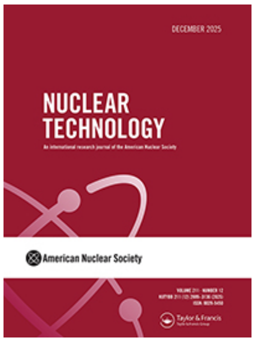

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Implementation of an Innovative Continuous Magnetic Filter for the Reduction of Secondary Waste Produced from Water Jet Abrasive Suspension Cutting

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Abstract — *When dismantling large radioactive steel components, the water jet abrasive suspension cutting process (WAS) offers many advantages compared to other dismantling processes. During the cutting process, a mixture of abrasive particles and radioactive steel particles is produced from the dismantled component, which must be disposed of as additional radioactive waste. When using the WAS process, the amount of radioactive waste increases considerably. In order to reduce the amount of additional radioactive waste, a separation process based on sieving and magnetic filtration was developed to obtain a fraction of the mixture that can be reused for the next WAS cut. The direct reuse of the separated abrasive means that less new abrasive is required and therefore the amount of secondary waste is reduced. A separation plant in batch operation was developed to assess the separation process. The testing phase showed an adequate separation grade and high potential for reduction of additional radioactive waste. A transfer from batch operation to continuous operation will be essential for future utilization and to upscale the processing of the particle mixture. In this regard, a concept for the continuous operation for a separation plant as well as a closed, continuously operating sieve and magnetic filter have been developed. This article presents a newly developed, closed and continuously operating magnetic filter and its initial results. This magnetic filter was designed as part of a separation system aimed at reducing additional radioactive waste during the dismantling of nuclear facilities.*

Keywords — *Continuous magnetic filter, secondary waste reduction, water jet abrasive suspension cutting, separation plant.*

I. INTRODUCTION

After the Fukushima accident in 2011, the German government decided to discontinue nuclear power. Presently, all nuclear power plants (NPPs) are shut down, and 29 NPPs are in the decommissioning phase [1]. A huge challenge is associated with the disassembling of the reactor pressure vessel (RPV) and its internals. After being exposed to neutron irradiation for years, the radioactive components must be disassembled and packed by remote-controlled techniques. Underwater dismantling technologies have the advantage that the water shields the radiation. To avoid the generation of aerosols, cold-cutting processes are preferred [7]. A cutting method that meets these requirements is the water jet abrasive suspension cutting process (WAS). There are basically two different types of water abrasive cutting technologies available that have already been employed in the nuclear industry: WAS and abrasive water injector jet (AWIJ). The AWIJ process is less complex, where a high-pressure water jet is first generated and abrasive particles are then added to the jet. In addition to the abrasive, air is also drawn into

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the water jet, which causes aerosol production during the cutting, making the process less suitable for cutting radioactive components. In turn, the process achieves a lower cutting performance [2,3].

The WAS process is based on the use of a suspension, a cutting medium made of abrasive, which is added to a high-speed water jet and directed onto the material to be cut. Garnet sand is often used for this purpose. A high-pressure pump is implemented to provide high pressure (here, 2000 bars) to the water. The special feature of the WAS process compared to conventional water cutting processes is that the added abrasive is already mixed into the water under high pressure in the so-called abrasive mixing unit. This reduces the required mass flow of the water-abrasive mixture and increases the cutting performance. This also results in very small kerf widths of less than 1 mm, which in turn significantly reduces the amount of secondary waste from the WAS cutting process [4,20]. The WAS process is therefore suitable for cutting the RPV. This method provides high flexibility and is immune toward mechanical stress in the components. During the cutting process of radioactive RPVs, a mixture of abrasive particles and radioactive steel particles from the cut components is generated. This secondary waste substantially increases the total amount of waste to be disposed of. Therefore, despite its intrinsic technical benefits, WAS has a significant disadvantage toward other cutting techniques due to the increased disposal costs of secondary waste [5–7,21].

One way to reduce the amount of secondary waste is the treatment and reuse of abrasive. Several reuse cycles can be carried out, but the particle size reduction is the limiting factor here, as only particles above a certain size can be used for cutting. The amount of reusable abrasive therefore decreases with each cycle [8]. To treat the secondary waste produced from the WAS technique, a separation method was developed. In the first step, the grain mixture is wet sieved, whereby fine particles are removed. This process mainly removes the radioactive steel particles and abrasive fragments, which are too small to be used for another WAS cut. In the second step, the remaining fraction is treated by magnetic separation. The magnetic separation is intended to remove the large steel particles from the secondary waste. By combining these process steps, on the one hand, the degree of separation of the steel particles can be increased. On the other hand, an abrasive fraction is obtained after the treatment, which can be reused for another WAS cut [4,9,10,21,22].

