Felix Gack* and Michael Pfau*

Development of a sampling system including quality assured sampling procedure for nonaccessible area (Bero)

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Abstract: The Bero research project aims to develop a method for sampling inaccessible areas. Specifically, this involves the drainage pipes beneath the reactor of a nuclear power plant. These are straight pipes made of mirror-welded polypropylene embedded in reinforced concrete. The aim is to obtain approval for installation by taking samples from the inside of the pipes, thereby avoiding the need for removal. Due to the adhesive bond between the pipes and the surrounding concrete, removal of the pipes is only possible at great financial and mechanical expense. Within the project, various approaches are being pursued and different prototypes are developed. These are intended to use various tools to take reproducible samples at a defined location within the pipe. To be able to make a qualitative statement about possible impurities and contamination, it is crucial that the sample taken is as homogeneous as possible and that the material properties of the pipe remain unchanged. However, individual methods for striping the surface present various difficulties when dealing with polypropylene. The different processes result in varying restoring forces, electrostatic charging, and different levels of heat generation. In order to investigate the problems mentioned above, a test rig including measuring systems was set up as part of the project. This enables different tools to be examined in terms of their suitability. By analyzing the influence of different tool specifications and operating parameters, a system can be developed that is geared towards solving the problem.

Keywords: sampling system; polypropylene; pipes; decommissioning; clearence of buildings; nonaccessible areas

***Corresponding authors: Felix Gack and Michael Pfau**, Karlsruhe Institute of Technology, Karlsruhe, Germany, E-mail: felix.gack@kit.edu (F. Gack), michael.pfau@kit.edu (M. Pfau)

1 Introduction

Due to the German government's decision to phase out nuclear energy, there is currently and will continue to be a high demand for new technologies, processes, and skilled workers for the decommissioning of nuclear facilities in the coming years. In order to meet the specific requirements of decommissioning, new processes must be developed or existing technologies further refined (BASE 2025). Currently, numerous nuclear reactors worldwide are undergoing decommissioning. As of 2025, 218 nuclear power reactors have been permanently shut down worldwide, the majority of which are located in Europe, where around 61 % of all closed reactors are situated. Many of these reactors are currently in different stages of the decommissioning process (Schneider et al. 2025). According to the International Atomic Energy Agency (IAEA), more than 200 nuclear power reactors have already been retired from service globally, and a significant share of the existing nuclear fleet is expected to reach the end of its operational lifetime in the coming decades, resulting in further decommissioning projects worldwide (IAEA 2024). One important aspect concerns the assessment and treatment of piping systems that were installed during the operation of a nuclear power plant and are still located in the building structure. These systems often require radiological assessment before they can be released in accordance with the applicable radiation protection regulations. One specific application concern concrete-encased pipe systems for building drainage, which are located in the foundation slab of the reactor building in the controlled area of the power plant and run below the reactor pressure vessel. These pipes are part of the building drainage system and serve to collect and drain seepage water, intruding groundwater, condensate, and other non-process-related liquids from the building structure. During operation of the nuclear power plant, this water was collected via a pipe network and transported to central collection points, known as sumps, where it could be monitored and, if necessary, further treated. The corresponding pipe systems are located to a large extent in the foundation slab of the reactor building and run several meters below the accessible rooms of the control area in some cases. The system is accessible via drains and collection points in the rooms above, so that inspections and maintenance measures can be carried out during operation.

According to various energy supply companies, the total length of these pipes in the floor slab of a reactor building is approximately one km. The pipes consist mainly of mirror-welded polypropylene (PP) plastic pipes with diameters of approximately DN80 to DN150 (80–150 mm) and wall thicknesses between 4 and 6 mm (MCM Systeme 2016). However, inventories carried out as part of current decommissioning projects show that other materials such as polyvinyl chloride (PVC), polyethylene (PE) or metallic materials such as gray cast iron were also used in some areas. The majority of the pipes run in straight lines, but there are also pipe sections with bends, for example in the area of building ring pipes with large bending radii. During the operating phase, various types of water were collected via these pipes and discharged via the connected sumps. However, due to the operating conditions, it cannot be completely ruled out that small amounts of radioactive contamination were also introduced into the pipes in this way, which could accumulate on the inner surfaces over time (RWE/PE 2025).

