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Convergence Methods for Practical Problem-Solving through the Generation of Diverse Ideas in the Semiconductor Industry: TRIZ & Design Thinking

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Abstract: This study proposes a practical approach to solving complex challenges in the semiconductor industry by integrating TRIZ, a systematic innovation methodology, with Design Thinking, a user-centered problem-solving framework. Utilizing this hybrid methodology, various solution ideas were generated and validated for industrial feasibility through a case study. Key problems were identified through direct observation of the work environment and empathy with field operators. These were then structured using function analysis and cause-effect chain analysis. Creative solutions were derived using the ARIZ-85C algorithm and grouped and refined based on their functional roles. Before full-scale application, prototypes were developed and tested to evaluate their feasibility and performance. To enhance worker safety, a redesigned powder trap was proposed, integrating a pulsing system to address issues such as hazardous odors and entrapment risks. The system's powder collection and removal functions were validated through prototype testing before being successfully implemented in an actual manufacturing environment. As a result, the required man-hours for maintenance operations were reduced from 6MH to 1MH, achieving an approximate 83% efficiency gain. Additionally, annual maintenance costs decreased by nearly 100 million KRW. The development and evaluation period was also significantly reduced from over two years to just three months. This case study confirms the practical value of integrating TRIZ and Design Thinking for addressing multifaceted problems in semiconductor manufacturing. Nevertheless, since the experiments were conducted under specific conditions, further validation across a broader range of tools and processes is necessary to generalize the findings.

Keywords: Convergence; Design Thinking; Semiconductor; TRIZ

1 INTRODUCTION
1.1 Research Background

With the recent proliferation of Generative AI, the demand for high-performance DRAM capable of handling large volumes of data at high speed has increased significantly. In response, the core component of DRAM—the capacitor—is evolving toward smaller and thinner structures while enhancing storage capacity. This advancement introduces new technical challenges in the semiconductor deposition process. As capacitor geometries become more intricate, it becomes increasingly difficult to uniformly deposit materials within narrow and deep trenches during the deposition phase. To address this, various chemical additives are used in the process, which often carry inherent risks such as flammability and explosiveness. After processing, by-products accumulate in the exhaust system as solids or liquids, and can react violently upon exposure to moisture. Currently, plasma treatment systems are employed to convert these hazardous by-products into solid powder or non-condensable gases. The solid powder is collected in a powder trap, and only the gas phase is discharged through the exhaust system (Fig. 1).

The powder collected in the trap is periodically removed using a vacuum cleaner through a designated clean port. However, in practice, this removal is often ineffective and frequently necessitates disassembling the filter and housing. These procedures release harmful substances and strong odors, requiring workers to wear gas masks. Moreover, repetitive operations in confined spaces elevate the risk of entrapment injuries, significantly compromising workplace safety.

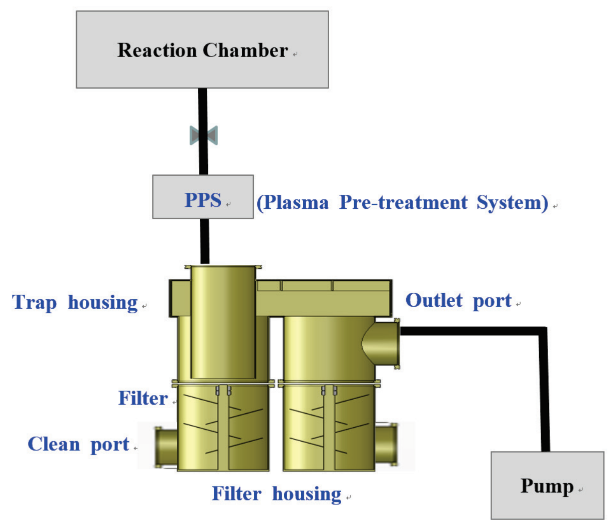

Figure 1 Configuration of the exhaust system and powder trap in DRAM deposition processes

1.2 Research Objectives and Methodology

The objective of this study is to address the issue of powder accumulation and removal in DRAM deposition processes through an integrated analysis from both technical and user-centered perspectives, and to derive creative yet practical solutions. To achieve this, the study employs a hybrid approach that combines TRIZ (Theory of Inventive Problem Solving), which provides systematic tools for contradiction analysis, with Design Thinking, a methodology rooted in empathy and user engagement. TRIZ was used to identify and structure technical contradictions and system-level problems, while Design Thinking contributed to concretizing viable ideas by reflecting actual user needs and on-site conditions. By organically integrating these two methodologies, the study seeks to establish a balanced problem-solving framework that connects technology-driven analysis with human-centered design.

1.3 Structure of the Paper

This paper is structured as outlined in Tab. 1.

