Detection of external impacts on pipelines

by continuous monitoring based on cathodic corrosion protection in combination with additional sensors

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Steel pipelines can be protected against external corrosion by two perfectly interlocking methods: passive corrosion protection by a high-grade pipe coating, with classic cathodic corrosion protection (CCP) serving as the active complement. But CCP can do much more. It is an indispensable part of condition-based maintenance and as such provides a valuable contribution towards management systems for the assessment of pipeline integrity (PIMS).

CCP and continuous monitoring also allow preventive observation of a pipeline's integrity so that, for example, external stresses, damage or direct attack can be reliably recognized.

Although it had been previously possible for CCP to detect major damage caused by heavy equipment such as excavators, the informative value of these results was very limited. With the technology available today – energy-saving sensors and software solutions that provide data in real time – it is possible to detect and localize even slight damage very quickly.

This article describes a method that combines a variety of sensors and CCP and was developed by the company Steffel KKS GmbH. The method was tested on a pipeline of Mannesmann Line Pipe GmbH. Its special feature is that it greatly facilitates the coupling of sensors to the pipe body. Besides the measured data and the resultant information on the pipelines, this method provides further optimization potential.

The fact that the basic unit is fitted right at the pipe mill will in future reduce on-site costs in the construction of new pipelines as well as facilitating the integration of other sensors in addition to those of the CCP system. In this way, the intelligent pipe will become reality.

Corrosion protection is an important element towards the conservation of the pipeline infrastructure. In Germany, damage caused by corrosion amounts to about 4 % of the gross domestic product. Expressed in figures, this corresponds to some 90 billion euros [1].

For this reason, cathodic corrosion protection (CCP) has been an indispensable part of condition-based maintenance and as such provides a valuable contribution towards management systems for the assessment of pipeline integrity (PIMS).

Besides corrosion, interference by third parties is among the most frequent causes of pipeline damage. Quite often, such incidents lead to leakage of the transported medium. Besides accidental damage, e.g. during earthworks by third parties or agricultural field treatment in the area of a pipeline route, theft of the pipeline medium also plays a not insignificant role.

For some years now, it has been possible to a limited extent to detect "third-party attacks" on the pipeline (e.g. by heavy equipment such as excavators) with the aid of CCP. The patents for these processes describe monitoring possibilities based on various approaches.

With one such process, a measured value representative of the protective current applied along the pipeline is recorded on at least two measuring points at given points in time. For each of the given points in time, a difference value that is representative of the protective currents flowing along the pipeline is determined between two measuring points situated at a distance from each other. Based on the time that has elapsed between the given points in time and the difference values determined between the two measurements, at least one value is derived which can indicate the advancing of a conductive body towards the pipelines between the two measuring points [2].

In another method, an electrical test signal relating to an object is measured and the state of the object is determined via the time course of the electrical test signal's frequency spectrum. In particular, the object's state is determined as a function of the time course of an amplitude in the range of a test frequency within the spectrum of the electrical test signal. This is preferably done dependent on the test signal's amplitude exceeding a threshold value. The method based on measuring an electrical test signal relating to an object and determining that object's state as a function of the time course of the test signal's frequency spectrum is intended to facilitate the detection and recognition of a specific state of the electrically conductive object that is under cathodic corrosion protection. In particular, monitoring the

frequency spectrum over a period of time should allow the observation of a frequency-specific property without interfering signals adversely affecting the determination of the object's state [3].
The task of the newly developed measuring technique introduced in the following was to combine state-of-the-art sensor technologies and software solutions. This created the possibility to detect and localize precisely and in real time even the slightest damage by means of energy-saving sensors.

