be underestimated. Whereas with polyethylene, for instance, the reduction in strength is not significant until comparatively late, there is a marked drop in the elongation at break after only 20 to 30 years with, consequently, a very fundamental change in the properties which are so relevant to mechanical fracture under external loads [3]. This change in the mechanical fracture properties indicates significant changes in the morphology of the polymer and prohibits any transfer to field applications of laboratory data, such as long term behaviour of stress-corrosion resistance on exposure freshly produced unchanged material to wetting agents [4, 5]. This aspect will be dealt with in more detail below under the aspect of rehabilitation planning. One key difference between plastic and ferrous materials is the fact that with plastic, this form of corrosion or embrittlement is a permanently ongoing process but one which does not involve any material loss. With ferrous materials, on the other hand, corrosion and wall thinning set in only in the event of damage to the corrosion protection.

Each system as such has its own disadvantages and weaknesses in relation to the customary conditions for buried pipeline construction. The intelligent solution to these shortcomings, which is expected today, lies in the synergetic combination of their strengths. The differences in the materials' properties are purposively exploited in today's steel line pipe production and they also provide the basis for the efficient use of cathodic corrosion protection (CCP) (**Fig. 1**). When steel and polyethylene are combined, the material strength and the elongation at break in a pipeline system are parameters which are independent of each other in time. The polyethylene functions as an insulator and prevents corrosion-induced wall thinning of the base material.

This plastic-steel synergy can only be disrupted by physical damage. **Figure 2** clearly shows the significance of the cathodic corrosion protection of steel pipelines in relation to the imponderable external interferences in pipeline systems. In the example of a gas distribution system, arrows represent the tendencies and manifestations of material properties that determine the pipeline's serviceability. In the diagram, it is presumed that the damage does not lead directly to leakage, given the mechanical strengths of the base material, but only becomes evident later through the corrosion behaviour of the materials. The difference in the scenarios illustrated in the two diagrams lies in the point in time at which the damage sets in; this highlights the significant differences in the corrosion processes. With plastics, corrosion is a permanently ongoing process which always leads to a reduction in the elongation at break, whereas in the case of a plastic-steel combination the corrosion process only sets in after the pipe has been damaged. Where cathodic protection is applied to ferrous materials, the electrochemical corrosion process can be purposively influenced, thereby keeping weight loss in the damaged area to a minimum.

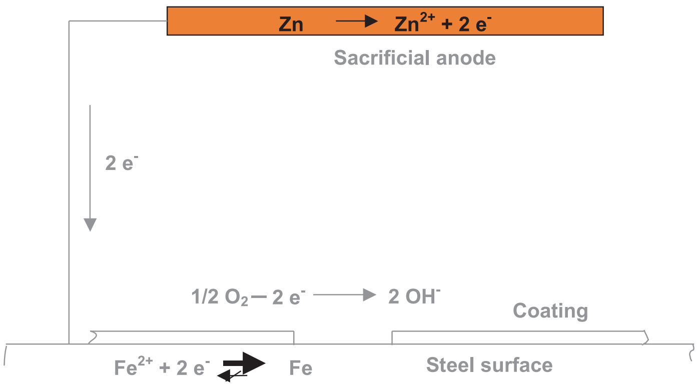

Fig. 3: The principle of cathodic corrosion protection

Cathodic corrosion protection has been the established system for buried steel components since about the mid 1950s. CCP serves not only as an additional anti-corrosion measure, but also for precise defect location and monitoring of external interference. This form of monitoring starts with the possibility for checking the care taken during pipe-laying operations and, when the pipeline is in service, it can also monitor third-party activities along the pipeline route. The system not only helps, in purely safety-related terms, to avoid the otherwise inevitable consequences of damage to the corrosion protection, it also allows the maximum exploitation in economic terms of the service-life reserves potentially offered by the system.

Such possibilities make CCP a key tool for condition-based maintenance, since the measured values can be retrieved at any time to provide information on the condition of the protected object. That is why rehabilitation planning does not, in principle, rank objects protected in this way on the basis of a potential service life or damage statistics but with the help of real measured data. These advantages and the resulting significance of cathodic corrosion protection will be examined in this article using examples drawn from practice.

