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Development of Micro-Blast Type Scabbling Technology for Contaminated Concrete Structure in Nuclear Power Plant Decommissioning

Kyungho Lee, Sewon Chung, Kihyun Park, and SeongHee Park*

ORION ENC, 37, Seongsui-ro 22-gil, Seongdong-gu, Seoul 04798, Republic of Korea

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In decommissioning a nuclear power plant, numerous concrete structures need to be demolished and decontaminated. Although concrete decontamination technologies have been developed globally, concrete cutting remains problematic due to the secondary waste production and dispersion risk from concrete scabbling. To minimize workers' radiation exposure and secondary waste in dismantling and decontaminating concrete structures, the following conceptual designs were developed. A micro-blast type scabbling technology using explosive materials and a multi-dimensional contamination measurement and artificial intelligence (AI) mapping technology capable of identifying the contamination status of concrete surfaces.

Trials revealed that this technology has several merits, including nuclide identification of more than 5 nuclides, radioactivity measurement capability of 0.1–10^7 Bq·g^{-1}, 1.5 kg robot weight for easy handling, 10 cm robot self-running capability, 100% detonator performance, decontamination factor (DF) of 100 and 8,000 cm^2·hr^{-1} decontamination speed, better than that of TWI (7,500 cm^2·hr^{-1}). Hence, the micro-blast type scabbling technology is a suitable method for concrete decontamination. As the Korean explosives industry is well developed and robot and mapping systems are supported by government research and development, this scabbling technology can efficiently aid the Korean decommissioning industry.

Keywords: Micro-Blast, Decommissioning, Scabbling, Nuclear power plant

*Corresponding Author.
SeongHee Park, ORION ENC, E-mail: shpark@orionenc.com, Tel: +82-2-3414-2038

ORCID

Kyungho Lee	http://orcid.org/0000-0002-8652-722X	Sewon Chung	http://orcid.org/0000-0002-8918-0460
Kihyun Park	http://orcid.org/0000-0002-9017-0489	SeongHee Park	http://orcid.org/0000-0002-8283-8469

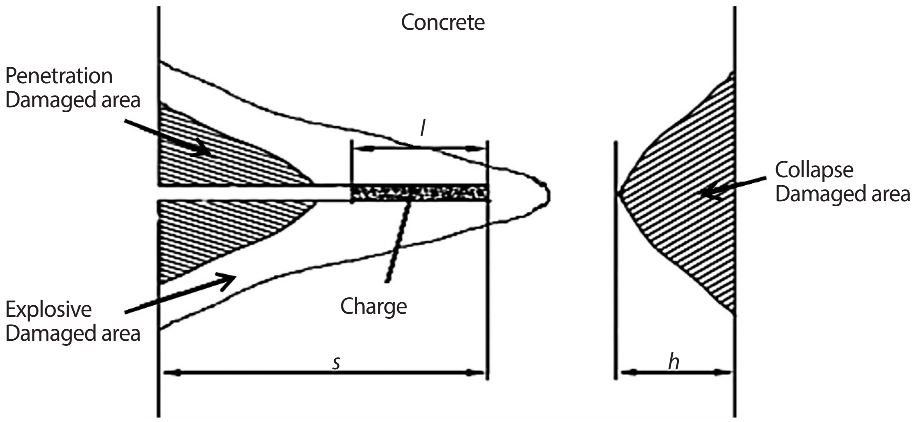


Fig. 1. Example of explosive blast in industrial field.

1. Introduction

During the nuclear power plant decommissioning, much concrete structure is needed to be demolished and decontaminated. For reducing the waste quantity and protecting the workers safely against radiation exposure, the more efficient technologies for concrete structure decontamination is required. So far, the decontamination technologies for concrete structure decontamination have been developed during the decommissioning of nuclear power plant over the world, but they have been faced the difficulties in the aspects of much secondary wastes production and higher exposure towards workers due to dust which is produced during the concrete cutting job. Hence for reducing the secondary wastes efficiently and protecting workers safely against radiation exposure, the micro-blast type scabbling technology using explosive material is under development by ORION for surface decontamination of concrete structure. This paper shows the micro-blast type scabbling technology as the conceptual basis by using explosive material together with the multi-dimensional contamination measurement and AI based mapping technology which can check the identification of the contamination status in surface of concrete structure. Through this suggestion the concrete structure decontamination can be efficiently adopted and utilized in decommissioning industry.