Table 1 Structure of the paper

Chapter	Title	Contents
1	Introduction	Background, research objectives, methodology, and overall paper structure
2	Literature Review & Methodology	Overview of TRIZ and Design Thinking; analysis of their integration potential
3	Problem Analysis	Problem structuring through user empathy, function analysis, cause-effect chain analysis, and contradiction analysis
4	Idea Generation	Development of creative solutions based on TRIZ principles
5	Idea Evaluation and Validation	Idea grouping, establishment of evaluation criteria, prototyping, and testing
6	Conclusion and Future Work	Summary of findings, identified limitations, and directions for future research

2 LITERATURE REVIEW AND RESEARCH METHODOLOGY
2.1 TRIZ (Teorija Rezhenija Izobretatelskih Zadach)

TRIZ (Teorija Rezhenija Izobretatelskih Zadach, Theory of Inventive Problem Solving) is a problem-solving methodology developed by Genrich Altshuller and his colleagues. It analyzes patterns of invention and innovation to provide systematic tools and techniques. Using principles derived from numerous patents, TRIZ formalizes tools for creative problem-solving. Key TRIZ tools include the 40 Inventive principles, 76 Standard solutions, the Effects Database, Separation Principles, the Contradiction Matrix, the Laws of Technological System Evolution, the Ideal Final Result (IFR), Function Analysis, Substance-Field (Su-Field) Analysis, Resource Analysis, System Thinking and Function-Oriented Search (FOS), a new TRIZ-based tool. One study using the FOS methodology in the semiconductor industry developed a system to prevent explosion accidents caused by hydrogen emissions. The system replaced hydrogen with steam using a Hydrogen Plasma Treatment Unit (HPTU) and proposed an optimal non-explosive model based on hydrogen usage [1]. As shown in Fig. 2, TRIZ systematically organizes solutions based on problem types, enabling structured learning of creative problem-solving methods.

A case study applied problem-solving methodologies to address defects in semiconductor encapsulation, a post-processing stage in manufacturing. The issue involved leakage of the Epoxy Mold Compound (EMC), a molding resin, leading to production defects. A physical contradiction was identified by analyzing the problem as a technical contradiction. Applying the principles of separation between parts and the whole, the conventional pellet form of EMC was transformed into a powder form, allowing for low-viscosity melting while maintaining the original process temperature. This solution provided a concrete method to resolve EMC leakage issues and improve manufacturing stability [2].

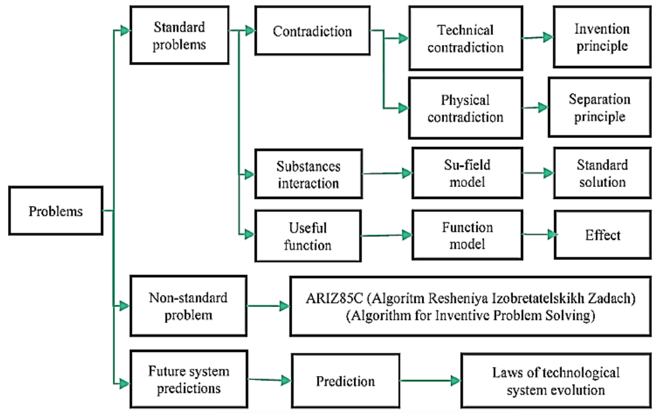

Figure 2 Solution based on the type of problem

2.2 Design Thinking

Design Thinking is a user-centered creative problem-solving methodology developed by Stanford University. It comprises five stages: Empathize, Define, Ideate, Prototype, and Test. Through a human-centered design approach, Design Thinking deeply understands users' needs and problems and develops innovative solutions based on this understanding (Tab. 2).

Table 2 Design thinking

Step	Explanation	Main activities
Empathize	It is the stage for deeply understanding the user's needs and problems.	Observations, Interviews, Surveys, Creating Empathy maps.
Define	Based on the insights gained in the Empathize stage, a clear problem is defined.	Write a problem Statement, Personas, Create a problem Definition document.
Idea Generation	Explore various solutions and generate creative ideas.	Brainstorming, Mind Mapping, SCAMMPER.
Prototype	Create low-fidelity prototypes, develop storyboards, and design wireframes.	Create low-fidelity prototypes, Develop storyboards, Design wireframes.
Test	Test the prototype with real users and gather feedback.	Collect user feedback, Make iterative improvements, Conduct user experience (UX) testing.

After the Ideation stage of Design Thinking, it is crucial to systematically organize the numerous ideas, group similar ideas (Clustering), and derive integrated solutions. The process of idea grouping involves visualizing ideas, identifying similarities, deriving themes, setting priorities, and integrating solutions. Benefits such as reduced complexity, enhanced collaboration, and improved efficiency can be achieved through idea grouping. The key aspect of this methodology is the iterative process, where insights gained in each stage may lead to revisiting the Empathize stage, modifying the problem definition, or restructuring ideas. This process has been applied in various fields, including the design development of water purifier products [3], self-diagnosis and remote healthcare endoscope camera products [4, 12], and baby toothbrush product design development [5].

2.3 TRIZ & Design Thinking

In highly technology-intensive industries such as semiconductor manufacturing, problems frequently emerge from the convergence of technical complexity and user-centered constraints. Addressing such multifaceted challenges requires a methodological framework that incorporates both technical and human dimensions. This study proposes a hybrid problem-solving framework that integrates TRIZ, a systematic approach for resolving technical contradictions, and Design Thinking, a user-centered methodology focused on empathy and iterative refinement. TRIZ supports logical and analytical problem-solving through tools such as function analysis, cause-effect chain analysis, and contradiction resolution, which are particularly effective in structuring and resolving engineering problems. On the other hand, Design Thinking emphasizes user observation, experience, and empathy, offering a practical path for generating ideas that are both creative and grounded in real-world needs. The complementary strengths of these two approaches enable the development of solutions that are not only inventive but also applicable in practice [11].