Fig. 4: Route map of the high-pressure gas pipeline examined

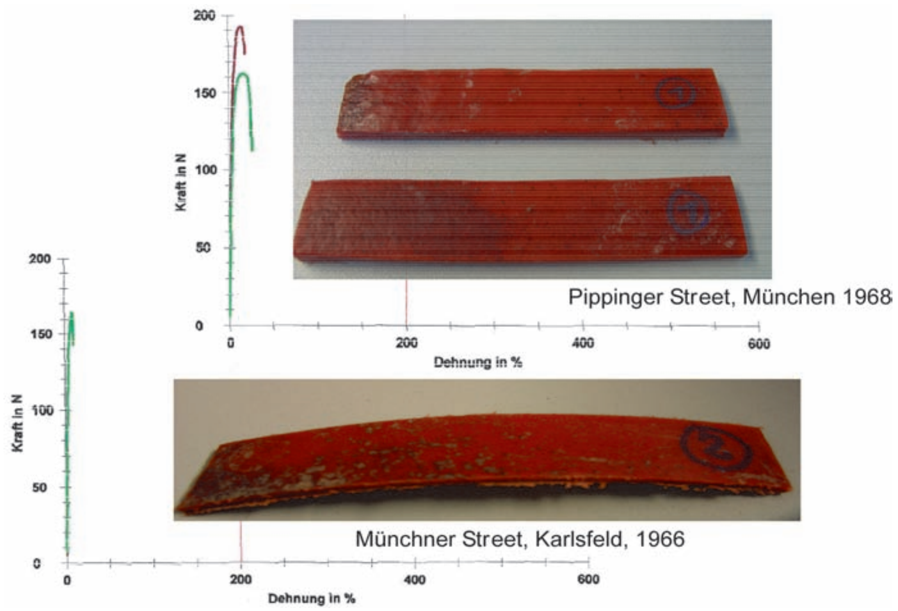

Fig. 5: Elongation at break of sintered polyethylene coatings

The principle of cathodic corrosion protection

Cathodic corrosion protection is a proven electrochemical protection technique for steel components with electrically insulating coatings. The protective measure takes effect when damage to the coating allows direct contact between the steel base material and the surrounding medium. In the corrosion process, iron from the affected area dissolves in the medium as positively charged ions, releasing electrons. That is why the process is called an electrochemical reaction. As it is known from the electrodeposition of metals, this process is reversible, depending on the direction of current flow. Whether a metal is dissolved or deposited depends on the electrons available on the metal surface in the area of the defect.

Cathodic corrosion protection supplies electrons to the steel surface in the area of the coating holiday. In the simplest case, the corrosion process is thereby transferred to a less noble element, a role assigned to a zinc electrode in the present example (**Fig. 3**). This "sacrificial anode" is what ensures the oversupply of electrons to the affected site. In this way the exposed steel surface of electrically conductive steel pipelines can be protected, irrespective of where the coating holiday is located. The essential advantage here is that these processes are connected to a current flow along the pipeline. This current flow can be measured and recorded, which enables the incidents around the protected component to be evaluated. The key requirements for cathodic corrosion protection in Germany are set out in the Recommendations of the *Arbeitsgemeinschaft für Korrosionsfragen* (AfK) and the DIN and DVGW codes of practice and regulations.

Technical inspection and tests of corrosion protection in a high-pressure gas pipeline

The advantages of CCP for rehabilitation planning can be exemplified in greater detail from the technical assessment of the corrosion protection of a high-pressure gas pipeline with the help of measuring methodology. The high-pressure DN 600 pipeline to be assessed was laid in two sections in 1966 and 1967 over a total length of some 8,000 m, so the service-life of both sections is very similar (**Fig. 4**).

The external corrosion protection consists of a sintered polyethylene coating. Compared with extruded polyethylene, the sintered material has the disadvantage of being harder to bond and its behaviour, from today's point of view, appears relatively brittle. Under the draft standard DIN 30670 of February 1974, sintered coatings in ex-mill condition had to have an elongation at break of at least 100 percent, a requirement which was reliably achieved with the then customary technology and methods.

The examination of specimens of such coatings shows that this material does indeed still achieve strengths comparable with new materials. However, due to its typical aging, the elongation at break is down to only 25 percent at maximum (**Fig. 5**). There is need for further research and development here, especially since aging predictions can be made only in respect of a material's strength, whereas the remarkably early reduction in elongation at break cannot even be qualitatively understood based on the current stage of knowledge. Yet despite the low elongation, the coating still forms a closed unit and provides the required barrier effect to prevent the base material from corrosion. Even with extremely low elongation values, the efficiency of corrosion protection remains unimpaired in such cases. Nevertheless, these findings only remain valid so long as no impermissible loads such as external interference, point loads or point supports cause stress peaks, for these often lead to net-like cracks in the coating.

Fig. 6: Log diagram of coating holiday location along the pipeline, with documentation of the appearance of the sintered polyethylene coating

This type of crack formation in embrittled material, which is quite common in practice, is also elusive to establish from the corrosion-induced stress cracking behaviour of the new material under the action of a wetting agent, because the material's fracture mechanism and the morphology of the polymer has changed during service.

