INSPECTION OF PIPES IN LEAK INDICATION SYSTEMS

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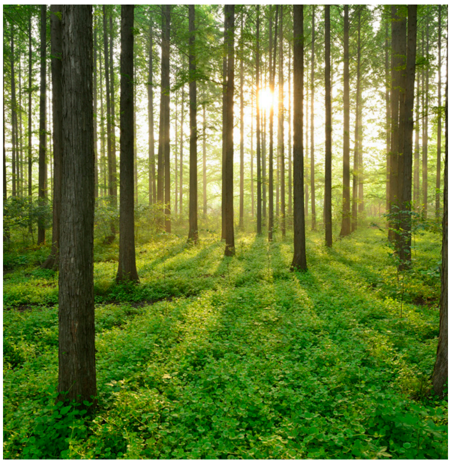

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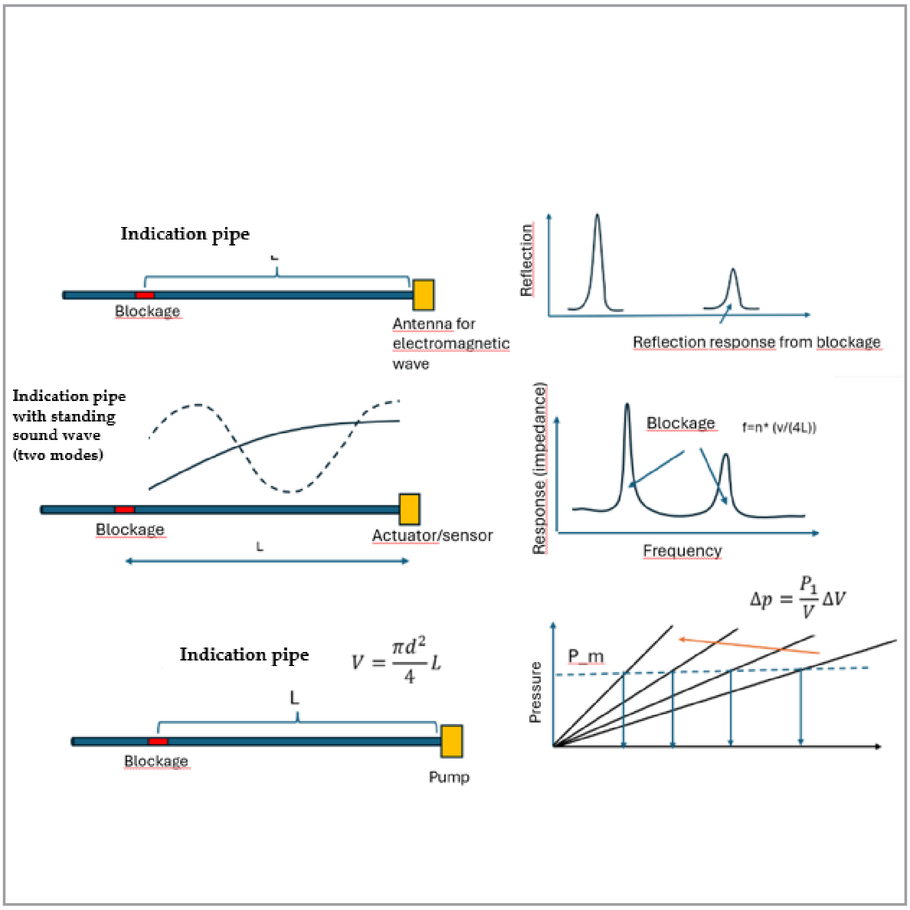

Energiforsk

Inspection of Pipes in Leak Indication Systems

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Foreword

Early detection of leakage from fuel pools is secured through leak indication systems, consisting of long systems of pipes with very small diameters. Blockages in these systems are important to mitigate, but finding methods for this is difficult due to the geometrical complexity.

This study examined possible methods for detecting and removing mineral blockages in narrow, embedded leak indication pipes with sharp bends. The aim was to identify potential methods for use in the Nordic nuclear power plants, and to define further development needs.

Several detection methods showed technical potential but require validation in realistic mock-ups, which is proposed as a follow-up project. Defining which cleaning methods are useable also needs further studies and could also be part of a follow-up.

This report forms the results of a project performed within the Energiforsk Nuclear Power Concrete Program, which is financed by Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft, Karlstads Energi, the Swedish Radiation Safety Authority and SKB.

The Concrete Program aims to increase the knowledge of aspects affecting safety, maintenance and development of concrete structures in the Nordic nuclear power plants. A part of this is to investigate possibilities to facilitate and simplify the work that is performed in the nuclear business.

The study was carried out by Andreas Bergh, Jonas Engblom, Christer Johansson and Christian Jonasson, RISE.

These are the results and conclusions of a project, which is part of a research program run by Energiforsk. The author/authors are responsible for the content.

Summary

The leakage indication system is a safety-related system used in nuclear power plants for the purpose of detecting leakage from the fuel pool. Over an extended period, operational issues have been observed in the form of blockages caused by deposits of mineral-based material. These blockages pose a risk to the system's functionality by reducing the reliability of leak detection. The objective of this project has been to investigate potential methods for identifying and removing such blockages. In cases where no mature solution has been identified, recommendations for further development and investigation have been provided.

The leakage indication system consists of concrete channels located behind the pool liner, connected to embedded steel pipes with a diameter of 20 mm. These pipes may be 20-30 meters in length and include both sharp 90° bends and curved sections, ultimately leading to a collection container. This geometry presents significant challenges for both inspection and cleaning. The combination of small diameter and sharp bends requires high flexibility of cables while also limiting the dimensions of tools. Furthermore, the pipe length increases friction during operation of long cables and may cause signal attenuation over longer distances.

Within the scope of the project, several plausible methods for blockage detection were identified, including pneumatic volumetry, standing acoustic wave analysis, electromagnetic wave propagation, and mechanical probing. None of these methods are currently established for this specific purpose. However, all are considered to have technical potential, provided they are verified through practical validation testing. For this purpose, the construction of a modular mock-up is recommended, consisting of pipe sections with dimensions and geometries corresponding to those of the leakage indication system. The mock-up should enable different types of simulated blockages to be installed at various locations. Endoscope-based inspection is also considered feasible, although custom manufacturing of the instrument is required to overcome the geometric challenges.

The identified cleaning methods require further investigation and development before they can be verified. Two of the proposed methods, chemical cleaning and ultrasonic cleaning, are currently limited by insufficient information regarding the mineral deposits. To enable further development, characterization of the deposits is suggested, including analysis of their chemical composition, crystal structure, and hardness. The third proposed method, hydromechanical cleaning, appears to be limited primarily by the system geometry. This method is plausible through additional development and specialized equipment design.