2. Development of Micro-Blast Type Scabbling Technology

2.1 Background

Concrete structure demolition and decontamination technologies are developed for large scale concrete structure during the decommissioning of nuclear power plant. Hence the contamination parts in large scale concrete structure such as containment vessel exist in shallow layer of the surface of concrete, surface contamination removal technology is needed. The concrete surface decontamination technologies are mainly wet and dry abrasive blasting technology, surface cutting technology, physical abrasive technology and chemical abrasive technology, etc. Physical abrasive technologies are grinding and scabbling technology, but these have the disadvantages such as much dust production, higher workers' exposure and long work time. Chemical abrasive technologies use the chemicals for decontamination of concrete surface, but these also have the disadvantages such as cost increase by much secondary works for removing the chemicals which pass through and remain in the inner of concrete and much secondary wastes production, etc. To achieve the effective decontamination performance towards large scale concrete structure surface and to minimize the waste

Table 1. Comparisons between several decontamination technologies

Division	Micro-blasting	Chemical	PFC (Perfluoro-carbon)	Foam	Rotating Brushing	Shaver	CO_2 pellet Blasting
Application capability	○	△	○	○	○	○	○
Secondary waste	○	×	○	○	×	△	○
Decontamination performance	○	○	△	△	△	○	△
Decontamination speed	○	○	○	△	○	△	○
Decontamination cost	○	×	○	○	△	○	○
Workers' Exposure	○	△	○	○	△	△	○

Remark: ○: Good, △: Average, ×: Bad

production, new concept technology such as micro-blast type scabbling technology is needed. Fig. 1 shows the example of explosive blast in industrial field and ORION refers this concept for micro-blast scabbling technology towards nuclear field.

2.2 Necessity of Adoption of Micro-Blast Type Scabbling Technology

2.2.1 Economical and Industrial Aspect

So far 201 nuclear power plants are shutdowned permanently over the world which include 3 units in Taiwan, and Korea will shutdown total 12 units till 2030. Hence, if the micro-blast scabbling technology will be developed, the market will be potentially increased [1].

2.2.2 Social Aspect

Korea made the efforts to build the core technologies for nuclear power plant decommissioning so far. The concrete decontamination technology is also the core technology to secure the advanced country position and to be a winner in the decommissioning market [2].

2.2.3 Environmental Aspect

To secure the efficient disposal site utilization by the reduction of waste production during the decommissioning and to reuse the concrete towards industrial use purpose which is exempted from the radioactive waste, the environment friendly technology is welcomed [3].

2.3 Characteristics of Micro-Blast Type Scabbling Technology

2.3.1 Innovative characteristics

Micro-blast type scabbing is limitedly utilized at research reactor decommissioning in Japan. And mechanical scabbling and shaving technology were secured for decommissioning industry, nevertheless remote-control technologies are not secured yet.

Good explosive material manufacturing technology and proven blasting process in Korean industry can be firstly introduced and utilized towards commercial nuclear power plant decommissioning over the world by combining with good contamination technology. And the remote-control system for micro-blast type scabbing also can be an

Table 2. Characteristics of thermochemical decontamination

Material	Maximal achieved temperature (℃)	Duration of process (min)	Efficiency of decontamination (%)	Radionuclides carry over (^{137}Cs) (%)
Metal	1,100	20	95–99	0.1–0.5
Asphalt	400	15	99.9	0.1–0.5
Concrete	1,300	20	95–99	0.1–0.5

innovative technology. Through micro-blast type scabbling technology, the minimization of secondary waste production, decontamination cost down, upgrade of decontamination work speed, and minimization of workers' exposure, etc. can be achieved. Table 1 shows the comparisons between several decontamination technologies used in nuclear power plant decommissioning [4].

2.3.2 Creative Characteristics

Micro-blast type scabbling technology uses robot apparatus for concrete surface contamination measurement, and AI based mapping technology is also used for radioactivity measurement in consideration of work efficiency and worker's safety.

In addition to this, core technologies such as 3D contamination mapping technology, horizontally moving micro-blast type scabbling process can be developed as self-reliable and creative technology.

2.3.3 Risk of adaptation

Micro-blast type scabbling may cause the problems such as the high levels of noise, smoke, and debris during the job. Especially the high level of noise (sound of explosion) may give the objection of approval of application during decommissioning by residents near to decommissioning site. And the smoke and debris may give the risk to workers at the point of internal exposure as well as the environmental contamination. To overcome these risks, the system may need full closed system to collect the dust and debris as reducing the sound of explosion. This may raise the cost increase and require the need the approval of PA (Public Acceptance).