The basic method

Cathodic corrosion protection allows statements to be made regarding the condition and state of a pipeline. For example, damage to the pipe coating can be detected and localized by a variety of measuring methods. Continuous monitoring with sensors installed along a pipeline makes it possible to reliably detect any changes, stresses and damage.
However, using the described methods, third-party damage can be detected only some time after is has occurred. The method outlined in the following therefore takes things a step further and provides real-time detection of damage to a pipeline.
For this purpose, absolute measured DC values are of subordinate importance to the system. The conceivable attack scenarios leave a typical frequency spectrum behind them (***Figure 1***), which is reflected in varying degrees in the current and voltage curves. Digital filtration of the signals (***Figure 2***) according to characteristic frequencies generated by contact with the soil makes it possible to detect and characterize attack sites.
In addition to the frequency spectrum, statistical evaluations of the signal paths over defined time periods are used for evaluation. The results of the frequency analysis as well as of the statistics modules and the current-voltage correlation module are all fed to a fuzzy controller that functions as artificial intelligence. A typical property of fuzzy controllers is their "soft" examination of signals received. This logic allows attack scenarios to be detected and recognized on the basis of an individual evaluation. No superordinate system is required for this purpose. The detection/recognition can be performed by the CCP sensor in place. If more sensors than one are installed along the pipeline, they can communicate with each other feed their results to a master sensor for correlation. This master sensor then evaluates the entirety of the results, again with the aid of fuzzy logic, to ensure an even more reliable detection rate. Moreover, fuzzy logic allows the inclusion of data from non-CCP sensors.

Basic metrological requirements

The metrological equipment used is subject to specific requirements for recording the relevant measurements. It requires potential-free measuring channels with a scanning frequency of 2 kHz and 24-bit accuracy. The channels must have high impedance (30 MΩ) and be capable of reliably measuring in the range of < ±1 µV to ±150 V. For the smaller ranges an accuracy of 1 µV is specified, while ranges of ±150 V require a resolution and accuracy of 1 mV.
For effective calculation of the AC voltage and for the required digital filters, high-speed analog-to-digital converters (ADCs) are essential. Furthermore, the sensors should accommodate the recording and processing of additional measurement signals. This allows measurement variables to be correlated that up until now were considered either independent from each other or not at all.