A separation plant was developed and tested in a batch process. The testing phase showed that the treatment of the large amount of abrasive particles leads to clogging or even destruction of the changeover valves; a transfer from batch operation to continuous operation was essential for the processing of this particle mixture. In this regard, a concept for the continuous operation for a separation plant and the individual components (sieve and magnetic filter) were developed. As the plant will be operated with radioactive material, the magnetic filter must also be closed and easy to decontaminate. A thorough literature search showed that there are no continuously operating, closed magnetic filters that can fulfill the purpose described, so an innovative magnetic filter was developed to handle this problem. A complete description of transfer from batch to continuous operation, the magnetic filter, and its initial results are presented in detail below [22].

II. WAS PROCESS, SECONDARY WASTE, AND REUSE

Fig. 1 shows the functional principle of WAS cutting. In this process, water is mixed with abrasive particles and forced through a thin nozzle at pressure of over 2000 bars. The jet created in this process cuts the material to be disintegrated step by step on impact [11].

Garnet is often used as the abrasive material as it has a high density and hardness. The particles also have sharp edges, which improve the cutting properties. The abrasive that has been sieved with a mesh size of approximately 180 μm achieves a high cutting performance, whereby the maximum particle size is approximately 400 μm [12].

In the dismantling of radioactive steel components, the WAS process has the advantages of both conventional mechanical dismantling processes and thermal dismantling processes. The advantages of conventional thermal dismantling processes are that they can be used remotely, are good at disassembling components under mechanical stress, and can disassemble complex geometries. The mechanical processes offer the advantage that there is no aerosol formation. However, the WAS process has one disadvantage, which is the generation of secondary waste as shown in Fig. 1. During the WAS cut, a mixture of abrasive particles and steel particles is produced. When the radioactive RPV and its internals are dismantled, the resulting mixture is also radioactive. When disposing of the dismantled parts, which are referred to as primary waste, the resulting particle mixture of the WAS cut must be treated as radioactive waste. The additional waste is referred to as secondary waste, and depending on the

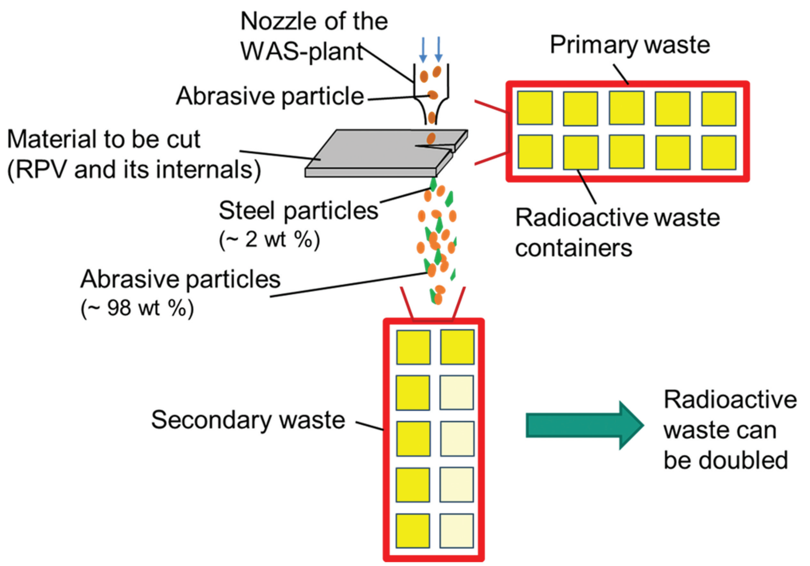

Fig. 1. Functional principle of the WAS cut and secondary waste problem.

complexity of the dismantled structure, it can double the radioactive waste. The reason for the enormous increase in secondary waste is due to the particle distribution; only 1% to 2% of the particles are radioactive steel particles [2,4,13]. The variation in the amount of secondary waste depending on the complexity of the structure to be decomposed is due to the WAS process. The more complex the structure to be broken down is, the more frequently the WAS cut must be repositioned and restarted, so that the amount of abrasive in the secondary waste increases and thus also the secondary waste [2,4].

