# Investigation of hydrodynamic and scaling of TRISO coaters for high temperature small modular reactors

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**Abstract**

The quality of TRISO-coated nuclear fuel particles is crucial for ensuring operational efficiency and safety of high-temperature gas-cooled small modular reactors (SMRs) that utilize TRISO technology. This is why the TRISO particles must be uniform in size, shape, and coating, as well as free of defects. The technique used for coating TRISO particles are gas-solids spouted beds via chemical vapor deposition (CVD). It has been reported that the quality of TRISO coated particles is strongly affected by the hydrodynamics of the spouted beds. The gas-solid spouted bed coating technology, integral to TRISO particles, is examined, with a focus on the impact of spouted bed hydrodynamics on the delicate coating layers surrounding the fuel kernel. The intricate interplay between successive coating layers and the scaling up of spouted beds, vital for large-scale TRISO particle fabrication for SMRs, represents a significant challenge in nuclear fuel particle manufacturing. In response to this challenge, our study presents our newly developed mechanistic scale-up methodology for gas-solids spouted beds, validated through an experimental examination of radial gas holdup profiles using sophisticated measurement techniques. This methodology is a pivotal advancement in understanding hydrodynamics and scale-up dynamics, crucial for the commercialization of SMRs utilizing TRISO technology. In light of current nuclear fuel requirements for SMRs, this research is of utmost importance due to the escalating demand for TRISO particles. Furthermore, our work presents a comparative analysis between the mechanistic scale-up methodology developed in our laboratory and traditional approaches, demonstrating the enhanced accuracy of the former in predicting the performance of spouted bed systems. The insights derived from this study hold significant implications for the development and commercialization of high-temperature gas-cooled SMRs employing TRISO technology, offering valuable contributions to the broader context of clean and sustainable energy solutions.

## INTRODUCTION

In the field of advanced new generation nuclear reactors, High-Temperature Small Modular Reactors (HTSMRs) stand out as particularly well-suited to address the energy needs of the 21st century [1-4]. These reactors combine the benefits of high-temperature operation with the modularity and scalability of small reactors, offering a flexible and efficient solution for diverse energy applications. HTSMRs are designed to operate at temperatures significantly higher than traditional reactors, which allows for improved thermal efficiency and the potential for a broader range of industrial applications, including hydrogen production, process heat for industries, and high-efficiency electricity generation [2]. HTSMRs are distinguished by their passive safety mechanisms, which are among their most critical features. These passive safety systems rely on natural physical principles such as gravity, natural circulation, and thermal conduction to maintain safety without the need for active controls or human intervention. This design significantly reduces the risk of accidents and enhances the overall safety profile of the reactors. Additionally, the modular nature of HTSMRs allows for easier and more cost-effective construction and deployment. The smaller size and factory-built components enable faster construction times and reduced financial risks, making them an attractive option for a wide range of applications, from remote locations to urban settings.

The performance and safety of HTSMRs heavily depend on TRISO fuel coated particles, making the technology and processes involved in fuel coating crucial [5-8]. TRISO (TRi-structural ISOtropic) fuel particles consist of a uranium, carbon, and oxygen fuel kernel encapsulated by multiple layers of carbon and ceramic materials. These coatings provide a robust barrier against the release of fission products, ensuring the integrity and safety of the fuel under extreme conditions. TRISO fuel particles are coated using gas-solid spouted beds through a method known as chemical vapor deposition (CVD). This coating process is highly intricate and demanding, requiring precision to meet stringent standards that allow no more than one coating failure per 100,000 particles [7-9]. The quality of these particles is paramount, as it directly influences the reactor's safety and efficiency. The literature has highlighted that the spouted bed coater is integral to the coating process. The hydrodynamics within the spouted bed significantly affect the quality of the TRISO particles produced [8, 9]. Consequently, a thorough investigation of the hydrodynamic behavior of gas-solid flow in spouted beds is essential. Understanding these dynamics is crucial for optimizing the coating process, ensuring the reliability and safety of HTSMRs in meeting high energy demands. The challenge of scaling up the TRISO spouted bed coater, or gas-solid spouted beds in general, has not yet been fully resolved. Despite their long-standing use for coating TRISO fuel particles, the design and operating conditions of these beds are still largely determined through empirical methods. There is a significant lack of fundamental knowledge in the chemical vapor deposition (CVD) processes of spouted beds that can be directly applied to optimize these processes. For the successful commercial implementation of nuclear reactors that use high-quality and safer coated fuel particles, it is essential to enhance our understanding and improve the performance of spouted beds. This necessity has motivated the current study, which aims to conduct comprehensive scale-up research on spouted beds. The study also integrates advanced non-invasive measurement techniques to better understand and optimize the coating process.