The proposed framework consists of seven sequential stages that span the entire problem-solving process from exploration to deployment in industrial settings: The first step, Empathy, involves direct observation of the workplace and interviews with users to gain deep insight into on-site problems. This step, central to Design Thinking, helps uncover human-centered issues that are often overlooked in purely technical analyses. The second step, Technical Analysis, utilizes TRIZ techniques including function analysis, cause-effect chain analysis, and contradiction resolution to identify structural causes and define technical contradictions and ideality targets within the system. The third step, Problem Definition, integrates insights from the empathy and analysis phases to articulate a clear and precise problem statement. This step represents the core integration point of TRIZ and Design Thinking, enabling a nuanced definition that simultaneously reflects technical constraints and user needs. In the fourth step, Idea Generation, creative solutions are developed using TRIZ's inventive principles and standard solutions. These ideas are further refined through Design Thinking’s grouping and integration methods to produce solutions that are both functionally robust and user-friendly. The fifth step, Idea Evaluation, applies TRIZ-based criteria such as degree of ideality, contradiction resolution, and applicability to assess the proposed solutions. While Design Thinking's SCAMPER technique is used as a supplementary tool, this study primarily employs TRIZ’s quantitative evaluation framework to ensure rigor and consistency. The sixth step, Prototyping, involves the physical implementation of the most promising ideas into testable prototypes. This step reflects Design Thinking’s experimental ethos and serves as a pre-implementation validation step to assess practical feasibility. The final step, Test and Implementation, places the prototype in real industrial settings for iterative testing under actual process conditions. Feedback from users is incorporated to refine the solution into its final, deployable form. This integrated problem-solving framework provides a balanced approach that unites technology-driven analysis with human-centered design. It offers a practical and replicable methodology for solving complex problems in high-risk, high-precision environments such as semiconductor manufacturing, where both technical performance and user requirements must be met simultaneously (Tab. 3).

Table 3 Integrated framework of TRIZ & Design thinking

Step	Key Activity	Methodology	Objective
1. Empathy	Workplace observation, user interviews	Design Thinking	Understand user needs and field-level issues
2. Technical Analysis	Function, cause-effect chain, and contradiction analysis	TRIZ	Identify technical structure and contradictions
3. Problem Definition	Integrate user and technical problem insights	Integrated	Define the core problem
4. Idea Generation	Generate, grouping, and integrate creative ideas	Integrated	Develop ideas with both functional and user focus
5. Idea Evaluation	Evaluate ideality, contradiction resolution, and Applicability	TRIZ	Select the optimal solution
6. Prototype	Design and build prototypes	Design Thinking	Verify practical applicability
7. Test & Implementation	Conduct user testing, incorporate feedback, finalize solution	Design Thinking	Apply and scale the final solution in practice

Research cases that combine TRIZ and Design Thinking demonstrate an approach that combines the strengths of both methodologies for innovative problem-solving. A study that improved a solar wood dryer showed significant performance differences depending on the weather by integrating TRIZ (Theory of Inventive Problem Solving) and Design Thinking. In this study, they successfully developed a biomass dryer with excellent performance unaffected by weather conditions [6]. The innovative Design Thinking process alongside TRIZ included methods for selecting attractive and trendy social and business issues, providing a way to discover problems and build an organization's innovation culture more effectively. This increased participants' passion and commitment to innovation [7]. Research also supports users in systematically establishing innovation projects by integrating Design Thinking and TRIZ. This study combines TRIZ’s systematic problem-solving methods with the creative thinking process of Design Thinking, presenting methodological tools to drive more effective innovation [8].

These studies demonstrate that better problem-solving and innovation can be achieved by leveraging the complementary characteristics of both methodologies.

3 PROBLEM ANALYSIS

3.1 Empathize

Through observations of the powder removal worksite, it was found that the primary workers and the assistants had to wear gas masks due to the poor working conditions. A large amount of powder was scattered around the work area, causing unpleasant odors. All workers reported discomfort, and significant time was spent cleaning the area after the work. In interviews with actual workers, 80% considered powder removal the most difficult task, while the remaining 20% found the cleanup process challenging. Specifically, all respondents reported discomfort when wearing gas masks during work. In interviews regarding improvements to the working environment, 80% expressed a desire for a work environment where gas masks would not be required, while 20% wanted the powder scattering issue to be addressed. Based on this feedback, the decision was made to improve the powder trap structure so that powder removal work could be performed safely without gas masks or powder scattering. This improvement is expected to greatly enhance the working environment and increase worker safety and efficiency.

3.2 Function Analysis

As illustrated in Fig. 3, during normal operation, powder flows through the inlet port (A). Heavier particles are partially captured by the filter, while others fall to the bottom of the filter housing (B). Lighter powder continues to flow through the trap housing, with some accumulating on the filter and some settling at the bottom of the housing (C).