A particular challenge during decommissioning is that these pipes are located deep within the foundation slab and in some cases up to 1.20 m below the concrete surface. They are also surrounded by reinforcement. Removal by completely removing the concrete cover would be technically complex, cost-intensive, and involve considerable structural intervention. There is therefore a need for technical solutions that allow sampling directly from the inner surface of the pipe in its installed position in order to enable radiological assessment. The aim is to remove a defined amount of material from the pipe wall and to determine the exact position of the sampling. If it can be proven that the release criteria are met, the pipes can then remain in the building structure. Currently, there is no commercially available system that fully meets these requirements. In particular, several technical challenges must be taken into account, including the precise determination of the sampling position within the pipe, the removal of a defined amount of material across the entire pipe cross-section, and the handling of geometric irregularities such as ovalities, weld seams, or eccentricities (RWE/PE 2025).

In addition, it must be ensured that the material removal is recorded with as little loss as possible in order to enable reliable radiological analysis. At the same time, there must be no contact with the surrounding concrete structure, as this could lead to uncontrolled spread of contamination. If it is not possible to release the pipes in their installed position, additional methods must be developed for the efficient removal of the pipes without having to completely remove the surrounding concrete structure. Figure 1 shows a schematic representation of the pipes in their installed position using the example of a pressurized water reactor. The diameter of the foundation slab of such a reactor building is typically around 50–60 m, with the basic structure of the drainage system being comparable between different plants. The BERO project (FKZ: 15S9444A+B) is funded by the German Federal Ministry of Research, Technology, and Space as part of the “FORKA – Research for the Decommissioning of Nuclear Facilities” funding program and aims to develop a demonstrator for quality-assured sampling from pipes in their installed position. The project is being carried out by IBASS GmbH & Co. KG in cooperation with the Institute for Technology and Management in Civil Engineering at the Karlsruhe Institute of Technology, while RWE Nuclear GmbH and PreussenElektra GmbH are providing advisory support.

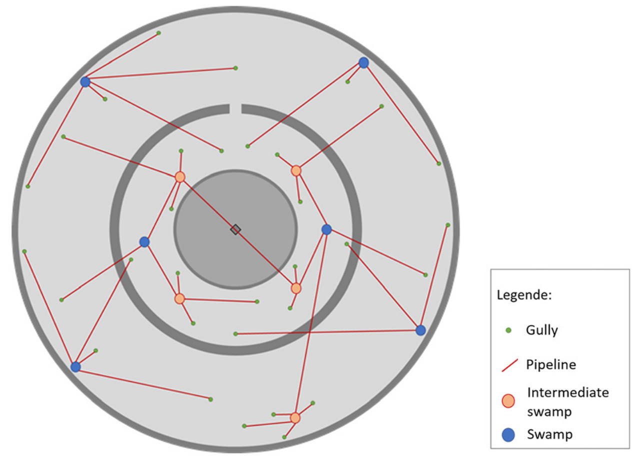

Figure 1: Schematic diagram of the pipes in the foundation of a pressurized water reactor (PreussenElektra 2025).

2 Materials and methods

In order to collect material for sampling the pipes, material removal methods from DIN 8580 were first consulted and examined for their suitability for sampling, and then potentially suitable methods were identified. Based on the analysis of the various manufacturing processes within DIN 8580, a test rig was designed, constructed, and equipped with suitable sensor technology. This ensures that the influencing factors and application limits are adhered to on the basis of defined, project-related criteria. The test rig (see Figure 2) is designed in such a way that different tools and tool types from different manufacturing processes can be tested and analyzed. Based on a preliminary utility analysis, the subgroups that offer the greatest benefit for the specific

Figure 2: Test rig for different tools at KIT-TMB with the drive motor for the pipe (a), the pipe holder (b), the radial feed unit (c), the measuring devices (d), and a tool holder (d).

requirements of sampling plastic pipes were identified. The criteria used here can be divided into three categories:

- Local conditions: This concerns the challenges in the nuclear power plant, such as accessibility issues, very small pipe diameters, and possible contamination.
- Characteristics of polypropylene pipes: This concerns the specifications for collecting samples from polypropylene, such as melting temperature, material hardness, or structural characteristics.
- Project-related specifications: Specifications developed in the project for the system, sample material, and removal parameters.