Keywords

Leakage indication pipes, inspection methods, detection methods, cleaning, resonance, endoscopy

Sammanfattning

Läckageindikeringssystemet är ett säkerhetssystem inom kärnkraften vars syfte är att möjliggöra detektion av läckage från bränslebassängen. Under längre tid har problem observerats i form av igensättningar av någon typ av mineraliskt material. Dessa igensättningar riskerar att försämra systemets funktionalitet genom att tillförlitligheten att upptäcka ett läckage minskar. Avsikten med detta projekt har varit att undersöka vilka metoder som skulle kunna vara möjliga för att identifiera och avlägsna dessa igensättningar. I de fall då det ej funnits ett färdigt koncept har förslag på vidare utvecklings-/ eller utredningsarbete getts.

Läckageindikeringssystemet utgörs av betongkanaler bakom bassängplåten vilka leder till ingjutna stålrör som är 20 mm i diameter. Dessa stålrör kan vara 20–30 meter långa och innehåller såväl skarpa 90^{o}-böjar som kurvaturer. Dessa rör leder till ett uppsamlingskärl. Geometrin på rören gör det utmanande för såväl inspektion som rengöring. En liten diameter i kombination med skarpa 90^{o}-böjar ställer höga krav på flexibilitet på kablar som förs in och storleken på eventuella styva objekt som förs in begränsas kraftigt. Kanalernas längd medför dessutom ytterligare begränsningar, bland annat i form av ökad friktion vid framdrivning av kablar, samt genom att signaler måste färdas längre och därmed riskerar bli försvagade.

Inom ramen för projektet har flertalet potentiellt tillämpbara metoder för detektering av igensättning av läckagekanaler identifieras, däribland pneumatisk volymetri, stående ljudvåg, elektromagnetisk våg samt mekanisk sondering. Ingen metod är idag etablerad för den aktuella applikationen, men den samlade bedömningen är att de har god teknisk potential, förutsatt att de verifieras genom praktiska valideringsförsök. För detta ändamål föreslås en mock-up konstrueras, bestående av rörsektioner motsvarande de dimensioner och geometrier som återfinns i läckageindikeringssystemet. Mock-upen föreslås konstrueras modulärt för att möjliggöra installation av olika typer av simulerade igensättningar på varierande positioner i systemet. Även endoskopibaserade inspektion bedöms som en möjlig metod, dock förutsätts specialanpassning av instrumentet för att klara de geometriska begränsningarna.

De identifierade rengöringsmetoderna kräver i varierande grad fortsatt utrednings- och utvecklingsarbete innan dess genomförbarhet kan verifieras. Två av de föreslagna metoderna, kemisk rengöring och ultraljudsrengöring, bedöms i nuläget begränsas av brist på information beträffande den mineraliska fasen. För att möjliggöra vidare metodutveckling föreslås noggrann karaktärisering med avseende på kemisk sammansättning, kristallstruktur och hårdhet utföras. Den tredje föreslagna metoden, hydromekanisk rengöring, förefaller begränsas av de geometriska förutsättningarna. Dock vore metoden möjligen lämplig efter utveckling och specialtillverkning av utrustning.

List of content

1 Introduction

The background to this project stems from the fact that nuclear power companies have experienced problems with clogging of the so-called leak detection pipes. These channels collect any leakage water from the fuel pools, which then drains through drain pipes out into collection containers. In this way, an indication of leakage can be obtained. However, over time, deposits are built up in the drain pipes, clogging the system, which reduces their reliability. Various methods have been tested both to detect blockage and to remove it, but none of the methods have proven satisfactory.

The aim of this study is to investigate the possibilities of both indicating that a blockage has occurred and removing such blockage. The primary focus is on proposing already existing methods, possibly with some degree of adaptation. If no suitable method is identified, the objective is to recommend development efforts to achieve the desired effect in both the detection and removal of the blockages.

The leakage indication system is a complex system consisting of many channels that run in the wall behind the weld of the stainless steel plates in the fuel pool, see Figure 1.

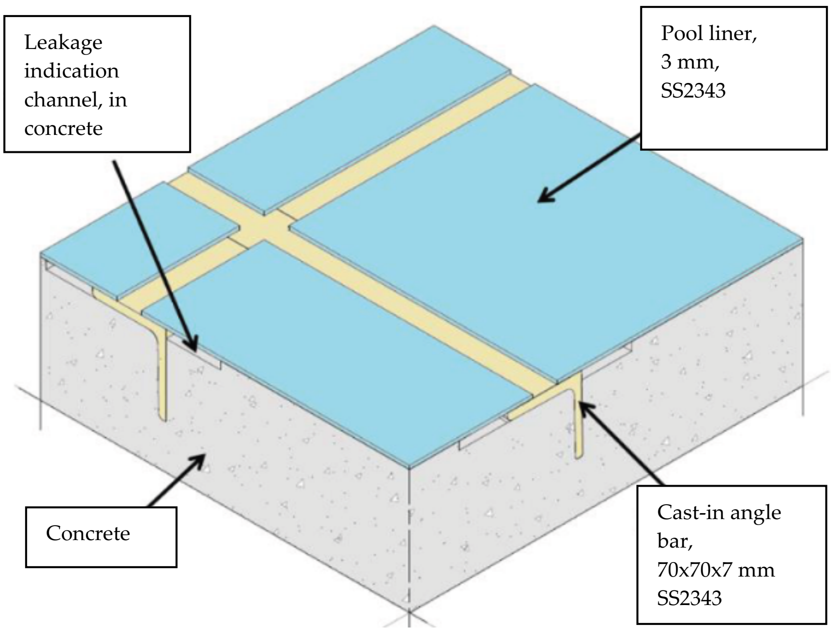

Figure 1: Schematic drawing of how the water is collected behind the welds inside the concrete wall.[1]

The channels are grouped based on different sections of the fuel pools, and each section is drained via its own drain pipe. The drain pipes are interconnected in different layers representing the different fuel pools as well as the transport channels. The drain pipes leads to three collection points, one for each pool, which

[1] (Nilsson, 2026)

are placed around the reactor containment. If any of the welds in the fuel pool is leaking, the leakage will be detected as water will be present in the collection point. As the different pipes represent different sections, an approximation of where the leakage has occurred is also possible. To simplify the discussion of detection methods, a basic schematic illustration, as shown in Figure 2, can be used. In the figure the channels behind the welds are not shown, but are placed on the surface of the cylinder. They then connect to the cast-in drain pipes which transport the leakage to the collection containers.