The principle of reuse in WAS cutting was developed to address this issue, as illustrated in Fig. 2. In the first step, the particle mixture produced during the WAS cut, which consists of abrasive and radioactive steel particles, is sieved. This produces a fine fraction and a coarse fraction. The fine fraction consists mainly of broken abrasive and steel particles and is treated as radioactive waste. In a further process step, the coarse fraction is treated with a magnetic filter, which filters out the large steel particles from the coarse fraction. These large steel particles are also treated as radioactive waste. The remaining fraction now consists mainly of intact abrasive particles, even though the particle size distribution has shifted to smaller particles, due to particle disintegration, and has a very low concentration of steel particles. This fraction is referred to as reusable abrasive and is returned to the WAS plant for a new WAS cut. The broken abrasive particles exhibit sharper edges and therefore have better cutting performance [3,12,21].

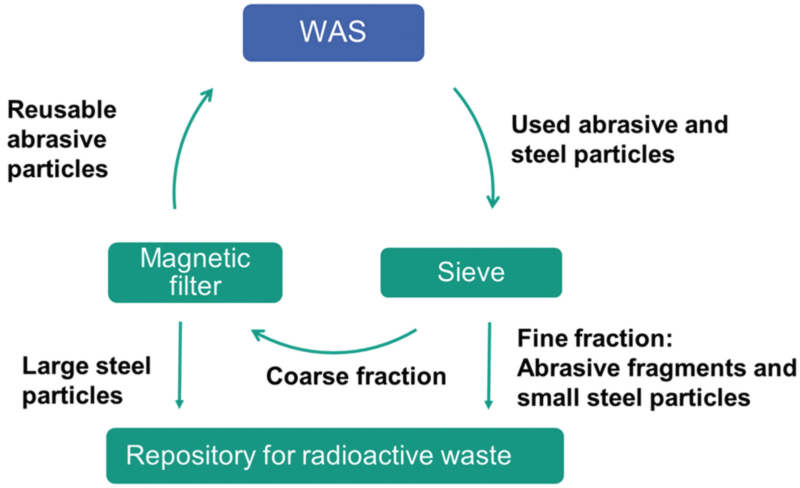

Fig. 2. Principle of reuse in WAS cutting [9].

III. SEPARATION PLANTS

There are two different ways of implementing the principle of treating the particle mixture of the WAS process. One option is batch operation, in which the individual process steps are carried out and then interrupted in order to obtain the fraction required for further treatment. In contrast, there is continuous operation, in which no interruption of the process steps is necessary.

A system in batch operation was developed for the analysis and to test the functionality. In the future, to apply this separation principle under real conditions, a transfer to continuous operation is essential.

III.A. Batch Operation

III.A.1. Mode of Operation and System

Fig. 3a shows a photograph of the separation plant in batch mode, and a process flow diagram is shown Fig. 3b. The plant performs four process steps, including three separation steps, namely, wet sieving (size classification), filtration (solid-liquid separation), and magnetic filtration.

All process steps are carried out with a steel-abrasive suspension. The agitator unit uses a stirring tank and a stirrer to create a homogeneous suspension with the material to be processed from the WAS. This suspension is pumped to the components through a diaphragm pump equipped with a pulsation damper. After passing through the respective component, the suspension is returned to the stirring tank. All process steps are carried out until over 99% of the particles in the suspension have passed through the respective component at least once.

The first processing step is wet sieving. Here, the suspension is pumped onto a vibrating sieve. The fine particles pass through the sieve, and the coarse particles collect on the sieve. A bag filter is placed after the sieve that collects the fine fraction from the suspension. After sieving and filtering, the coarse particles are flushed back into the stirring tank by turning the sieve 180 deg.

The coarse fraction then passes through a magnetic filter, where the large steel particles are filtered out. The material now in the stirred tank is the reusable abrasive.

A specially designed magnetic filter was used for the batch operation. This magnetic filter consists of one to several magnetic grids. These magnetic grids have a cylindrical shape through which three cladding tubes run. There is a design with three rods to match these cladding tubes, which consist of several magnetic rods that can be guided into the cladding tubes. To clean the magnetic filter from the separated steel particles, the construction with the magnetic rods is pulled out of the cladding tubes. Removing it deactivates the magnetic field in the filter, so that the magnetic filter can be cleaned with the supernatant water from the stirring tank and the particles are also collected in a bag filter [9,10,21,22].