2.4 Technology Situation for Decontamination of Concrete Structure

2.4.1 Korean Situation

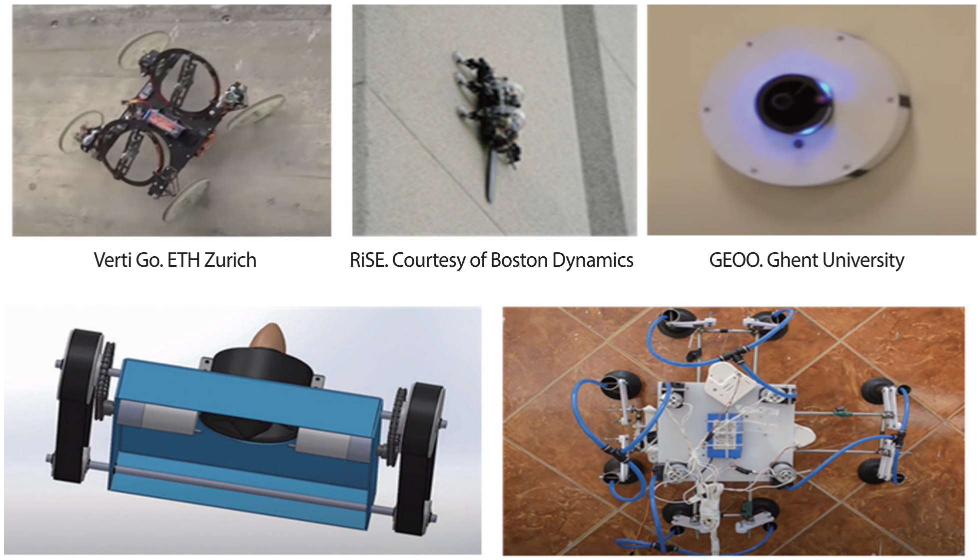
Generally, mechanical scabbling, shaving, milling, grinding and hammering technology were used for radioactive concrete structure together with chemical methods in decommissioning field.

KAERI used mechanical scabbling technology using wire saw towards research reactor 1&2 decommissioning site and developed hydrogel basis spray coating technology for future projects. Hydrogel basis spray coating technology shows 57% removal of ^{137}Cs, and DF (Decontamination Factor) shows two times rather than abrasive technology [4].

KEPCO KPS developed scabbling method using laser thermal shock towards Kori 1 bio-shield, etc. But Robot system and AI based mapping system for concrete structure decontamination were not commercialized yet. Still R&D for Robot system and AI based radioactivity mapping system for concrete structure decontamination are under development through universities and KAERI, etc. [5].

2.4.2 World Situation

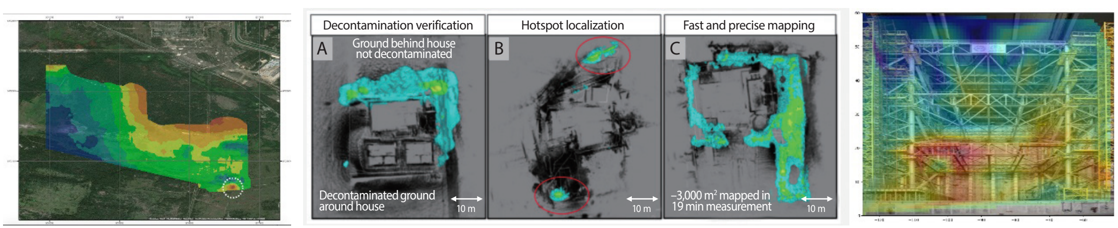
USA developed AWD-CON (AWD Technologies Inc.) process, ROVCO2 (Remote Operated Vehicle CO_2) surface decontamination system and soda spray decontamination, etc., and Germany developed several decontamination



Verti Go. ETH Zurich | RiSE. Courtesy of Boston Dynamics | GEOO. Ghent University

Air Chamber decompression | Vacuum inhalation cup

Fig. 2. Several types of robot system for concrete structure.



UK NCNR | University of California | Boston Dynamics

Fig. 3. Example of radioactivity mapping system.

technologies by Karlsruhe Institute and VKTA Rossendorf company. France CEA developed laser ablation technology which can be used towards metal decontamination. Japan developed thermochemical decontamination technology by NUPEC whose technique is based on application of PMF (Powder Metal Fuels) to decontaminate a surface of asphalt, concrete, metal. The characteristics of thermochemical decontamination are shown in Table 2.

Together with concrete structure decontamination technologies, the robot systems which can be applied for concrete structure decontamination were developed by Swiss Confederation, USA, France, UK, etc., and these robot types were propeller, air chamber decompression, vacuum inhalation cup, magnet, drill, etc. (Fig. 2).

Radioactivity mapping system are developed by USA, Japan and European countries. For example, TRAD company in UK developed simulation technology for 3D mapping system based on Monte Carlo method, and NCNR (National Center for Nuclear Robotics) also developed mapping system using drone and achieved the mapping work at Chernobyl site successfully. In USA, California university developed gamma ray visualization method by using SLAM (Simultaneous Localization And Map-Building) and LIDAR (LIght Detection And Ranging) technology, but these methods can't provide the quantitative data for radioactive contamination depth. Boston Dynamics developed radiation mapping and visualization system using walking robot and demonstrated this system at Chernobyl site as showing

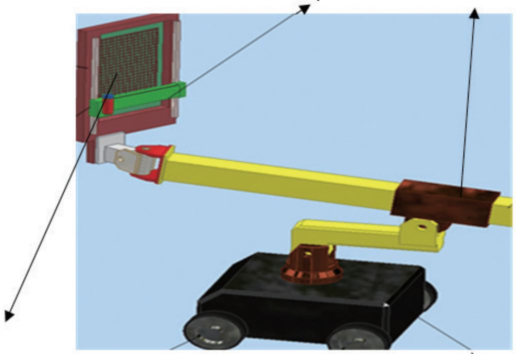


Fig. 4. Robot system for micro-blast type scabbling technology.

radioactive contaminated space (Fig. 3). Japan and China also developed 2D mapping systems, but these systems also can't analyze the depth of contamination [6].