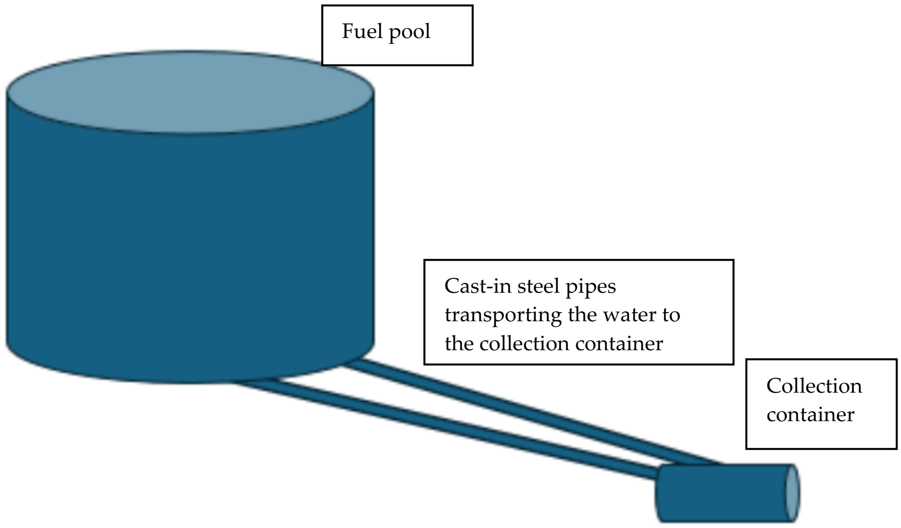

Figure 2: Simplified schematic of the fuel pool and associated leak indication pipes leading to the collection container

The steel pipes leading to the collection container have a diameter of 20 mm with a material thickness of about 1 mm and are made of carbon steel. Typical lengths of the pipes from the start of the pipe to the connection to the collection container are about 10 m - 30 m. The leakage indication pipes have several bends, of which the sharpest are 90^{o} with a very small radius of curvature. The leakage system and how it is connected to the collection containers can be seen as drainpipes that are connected to roofs and where the sampling containers are a closed system to the basin, i.e. if the leakage indication system is pressurized, no air will be able to pass from the container to the surroundings. The proposed sensor methods also work on a more open system where the collection container is not mounted closed to the basin.

During the project, Microsoft Copilot with enterprise data protection was used to a limited extent for text editing and basic reference searches.

2 Indication methods

2.1 PNEUMATIC VOLUMETRY

The utilization of compressed air is commonly used to indicate leakage by filling a known volume with compressed air and monitoring the pressure decay and inferring volume/leak properties[2,3,4]. A similar methodology could be applied here. When there is no blockage, there is a clear path from the start of the channel to the collection container. The collection container is tightly mounted to the basin, which means that if you pressurize with a little air or pump to create a small negative pressure in the pipe (and at the same time control the volume that is introduced or removed from the pipe, i.e. a volume measurement) at the start of the pipe, and there is no blockage in the pipe, it will be possible to build up a small overpressure or negative pressure in the pipe with a total volume that corresponds to the volume of the entire pipe and the sampling container. It is important to emphasize that no high pressures/vacuums are needed in this method, and it is important to stay within approved pressures/vacuum in the pipes/collection containers (below 10 mbar) so that nothing is damaged in the systems (e.g. weld joints). If, however, there is a blockage in the pipe, this blockage will also be detected as a small overpressure or underpressure but now with a smaller total volume of air (from the start of the pipe to the blockage) at a certain given pressure. A simple sketch of this sensor method can be seen in Figure 3. The pressure/vacuum method showing a leak pipe with a blockage (left in Figure 3) and how pressure varies with the flow at a blockage (right in Figure 3). P_m is the permissible pressure in the pipe and the collection container (e.g. 10 mbar), P1 is the atmospheric pressure without pumping the system (approx. 1 bar), V is the volume in the pipe from the start of the pipe to the blockage and ΔV is the volume that can be pressed into the pipe to achieve ΔP = P_m. ΔV can be measured with a flow sensor and the time it takes to fill this volume (flow * time). In order not to exceed P_m, a pressure relief valve can be installed. The orange arrow in the figure on the right shows the cases where the blockage is closer and closer to the start of the pipe (i.e. closer to the start of the pipe, less volume can be injected to achieve the pressure P_m). This method can be seen more as a volumetric method since it is the volume that can be filled in the total system at a given pressure that is measured (via flow and time).

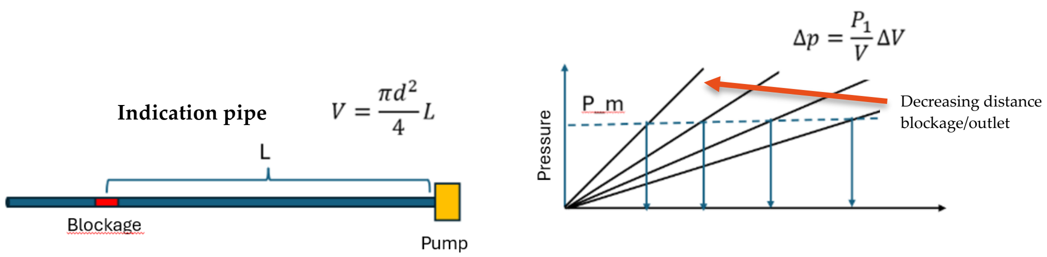

Figure 3: Schematic illustration of how the pneumatic volumetry is arranged (left), and how the results might look (right). The orange arrow shows decreased distance between blockage and outlet.

[2] (Technologies -- Leak Test: Pressure Decay, 2026)
[3] (Pressure Decay Test Systems, 2026)
[4] (Bäckström, Ejdeholm, Johansson, & Norgren, 2024)

If a blockage builds up in the pipe, different volumes will be required to achieve a given overpressure in the pipe (P_m, for example 10 mbar), see Figure 3. By measuring this volume, ΔV, it is possible to calculate the position of the blockage in the pipe, based on knowledge of the pipe diameter and by measuring both pressure and flow/time. The same principle can also be applied if the flow is reversed, i.e., by generating a vacuum. However, it is not possible to determine the positions of multiple blockages within the pipe using this method.

If 10 mbar is the upper limit for pressurization (i.e., p_m = 10 mbar) and P_1 = 1 bar (approximately 1 atm), this means that the volume to be injected into the pipe (and measured using a flow sensor and the time required to introduce the air into the pipe) is about 1% of the volume from the start of the pipe up to the blockage. As an example, consider the following case: assume that a blockage is located 1 m from the start of the pipe and that the pipe diameter is 20 mm. This corresponds to a volume resolution of approximately 13 cm^3, which should be achievable using a flow sensor. Detecting a pressure of 10 mbar with a pressure sensor for air is also entirely feasible. Typical resolutions for commercial flow sensors are 0.1 % to 1 % of full-scale readout (meaning in the range of 0.02 m/s that gives a volume flow resolution of 0.006 m/s for a 20 mm diameter pipe) and 0.01 % and 0.1 % of full scale read out for commercial pressure sensors (meaning a resolution in the range of 1 mbar to 10 mbar). This means that there are commercial sensors that can be used for this method.

A volumetric method like the one described above should be able to detect total blockage. However, it cannot detect multiple total blockages.

Given that pressure has been built up, evaluation of the appearance of the pressure curve upon pressure release should also be done. When the pressure is released, especially if this can happen relatively quickly, a partial blockage may possibly be detected as the flow should be limited by this partial blockage. The probability of detecting a partial blockage should increase with the extent of the blockage (for example, a 20% blockage should affect the flow less than a 90% blockage). Furthermore, the maximum pressure and the speed at which the pipe can be emptied should also affect.