III.A.2. Results

With the separation system in batch operation, the steel concentration in the reusable abrasive could be reduced to less than approximately 0.03% by mass with a mesh size of 180 μm during sieving and to less than approximately 0.01%

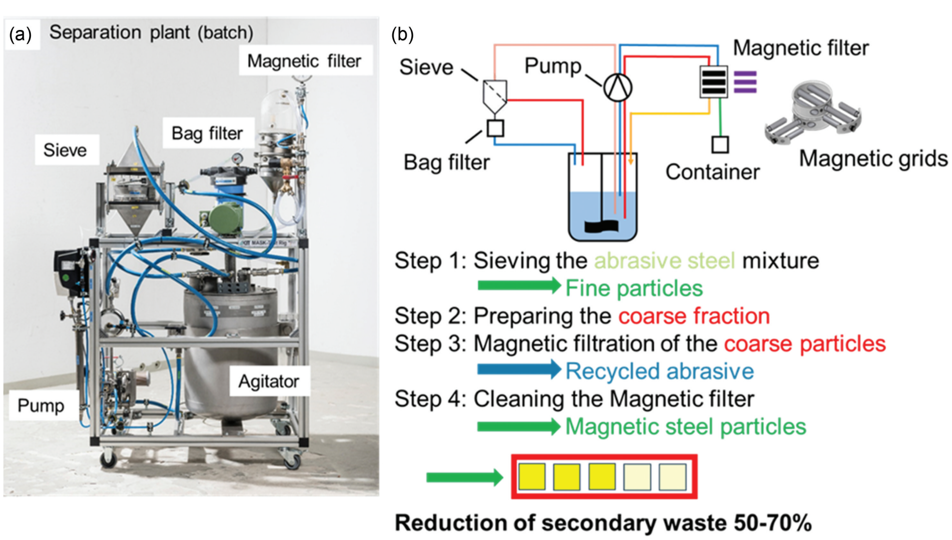

Fig. 3. (a) Photograph of the separation plant in batch operation. (b) Process flow diagram of the separation process in batch operation [9].

with a mesh size of 250 µm. With the combination of sieving and magnetic separation, approximately 98% to 99% of the radioactive steel particles can be removed, which facilitates the handling of the reusable abrasive. The abrasive treatment makes it possible to reduce secondary waste by 50% to 70% [9,10,21].

III.B. Continuous Operation

To treat larger quantities of secondary waste, the separation plant needs to be upscaled. There are also other issues that severely restrict the use of a separation plant in batch operation for processing the particle mixture from the WAS cut. For example, the abrasive particles cause blockages and damage the changeover valves, which are essential for batch operation. Furthermore, the use of abrasive particles made it difficult to operate the changeover valves after a short time. It was also found that the magnetic filter was already overloaded with particles after treating small quantities of material so that no further steel particles could be separated from the particle mixture. When treating larger quantities of secondary waste, the interruption of the individual process steps represents a further limitation. A transfer to continuous operation is necessary.

III.B.1. Process Flow Diagram of the System

Fig. 4 shows the process flow diagram of the separation plant in continuous operation. A suspension containing the abrasive-steel mixture from the WAS cut is produced in the agitator unit. This particle mixture is continuously fed into the agitator unit. The suspension then enters the continuously operating sieve. Here, the fine and coarse material are separated. The fine fraction is collected in a bag filter, and the cleaned water is returned to the agitator unit. The coarse fraction reaches the magnetic filter, and the coarse steel particles are separated. The reusable abrasive that comes out of the magnetic filter is collected in a bag filter. The cleaned water is also fed back to the agitator unit. In a further development, the reusable abrasive is to be fed directly to the WAS plant for recutting.

Fig. 5a shows the functional principle of the continuously operating sieve. It consists of a closed housing in which there is an inclined hanging sieve. It also has four openings at the top of the housing. A vacuum is created inside the housing through the inlet with the help of a pump that draws the air outside. This negative pressure draws the suspension from the agitator unit onto the sieve. The pumps are regulated so that a constant water level is formed inside the housing, so that the bottom side of the inclined sieve is in the water and the top side is above the water. On the upper side, the suspension with the particle mixture to be separated reaches the sieve. The particle mixture moves downward on the sieve grid due to the inclination and movements of the vibrator attached to the sieve. The fine fraction passes through the grid, and the coarse fraction remains on the grid. At the bottom of the sieve, the coarse material is removed with the aid of a pump through a suction hose and collected in a bag filter. The fine particles are pumped from the bottom of the housing.