Among the powder that settles at the bottom of the filter housing, a portion tends to accumulate on the side opposite the clean port (D). As the amount of accumulated powder increases, the system is shut down, the clean port is opened, and the powder is removed using a vacuum cleaner (E).

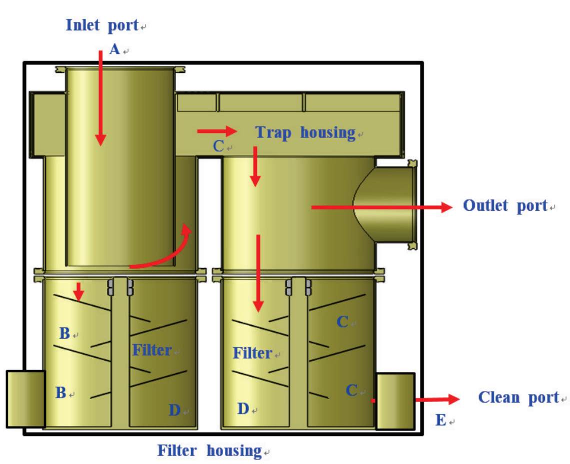

Figure 3 Operational description of a powder trap

When opening the clean port, a gas mask must always be worn. However, as shown in the following functional diagram (Fig. 4), vacuum cleaning does not effectively remove the powder, requiring the disassembly of the filter and filter housing. This process requires wearing a gas mask for an extended period, which is physically demanding and presents a risk of discomfort due to the confined space.

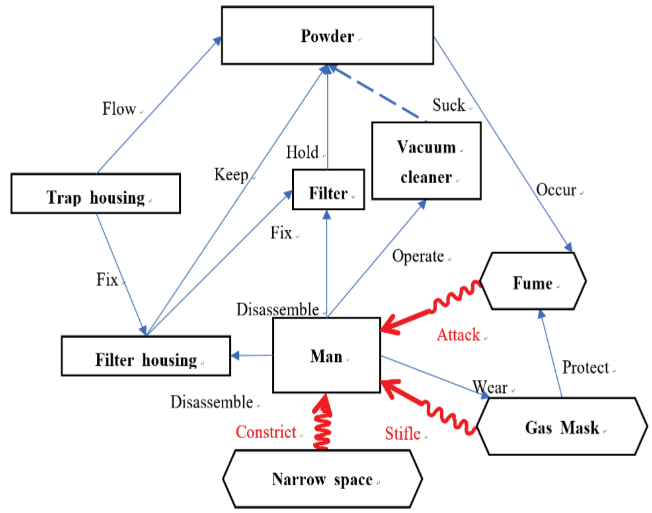

Figure 4 Function diagram of disassembly operation

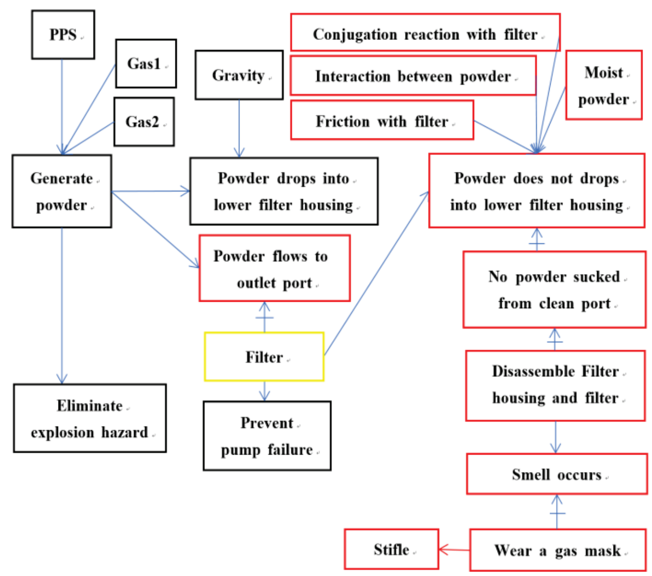

Figure 5 Cause-effect chain analysis

3.3 Cause-effect Chain Analysis

As illustrated in the cause-effect chain analysis in Fig. 5, powder is generated to mitigate the explosion risk by introducing byproduct and oxidation gases into the PPS after the process. However, the generated powder is intended to fall and be captured at the bottom of the filter housing; instead, some of it flows into the pump through the outlet port, leading to equipment failure. To address this issue, an additional filter was installed to prevent the powder from entering the pump. However, the powder does not flow into the lower part of the filter housing, resulting in the inconvenience of having to disassemble both the filter housing and the filter during the removal process. This task generates odors from harmful substances, requires wearing a gas mask, and poses a risk of discomfort due to the confined working space.

3.4 Contradiction Analysis

Adding a filter to prevent the powder from flowing into the outlet port addressed the pump failure issue. However, it introduced the problem of requiring a gas mask and performing difficult tasks during removal process because the powder does not flow into the bottom of the filter housing. While a filter is necessary to prevent the powder from entering the outlet port, there is a physical contradiction: the filter must not be present for the powder to flow into the filter housing. Analyzing the physical contradiction at a micro level, the filter must be located on the outer walls, where the powder flows, to prevent it from reaching the outlet port. At the same time, for the powder to flow into the filter housing, the filter in the center must be absent (Fig. 6).