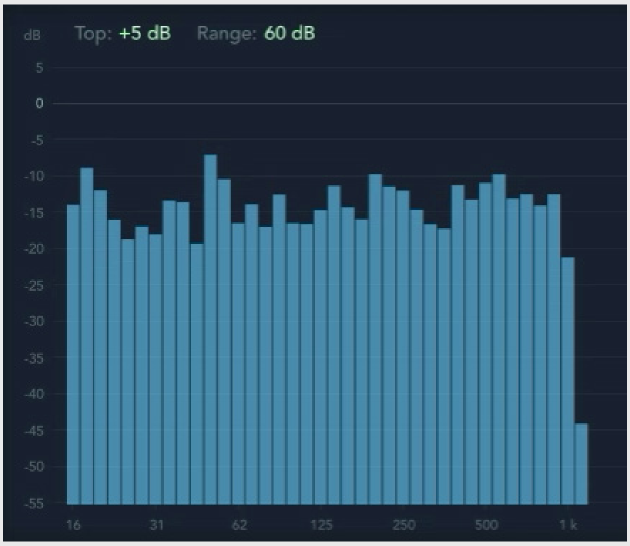

Figure 1*: Before filtration*

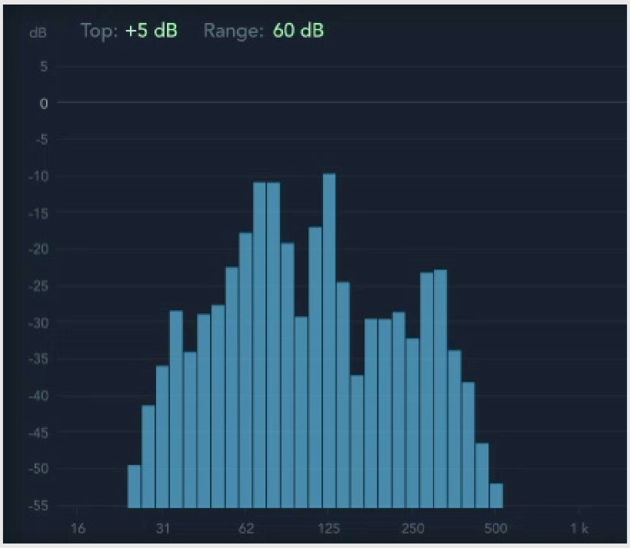

Figure 2*: Frequency spectrum of an attack*

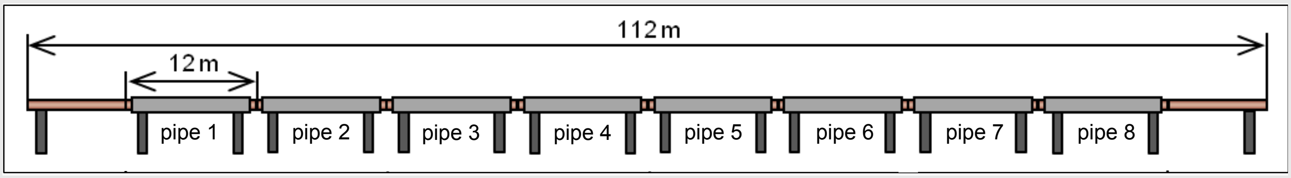

Figure 3: *Layout of the test pipeline*

Figure 4: *Test pipeline*

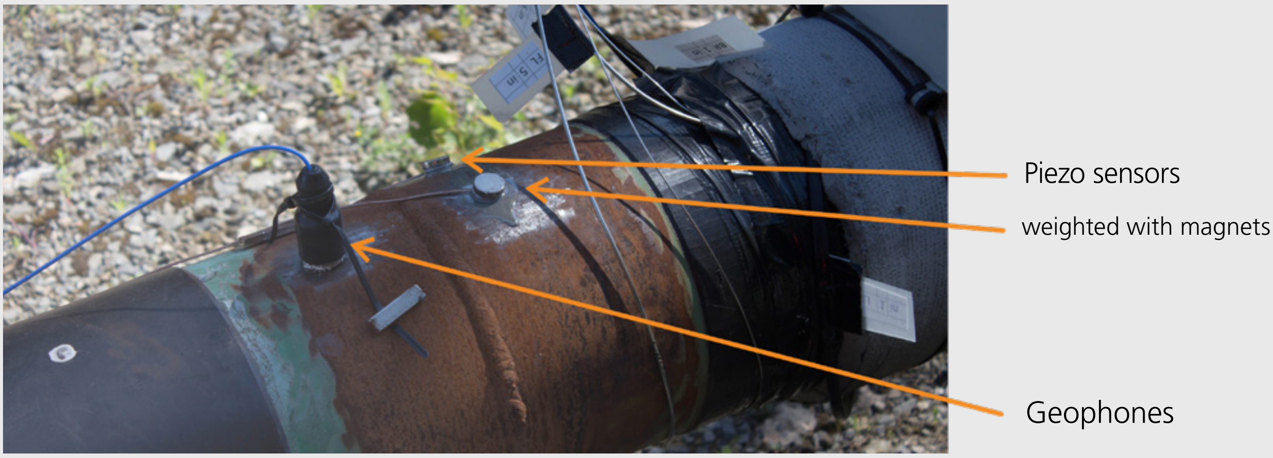

Figure 5: *Fitting the structure-borne sound sensors*

Combination with additional sensors
To verify and refine the detection results, measurement signals from the most diverse sensors installed along the pipeline can be used.

Thus, the sound propagated through the pipeline (structure-borne sound) can also serve as a damage detector. The use of the most sensitive sensors available (geophones) allows the signals received to be fed to the fuzzy controller after appropriate