As a result, different designs and tools from the subgroups milling, planing, sawing, and scraping, which belong to group "Cutting with geometrically defined cutting edge," are being tested. The test rig is designed in such a way that a very wide range of parameters can be investigated.

The rig is used to investigate and optimize the processing of polypropylene pipes in the context of nuclear facilities, particularly for applications such as the decontamination of radioactively contaminated pipes. The modular design of the system ensures that a wide range of different manufacturing processes, tool types and designs can be systematically tested in order to identify and validate process specific parameters. During the tests, the electrostatic charge of the pipe and the sample material, the heat generation at the probing point and, if necessary, the dust generation are continuously recorded. Currently, however, there is no significant dust generation, as the primary goal is to produce chips that are as large and cohesive as possible, which facilitates the handling and collection of the sample material and minimizes potential of contamination spread. The image in Figure 2 illustrates the connection between the drive motor for the pipe (a), the pipe holder (b), the radial feed unit (c), the measuring devices (d), and a tool holder (d). The control and output of the individual operating parameters and the data obtained from the measuring sensors can be entered and displayed via a display integrated into the control cabinet. The programming is designed so that all components can be controlled individually and the various operating parameters and evaluations remain flexibly adjustable and selectable.

The basic structure of the system is based on open-source software to ensure maximum flexibility, adaptability, and reproducibility, which is crucial in scientific research and especially in sensitive areas such as nuclear facilities. The manufacturers of the sensor components provide both proprietary and open systems, supplemented by standardized code libraries that enable the development of custom software solutions. Python libraries are provided for this purpose, allowing efficient and seamless programming, for example for real-time data processing and analysis. A Raspberry Pi 5 serves as the central hardware basis, on which Docker Container are implemented to rule out potential interference between the individual software modules and create a stable, isolated operating environment. This reduces system failures and increases reliability during lengthy test series. The control system is visualized using the user-friendly Node-RED platform, which offers an intuitive graphical interface for process design, while the underlying control logic was programmed in Python to implement complex algorithms and automations. The variable structure of the custom Node-RED dashboard allows both the control of individual tests (A) and the evaluation and visualization of tests that have already been carried out (B). Finally, the data sets from completed tests can be converted into CSV format for more extensive analysis of the sensor values. Both the dashboard for controlling the test rig (A) and the area for evaluating and exporting previously recorded data (B) are shown as examples in Figure 3. Figure 3A shows various setting options such as the selection of the tool, the tool motor, and the pipe motor, as well as the parameters assigned to these motors, such as speed or number of rotations. Furthermore, you can also choose between automatic feed via the distance sensor and manual feed. In the second part, Figure 3B shows the recorded measurements. The curves for the force in the *X*, *Y*, and *Z* directions are recorded on the left-hand side, while the graph on the right shows the corresponding moments of the respective axes. The graph at the bottom shows the distance between the tool and the inner surface of the pipe, thus clearly illustrating the ovality of the pipe.

In addition, a MariaDB database with MySQL was set up to continuously record and archive relevant data such as timestamps, sensor values, and parameter values for each individual test. This database structure not only enables precise tracking of the experiments, but also advanced analyses such as correlation studies between process parameters and material behavior, which is essential for optimizing the decontamination processes.

A comprehensive range of measuring sensors is available for data acquisition, enabling multidimensional characterization of the machining process. The 6-axis force/torque sensor (model K6D110 8kN/500Nm from ME Meßsysteme) records all forces and torques generated during the machining process with high accuracy. This ensures that the tension of the subsequent carriage, a mobile pneumatic system that will carry the tools along the pipes, is adjusted to the determined restoring forces in order to guarantee mechanical stability and precision in real-life application scenarios. The electrostatic charges generated by the processing of polypropylene are recorded during the tests using the portable IZH10 measuring device from SMC, which is attached to a self-constructed holder on the tool head. An effective reduction of this charge is particularly

Figure 3: Various dashboards for controlling the test bench (A) and visualizing the recorded data (B), developed with Node-RED.