Crack formation leads to a reduction in the electrical insulation resistance of the Coating. Possible consequences are an impairment of the effectiveness of the CCP and impermissible electromechanical interference with adjacent objects. Corrosion protection measurements along approximately 7400 m of this pipeline (**Fig. 6**) show that, apart from a few isolated dot-shaped holidays which probably date right back to the laying of the pipeline, the coating is in excellent condition. The diagram of the measurements along the remaining approximately 600-m section (**Figs. 7 and 8**) show a very different picture indeed.

The coating is in poor condition. The pipeline section in this district is exposed to heavy and dynamic traffic loads. Roadworks and pipe-laying operations carried out in the past have only added to the damage. Based on the measured data, it was decided that rehabilitation planning should cover the renewal of about 400 m of this section, with simply coating repairs for the remaining 200 m. No action is required, even in the long term, for by far the largest part of the pipeline (some 7400 m).

The present example clearly illustrates a very fundamental aspect of pipeline operation without cathodic corrosion protection: without CCP, consideration would certainly have been given to replacing the entire pipeline for safety reasons as damage frequency increased in the critical section, particularly in view of the condition of the coating, which would be assessed at the same time. The conclusions derived from the measured CCP data regarding the condition of the pipeline, however, permit a selective and cost-effective approach in rehabilitation planning.

Cathodic protection retrofit on an urban gas distribution network

The influence of cathodic corrosion protection on the service life of a pipeline emerges very clearly from the example of a retrofit on an urban network. The case in point is an urban network currently some 100 km in length. Extension work on the system started in about the early 1960s. First corrosion damage occurred after only about ten years (1974), with the number of incidents increases in the years thereafter. Inspections of the corrosion protection at the sites of the individual faults show that by far the largest number of these faults are due to electrochemical influences with external cathodes (reinforced concrete structures) (see also for example German DIN 30675-1).

The formation of such cells is only possible where the pipe coating suffers damage as a result of negligence when the pipe was being laid or other external influences. The higher number of damage incidents observed here supports the conjecture that their origins mostly go right back to the pipe laying. When external cathodes, e.g. steel in concrete, can be activated, the decisive factor for the corrosion rate is the cathode-to-anode area ratio. Here the comparatively small areas of buried steel which are unprotected due to coating damage (**Fig. 9**) form the anode. **Figure 10** shows the extent of the area an external cathode can cover.

The vast area of the reinforced concrete structure and earth electrodes for which equipotential bonding is mandatory for example in accordance with German VDE 0100, form the cathode. With such a constellation, then, it is understandable that the corrosion rate can rise to between 0.5 mm and 1 mm per year if the damaged anti-corrosion coating of a steel pipeline is affected in such a way. **Figure 11** is a diagrammatic representation of the effects of exposure to external cathodes.

Between 1975 and 1978, in order to fully exploit the considerable service-life reserves inherent in steel pipeline systems, the constructional prerequisites for the retrofit of cathodic corrosion protection were completed and commissioned (e.g. insulation spacers,

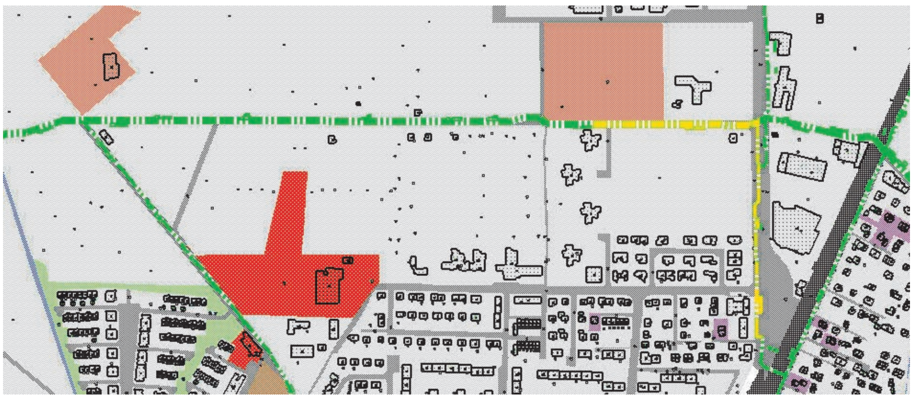

Fig. 7: Route map of the pipeline section with damaged coating (highlighted in yellow)