He et al. [10] made a pioneering contribution by defining the first scaling relationships for spouted beds using matching dimensionless groups. However, this foundational work still requires further investigation to fully address the scale-up challenges. The gas phase plays a crucial role in dictating the flow dynamics of gas-solid spouted beds. Recognizing this, Al-dahhan et al. [11] and Aradhya et al. [12] proposed a mechanistic scale-up methodology based on radial gas holdup profiles. However, acquiring accurate radial gas holdup profiles is complex and necessitates the development of reliable experimental and numerical techniques, which remains an active area of research. In addition to the need for better techniques, further studies are necessary to understand the impact of other operating parameters, such as the solids circulation rate and gas flow rate, on the flow dynamics within the spouted beds. According to Al-Dahhan et al. [11], Aradhya et al. [12], and Ali et al. [13, 14], the new method for scaling up gas-solid spouted beds involves ensuring that spouted beds of different sizes and conditions are geometrically similar and have closely matched gas phase holdup radial profiles at a desired bed height within the developed flow region. This approach ensures that the local dimensionless values of the hydrodynamic parameters and their trends are similar or closely aligned in these spouted beds at corresponding bed heights. By ensuring geometric similarity and matching gas phase holdup profiles, it is possible to achieve a more reliable scale-up of spouted beds, leading to better performance and safer fuel particles for nuclear reactors. This research direction not only addresses the empirical gaps in our current understanding but also paves the way for more efficient and commercially viable nuclear energy solutions.

As part of this research, the new methodology for scaling up spouted beds is validated and analyzed by assessing key parameters of solid particle flow using advanced radioisotope techniques. These include gamma ray computed tomography (CT) [15, 16] and radioactive particle tracking (RPT) [17-20]. Through these advanced techniques, the flow dynamics of solid particles in spouted beds can be more accurately measured and understood, leading to improvements in future applications. The validation process involves a detailed examination of solid particle behavior within the spouted beds, using the high-resolution imaging capabilities of gamma ray CT. This method provides a non-invasive way to capture the internal flow structures and distributions of the particles. Additionally, RPT offers precise tracking of individual particles, allowing for a comprehensive analysis of their movement and interactions within the spouted bed. By employing these sophisticated techniques, the study aims to provide a deeper insight into the hydrodynamics of spouted beds, addressing the empirical limitations of previous methodologies. The enhanced understanding gained from these evaluations will contribute to optimizing the design and operation of spouted beds, ensuring better performance and efficiency. Ultimately, this will support the development of more effective and commercially viable nuclear reactors that utilize high-quality and safer coated fuel particles.

## Description of the Actual Work

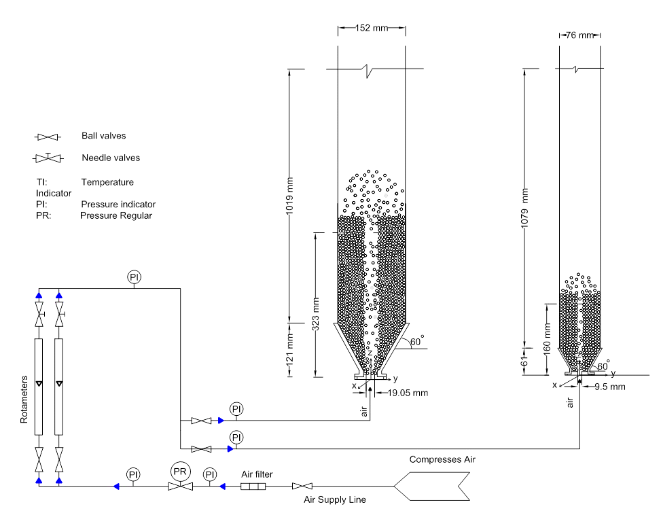
In this study, a comprehensive set of experiments was conducted using conventional spouted beds, specifically conical-cylindrical spouted beds, at two different scales. The aim was to evaluate the effectiveness of a new scale-up methodology for gas-solid spouted beds. The experiments involved both laboratory-scale and pilot-scale spouted beds to assess the scalability and robustness of the proposed methodology. The laboratory-scale spouted bed had an inner diameter of 0.076 meters, while the pilot-scale spouted bed had an inner diameter of 0.152 meters. Both beds were designed to be geometrically similar and were constructed from Plexiglas to allow for visual observation and to maintain consistency with previous studies [13, 14, 21-25]. These studies provided a solid foundation and framework for the experimental setup used in this research. The schematic details of the two spouted beds are depicted in Figure 1, illustrating the key dimensions and configurations of the beds. To validate the new scale-up methodology, the Radioactive Particle Tracking (RPT) technique was employed. RPT is a sophisticated method that provides detailed insights into the flow dynamics of solid particles within the spouted beds. To rigorously test the scale-up methodology, three sets of experimental conditions were systematically designed. These conditions aimed to evaluate the accuracy and reliability of the new methodology under varying scenarios. Table 1 summarizes the three sets of conditions investigated:

**Reference Case:** The first set of conditions was designed for the large spouted bed, serving as the baseline or reference case. This set was intended to establish a standard gas holdup profile and flow dynamics that could be compared against other conditions.