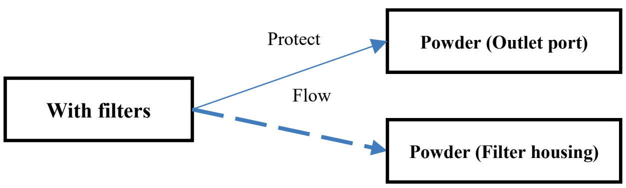

Figure 6 Technical contradiction (TC1)

4 PROBLEM SOLVING IDEAS

4.1 Contradiction Solving Idea

The problem is modeled using 39 engineering parameters to resolve the technical contradiction. The proper parameter is productivity, as preventing pump failure contributes to increased productivity, while the harmful parameter is the ease of maintenance, as the powder removal process has become more difficult. Among the inventive principles recommended in the contradiction matrix, the "preliminary action" principle led to adding a vibration motor to reduce vibration before the powder accumulates on the filter (Fig. 7). As a solution to the physical contradiction, the concept of applying spatial separation was developed, where the filter is removed from the center of the filter housing, and a filter is installed on the outer walls, which are the powder flow passages (Fig. 8). The arrows indicate the direction of powder flow.

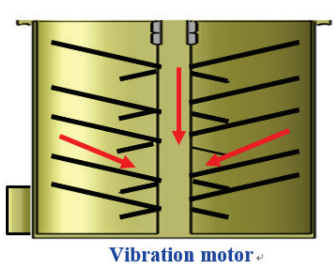

Figure 7 Add Vibration motor (Inventive principle)

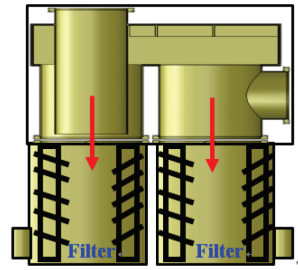

Figure 8 Physical separation of the filter area

4.2 IFR (Ideal Final Result)

The tool's goal is to solve the problem without increasing the system's complexity or causing additional harmful effects. The issue arises when the filter remains at the center due to the friction of the powder, moisture, reactions between the powders, and bonding reactions, preventing it from moving to the lower part of the filter housing. To resolve this problem, the filter's angle can be sharply adjusted so that it does not retain the powder, effectively addressing the issue of the powder not flowing to the lower part of the filter housing (Fig. 9). The arrows indicate the direction of powder flow.

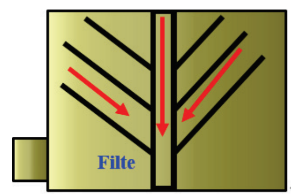

Figure 9 Steeply inclined filter

4.3 Trimming (Eliminate Functionally Unnecessary Elements)

If the functional elements can transfer their functions to other surrounding elements, the functional elements can be removed. The function of allowing the powder to flow to the lower part of the filter housing and preventing it from flowing into the outlet port, which is currently performed by many filters in the center, can be transferred to the filter housing. This would allow for removing the many filters in the center (Fig. 10). The arrows indicate the direction of powder flow.

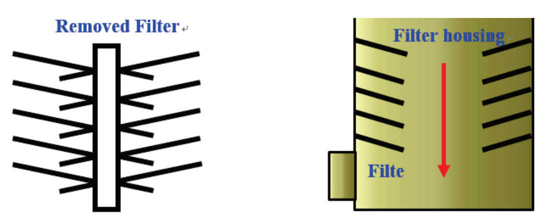

Figure 10 Integrated the filter function into the filter housing

4.4 Take a Step Back from IFR

By minimizing the number of filters in the center, only part of the function of blocking the powder flow to the outlet port is performed while allowing the powder to be effectively directed into the bottom of the filter housing. The issue of powder flow into the outlet port is addressed by installing a barrier wall (A) (Fig. 11). The arrows indicate the direction of flow of the gas and powder.

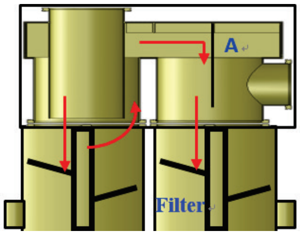

Figure 11 Streamlined the filter design

4.5 Standard Solution

To solve the issue of powder removal using a vacuum cleaner, Nitrogen is used from the upper system to apply mechanical pressure to the powder and filter. By injecting it into the powder that did not flow to the bottom, the powder flows into the filter housing and then into the filter, causing the filter to vibrate. Nitrogen is supplied in a pulsed manner to facilitate the movement of the powder (Fig. 12). The arrows indicate the direction in, which nitrogen and powder flow in the same direction.

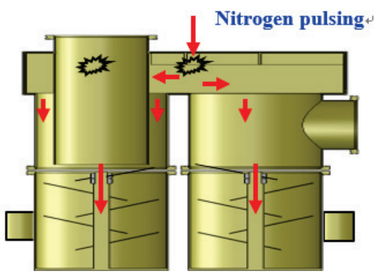

Figure 12 Add Nitrogen pulsing

Powder that does not flow to the bottom of the filter housing due to friction with the filter is made to flow naturally to the bottom by adding ultrasonic to the filter, utilizing gravity and the direction of the filter (Fig. 13).