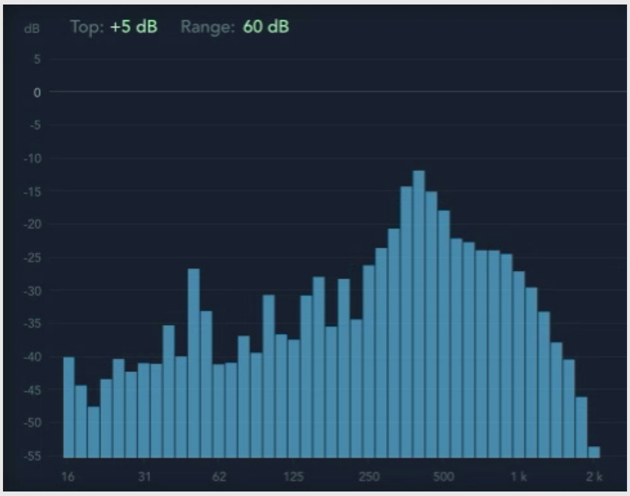

Figure 6*: Before filtration*

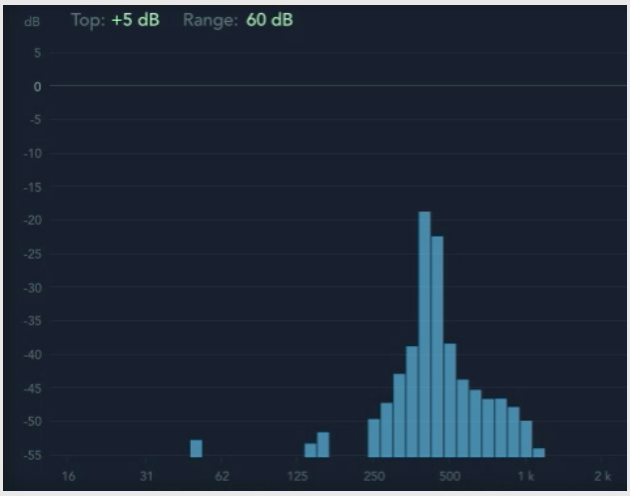

Figure 7*: Drilling test with 3 mm drill*

filtration. The damage site can then be localized via the travel time of the sound. If several structure-borne sound sensors are used, their results can also be verified, since all the sensors take their measurements absolutely synchronously (GPS).
To ensure that even minor incidents are detected, the system uses complementary information from strain sensors, which change their electrical resistance even in the case of slight deformation, as well as measurements from temperature, pH-value, position and acceleration sensors. The correlation of all these measurements greatly facilitates the detection and characterization of direct attacks on a pipeline's integrity.

Testing the method in combination with structure-borne sound sensors

Test pipeline
For the tests in conjunction with structure-borne sound sensors, a test pipeline was constructed using high-frequency induction (HFI) welded pipes from Mannesmann Line Pipe GmbH (***Figure 3*** and ***Figure 4***) [4]. The pipes in size DN 300 with a wall thickness of 6 mm were protected by a MAPEC® 3-layer plastic coating.

Measuring equipment used
For measuring the structure-borne sound and subsequent practical applications, two Piezo sensors were installed on the test pipeline. To verify the effectiveness of these sensors, high-performance geophones were employed for reference measurements (***Figure 5***). Parallel to this, the signals from the structure-bound sound sensors were recorded using Steffel iCorrLog measuring equipment and professional audio studio equipment. The Steffel iCorrLog devices, which have proven themselves for CCP measurements, were also used for recording all the electrical signals, such as the current flow in the pipe.

Test procedure
The sensors for recording the relevant measurement data were fitted on one side of the test pipeline (Figure 5). To simulate the most varied attack scenarios, the following action was taken approximately every 20 m:

- » Blows of varying intensity with a 50-g hammer, directly on coated and bare parts of the pipe body.
- » Saw cuts using hacksaws with varying TPI (teeth per inch), directly on coated and bare parts of the pipe body.
- » Drill tests along the pipeline, using drills with different bit diameters.

Evaluation of recorded signals
The signals recorded by the structure-borne sound sensors were processed in a DAW (Digital Audio Workstation). For this purpose, the data of the acoustic and electric signals from the Steffel iCorrLog measuring devices were converted into an audio format (WAV). The evaluation of the data from the iCorrLog measuring devices (***Figure 6*** and ***Figure 7***) and of the reference record from the high-performance audio equipment showed the same significant signals of the simulated attack scenarios. Additional signals from the audio equipment in a higher frequency range did not provide any additional contribution to the detection of attacks and are therefore irrelevant.
The evaluation of all the data and a comparison with the higher-grade geophone showed that the Piezo sensors are perfectly suited for the capture of structure-borne sound.
The use of all data gained showed that any damage can be detected and localized. In addition, the tests confirmed that the capture of structure-borne sound signals is an optimal complement to the recognition of attack scenarios verified on the basis of CCP data. The corre-

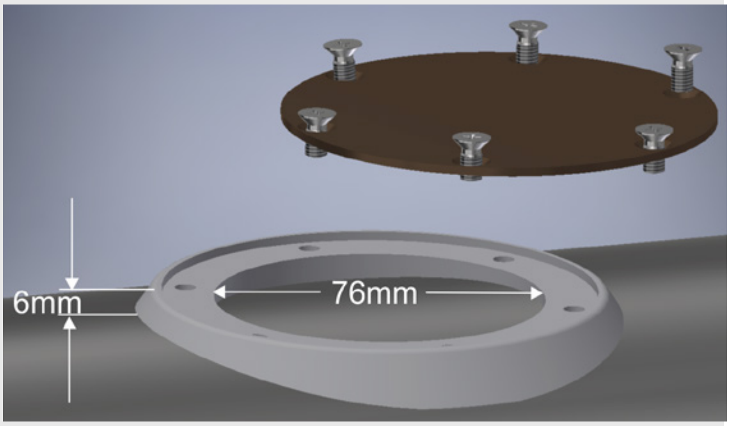

***Figure 8**: Basic unit of the sensor interface fitted on the pipe before mill coating (schematic illustration); protective lid above the basic unit*

lation of electric and acoustic signals can even further increase the efficiency of attack detection.