**Similar Profile:** The second set of conditions was configured for the small-scale spouted bed to achieve a similar gas holdup profile to that obtained in the reference case. This involved adjusting operational parameters to match the hydrodynamic behavior observed in the larger bed.

**Dissimilar Profile:** The third set of conditions was designed to produce gas holdup profiles that were deliberately dissimilar to those in the reference case. This was done to test the boundaries and limitations of the scale-up methodology by introducing variations that challenge its applicability.

The second and third sets of conditions were particularly crucial as they allowed for a comparative analysis of the results obtained from different bed sizes under varying operational conditions. The data from these experiments were meticulously collected and analyzed, focusing on key flow parameters such as gas holdup profiles, particle circulation rates, and overall bed hydrodynamics. By comparing the results from the small and large spouted beds against the reference case, the study aimed to validate the accuracy and effectiveness of the new scale-up methodology. The comprehensive data analysis provided insights into the scale-dependent behavior of the spouted beds and helped refine the scale-up techniques to ensure better performance and efficiency in industrial applications. The ultimate goal of this research was to enhance the understanding of spouted bed hydrodynamics and to develop a reliable scale-up methodology that can be applied to the commercial implementation of nuclear reactors using high-quality and safer coated fuel particles. The findings from this study are expected to contribute significantly to the optimization of spouted bed designs and operations, paving the way for more efficient and effective industrial processes.



*FIG. 1. Illustrates the schematic diagram depicting both the small and large-scale configurations of gas-solids spouted beds. The diagram provides a visual representation of the structural details and dimensions of these spouted beds at different scales.*

TABLE 1. The experimental setups were designed to replicate gas holdup profiles—both similar and dissimilar—critical for understanding the hydrodynamic similarities in spouted beds, as highlighted by [12]

|  |  |  |  |
| --- | --- | --- | --- |
| Condition/Case | Reference | Similar gas-holdup profile | Dissimilar gas-holdup profile |
| Bed scale | Large | Small | Small |
| *Dc* (m) | 0.152 | 0.076 | 0.076 |
| *Di* (mm) | 19.1 | 9.5 | 9.5 |
| *L* (m) | 1.14 | 1.14 | 1.14 |
| *H* (m) | 0.323 | 0.16 | 0.16 |
| *T* (K) | 298 | 298 | 298 |
| *P* (kPa) | 101 | 364 | 101 |
| Particles | Glass | Steel | Glass |
| *dp* (mm) | 2.18 | 1.09 | 1.09 |
| *ρs* (kg/m3) | 2400 | 7400 | 2450 |
| *ρf* (kg/m3) | 1.21 | 3.71 | 1.21 |
| µ (x 10^5) (Pa.s) | 1.81 | 1.81 | 1.81 |
| *U* (m/s) | 1.08 | 0.64 | 0.74 |
| *Ums* (m/s)  Experimental Values | 0.89 m/s | 0.58 m/s | 0.68 |

## Results and discussions

### Solids holdup profiles and cross-sectional distributions of the spouted beds–reference case

The visual representations in Figure 3 provide a detailed interpretation of how solids are distributed along the dimensionless height (z/D) of the 6-inch spouted bed, where Z represents the actual measurement height and D denotes the column diameter. A notable disparity in solids holdup is observed between the annulus and spout regions of the spouted bed. In the annulus region, the profiles along different z/D levels exhibit relatively consistent behaviors akin to loosely packed beds. This consistency suggests that solids in this area experience gradual movement and settling patterns. Conversely, in the spout region, the solids holdup decreases notably at lower axial heights, primarily due to the intensifying gas velocity generated by the turbulent gas jet. This turbulence exerts high shear forces on the particles, preventing them from settling and causing them to accumulate preferentially in the more uniformly flowing annulus region. The observed solids concentration around the fountain area highlights an increase by an average of 31.86% from z/D 0.8 to 1.1, followed by a 24.63% increase from z/D 1.1 to 1.8. This phenomenon is attributed to particle scattering, where the fountain's swirling motion redirects particles back into the annulus. Additionally, inertia prevents particles from straying far from the fountain, contributing further to their concentration in this region. The analysis of gamma ray computed tomography data, processed using Alternating Minimization (AM) algorithms, provides detailed insights into these solids holdup distributions. Figure 4 displays cross-sectional distributions of solids holdup at z/D levels of 0.8, 1.1, 1.8, and 2.4 for the 6-inch spouted beds. The color-coded scale bar in the images distinguishes areas of higher solids holdup (red) from lower holdup (blue), effectively illustrating the distinct characteristics of the spout, annulus, and fountain regions. These findings underscore the complex and region-specific dynamics of solids holdup within spouted beds, influenced significantly by varying gas velocities and turbulence levels. Such insights are pivotal for optimizing spouted bed designs and operational parameters, aiming to enhance efficiency and performance in industrial applications.