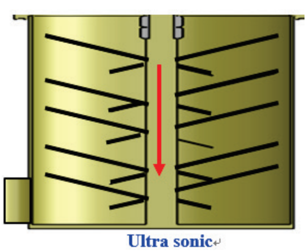

Figure 13 Add Ultra-sonic

Powder that does not flow to the bottom due to its moist characteristics can be made to move downward by adding heat during the drying process, preventing it from adhering to the surface and allowing it to flow downward (Fig. 14).

Due to interactions between powder particles, some powder does not flow downward as expected. To address this, a non-reactive external agent is introduced to facilitate separation and induce downward movement of the remaining powder (Fig. 15).

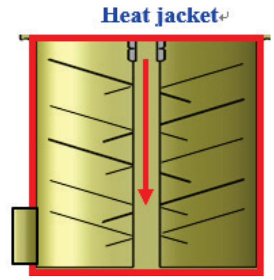

Figure 14 Add Heat jacket

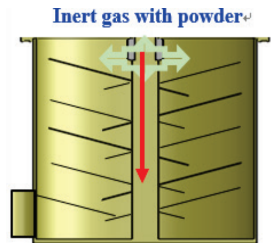

Figure 15 Add inert gas

Powder that does not flow to the bottom due to bonding reactions with the filter surface can be made to flow naturally by coating the filter surface and minimizing the reaction time, allowing gravity to carry the powder downward (Fig. 16).

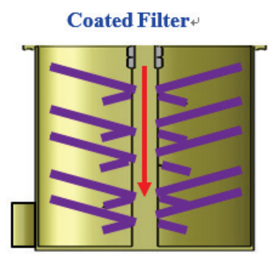

Figure 16 Coated filter

4.6 Void (Reserve as Empty Space)

An empty space is introduced to eliminate the issue of powder not flowing to the bottom of the filter housing. By leaving the filter empty, the powder flows effectively to the bottom of the filter housing, and the function of blocking the powder flow to the outlet port is reinforced by installing a barrier wall (A) (Fig. 17). The arrows indicate the flow direction of the gas and powder.

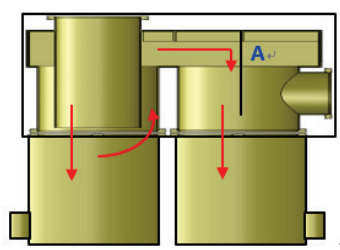

Figure 17 Omitted the filter installation

4.7 FOS (Function Oriented Search)

The problem is defined as the failure of powder to concentrate at the bottom of the filter housing. The required function definition to search for similar functions in major industries is that the powder accumulates in the housing and does not move outward. References include a paper on the optimization design of dust collector inlets for separating powder from gas (air) [9] and a patent on centrifugal filters and dust collectors [10]. Cyclone technology (A), which applies centrifugal force and rapidly rotating gas or powder flows, was used based on this. Using the cyclone method, the powder naturally concentrates on the outer wall (B) (Fig. 18). The arrows indicate the flow direction of the gas and powder.

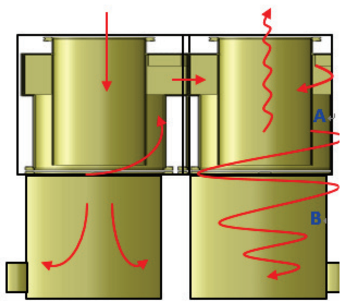

Figure 18 A Structure with an integrated cyclone function

5 EVALUATE IDEAS AND SOLVE PROBLEMS

5.1 Concept Solution

The various problem-solving solutions identified above are summarized in Tab. 4.

Table 4 Concept solution

NO	Tool	Concept solution
1	Inventive principle	By applying the inventive principle of "preliminary counteraction," a vibrating motor is introduced to prevent the powder from coming into contact with the filter in advance.
2	Separation	Install a filter on the outer wall of the primary side flowing toward the outlet and remove the central filter.
3	IFR	Increase the inclination of the filter.
4	Trimming	Introduce obstacles to the filter housing and remove the central filter.
5	Take a step back From IFR	Place the filter at a minimal angle and install a blocking wall in the trap housing leading to the outlet port. Reinforce it to prevent powder flow.
6	Standard solution	By adding nitrogen, mechanical pressure is applied to the powder and filter.
7	Standard solution	Powder that exists due to friction with the filter is resolved by introducing ultrasound.
8	Standard solution	Add heat (thermal field) to activate the movement of moist powder.
9	Standard solution	Powder interactions are resolved by adding a substance that does not react with the powder, using a chemical field.
10	Standard solution	Powder bonding with the filter surface is resolved by applying a coating, using a mechanical field.
11	Void	Leave the filter section as an empty space and install a blocking wall in the trap housing. Reinforce this area to prevent powder flow to the outlet port.
12	FOS	By modifying the flow of gas and powder using the cyclone method, the powder naturally concentrates on the outer wall, and the filter in the middle is removed.