2.5 Outline of Development of Micro-Blast Type Scabbling Technology

2.5.1 Summary

Korea expects concrete waste will possess about 35% among total decommissioning waste and concrete waste is classified as not easy waste to treat for disposal [7]. Hence the minimization of concrete waste by the reduction technologies is important during decommissioning. The contamination at surface of concrete structure shows several levels partly before the decontamination work, so the identification of contamination levels is necessary. In consideration of this situation the robot system in micro-blast type scabbling technology under development is designed shown in Fig. 4. The system composes with explosive material load screen, squeeze to supply explosive material, attaching type robot arm and main body, together with operation control system equipped by 3D contamination measurement and radioactivity mapping, decontamination AI, GCS (Ground Control Station), etc. The system also equips dust collection device, filtering system and the variable explosion control system according to contamination depth.

The explosive scabbling method uses an explosive which is normally formed in a geometric shape such as detonating tube type fuse especially designed and sized to produce the desired scabbling. The shock wave during explosion cuts the target material. Explosive scabbling must be performed by a licensed men towards concrete structures. But its use is sometimes limited, because blast may affect the structural integrity of surrounding structures or produce an uncontrolled spread of radioactive materials. Therefore, it is particularly used in the situations where other cutting methods are not practical or access is limited. Containment control is required due to high levels of noise, smoke, and debris. ORION made a conceptual idea for micro-blast type scabbling technology to overcome these handicaps.

The main specifications of this system are as follows,

a. Nuclide identification capability: More than 5 nuclides
(^{137}Cs, ^{60}Co, ^{54}Mn, ^{22}Na, ^{152}Eu, etc.)
b. Measurement of radioactivity < 10^7 Bq·g^{-1}
(MDA: 0.1 Bq·g^{-1})
(NaI(Tl) detector itself can measure more than 10^7 Bq·g^{-1} but this system adjusts at the value below 10^7 Bq·g^{-1} to consider higher contamination level)
c. Self-running length: 5 cm
d. Detection time: 15 min
e. Decontamination Factor: 100
f. Decontamination speed: 8,000 cm^2·hr^{-1}
[Reference: TWI laser system's removal speed = 7,500 cm^2·hr^{-1}]
g. Duty weight (sensor and mission board load weigh): 1.5 kg

2.5.2 Main Performance

2.5.2.1 Spectrum analysis for nuclide identification

The system loads MCA to analyze spectrum of each nuclide using NaI(Tl) detector for ^{152}Eu and ^{57}Co, etc. under the conditions of background stabilization, lead shielding and room temperature measurement.

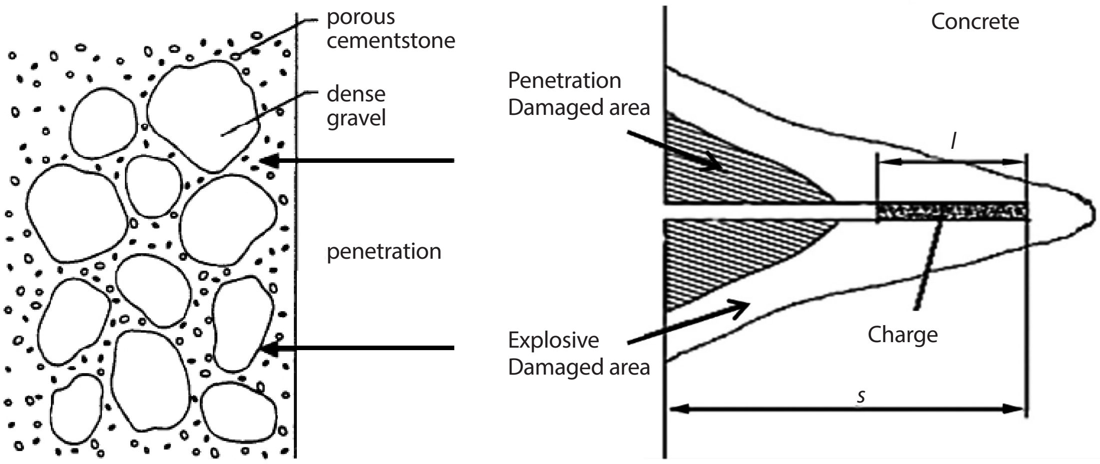


Fig. 5. Sketch of inner concrete structure (Charge is done thru non-dense gravel).