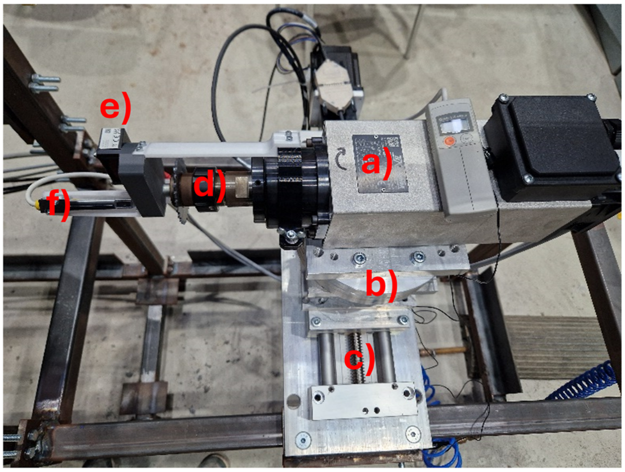

Figure 4: Special tool (d) and sensor head (e, f) with a high-frequency motor (a) from Teknomotor, mounted on a 6-axis force sensor (b) with the possibility of radial adjustment via the linear unit (c).

important for the collection and removal of the sample material produced, as it prevents electrostatic adhesion and associated contamination transfer. To ensure a consistent ablation depth across the entire surface of the area to be sampled, the ILD1325 laser distance sensor from Micro Eplison is also mounted on the tool head. This sensor continuously measures the distance between the ablation tool and the inner wall of the pipe. The distance can then be adjusted using a backlash-free linear unit from Igus to compensate for manufacturing tolerances in the pipes. This means that pipes with ovality at the sampling point can also be sampled. The tool head shown in Figure 4 illustrates which components have been installed. In this illustration, a spindle motor (a) is mounted on the 6-axis force sensor (b), while this unit is radially fed via a linear unit (c). The tool currently in use (d) is connected to the motor by a tool holder. With the help of 3D-printed parts, a distance sensor for the feed (e) and a measuring device for electrostatic charging (f) were placed directly in front of the tool.

The Testo 872 thermal imaging camera is used to monitor the cutting temperature of the tool and the polypropylene. It has a material-dependent adjustable emissivity coefficient, enabling precise temperature measurements. This is highly relevant, as exceeding the melting temperature of polypropylene must be avoided in order to prevent thermal degradation, contamination spread and uncontrolled melting of the material. These are all aspects that require strict safety standards in nuclear facilities. After sampling, the cut quality is evaluated using the 2910-25/PT laser scanner from Micro-Epsilon, which analyzes the sample in terms of width, length, and depth to ensure a high-quality groove. Chip formation is checked, particularly with regard to possible melting or other defects, using the Stemi 305 trino microscope from Zeiss, which enables high-resolution microscopic examinations. The correlated combination of these different data sets enables well-founded qualitative and quantitative statements to be made about the sampling, which in turn forms the basis for iterative improvements to the system in nuclear facilities.

3 Results

3.1 Preliminary tests with commercial tools with defined cutting edges

A wide range of tools are suitable for processing polypropylene in accordance with project-specific requirements. Within the project various designs of saw blades, disc cutters, and parting inserts are analyzed. The influence of the tool material (HSS, solid carbide), the number of teeth and geometry, as well as the operating parameters of speed, feed rate, and depth of cut are examined. The main focus is on the restoring forces generated, heat development or heat build-up, electrostatic charging, and the general cut and sample quality. The results show that lower restoring forces occur at higher speeds, lower feed rates, or more cutting teeth. These are desirable because the sampling tool must clamp itself in the pipe. With non-rotating tools, such as parting inserts, these restoring forces increase and must be minimized. Due to the poor thermal conductivity of polypropylene, heat generation is another problem that occurs when machining polypropylene. Smaller distances between the teeth and higher operating parameters for speed, cutting depth and feed rate cause heat to build up at the cutting point. With scraping tools, heat generation is lower and heat build-up can be better controlled. Such heat accumulation should be avoided, as it can lead to a change of material samples and also to the spread of contamination. A major problem with material striping on polypropylene arises due to electrostatic charging occurs at the cutting edge. This causes the sample material to stick and makes it very difficult to collect in whole. By varying the operating parameters, the tool material and the geometry, it was possible to influence the electrostatic charging but not eliminate it. Further test series and parameter studies are still pending. However, non-rotating tools do not exhibit electrostatic charging, which is why a parallel research path towards a single-blade system (see Section 3.2) was pursued. Reliable quality for sample removal was achieved with various tools.