2.2 STANDING SOUND WAVE

A somewhat similar pressure/vacuum method is to mount a pump/speaker diaphragm at the start of the pipe and generate sound with a certain frequency or to generate sound pulses (which contain many frequencies). The utilization of acoustic techniques, such as standing sound wave, are well documented in the literature.[5,6,7] Just like the method described in 2.1, no high under- or overpressure is needed, but only enough to create a sound in the pipe. The frequency is swept or the repetition/pulse ratio of the pulses is changed, to obtain standing sound waves in the pipe. Since the system is closed, standing sound waves can be generated

[5] (Liu, Man, & Li, 2024)
[6] (Wong & McCann, 2021)
[7] (Global, 2026)

even if there is no blockage in the pipe, but then with resonance frequencies that are low because the length is then for the entire system including the sampling container. On the other hand, if there is one or more blockages in the pipe, standing sound waves are created between the start of the pipe up to the first blockage at higher frequencies compared to the case of no blockage. A schematic diagram of this method can be seen in Figure 4. What a frequency sweep with measurement of the impedance can look like in the presence of a blockage. In the impedance spectrum, characteristic multiple peaks are obtained at specific frequencies, f, which correspond to standing sound wave patterns with a certain mode, where L is the length of the pipe from the start of the pipe to the position of the blockage, v is the speed of sound and n is the mode number of the standing sound wave.

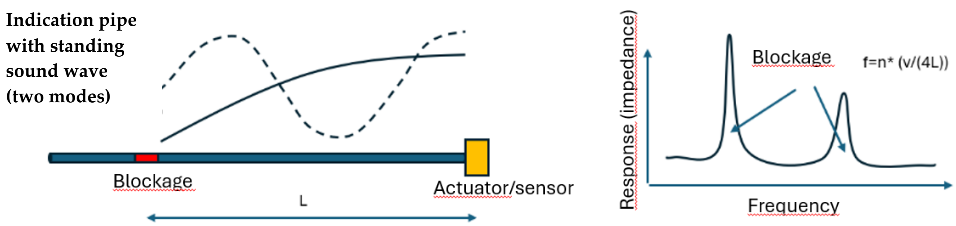

Figure 4: Schematic illustration of the standing sound wave method (left) and an example of an impedance spectrum obtained during frequency sweeping in the presence of a blockage (right).

If it is possible to create a standing sound wave in a certain frequency range (i.e. at a blockage in the pipe), this can be seen from the result that it is possible to measure specific frequency peaks in the electrical impedance of the loudspeaker membrane/speaker system when sweeping the frequency in this frequency range. The position of the blockage can be calculated from the frequency at which the largest change in electrical impedance is obtained. However, the positions of several blockages one after the other in the pipe cannot be measured. A standard electromagnetic loudspeaker system could be used with some adaptation to be connected to the pipe. To measure the frequency-dependent electrical impedance of the electromagnetic system, commercial measurement systems can be used (for example, an Analog Discovery from Digilent together with a laptop to control and store data). Sound will also be generated in the material of the pipe, but this is something that must be studied in a subsequent experimental study.

Another possibility is to generate sound in the metal material of the pipes by, for example, using piezoelectric actuators mounted directly on the pipes and studying the electrical impedance of the actuator or measuring oscillations in the pipe. In a previous project, changes in resonance frequencies in the material structure have been correlated to applied forces against metallic samples using magnetic sensors.[8] When the frequency is swept, mechanical resonances in the pipe will be obtained at specific frequencies. If there is a blockage, this will probably be seen as a change in the resonance properties (amplitude and/or change in resonance frequency). One could also consider measuring the frequency-dependent impedance of the actuator/sensor (piezoelectric sensor), which is performed in electromechanical

[8] (Carlsson, o.a., 2019)

impedance analysis, to detect that there is a blockage in the pipe.[9,10,11,12] In these cases, it is important to study how a specific signal pattern with respect to frequency changes when a blockage is formed in the pipe. The further the blockage is from the start of the pipe, the more difficult it becomes to measure the changes due to the blockage, and a maximum reading distance must be determined from experimental studies.

A method based on a standing sound wave similar to the one described above should be able to detect both total and partial blockages.

We believe that the described acoustic methods work both for straight and curved pipes and that potential damping of the signals due to the surrounding concrete structure has minor effects on the methods. However, this needs to be investigated further in next project phase.

2.3 ELECTROMAGNETIC WAVE

Instead of sound, one could imagine a high-frequency electromagnetic wave being sent into the pipe. This is similar to waveguides in microwave technology, which previously has been shown to detect dielectric objects in metallic pipes,[13] as well as to detect internal defects and material discontinuities.[14] However, it is also somewhat uncertain whether this works, given that each strong bend in the pipe causes a strong attenuation/reflection of the electromagnetic wave. If the bends in the pipe are smaller (smaller radius of curvature), it will be possible to send an electromagnetic wave through the pipe that is not attenuated as strongly. Simpler experiments according to this concept have previously been tested in another type of application and the outcome was positive. A simple antenna (roughly like an electrical conductor) is mounted at the beginning of the pipe and with a VNA (vector network analyzer) reflection parameters are measured that depend on whether there is a blockage in the pipe (in this case of a dielectric material), see Figure 5. The position of the blockage can be measured if the electromagnetic wave is pulsed, similar to how a radar works.

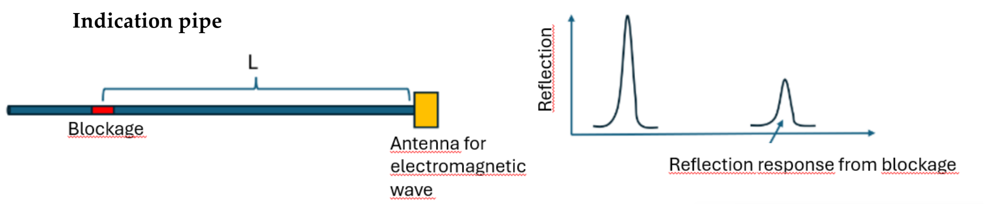

Figure 5: Schematic illustration of the electromagnetic measurement setup (left) and examples of the reflected signal for an unblocked and a blocked pipe (right).

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9 (Na & Baek, 2018)
10 (Silva, Monteiro, Vidal, & Netto, 2014)
11 (Monteiro Jr., da Silva Monteiro, Netto, & Vidal, 2021)
12 (Products, 2026)
13 (Nohlert, Rylander, & McKelvey, 2015)
14 (Sobkiewicz & Bieńkowski, 2021)

2.4 ENDOSCOPY

Several commercially available endoscopic inspection systems are currently used for applications such as leak detection in pipes. These systems typically consist of a camera mounted at the end of a flexible wire that can be steered and rotated in multiple directions, see Figure 7. Such systems enable visual inspection of blockages within a pipe, provided that the camera can be inserted and guided through the pipe system, including sections with sharp bends and complex geometries. The main challenge is to identify a system the provides sufficient maneuverability, allowing steering through bends exceeding 90° over long distances, while also being compact enough to fit within the drain pipes which have a diameter below 20 mm.