Measurement technology interface

For economic reasons, the use of structure-borne sound sensors is mostly limited to new pipeline projects. To minimize installation cost and time, Mannesmann Line Pipe and Steffel developed an intelligent pipeline interface. This consists of a basic unit and a matching carrier unit. The basic unit is permanently fixed to the pipe at the pipe mill and then coated, together with the pipe, with a multi-layer coating (e.g. 3-layer polyethylene coating) with integrated corrosion protection (***Figure 8***).

At the construction site, the coating on the upper surface of the basic unit is removed. Now the corrosion-protected carrier unit complete with sealing and sensors can be connected with the basic unit (***Figure 9***). This greatly facilitates on-site work in that it renders unnecessary the removal of the coating from the steel surface, fitting of the sensor unit(s) and field coating.

The cathode connection required for CCP, which previously involved stud welding and field coating, is also provided by the fully prepared interface. Moreover, the described technology also allows flexible expansion of the system through the integration of additional sensors besides those of CCP.

After application of the mill coating, the prototype interface was equipped with a structure-borne sound sensor, two strain gauges and a temperature sensor. These were all fitted on the pipe inside in the basic unit (***Figure 10***). In the carrier unit, a quick connector was installed (***Figure 11***).

Additional sensors

Besides the described integrable connections for the CCP sensors including attack monitoring and structure-borne sound sensors, the intelligent pipeline interface offers many and varied possibilities for additional sensors each of which can then enhance the efficiency and reliability of attack monitoring. Mechanical stresses are monitored with strain gauges whose installation used to be comparatively complex. With the intelligent pipeline interface it is now possible to install and check the strain gauges before the pipe leaves the mill (see Figure 9 as example). This means the recording of a pipeline's life cycle and con-