2.5.2.2 Self Running Capability

The self-running capability of robot system is important in robot system to assure the radiation mapping. And the accuracy of self running is calculated by following formula.

$$D_\alpha = \frac{\sum_{i=1}^{5} D[P_{E\cdot i} - P_{R\cdot i}]}{5}$$

Here the D_α is average length of 5 measurements lengths, $P_{E\cdot i}$ is the location at measured i_{th}, $P_{R\cdot i}$ is the location of robot moved to target position via self-running, and $D[P_{E\cdot i} - P_{R\cdot i}]$ is the length between $P_{E\cdot i}$ and $P_{R\cdot i}$.

2.5.2.3 Mapping Accuracy

Mapping accuracy is important to assure radioactivity contamination level by depth whose work is done by AI. The AI's performance is evaluated by following formula.

$$A = \frac{A = \sum_{i=1}^{\pi} |C_{s\cdot i} - C_{AI\cdot i}|}{n} \times 100[\%]$$

Here A is average radioactivity measurement rate in n_{th} measurements at various locations, $C_{s\cdot i}$ is radioactivity measurement rate evaluated i_{th} location via Monte Carlo simulation code, and $C_{AI\cdot i}$ is radioactivity measurement rate evaluated at i_{th} location via AI based mapping technology. Generally, more than 10 times evaluation information is needed for accuracy.

2.5.2.4 Detection Time

Detection time is important for measurement device to assure the capability of detecting radioactively activated locations at surface. The time is calculated as the time to detect the exact contaminated wall location by self-running of robot.

2.5.2.5 Decontamination Speed

Decontamination speed is calculated the decontamination area per unit time to reduce the radioactivity concentration below the VLLW (Very Low Level Waste) after scabbling.

2.5.2.6 Hardware Configuration

Generally inner concrete structure composes porous cement stone and dense gravel as shown in Fig. 5 and the explosive charge is done thru non-dense gravel.

The depth of contamination in concrete structure depends on the distribution of cement stone and dense gravel. Hence the hardware configuration needs adequate arrangements

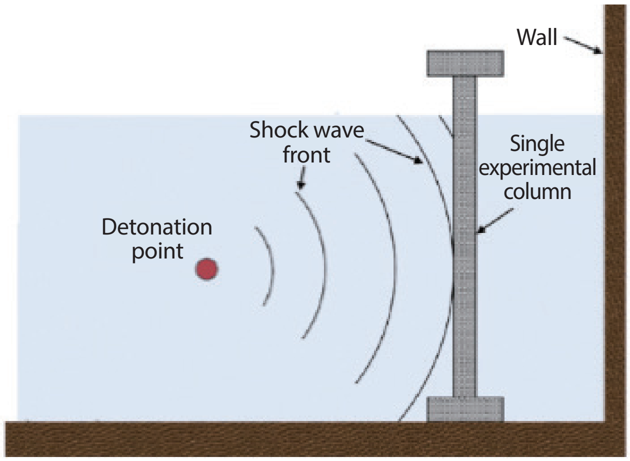


Fig. 6. Sketch of experiment of detonation energy transfer.

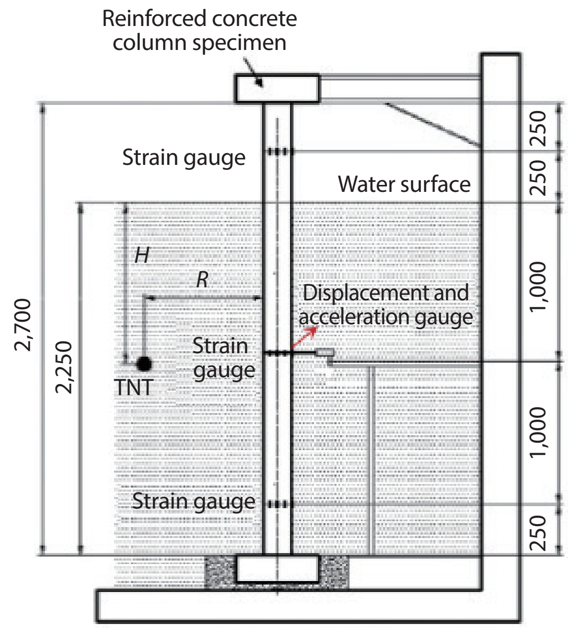


Fig. 7. Sketch of arrangement of test towards Reinforced Concrete (RC) column.