3.2 Single-blade system

A series of tests were carried out with various scraping tools. However, as none of the commercially available single-blade systems were entirely satisfactory, a proprietary sampling tool was developed and tested based on the previous results from tests and the project-specific requirements. This tool design, developed at KIT-TMB, is shown in Figure 5. Compression springs of varying hardness can be clamped between the two interlocking parts of the sampling head, causing the blade to press against the inner wall of the pipe with a specific pressure defined by the compression spring. This allows the problems encountered in the test series, such as jamming during the cutting process and slipping during chip formation, to be remedied by allowing the tool to adapt to the irregularities of the pipe. The upper section (see component A exploded view Figure 5) is positioned at the level of the center axis of the pipe and clamped in a tool holder or mounted on the subsequent carriage vehicle developed by Ibass GmbH (see Section 3.3). The interlocking connections between the two parts ensure that transverse forces are absorbed during the cutting process, thus preventing twisting (see rectangle 1, Figure 5), which was a particular problem with tools with clamped blades. A cavity is located at the front of the sampling head (component B), directly below the cutting edge of the blade (see rectangle 1b, Figure 5). This cavity serves to remedy the problem of controlled chip removal and collection. In addition, the supply of compressed air can reduce another problem that has arisen, namely heat build-up during the cut. Below the blade, next to the cavity, there are also two channels for heating elements, which heat the screwed-in blade (see rectangle 2, Figure 5). Initial test series showed a significant improvement in the cut pattern and a reduction in the restoring forces when the blade was heated. The blade is fixed to the sampling head (component B) with three screws, which reduces twisting and bending due to the cutting forces that occur. In addition, the simple fixation ensures quick and easy blade replacement (see rectangle 3, Figure 5). The blade hits the inner wall of the pipe at an angle of approx. 20° and has a slight protrusion of the sampling head towards the rear of the blade. Previous test series have shown this to deliver the best results. This geometry prevents the blade from penetrating too deeply and improves both the cutting quality and chip formation.

Figure 6 shows the prototypes, which were initially produced using 3D printing and are primarily used for initial functional testing. Since the sampling head was designed for quick and easy blade replacement, different blade designs can be tested. Initial tests showed that a curved blade shape (see prototype B with hollow chisel blade made of stainless steel, Figure 6) has a beneficial effect on chip formation. In addition, the blade shape, hardness and width must be adapted to the specific application. For this reason, different geometries and designs are being tested. Prototype A (Figure 6) has a wide, double-sided scalpel blade made of hardened carbon steel, while prototype C has a strong lawnmower blade made of titanium-coated stainless steel. Once the findings from these tests are convincing, the plan is to manufacture an advanced version made of metal in order to test the function of the heating elements under realistic conditions.

3.3 Carriage vehicle developed by Ibass GmbH

Parallel to the designs and test series at KIT-TMB, the corresponding carriage vehicle is being developed by our partner IBASS GmbH. The current status can be seen in Figure 7 (left: clamped in the pipe, right: unclamped). Fixing and centering in the pipe is achieved by three individual