IV. CONTINUOUS MAGNETIC FILTER

IV.A. Requirements for the Magnetic Filter

In the nuclear sector it is necessary to use a closed system that can be operated continuously and remotely. There are various magnetic filters on the market that are operated with electromagnets or permanent magnets. However, the commercially available magnetic filters are either open and operated continuously or closed and operated discontinuously. The newly developed magnetic filter described in the following section is a closed and continuously operating magnetic filter that, according to

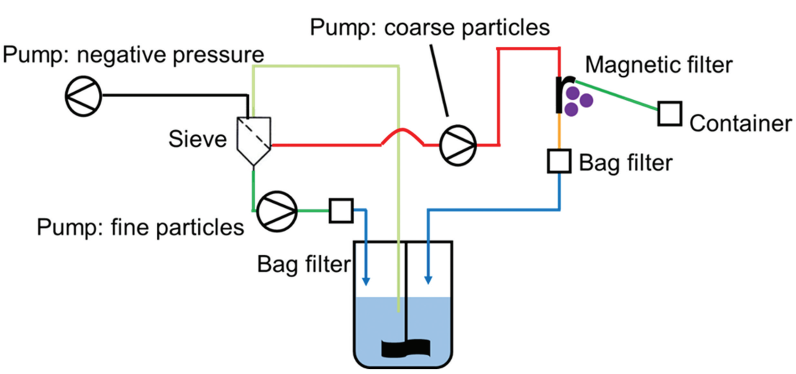

Fig. 4. Process flow diagram of the continuously operating separation system.

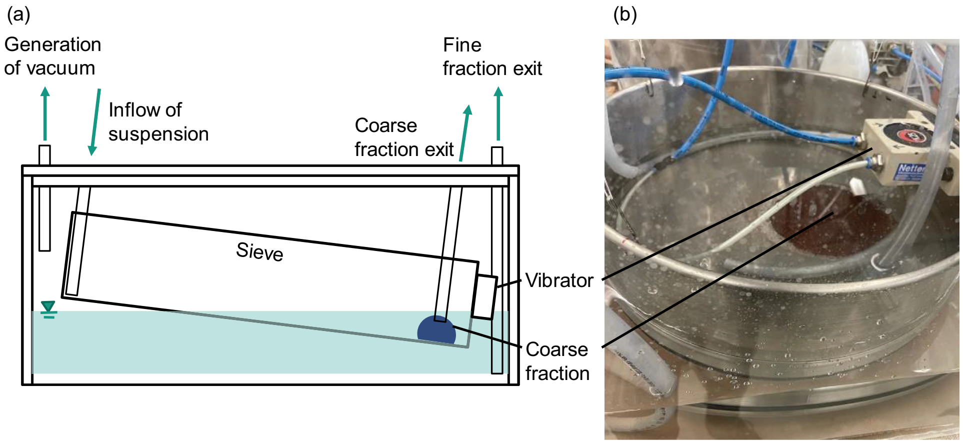

Fig. 5. (a) Functional principle of the continuously operating sieve. (b) Photograph of the sieve.

current literature research, is not yet available on the market [14–18].

IV.B. Description of the Magnetic Filter

The magnetic filter consists of a structure that is referred to as an r-divider. This r-divider consists of a pipe section, in which the suspension passes through the magnetic filter, and a separator pipeline, which is filled with a stagnant fluid. Magnetic rods move along the pipe section and the curved separator pipeline, which are positioned in such a way that the maximum magnetic field touches the inside of the pipe section and the separator pipeline. As the particle suspension flows through the pipe section, it passes through the magnetic field of the magnetic rods. This causes the magnetic particles to be attracted by the magnetic field. These are then discharged into the separator pipeline by the rotation of the magnetic rods. In the case of separation of a particle mixture, the nonmagnetic particles pass through the pipe section from the inlet to the outlet. The operating principle is shown in Fig. 6. In Fig. 6a, the filtration process is shown, where a suspension of steel particles flows through the magnetic filter to be filtered out of the fluid. Similarly, in the case of separation shown in Fig. 6b, a particle mixture of abrasive (nonmagnetic particles) and steel (magnetic particles) passes through the magnetic filter, the steel particles are separated into the separator line, and the abrasive particles pass through the pipe section.

Fig. 7a shows the technical implementation of the magnetic filter. The r-divider is visible at the front. This component is currently a three-dimensional–printed structure made of transparent plastic, as can be seen in Fig. 7b. This enables a quick, visual, and qualitative assessment of the experiments. The magnets are attached in the curve of the r-divider. These magnets are screwed onto a plate. The plate is rotated by a shaft and a motor, whereby the magnets are guided along the inside of the curved separator line. The stepper motor speed is smoothly adjustable throughout its full range.