of the explosive load part in consideration of contamination depth. The detonation energy transferred to inner concrete structure in explosion affects the depth of scabbled surface. Previous attempts to apply explosives for scabbling were applied in the form of flexible sheets of explosive (typically pentaerythritol tetranitrate (PETN) embedded in a rubber sheet). The results have been mixed, partially owing to the inevitable gaps between the explosive sheet and the surface to be scabbled. Intimate contact is required to effectively transmit the required shock wave into the (typically very rough) surface to be removed. Such contact could be approximated by using, e.g., prior art plastic explosives "buttered" onto the surface. However, such formulations are difficult to apply with the delicacy required for controlled scabbling, and the extensive handling required dramatically raises both safety concerns and the ultimate cost of the scabbling operation. In USA various conventional means were used to initiate the sprayed explosive layers. These included firing a bridge wire detonator in contact with the explosive layer, driving a flyer plate into the explosive layer, and driving a 6 mm steel ball into the explosive layer at velocities above 200 m·sec^{-1}. All initiation methods which supplied more than 20 joules of energy to a millimeter-sized region were successful. The Chapman-Jouget pressure (detonation pressure) of the detonation was about 3 GPa-more than sufficient to scabble concrete [8].

We do not explain in detail the theoretical approach method of detonation phenomena here. But we consider and reflect the detonation energy for determining the depth of contaminated surface in conceptual idea, and we upgrade industrial application case as shown in Figs. 6 and 7.

The shock wave (detonation energy) depends on the distance between detonation point and target surface (R) and the distance detonation depth (H) shown in Fig. 7. For the reference, Fig. 9 shows the time history of pressure based on explosive quantity (0.05 kg and 0.1 kg), where the primary peak corresponds to reflection shock wave, and the secondary peak corresponds to bubble pulsation. It can be seen from Fig. 8 that the time difference between two peaks increases with the increase of the explosive [6]. ORION idea reflects the primary peak only for micro-blast scabbling.

Based on above considerations, the total conceptual micro-blast type scabbling system composes attaching type robot system which includes attaching part, wheel drive

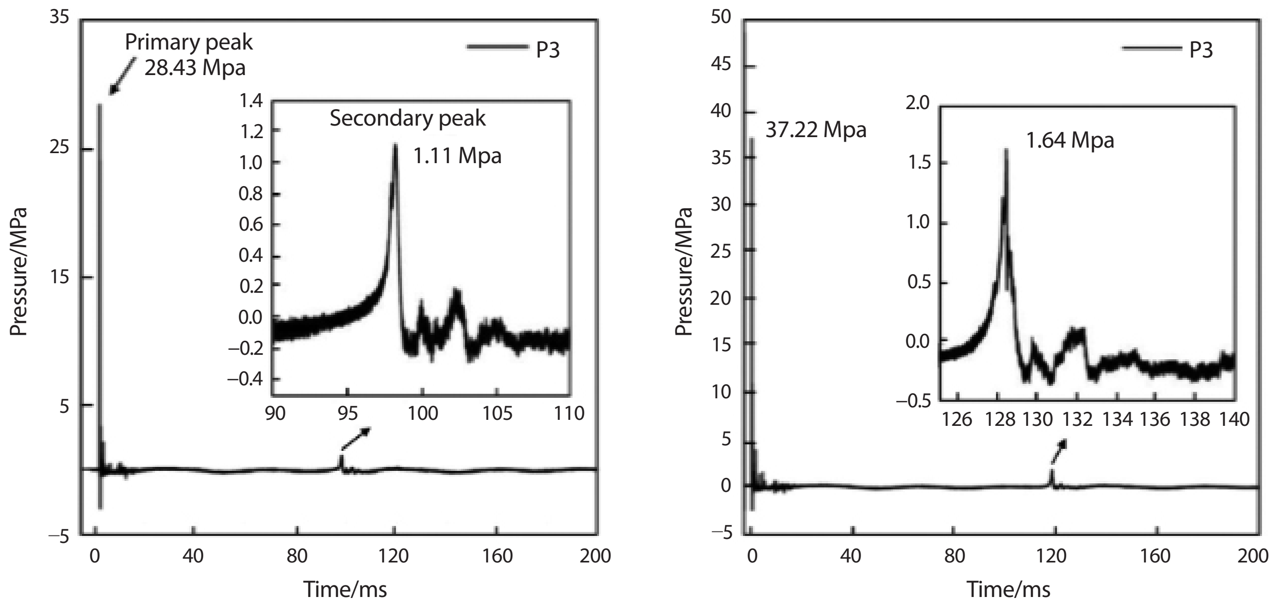


Fig. 8. Detonation pressure transfer upon time lapse based on quantity of explosive [9].

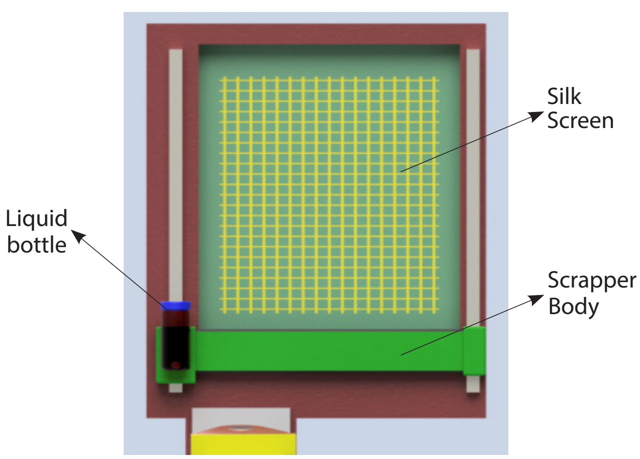


Fig. 9. Sketch of blast body.