After discussions with several manufacturers of endo-/boroscopes, it appears that the current geometry (long and narrow tube, with several 90^{o} bends) is very challenging for commercially available products. The background to this is that the commercial products can be somewhat simplified and divided into two segments; borescopes (pipe cameras) and endoscopes, each adapted for a specific application.

Pipe cameras can be used, for example, for inspecting drainpipes. This means that they can be found in lengths over 150 m. The diameter is often a few millimeters, and they can have a more or less flexible camera at the top. One example is shown in Figure 6. From a dimensional perspective, a borescope is thus possible. However, the cables of pipe cameras are generally not flexible enough to handle the sharp 90^{o} bends in the pipes.

Figure 6: Example of a commercially available boroscope/pipe camera, consisting of a long camera cable, and a larger camera at the tip.[15]

Endoscopes are smaller and more flexible and are used in smaller, more complex applications. The cable is very flexible and can be steered. One example is shown in Figure 7. Depending on the steering requirements, the width of the cable can be a few millimeters down to under a millimeter, where the smallest diameter is unsteered. After discussions with manufacturers, it became clear that they are not manufactured in sufficient lengths, and given a steering function, the friction in the steering cables will limit how many 90^{o} bends the cable can pass.

[15] (Visionome, 2026) Courtesy of Visionome

Figure 7: Example of a commercially available endoscope, consisting of a flexible cable and tip and an integrated camera and display unit.[16] Similar systems are also commonly used for inspection of confined spaces and piping systems.

According to information from a manufacturer, it would be possible to custom manufacture an endoscope based on existing endoscopy products. Given that the steering function is removed, the cable should be flexible enough to handle repeated 90^{o} bends. As the pipes do not have branches and are narrow, there is no need to be able to control the camera head. To reach far enough, the cable can then be extended to the required length. However, this would require development and validation.

A visual method similar to the one described above should be able to detect both total and partial blockages. However, it cannot detect multiple blockages.

2.5 MECHANICAL PROBING

A method similar to the previously described visual method is to simply use a flexible mechanical wire (made of metal or polymer) similar to the systems used by plumbers (drain cleaning cables when cleaning pipes) or electricians (cable pulling tape when laying cables). No camera needs to be mounted at the end of the wire, but you measure how far you can insert the mechanical wire at the end of the pipe

[16] (Visionome, FlexLumen B, 2026) Courtesy of Visionome

by the collection container. An example of a flexible pull-through wire is shown in Figure 7 below. If there is a blockage in the pipe, this will be shown by the fact that the wire cannot be inserted all the way. Cleaning the pipe from the blockage can be done in conjunction with the measurement (similar to the plumber's system). There is a wide range of these systems, and it is important to find a mechanical wire with an optimal material that has a sufficiently small diameter and is sufficiently flexible/rotatable to pass through complicated bends in the pipe. Mechanical probing should be able to detect total blockages and possibly some partial blockages. Given that it is a partial blockage, it is possible that an experienced operator can identify it and move on. If the blockage is extensive enough to prevent the wire from moving forward, it will be interpreted as a total blockage. Mechanical probing is further limited as it cannot detect multiple blockages.

Figure 8: Example of a flexible pull-through wire that could potentially be adapted for mechanical probing of pipes.[17]

[17] (Nelco, 2026) Courtesy of Nelco

2.6 INSTALLATION OF SENSORS DURING MANUFACTURING

If it is possible to mount thin Cu wires/stripes (it does not have to be Cu in the wire/stripes as long as the material has high electrical conductivity) or optical fibers inside the pipes (mounted along the tube surface), then one could use impedance analysis/time domain reflectometry (TDR) for the Cu wire/stripe and Fiber Bragg Grating (FBG) analysis for the optical fibers. When a blockage is obtained, the dielectric/capacitive environment will change where the blockage is and will give a change in impedance or electrical reflection. In TDR, an electrical pulse is sent through the wire/pulse and when a change in, for example, dielectricity (if there is a blockage) is obtained, a reflection of the pulse is obtained and can be read with the detector at the entrance to the pipe. The position of the blockage can be obtained if the speed of the pulse in the wire/stripes is known. Multiple blockages can be detected. It is also possible to measure the impedance in the entire wire/stripes, but then it is not possible to determine where the blockage is, but the measurement and analysis are simpler than with TDR.

The FBG method is an optical measurement method where a Bragg grating is "carved" into the optical fiber with a laser. At the entrance to the optical fiber, a broadband light (many different wavelengths) is sent in, and a reflection of the light is obtained when the light reaches the FBG areas, and the reflected light is analyzed. When a blockage is obtained, it will mean a change in strain in the optical fiber, and this will be measured by analyzing the reflected light (roughly like an optical version of a wire strain gauge). Several blockages in the pipe can be measured. The disadvantage is that the strain measurement is only performed at FBG areas (or in the vicinity of the FBG) and if there is no blockage in the pipe that is not in the vicinity of an FBG area, it may be difficult to detect the blockage with this optical method, but this needs to be studied in more detail. Schematic sketches of the two techniques are shown in Figure 9.

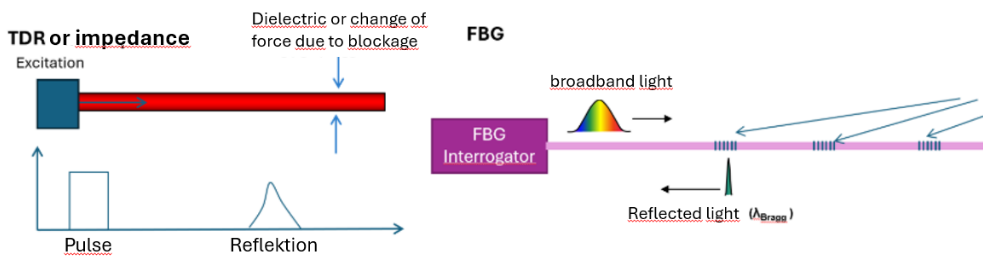

Figure 9: Schematic pictures of impedance/TDR using thin metallic wire (right), and optical measurement using FBG-technique (left).

These two methods are best suited for new installations or major service of the pipes, where wires/strips or optical fibers can be installed.

TDR and FBG methods are established sensor technologies that have previously been used for condition monitoring and structural health monitoring applications

TDR is commonly used for fault localization in cables and conductors,[18,19] while FBG sensors are widely used for strain monitoring in infrastructure and pipeline systems.[20,21] Although no references have been identified for blockage detection in leak indication systems specifically, the underlying measurement principles are well established and considered applicable to this type of system.

2.7 ASSESSMENT OF INDICATION METHODS

Below in Table 1, the aforementioned indication methods are compiled and graded according to various factors. A scale between 1-5 is used, where 1 is the lowest score and 5 is the highest. There are no clear criteria for the different grades, but they are mainly intended to provide a rough qualitative indication. The ranking is merely preliminary and based on the theoretical understanding of the respective methods. Additionally, several methods require additional development and/or additional analysis of the intended application. Hence, there is an uncertainty related to ranking in all categories of the different methods. All methods require practical validation and evaluation before a final ranking can be made.