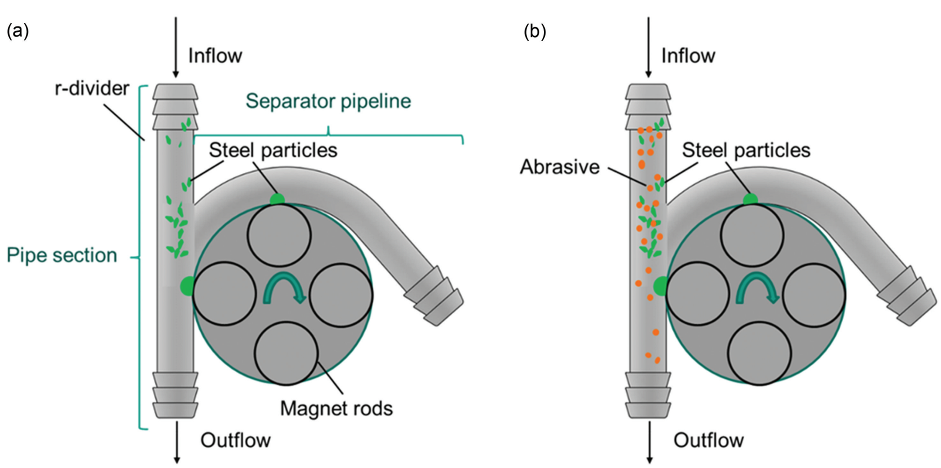

Fig. 6. Functional principle of the newly developed, continuously operating magnetic filter. (a) Filtration and (b) separation.

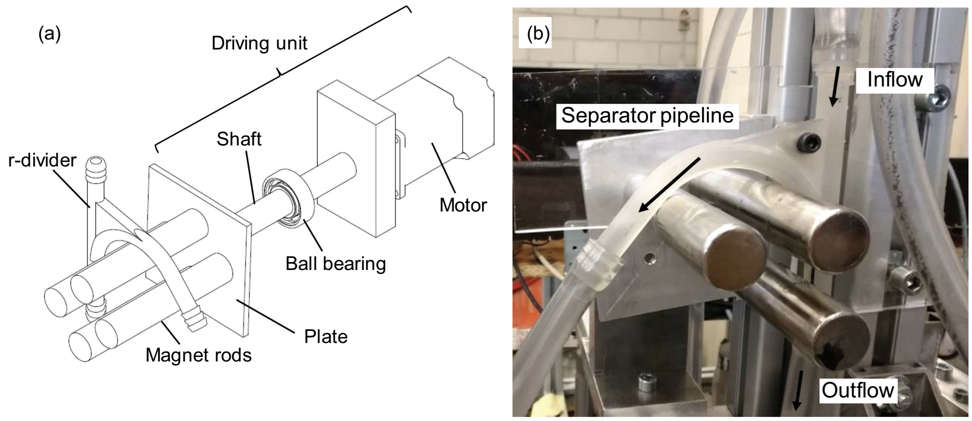

Fig. 7. (a) Technical implementation of the magnetic filter. (b) Photograph of the magnetic filter.

IV.C. Experiments

To prove the feasibility and to determine the separation efficiency of the continuous magnetic filter, experiments were carried out with only steel particles in batch operation. The steel particles consist of high-alloy stainless steel (1.4404) with a particle size of 10 to 100 µm. In the current stage of the project, tests were limited to single-component suspensions for two main reasons. First, the use of steel particles alone allows for a straightforward and precise quantification of separation efficiency using a particle counting device. This method enables real-time measurement of steel particle concentration and its reduction during filtration, which would not be possible with the time-delayed nature of chemical analysis required for multicomponent suspensions. Second, the preparation of a reproducible steel-abrasive suspension is associated with considerable effort and resources. As the primary objective at this stage is to verify the fundamental functionality of the magnetic filter, preliminary tests were carried out under simplified conditions.

Fig. 8 shows the process flow diagram of the experimental setup. This consists of an agitator unit, a pump with a pulsation damper, a magnetic filter, a particle counter, and a collecting container.

A homogeneous suspension of steel particles and water is produced in the agitator unit. This suspension is pumped through the magnetic filter by a diaphragm pump and flows back into the agitator unit. A particle counter (Type: Particle Sensor LDS 1/1, Markus Klotz GmbH) was used to determine the separation quantity. This measures how many particles of a certain size range pass through the particle counter in a specified time (1 min). The size range in terms of particle diameters measured with the particle counter is shown in Fig. 9.