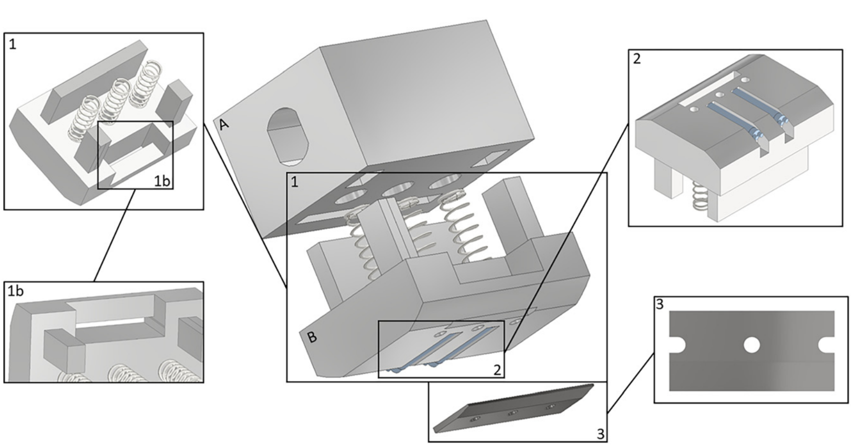

Figure 5: Exploded view of the sampling head designed at KIT-TMB, including detailed images of the most important components.

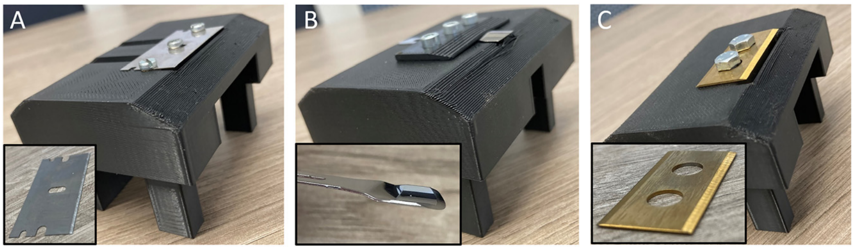

Figure 6: Prototypes manufactured using 3D printing with different blade types for initial functional testing.

Figure 7: Carriage vehicle developed by Ibass GmbH.

roller arms, which allow variable adjustment to the pipe diameter. This also ensures that narrow sections within the pipe or obstructions such as weld seams can be passed. In addition, the individual adjustment allows the buildings ring pipes, mentioned in Section 1 Introduction, to be sampled. The roller arms are set up pneumatically via a compressed air hose carried along with the carriage vehicle. Fiberglass rods can be screwed onto the rear end of the carriage vehicle. These ensure the movement of the carriage vehicle and offer a high level of flexibility and stability, allowing any pipe sections and lengths to be traversed. Various additional components (camera, lights, position sensor, etc.) are used to meet the special challenges posed by sampling plastic pipes.

4 Discussion

Our studies have shown that sampling from plastic pipes in inaccessible areas is possible, but that various factors must be taken into account. The key problems mainly relate to the tool used to take the sample. In the first step, it was shown that saw blades with a large number of teeth exhibit a significantly higher level of static charge than disc cutters with fewer teeth, while the restoring forces could be reduced as the number of teeth increased. Accordingly, preliminary tests were carried out on tools with a single cutting edge in the next step. These preliminary tests showed that the angle of the blade is a decisive factor in terms of the restoring forces that occur and the removal behavior. In order to counteract increasing restoring forces, a series of tests were carried out with blades at different temperatures. It was observed that higher temperatures resulted in lower restoring forces. This shows that all methods investigated to date encounter different problems that cannot be solved in a generalized manner. In order to further optimize the various approaches in the course of the project, investigations are necessary with regard to possible tools with geometries and designs not yet considered, as well as the operating parameters used.

5 Conclusion and outlook

During the course of the research project Bero, it has been demonstrated that a system for sampling nonaccessible areas is feasible. Based on the results of tests carried out so far, the next step should be to examine a differentiated approach. The aim should be to minimize any restoring forces and electrostatic charging as far as possible. One approach to this involves the tool used. The next step will be to investigate the use of indexable inserts for parting workpieces. In addition to previous parameter studies, different geometries such as flat or round cutting edges will also be considered. It is hoped that this will minimize both the restoring forces and electrostatic charging and maximize the quality of the sample material. The goal should be to obtain chips that are as homogeneous and cohesive as possible. For this reason, the prototypes developed so far must be optimized through further iteration loops so that a functional sampling system is available at the end of the project.

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