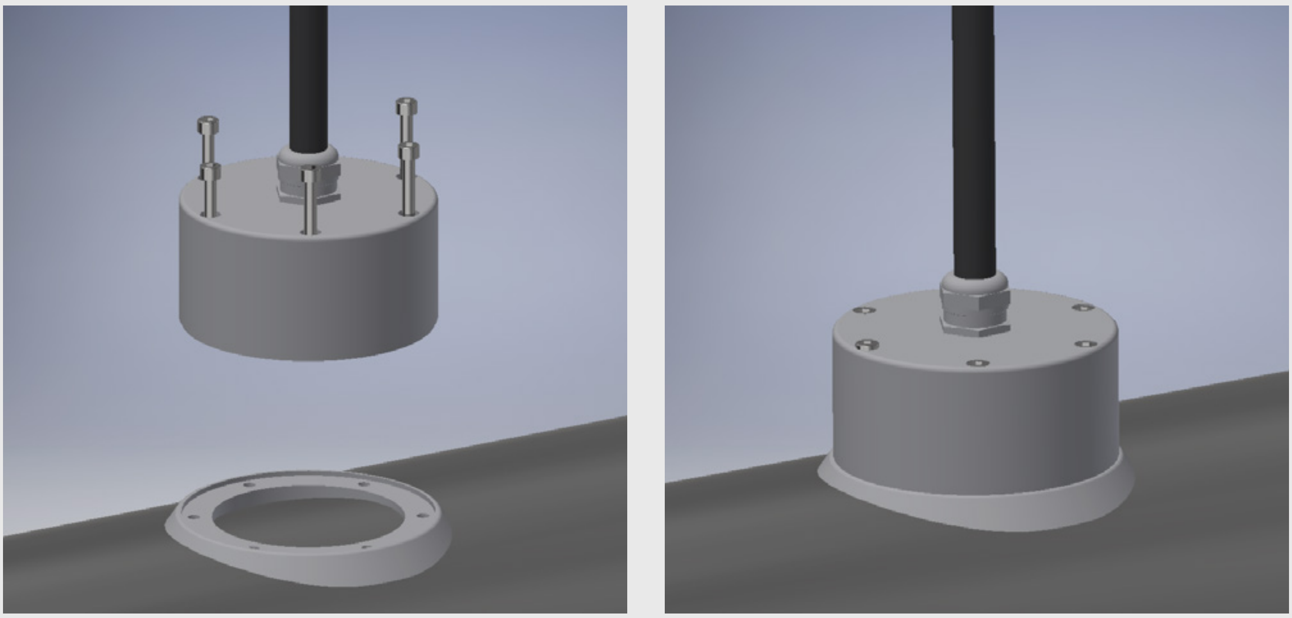

***Figure 9**: Basic unit of the sensor interface on the pipe, after mill coating and removal of the protective lid, with appropriate sensor carrier unit (schematic illustration)*

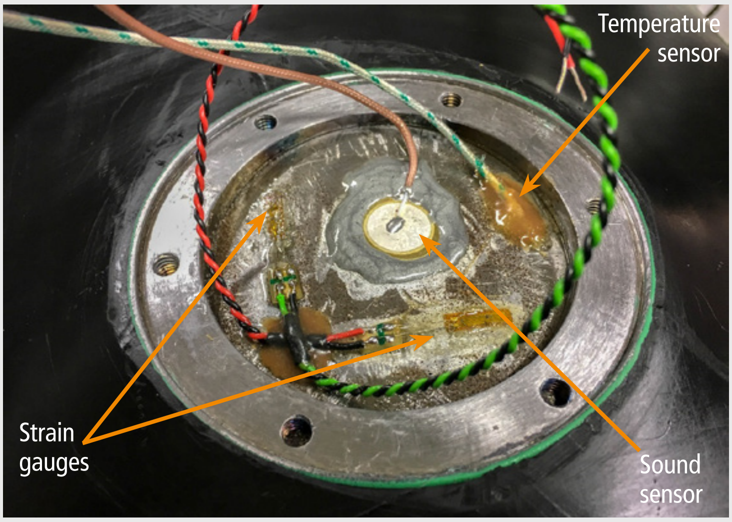

***Figure 10**: Basic unit of the sensor interface on the pipe, after mill coating and removal of the protective lid, with installed sensors*

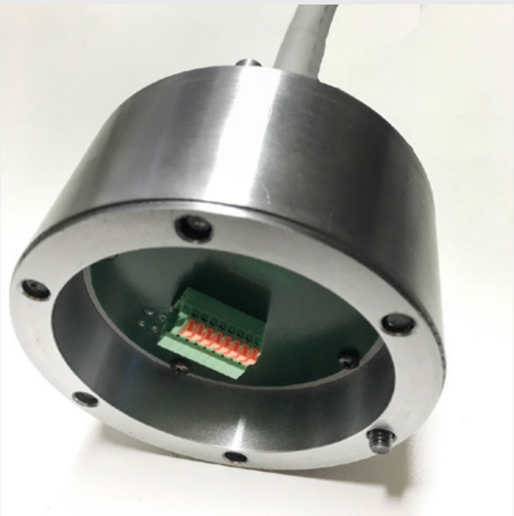

***Figure 11**: Carrier unit of the sensor interface, including installed quick connector and pre-fabricated cable loom with data and measuring wires for the sensors and the CCP electrode*

dition can be supplied together with the pipe, ex works. In tectonically active regions, integrated position and acceleration sensors could record mechanical loads and positional changes and feed their data to the attack monitoring system. The same holds for temperature sensors, which are of particular interest in the case of liquid media. The integration of long-life pH value sensors may prove to be trend-setting in cathodic corrosion protection since the Pourbaix diagram, which describes the relationship between the protection potential and the pH value, provides reliable evidence whether or not corrosion is taking place.

Summary and outlook

The described test has shown that the detection of third-party attacks based on CCP data can be efficiently complemented and enhanced through the capture and recording of structure-borne sound.

A unit for the effective and economic installation of CCP and structure-borne sound sensors has been introduced. This intelligent pipeline interface will in future not only reduce on-site costs in pipeline projects, but it also allows flexible expansion of the system through the integration of additional sensors besides those of CCP. In a next step it is planned to optimize the interface. The intelligent pipe has become reality.

Literature

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