Table 1: Summary and preliminary rating of the indication methods

Method	Simplicity	Affordability	Sensitivity	Maturity	Safety	Sum
Pneumatic volumetry	4	4	1	2	4	15
Sound wave	3	3	3	2	5	16
Elecromagnetic wave	3	2	4	3	5	17
Endoscopy	4	2	4	3	5	18
Mechanical probe	5	5	2	4	5	21
(Optic fiber/metallic conductor)	2	2	4	4	5	17

As a complement to Table 1, it should be mentioned that no method can reliably identify multiple consecutive blockages. However, it is possible that it can be detected using electromagnetic waves and optical fiber/metallic conductors.

Furthermore, it is possible that all methods can, to some extent, detect partial blockages. However, this will largely depend on the percentage of blockage and

[18] (Cataldo, Cannazza, De Benedetto, & Giaquinto)
[19] (Lundgaard, Hansen, Linhjell, & Nordgaard, 2006)
[20] (Hill, 1997)
[21] (Kersey, o.a., 1997)

how the methods are applied. Endoscopy is probably the only technique that reliably can detect precipitates before they become obstructive.

As seen in Table 1, the total ratings of the different methods are fairly equal, with only the mechanical probe clearly at the top, mainly due to its simplicity and low cost, while maintaining around the same, or better, sensitivity and maturity as the other. Several of the comparatively more technically complex techniques require more validation, and more specialized equipment. However, once suitable equipment is validated, the investigation would be more repeatable, as the operation is less person dependent, and there are fewer practical moments that could cause errors, such as snagging, human errors etc. Endoscopy could be argued as a middle path, as while its operation is relatively simple, it does provide an enhanced awareness of the position of the probe in the pipe.

The optical fiber/metallic conductor will not be discussed in this section as it is only relevant during reconstruction.

2.8 DEVELOPMENT AND VALIDATION NEED

Above, several possible methods for detecting blockages in the pipes have been listed. However, how the methods work in practice is not clear. To investigate this, it is proposed that one or more methods will be tested in mock-up setups. The scope and design of these experiments are briefly described in this chapter.

Mockups have previously been utilized in similar experiments. The authors have, however, only been able to find literature primarily describing adjacent situations. In a study investigating blockage detection in pipe systems by high frequency ultrasonic, a mockup was constructed. In this case the blockage was introduced by using a pipe section with an outer radius smaller than the experimental tubes inner radius. This allowed the blockage to be moved back and forth to investigate the methods viability at different distances. Worth noting is that the experimental pipe was straight, whereas it is seen as important for the mockup proposed in this report to have sharp bend to properly simulate realistic difficulties.[22]

In another article focused on mockups used for detection of blockages by transient tests, it was noted that the introduction of a small diameter pipe in the mockup was by far the most commonly used strategy to simulate a partial blockage. The second most common was the introduction of in-line valves.[23] Additionally, one study was found in which the partial blockage was constructed with rock aggregates and coconut coir.[24]

Depending on which detection method is intended to be validated, there are different limiting factors. A mutually important factor is, however, that a pipe system of the correct dimensions, material thickness and bends is required to provide the right conditions. Furthermore, it is of interest to verify the different methods with a wide variety regarding location and extent of blockage. Ideally, a

[22] (Nasraoui, Louati, & Ghidaoui, 2023)
[23] (Brunone, Maietta, Capponi, Duan, & Meniconi, 2023)
[24] (Duan, o.a., 2017)

modular system, like some described in literature[22,23,24,,25], would be of interest. In such a modular system, an array of different pipe sections could be manufactured to achieve a variety of different lengths, curvature and extent of blockage. Depending on how the parts are assembled, the position of the blockage could then be altered. A modular system, like the one outlined above, would probably be suitable for most of the indication techniques. It is, however, unclear how much the joints would interfere with the signal in standing wave measurements in the pipe wall.

For the pneumatic volume determination, the length of the mock-up system is likely to be of minor importance, although it is clearly advantageous to have a full-length system. For the other methods (standing sound wave, endoscopy and mechanical probing), it is important that the length of the mock-up corresponds to the actual length of the pipe system. This is because these three methods will probably be negatively affected, or limited, by increasing length.

Provided that validation is carried out with satisfactory results, the method(s) can then be tested in the real application.

[25] (Chahardah, Fathi, & Haghighpour, 2021)

3 Cleaning methods

3.1 CHEMICAL DISSOLUTION

Based on the available information, the deposits found in the leak detection systems appear to be some type or combination of precipitates. Some chemical analyses have been performed and have shown content of, among others, boron, calcium, aluminum and iron, with boron clearly being the largest proportion. Given the appearance (white and somewhat opaque) and the circumstances (process water that has been in contact with concrete), the assessment is that it is likely to be some, or a combination, of salts. If the starting point is that the precipitate consists of different types of borates, or to a lesser extent carbonates, chemical dissolution is a possible method.

Some crystalline forms of boron chemicals can be relatively easy to dissolve, such as boric acid or borax, which dissolve in water. Calcium borates, however, can be more difficult to dissolve and require the use of acids. A variety of different acids are used industrially to dissolve different calcium borates to produce boric acid. These are both organic acids (including citric acid, acetic acid, oxalic acid and propionic acid), and strong inorganic acids (hydrochloric acid, sulfuric acid, phosphoric acid and nitric acid).[26,27] Furthermore, there are also studies that show that citric acid increases the solubility of poorly soluble calcium salts. This occurs by complexing calcium and thus facilitating its removal.[28,29] Sometimes additional chelating substances can also be added, such as EDTA (ethylenediaminetetraacetic acid) or HEDTA (hydroxyethylethylenediaminetriacetic acid).[30] Based on this, it would be reasonable to assume that citric acid is primarily used.

The disadvantage of using acidic solutions to dissolve a blockage is that they are corrosive and can thus have a negative effect on the steel pipe. This risk is often managed industrially by adding different types of corrosion inhibitors. There are many types of corrosion inhibitors, and depending on the circumstances, some are more suitable than others. In a system where carbon steel is to be protected in an acidic solution, organic inhibitors are often used. These work by binding to the metal surface and creating a hydrophobic film, which protects the metal surface from the acid. Examples of corrosion inhibitors in acidic systems include imidazoline, aromatic aldehydes, amines, amides, pyridine and thiourea. These can also be mixed with each other or with excipients for a stronger inhibitory effect.[31] In studies, the effect has been shown to be as high as 90-98% corrosion reduction, depending on the inhibitor formulation and temperature.[32,33] In one

[26] (Kuskay. B, 2011)
[27] (Elbeyli, 2015)
[28] (Gácsi, o.a., 2016)
[29] (Melia Rodrigo, Ribeiro, Verissimo, Esteso, & Leaist, 2019)
[30] (Mail, Gonzáles-Gutiérrez, Calderón-Anaya, & Casillas, 2023)
[31] (Finsgar & Jackson, 2014)
[32] (Kousar, o.a., 2021)
[33] (El-Nagar, Khalil, Atef, Nessim, & Ghanem, 2024)

example, it is shown that the corrosion rate of carbon steel in 1.0 M hydrochloric acid at 60°C is reduced by 94% from 46 μm/h to 2.6 μm/hour.[34]

To ensure that no acid remains at any low point, the entire pipe system can be rinsed afterwards with a weak alkali/buffer solution.