5.2 Idea Grouping

The concepts of IFR, Trimming, "Take a Step Back" from IFR, Void, FOS, and Separation are implemented to ensure efficient powder flow into the filter housing while preventing any flow into the outlet port. Given that these solutions necessitate structural modifications, they have been incorporated into a new conceptual design for the powder trap structure, as presented in Tab. 5.

Table 5 Idea grouping and integration

Principle	Separation, IFR, Trimming, Take a step back from IFR, Void, FOS.
IDEA	The centrally located filter is removed, and an obstacle with a steep inclination is installed on the outer wall of the filter housing. The flow direction within the trap housing is altered, and the outlet port is repositioned to the top. The flow of gas and powder is redirected to follow a cyclone flow method. (The filter is no longer located at the center but is instead positioned on the outer wall.)

5.3 Evaluate Ideas

Among the twelve initially generated ideas, a total of seven were retained after grouping and integration. These included both functionally integrated concepts and ideas derived from TRIZ inventive principles and standard solutions. All creative ideas were generated using the TRIZ methodology. For idea evaluation, a 5-point scale was employed based on three TRIZ-defined criteria: ideality, contradiction resolution, and applicability. Based on the total evaluation scores, two ideas were selected for implementation: a novel powder trap concept and a solution involving the introduction of nitrogen gas (Tab. 6).

Table 6 Idea evaluation

NO	Principle	Idea	Idea evaluation (5-point scale)			
			Ideality	Contradiction resolution	Applicability	Score
1	Integrated	Modified powder trap and filter.	5	5	5	15
2	Inventive principle	Add vibration motor.	3	3	3	9
3	Standard solution	Add nitrogen.	4	4	5	13
4	Standard solution	Add ultrasound.	3	3	3	9
5	Standard solution	Add thermal.	3	3	3	9
6	Standard solution	Add substance that does not react with the powder.	3	3	3	9
7	Standard solution	Add coating.	3	3	3	9

5.4 Prototype

A prototype was developed to test and evaluate the new powder trap concept, which was selected during the idea integration process. The central filter was removed, and a plate, which functions as a filter, was placed at a steep angle on the outer wall, following the powder's flow direction (A). The section before the outlet port was modified to a cyclone method (B), allowing the powder to be collected on the outer wall. Arrows indicate the direction of gas flow, while circular particles represent the form of powder collection. To address the possibility of incomplete powder removal, a pulsing system was integrated into the upper system, using nitrogen to apply strong pressure to both the powder and the filter, as illustrated in Fig. 19.

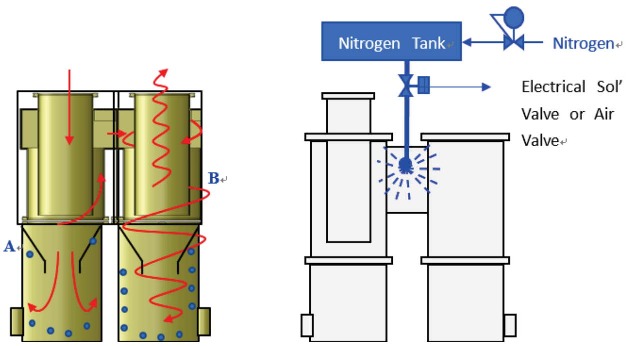

Figure 19 New concept powder trap and nitrogen pulsing system

5.5 Test

To quantitatively validate the performance of the designed powder trap and nitrogen pulsing system, two experiments were conducted under conditions simulating an actual production environment. The first experiment focused on evaluating powder collection performance, while the second assessed the powder removal efficiency using the nitrogen pulsing system. In the powder collection experiment, 1000 g of actual process powder was applied at point (A) of the trap (Fig. 21). A vacuum was then generated using a pump with a capacity of 100,000 liters per minute, and 10 liters of nitrogen gas was injected. The system was maintained in this state for 30 minutes, after which the remaining powder mass was measured. A total of 30 repeated trials were conducted (Tab. 7), resulting in an average collection efficiency of 90.35%, with a standard deviation of 0.49%. The minimum and maximum values were 89.56% and 91.72%, respectively. The results were closely distributed around the mean, indicating high reproducibility and experimental reliability. In the powder removal experiment, a vacuum cleaner was connected to the clean port, and nitrogen was instantaneously released once the supply tank reached a pressure of 60 psi by opening a pneumatic valve. The nitrogen supply line had a diameter of 25 mm (B), and the powder application method and quantity were consistent with the collection experiment. Based on 30 repeated trials (Tab. 7), the average removal efficiency was 91.51%, with a standard deviation of 1.01%. The removal efficiency ranged from 90.20% to 95.00%, with over 90% efficiency achieved in the vast majority of tests (Fig. 20). These results confirm that the nitrogen pulsing system delivers high-efficiency and repeatable performance in powder removal. Overall, the experimental results demonstrate that both the powder collection and removal mechanisms meet or exceed the performance requirements for industrial applications. The design has been experimentally validated as stable and reliable. Furthermore, to enhance maintenance accessibility and ensure operator safety, the clean port was finalized using a double-cap structure (C) (Fig. 21).