At the beginning, the stirring tank was filled with 10 l of distilled water and 5 g of steel particles. This was brought into a homogeneous suspension and passed through the particle counter. The measured volume of particles was compared with the 5 g of added steel particles. The suspension that passed through the particle counter during the measurement was collected in a collecting container and returned to the agitator unit after the measurement. During the separation cycle, the homogeneous suspension was pumped through the magnetic filter with a volume flow of 0.25 l/s. To collect data, five separation cycles were run with a duration of 30 min. A particle measurement was carried out after each separation cycle. These data were used to

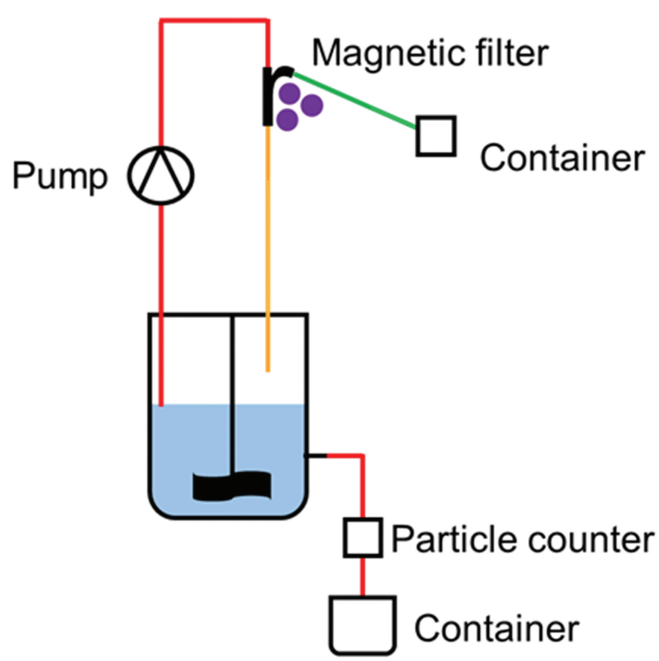

Fig. 8. Process flow diagram of the experimental setup for the filtration experiment with the magnetic filter.

d_p [µm]	5	6	8	10	12	16	20	24	32	40	45	50
	63	80	100	125	160	200	250	315	400			

Fig. 9. Range of particle diameters measured with the particle counter [10].

determine the amount of steel particles separated by the magnetic filter. The experiment was repeated three times.

IV.D. Results

Fig. 10 highlights the filtration of steel particles from a suspension containing water and steel particles. The magnetic rods rotate counterclockwise. The red arrow in Fig. 10 points to the filtrated steel particles. The left-hand image shows how the steel particles have accumulated at the maximum magnetic field and have already been drawn into the separator line. The middle image shows how the steel particles have been drawn over the apex of the separator line. The right-hand image shows how the magnetic force loses its effect on the separated steel particles due to the spatial distance of the magnetic field and how the particles are drawn into the hose attached to the separator line by gravity. The steel particles were thus separated from the suspension.

Fig. 11 shows the decrease in steel particles in the stirred tank over time. If this result is compared with an approximation function, it can be seen that the magnetic filter can filter between 0.5% to 1% of the steel particles during a separation cycle.

Fig. 11 also highlights the fact that the measuring accuracy and the reliability of the results decrease with the duration, as the particle concentration in the stirred tank decreases and therefore the formation of a homogeneous suspension in the stirred tank decreases. This explains the large scatter with a separation time of 120 min. With a separation time of 150 min, only the measurements from two experiments were usable, which explains the low scatter.

V. CONCLUSION

This paper highlights the innovative separation technique to reduce radioactive waste by reusing the abrasive material utilized in the dismantling of nuclear facilities using the WAS process. In this regard, a separation plant for batch operation was designed and built for analysis. This separation plant was able to demonstrate that the secondary waste (additional radioactive waste) can be reduced by 50% to 70% depending on the implemented mesh size of the sieve [13].