However, it is impossible to give a clear suggestion as to which chemical/temperature/corrosion inhibitor is suitable without properly investigating what the precipitates consist of. Possible methods for this would be, for example, a combination of glow discharge optical emission spectroscopy (GDOES), X-ray diffractometry (XRD), wavelength dispersive spectrometry (WDS) and possibly Fourier transform infrared spectroscopy (FTIR). This is because the elements, crystal structures and/or chemical bonds present in the sample would appear, which would facilitate a determination of what the sample contains. The composition of the acid and corrosion inhibitor can then be determined.

3.2 ULTRASONIC

This type of method is common for removing various types of mineral blockages and there are many commercially available products. What limits its use in this case is that they must be small, long and flexible enough to enter far into the leak indication system, something that the commercial systems do not seem to be designed for.

It is difficult to find information in the literature about what is required of an ultrasonic system to remove mineral blockages of borates. However, there is literature on how calcium carbonate is removed with ultrasound. There, frequencies between 18 and 50 kHz and intensities between 1.9 - 250 W/cm^2 seem to be used, where higher values generally have better effect, although the benefit decreases above a certain point.[35,36,37,38,39]

In dental hygiene applications, ultrasonic technology is used to remove tartar. The peaks on these can be relatively small, and with intensities around 15 W/cm^2.[40]

The possibility of custom manufacturing a dedicated ultrasound probe may exist. This would require a long, very flexible cable, and a piezo element on top. However, there is uncertainty about how much power can be obtained from a sufficiently small piezo element, and what power is required to affect the currently unknown mineral precipitation. It is possible that lower power can be compensated for by a longer period of time, to a certain extent.[41]

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[34] (Zhang, o.a., 2015)
[35] (Vasyliev, Vasylieva, Novosad, & Gerasymenko, 2018)
[36] (Pecnik, Hocevar, Sirok, & Bizjan, 2016)
[37] (Kojima, Tamaguchi, & Nishimiya, 2010)
[38] (Nishida, 2004)
[39] (Zhang, Zang, Ma, & Wang, 2020)
[40] (Price, Tiong, & King, 2014)
[41] (Qu, Luo, Xu, Li, & Fu, 2026)

3.3 MECHANICAL CLEANING

A common method for cleaning pipes is with a so-called high-pressure nozzle with a backward jet. This means that the nozzle is driven forward by itself. Based on what the manufacturers state, this method appears to be able to be used for, among other things, limescale blockages. These systems also appear to be limited by the geometry of the duct system. There are several different variants and dimensions, but no system is found on the market that can safely get past the tight bends. After discussions with manufacturers, it appears that there are a number of different types of nozzles, several of which are found with a small diameter, between 10–15 mm, which makes them suitable for the ducts. However, the length of these small nozzles is 15–20 mm, which is why it is uncertain whether they can get past the sharp bends. Even if the nozzle itself is shortened, at least 10 mm is required for the threads to be able to connect a high-pressure hose with 1/8", which seems to be the smallest coupling that larger companies manufacture. There seem to be very small nozzles on the market that connect to 1/16", however, the supply seems to be very limited, and it is uncertain whether the geometry works.

It would possibly be possible to custom manufacture a high-pressure nozzle with dimensions that enable use in the pipes. However, in discussions with manufacturers, the threading was highlighted as a limiting factor in handling the 90^{o} bends. If the dimensions are too small, there is also the question of whether the pressure will be able to drive the entire nozzle and hose in the sections that slope upwards.

There are also commercially available products that are based on rotating chains, which are claimed to be effective in removing hard coatings. The limitation, however, is that the tip must pass the deposit for the rotating chains to break up the deposit. There is probably a limit to how large a partial blockage can be for the cables and chains to pass. Furthermore, there is uncertainty as to whether the tight bends restrict rotation too much for the expected effect to be achieved.

3.4 EVALUATION OF CLEANING METHODS

Below in Table 2, the mentioned cleaning methods are compiled and graded according to various factors. A scale between 1-5 is used where 1 is the lowest score and 5 is the highest. There are no clear criteria for the different grades, but they are mainly intended to provide a rough qualitative indication. The ranking is merely preliminary and based on the theoretical understanding of the respective methods. Additionally, all methods require additional development and/or additional analysis of the intended application. Hence, there is an uncertainty related to ranking in all categories of the different methods. All methods require practical validation and evaluation before a final ranking can be made.

Table 2: Summary and preliminary rating of the cleaning methods.

Method	Simplicity	Affordability	Accuracy	Maturity	Safety	Sum
Chemical dissolution	3	4	4	3	3	17
Ultrasound	3	3	2	2	5	15
Mechanical cleaning	4	4	2	2	4	16

According to the assessment above, all methods rank fairly equal, but with chemical dissolution at the top. The main advantage of chemical dissolution would be that it is the most likely method not to be limited by sharp bends and complex geometry. Additionally, dissolution of precipitates and deposits in acid is a common method. The drawback on the other hand is that it does require handling of corrosive chemicals, and caution needs to be taken to avoid injury or damage. Both ultrasonic and mechanical cleaning are generally more forgiving to handle, but both techniques require developmental work, custom manufacturing and subsequent validation, before being ready to put to practical use.

3.5 DEVELOPMENT AND VALIDATION NEEDS

Unlike the indication methods, there are several important steps that should be taken before a mock-up study would be relevant.

3.5.1 Chemical cleaning

To ensure that the chemical cleaning gives the expected result, a proper characterization of the deposits causing the blockage is required. Without such, the design of the cleaning solution, methodology and the choice of corrosion inhibitors become uncertain. The characterization should strive to analyze the samples quantitatively as much as possible with respect to B, Ca, C, O, S, Na, K, Al, Fe. This would provide a better basis for which types of mineral substances may be relevant. Possible methods for doing this would be, for example, GD-OES (Glow Discharge Optical Emission Spectroscopy)[42,43], or WDS (Wavelength Dispersive Spectroscopy)[44]. Both methods analyze the elemental composition, the first through analyzing the emitted light from atoms excited by the plasma, and the latter by measuring the X-rays at specific wavelengths. Furthermore, identification of the crystalline phases present in the sample would be important. For this purpose, XRD (X-ray diffraction) is suitable. XRD works by measuring how X-rays are diffracted by different crystalline materials.[45] Finally, it would be possible to use FTIR (Fourier Transform Infrared Spectroscopy) to map the bonds that occur in

[42] (Determine chemical concentration depth profiles of thick layers with glow discharge optical spectroscopy (GDOES), 2026)
[43] (Glow Discharge Optical Emission Spectrometry (GDOES), 2026)
[44] (What is WDS? Introducing Wavelength Dispersive Spectroscopy, 2026)
[45] (X-ray Diffraction (XRD) Academy, 2026)

order to identify any amorphous structures that XRD cannot detect.[46] The methods measures the absorption of infrared radiation as a function of wavelength, This is then correlated to the presence of chemical bonds or structures. FTIR can also identify which different groups are present in the sample, such as borate groups[47] or carbonate groups.[48]

After characterization has been performed, a cleaning methodology can be designed with regard to type of chemicals, concentration, temperature, exposure time, pressure, corrosion inhibitors and post-rinse. Lab tests aimed at verifying the dissolution of the mineral phase and the effect of corrosion inhibitors would be important.