Table 7 Test result

Powder trapping				Powder elimination			
No	Before (g)	After (g)	Efficiency (%)	No	Before (g)	After (g)	Efficiency (%)
1	1005	905	90.0	1	1003	85	91.5
2	1001	906	90.5	2	1002	86	91.4
3	1003	903	90.0	3	1003	75	92.5
4	1002	911	90.9	4	1000	86	91.4
5	1004	910	90.6	5	1005	95	90.5
6	1005	905	90.0	6	1000	96	90.4
7	1002	903	90.1	7	1000	90	91.0
8	1003	920	91.7	8	1005	85	91.5
9	1002	901	89.9	9	1000	80	92.0
10	1001	905	90.4	10	1000	98	90.2
11	1000	910	91.0	11	1004	80	92.0
12	1000	912	91.2	12	1000	84	91.6
13	1000	905	90.5	13	1000	85	91.5
14	1005	907	90.2	14	1003	90	91.0
15	1003	901	89.8	15	1000	50	95.0
16	1002	910	90.8	16	1000	90	91.0
17	1002	904	90.2	17	1001	96	90.4
18	1000	906	90.6	18	1001	72	92.8
19	1000	902	90.2	19	1000	85	91.5
20	1000	905	90.5	20	1002	90	91.0
21	1005	903	89.9	21	1002	75	92.5
22	1005	902	89.8	22	1005	85	91.5
23	1006	901	89.6	23	1000	95	90.5
24	1002	903	90.1	24	1000	77	92.3
25	1001	905	90.4	25	1005	67	93.3
26	1002	901	89.9	26	1000	92	90.8
27	1002	903	90.1	27	1000	95	90.5
28	1000	911	91.1	28	1003	85	91.5
29	1002	903	90.1	29	1000	92	90.8
30	1000	901	90.1	30	1004	90	91.0

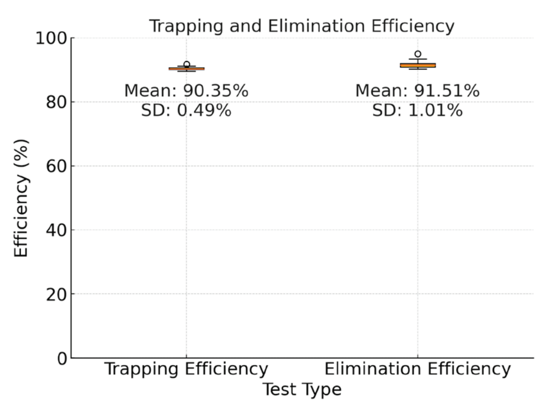

Figure 20 Test result

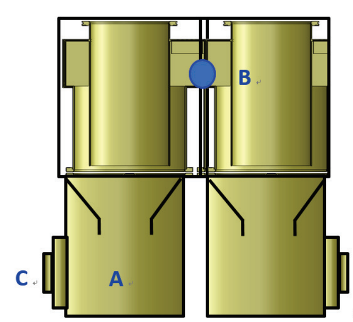

Figure 21 Double cap

5.6 Apply

The new concept of the powder trap was implemented in the industry. Powder collection efficiency was enhanced, and the issue of powder flow into the outlet port was resolved. The pulsing system effectively eliminated any powder that was not fully removed.

6 CONCLUSION AND FUTURE WORK

This study applied an integrated problem-solving framework that combines TRIZ and Design Thinking to address recurring and complex challenges observed in semiconductor manufacturing environments. To evaluate the feasibility of implementation in real process settings, we conducted field observation and empathy-based problem identification, performed structural analysis using function and cause-effect chain analysis, and generated creative solutions using the ARIZ-85C algorithm. As a result, the developed system significantly reduced labor effort, enabling a task that previously required three workers for two hours to be completed by two workers in just 30 minutes, achieving a total reduction of 5.5 man-hours. Additionally, the one-time preventive maintenance (PM) cost was reduced from 2.1 million KRW to 100,000 KRW, leading to an estimated annual maintenance cost saving of approximately 100 million KRW. These figures are based on specific equipment and maintenance scenarios, providing a quantitative basis for the cost-reduction potential. Moreover, the system also contributed to reduced exposure to hazardous substances and the prevention of entrapment accidents, indicating improved worker safety and potential for industrial accident prevention.

The idea grouping and integration process also contributed to a reduction in the idea evaluation period from two years to three months, while eliminating functional redundancy and minimizing trial-and-error. These outcomes confirm that the fusion of TRIZ and Design Thinking can serve as a practical and repeatable problem-solving methodology in high-risk, high-complexity industrial settings.

However, this study has several limitations. First, some experiments were conducted under simulated rather than full-scale process conditions, limiting the precision of powder collection validation. Future work should consider real-time monitoring or long-term tracking systems. Second, the applicability of the proposed solutions was tested under limited equipment and process settings. Additional validation across various semiconductor tools and powder types is needed. Third, while operator feedback was partially considered, a systematic usability evaluation and iterative refinement process were not fully implemented. Future studies should incorporate structured user-centered design approaches.

Despite these limitations, this study provides an empirical demonstration of how integrating technical analysis with user-centered design can effectively address complex industrial problems. The proposed framework is expected to be extended and validated in other high-risk industrial domains beyond the semiconductor sector, enhancing both its generalizability and practical value.

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