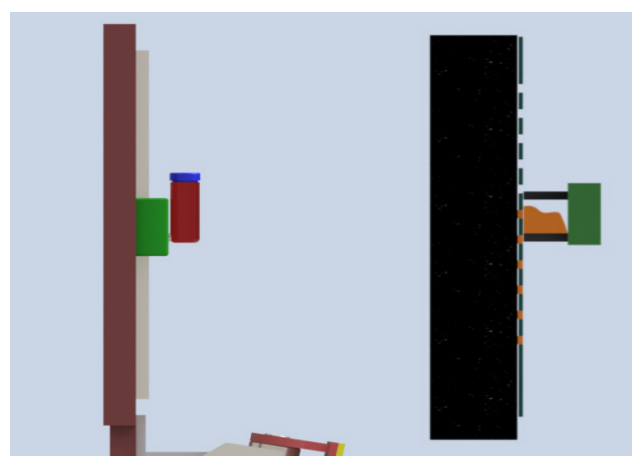


Fig. 10. Sketch of explosive distribution to the surface via screen mesh.

part, robot main body, robot arm, explosive load part, explosion part, concrete dust collection part, dust filtering part, radioactivity measurement part, data communication module part, power circuit part, MCU (Main Control Unit) part, camera, GCS, etc. (Figs. 4 and 9). Fig. 9 shows the blast body which composes scrapper body and silk screen and blast gel type liquid bottle.

Fig. 10 shows the distribution method of explosive to the targeted surface. Scrapper body moves up and down with spraying the explosive gel type liquid and the explosive liquid remains in targeted surface via screen mesh (mesh size is very narrow).

2.5.2.7 Software Configuration

Software composes merged operation control system, radioactivity measurement system using Monte Carlo code,