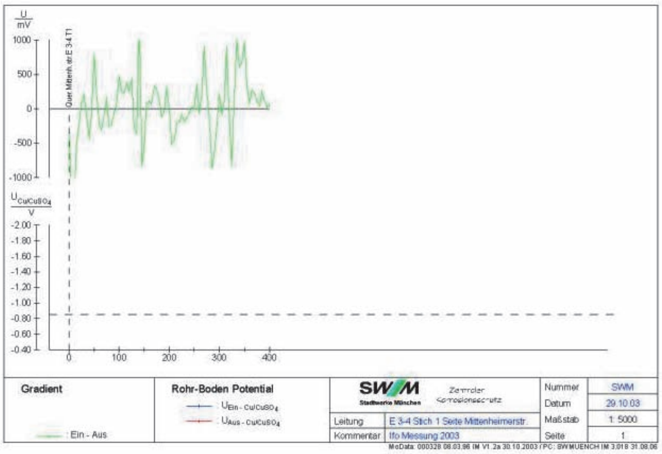

Fig. 8: Log diagram of coating holiday location in the pipeline section with damaged coating

Fig. 9: Example of a coating fault caused by external influences

monitoring points, supply of protective current) in the network sections particularly affected by electrochemical influences through external cathodes (**Fig. 12**).

This meant that about 43 percent of the pipelines were still without cathodic corrosion protection at that time. The consequence of these measures was a sharply declining trend in the damage ratio. However, from about 1985 onwards, notifications of damage began to rise again, primarily in those areas where previously hardly any damage had been recorded. Now the results of investigations pointed in most cases to the formation of corrosion cells as a result of differing levels of soil aeration. **Figure 13** shows the corrosion process with cell formation due to variations in soil aeration. The corrosion load depends essentially on the aggressiveness and the aeration of the soil. Here again, the basic precondition for corrosion damage of this type is impairment of the coating due to insufficient care in pipelaying or to external interference. This type of corrosion process, however, does not lead to the high weight loss rates recorded for corrosion due to exposure to external cathodes. For this reason, the renewed accumulation of corrosion damage incidents in the urban gas network concerned some 20 to 25 years after laying is quite plausible.

Retrofitting cathodic corrosion protection in network sections that had not previously been protected with CCP then went ahead as a priority task, with the result that the urban gas network was 100-percent cathodically protected by about 1988. No more damage has been reported since 1996.

Here it should be noted that there has been no need to date to replace any components in this urban distribution network. Since damage to an anti-corrosion coating is either incidental or attributable to external influences and/or pipe-laying faults, damage statistics can provide no information at all as to the real