With the small-scale separation plant in batch operation, however, it is not possible to treat the quantities that arise when dismantling the RPV and its internals [19], which is the reason why a transfer to continuous operation was necessary. A concept for the operation of

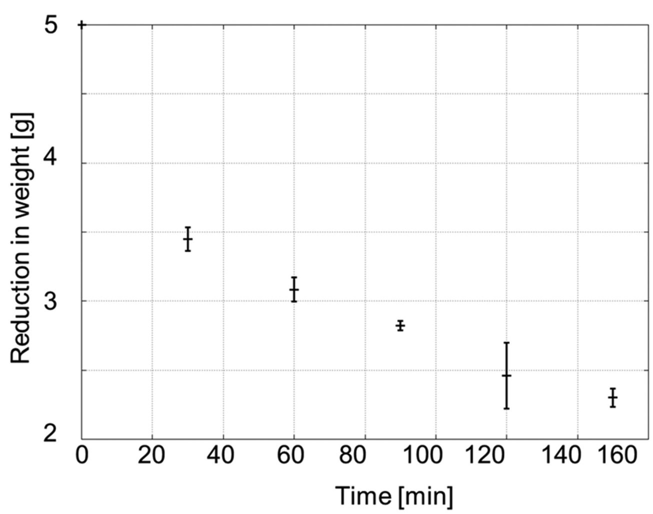

Fig. 11. Decrease in steel particles in grams plotted against time in minutes.

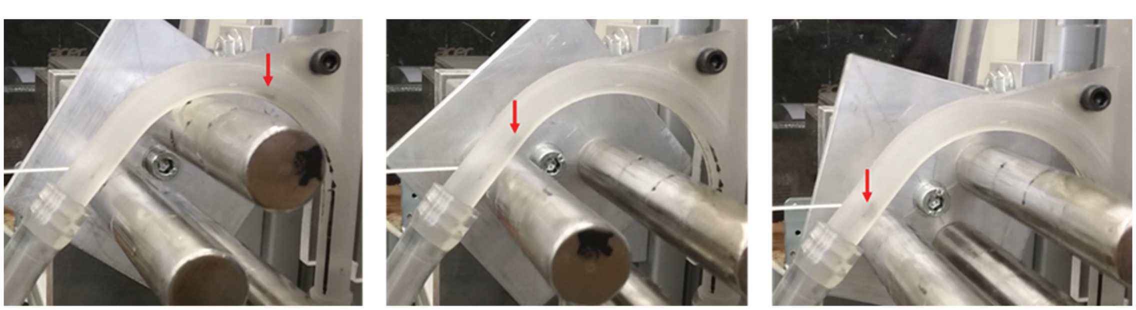

Fig. 10. Photographs of the newly developed magnetic filter, with the red arrow pointing to the separated steel particles.

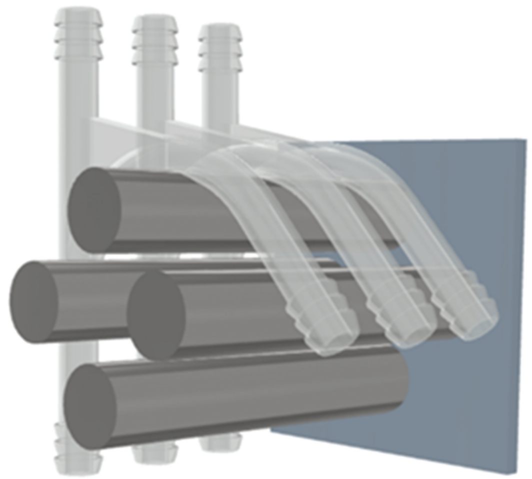

Fig. 12. Serial arrangement of three r-dividers in the magnetic filter, where suspension is fed back into the next r-divider from above after flowing through the first r-divider.

a separation plant and the individual components (sieve and magnetic filter) was developed for this purpose.

An innovative closed magnetic filter was developed for continuous operation. This can be used for both filtration and separation. A visual assessment of the functionality is included in this paper. Furthermore, tests with the continuous magnetic filter were carried out in batch mode with only steel particles. The analysis was carried out with a particle counter. The preliminary result shows that the magnetic filter separates 0.5% to 1% of the steel particles during each round movement.

The discussed magnetic filter is a new development, so there is still enormous potential for improvement. For example, the geometry of the r-divider can be improved by making the pipe section even longer and placing the magnetic rods in such a way that they get longer contact time. Moreover, another simple way to increase the filtration rate is to use several r-dividers, as shown in Fig. 12.

Improvements of the design that will in turn uplift the efficiency and adaption to different media will open new terrains for possible other applications (refineries, food processing, sewage water treatment, battery recycling, etc.

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Author Contributions

CRediT: **Carla-Olivia Krauss:** Investigation.

Disclosure Statement

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