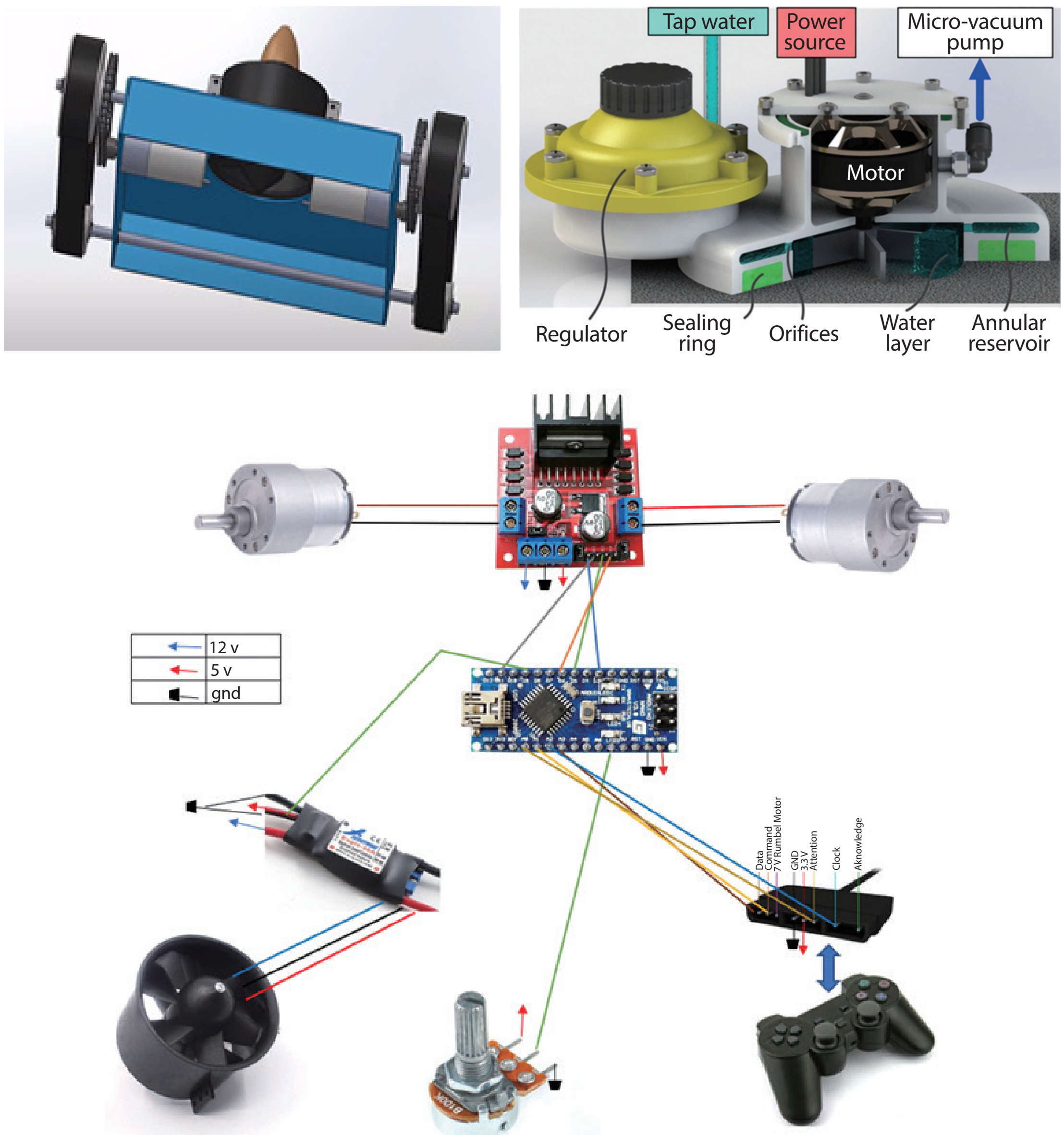


Fig. 11. Conceptual Design for attaching type robot's telecommunication, power and control system.

self-running software, running & pathway identification algorithm, 3D mapping AI system with AI network architecture, deep learning algorithm for location-radioactivity interface mapping, SLAM (location estimation purpose), etc. Fig. 11 shows the conceptual design for attaching type AI robot's telecommunication, power and control system which operate AI based micro- blast scabbling system.

At present, ORION expects the TRL (Technology Readiness Level) is 3 step (final step is 9) and CRL (Commercial Readiness level) is also 3 steps (final step is 8) but if ORION starts the pilot scale system development TRL 6 and CRL 4 may be completed. Table 3 shows the technical target for development towards pilot system.

Micro-blast scabbling system merged with Robot

Table 3. Technical Target for development

Technical situation (Specification)	Unit	Importance Ratio (%)	World Best Level (Performance)	Korea Level (Performance)	ORION Target
Nuclide Identification	ea.	15	More than 5	More than 5	More than 5 Including ^{22}Na, ^{137}Cs, ^{54}Mn, ^{60}Co, ^{152}Eu (NUREG-3474 [10])
Radioactivity Measurement	$Bq·g^{-1}$	15	Comparison is impossible because no micro-blast system exists.	Comparison is impossible because no micro-blast system exists.	$< 1×10^7$
Robot Duty Weight	kg	15	Comparison is impossible because no micro-blast system exists.	Comparison is impossible because no micro-blast system exists.	1.5
Robot self-running	cm	10	Comparison is impossible because no micro-blast system exists.	Comparison is impossible because no micro-blast system exists.	10
Explosive and Detonator performance	%	10	100 (Other technology case)	100 (Other technology case)	100
DF performance	%	15	100 (Other technology case)	100 (Other technology case)	100
Decontamination speed	$cm^2·hr^{-1}$	20	7,500 (TWI case (UK)) [Reference: WM2010 Conference, The Potential of High Power Lasers in Nuclear Decommissioning]	2,500 (KAERI)	8,000

system AI is the first concept over the world and based on above technical specifications the technical merits of micro-blast scabbling system may much contribute the dismantling and decontamination of concrete structure in near future.

3. Conclusions

This paper presents the micro-blast type scabbling technology as conceptual design basis. The technology shows the several merits in nuclide identification more than 5 nuclides (^{60}Co, ^{137}Cs, ^{152}Eu, ^{54}Mn, ^{22}Na), 0.1–10^7 $Bq·g^{-1}$ radioactivity measurement capability, 1.5 kg robot duty weigh for easy handling, 10 cm robot self running capability, 100% explosive detonator performance, DF 100 performance and 8,000 $cm^2·hr^{-1}$ decontamination speed which is better than TWI case (7,500 $cm^2·hr^{-1}$), etc. For better performance the system composes with explosive material load screen, squeeze to supply explosive material, attaching type robot arm and main body, together with operation control system equipped by 3D contamination measurement and radioactivity mapping, decontamination AI, GCS (Ground Control Station), etc. The system also equips dust collection device, filtering system and the variable explosion control system according to contamination depth. This system will be helpful for decommissioning of nuclear power plant as good method for concrete structure decontamination. Because the explosive material is well developed in Korea and the basis of robot system and mapping system is under development by governmental support. Hence, the micro-blast type scabbling technology can be helpful towards Korean decontamination industry when the pilot scale system will be ready and successfully operated in near future.

ORION expects pilot scale system will be settled from 2022 thru 2024 step by step when the planning of R&D center for decommissioning is established and the necessary equipment is required.

Acknowledgements

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