Fig. 10: Construction of a reinforced concrete structure

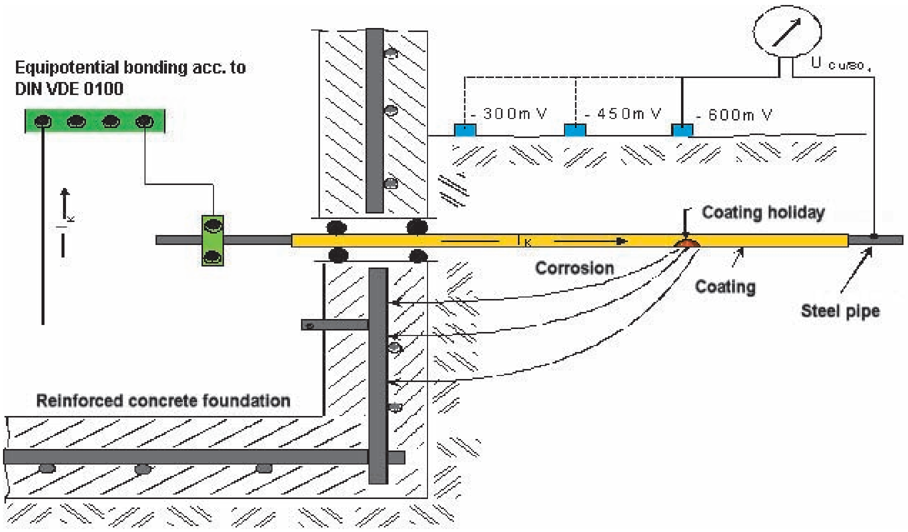

Fig. 11: Systematics of the effects of an external cathode

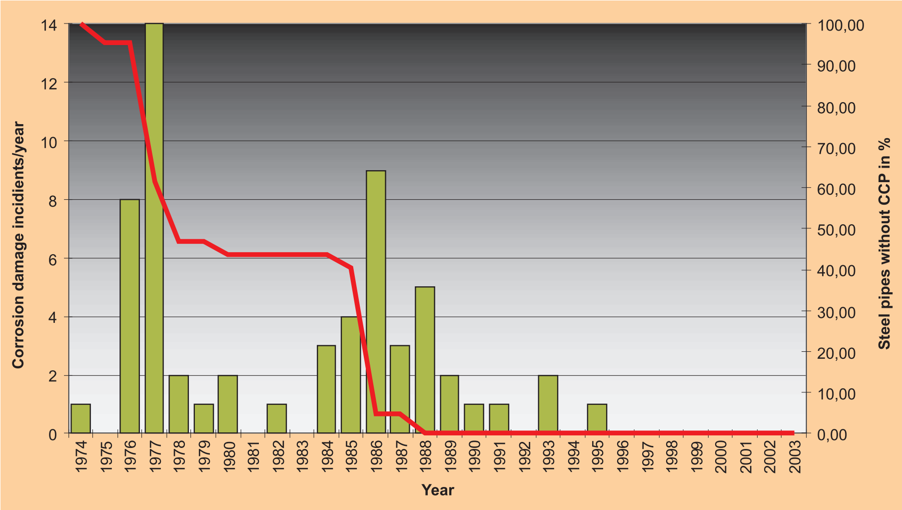

Fig. 12: Correlation between the rate of damage and cathodic protection retrofit

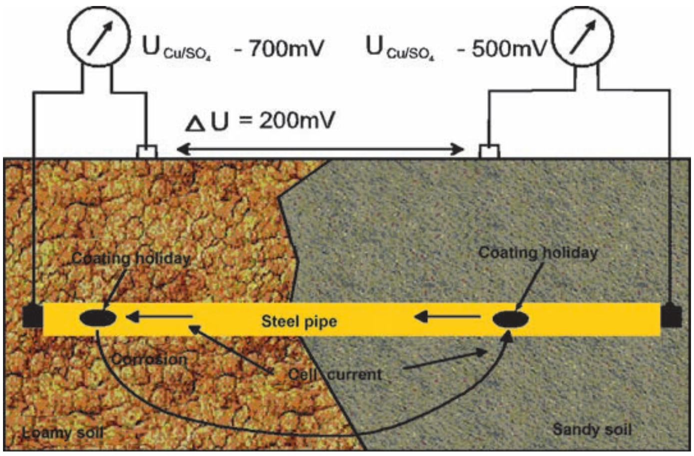

Fig. 13: Cell formation as a result of variations in soil aeration

technical service life of properly protected and correctly laid steel pipelines. Corrosion damage due to external influences and pipe-laying faults is effectively stopped with the help of cathodic corrosion protection.

Conclusions

Irrespective of the pipe material, damage in pipeline systems today is primarily attributable to external influences and lack of care during pipe laying. Depending on the strength of the material, such damage will lead either directly to leakage or to failure in the medium term due to corrosion processes. Steel is the only material which offers the opportunity to influence and measure these processes through cathodic corrosion protection. Exploitation of the synergetic effects of a combination of polyethylene and steel assures the best preconditions for the high efficiency of this electrochemical protective method. Cathodic corrosion protection not only affords the possibility of minimising wall thinning due to corrosion and thereby making full use of service-life reserves, it also permits condition-based maintenance and with it the appraisal of buried structures from the surface. For safety reasons, this form of monitoring is mandatory for all pipelines in high-pressure gas systems as well as pipelines used for transporting media hazardous to ground water. Recent years have seen a development in measurement engineering related to cathodic corrosion protection which should not be underrated. The location of coating holidays has been simplified. The control of the installations and the monitoring of the components to be protected can all be managed through remote control systems [6].

In economic terms, the service-life reserves inherent in a steel pipeline system can be fully exploited through cathodic corrosion protection, which minimises external influences on the pipeline system. Today a service life of 100 years in minimum for a cathodic protected steel pipeline is agreed. The change in damage frequencies in a previously unprotected urban network parallel to the progressive extension of cathodic corrosion protection documents the sustained effectiveness of this method. In most cases, retrofitting CCP for buried components makes sense technically and is economically feasible [7]. In addition, the imponderables in maintenance cost planning can be translated to a large extent into tangible expenditures through the use of cathodic corrosion protection. Where faults can be located, not only can repair scheduling be spread over a longer period of time, the party responsible for the fault can also often be traced. In such cases, repair costs can then also be passed on to them.

Further cost savings are achieved because CCP allows a realistic evaluation of the pipeline system. The evaluation of the components presented here with the example of a high-pressure gas pipeline shows the advantages of such targeted rehabilitation planning. Projected activities can be restricted to those components which actually need repairing. A purely statistical appraisal of such components would necessarily lead to a false assessment. Purely statistical appraisal therefore remains reserved for pipeline systems with pipe materials and designs that do not support this form of condition-based maintenance.

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