3.5.2 Ultrasound

The availability of small ultrasonic probes that are mounted on a sufficiently long and flexible cable is low. Instead, it is proposed to manufacture one yourself by placing a piezo element that meets the dimensional requirements on a flexible cable. A first step would be to investigate how large an effect such small piezo elements have on the mineral material in question. In order to validate this, hardness measurements must be carried out on the mineral material, after which the corresponding material can be examined. Alternatively, a chemical characterization similar to that in the chapter above can be carried out, after which it may be possible to estimate a hardness. To ensure that the probe not only provides a sufficiently high effect, but can also move in the pipes, it is proposed that the probe be tested in a mock-up of the pipe system, similar to the mock-up that is proposed to be used for the indication methods. Validation of accessibility and effect is proposed to be carried out in parallel and iteratively.

3.5.3 Mechanical cleaning

Regarding mechanical cleaning, custom manufacturing of a hydromechanical nozzle would be a possibility. This would need to be small enough to be driven through the pipes, while at the same time requiring sufficient force for propulsion and cleaning effect. Here too, it would be possible to custom manufacture a hydromechanical nozzle that is small enough to function in the complex geometry.

[46] (Pisciella & Pelino, 2005)
[47] (Doweidar, El-Damrawi, & Al-Zaibani, 2013)
[48] (Grunenwald, o.a., 2014)

4 Summary and suggestion for continuation

Within this project, possible detection and cleaning methods targeting mineral blockages in leak indication system pipes have been theoretically studied. The primary goal has been to identify methods that can work with less validation. Secondarily, methods that can work after development work have been presented. Overall, the complex structure and geometry have been the limiting factor for several techniques, where the 90° bends can be pointed out as particularly challenging. Despite this, several plausible detection and cleaning methods have been identified. These methods, as well as any recommended development/investigation/validation work, are presented below.

4.1 INDICATION METHODS

Most of the detection methods presented are relatively mature technologies but have not been validated in the specific application before. Thus, a suitable next step would be to validate these technologies in the lab in mock-ups. These mock-ups are proposed to be designed from metal pipes with corresponding dimensions as a leak indication system, these pipes can then be bent and flexed to mimic the geometry found in reality. To mimic the mineral blockages, it is proposed to design a modular system where smaller pipe segments with different levels of blockage can be inserted at different places in the mock-up. This would be a suitable first step.

If the outcome is favorable, the mock-up should then be scaled up to full length, preferably also with the same vertical incline as in reality. This is because most technologies can be negatively affected by increasing length, number of bends and steep incline

Below are listed the techniques that, with only minor modifications, are considered mature enough to be validated in a mock-up directly in the next step.

- Pneumatic volumetry
- Standing sound wave
- Electromagnetic wave
- Mechanical probing

The above validation in mock-up is also relevant for the endoscopy method, but only after the previously mentioned development work/special manufacturing has been carried out. Since the majority of the methods are considered ready for a validation step, it is proposed that all methods be included in a validation step. This is because the production of prototypes for the methods is considered to correspond to a relatively low effort in relation to a full-scale mock-up system. If none of these methods perform satisfactorily, the endoscopy method can begin to be developed.

4.2 CLEANING METHODS

Like the detection methods above, possible cleaning methods are also severely limited by the geometry of the pipes. None of the possible cleaning methods are currently considered to be in a verification stage, but all methods are in need of further investigation and/or development work.

- Chemical cleaning methods are considered to be relatively proven. However, there are uncertainties regarding how the method should be formulated in this specific case as there are still uncertainties regarding the composition of the mineral substance that forms a blockage in the pipes. A first step would therefore be to properly characterize the mineral substance. Examples of suitable methods would be GDOES/WDS for elemental composition, XRD for analysis of crystal phases, and FTIR for analysis of any amorphous phases and functional groups. Proposals for the formulation of a chemical cleaning method can then be made.

- There are several ultrasonic actuators on the market, however their use is limited by the fact that they are too large to enter the pipes. However, it is possible to build your own piezo elements that are small enough to enter the pipe. This accessibility can be evaluated in the same mock-up used for the detection methods. Furthermore, validation is required that the actuator's effect is high enough to affect the mineral material that the blockage consists of. This means that this cleaning method also requires identification of the mineral substance in order to be validated. It would also be advantageous if hardness measurements could be performed in order to have a reference value to refer to in laboratory tests. Validation of accessibility and effect is proposed to be done in parallel and iteratively

- Mechanical cleaning is also severely limited by the geometry of the pipes. There are many different types and sizes of nozzles intended for cleaning and unblocking high-pressure pipes. There are nozzles that have a suitable diameter to fit the pipes, but they are probably too long to cope with the sharp 90° bends. This is due to the required length of the thread for a 1/8” hose. Few nozzles seem to exist for 1/16”, but it is unclear whether the geometry is suitable. To develop this method, contact should be established with nozzle manufacturers to investigate the possibilities of custom-manufacturing a nozzle.

As a first step, it is suggested that a thorough characterization (both chemical, structural, and hardness) of the mineral substance be carried out. After that, the formulation of chemical cleaning and development of an ultrasonic actuator can begin.

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INSPECTION OF PIPES IN LEAK INDICATION SYSTEMS

Leak indication systems in nuclear power plants are used to detect leakages from fuel pools. In draining pipes, blockages due to mineral deposits have been noticed, reducing their functionality. This project investigated methods to detect and remove such blockages. Leaking water drains through narrow (~20 mm), long (20–30 m) cast-in steel pipes with sharp bends, making inspection and cleaning difficult due to limited tool size, flexibility requirements, friction, and signal transmission challenges.

Several potential detection methods were identified, including pneumatic volumetry, standing wave techniques, electromagnetic methods, and mechanical probing. While not yet established for this application, they show promise and should be validated using a modular mock-up system replicating real pipe geometry and allowing controlled blockage placement. Endoscopic inspection is also possible but would require specialized equipment.

Proposed cleaning methods (chemical, ultrasonic, and hydromechanical) require further development. Chemical and ultrasonic approaches are limited by insufficient knowledge of the clogging material, and detailed mineral characterization is recommended. Hydromechanical cleaning may be feasible but would require specially designed equipment due to dimensional limitations.

A new step in energy research

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