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|  |
| (a) |
|  |
| (b) |

*FIG. 2. Radial profiles of solids holdup in the larger spouted beds at various measurement planes (z/D) within (a) the spout and annulus region, and (b) the fountain region.*

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|  |
| (a) |
| C:\Users\tmap8b\Desktop\2rainA.jpg |
| (b) |

FIG. 3. Cross-sectional distribution of solids holdup along the vertical height of the larger spouted beds at z/D ratios of (a) 0.8 and (b) 1.1.

### Similar gas-holdup profiles for gas-solids spouted beds using CT

Building upon the mechanistic scale-up methodology developed by [12], a comprehensive set of experimental conditions was established to explore both similar and dissimilar gas holdup profiles within spouted beds. This methodology was crucial for evaluating the scalability of spouted bed operations from laboratory-scale to pilot plant-scale applications. Gamma-ray computed tomography (CT) provided detailed insights into the cross-sectional distribution of gas holdup at various dimensionless heights (z/D) within both the large and small-scale spouted beds. Figure 5 illustrates the successful validation of this approach, showcasing comparable gas holdup distributions and radial profiles between the two scales. The close alignment in mean values and standard deviations between the reference and similar gas holdup profiles underscored the effectiveness of the scale-up process in replicating results across different bed sizes. However, while these initial findings demonstrate promising consistency in gas-solid holdup dynamics, further scrutiny of hydrodynamic parameters is essential for comprehensive validation. Key parameters such as spout diameter, cumulative probability distribution of particle velocities, fraction of cycle time occupied by solid particles, and radial profiles of solids eddy diffusivity are critical for assessing the true similarity between scales. These parameters play pivotal roles in determining the overall efficiency and operational reliability of spouted beds in industrial applications. The focus on solids cycle time in the spout region under the investigated conditions highlights one aspect of this broader evaluation. Understanding the dynamics of particle movement within the spout region is crucial, as it directly impacts the efficiency of particle circulation and residence time within the bed. This knowledge informs optimization strategies aimed at improving particle coating uniformity, reactor performance, and ultimately, the economic viability of large-scale spouted bed systems. In conclusion, while the initial results are promising, ongoing research efforts are necessary to refine and expand our understanding of spouted bed dynamics across different operational scales. The integration of advanced measurement techniques like RPT will further enhance our ability to validate and optimize the scaling-up process, ensuring robust and reliable performance in industrial applications of spouted bed technology.

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|  | C:\Users\tmap8b\Desktop\untitled10.jpg |
| (a) | (b) |

*FIG. 4. The distribution across cross-sections and the corresponding frequency distribution of gas holdup are shown for (a) the reference scenario of pilot plant-scale spouted beds at z/Dc=1.8 and (b) the similar gas holdup radial profile of laboratory-scale spouted beds at z/Dc=1.8.*

### Percentage of time spent by solids in the spout region of gas-solid spouted beds as determined by Radioactive Particle Tracking (RPT)

The analysis based on Radioactive Particle Tracking (RPT) data provides valuable insights into the dynamics of solid particle movement within gas-solid spouted beds under different gas holdup profiles. By examining the cycle times of particles in the spout, annulus, and fountain regions across various experimental conditions, we aimed to assess how gas holdup influences the hydrodynamic behavior of these beds. Firstly, normalizing the cycle times allowed us to compare the relative contributions of each region to the overall particle residence time within the beds. This approach revealed that beds with similar gas holdup profiles to the reference case exhibited minimal deviations in cycle times across all regions. This consistency suggests that maintaining uniform gas holdup profiles contributes to predictable and stable hydrodynamic performance. In contrast, beds with dissimilar gas holdup profiles showed larger deviations, particularly in the spout and fountain regions, indicating less predictable particle behavior and potentially less efficient operation. The significant impact of gas holdup on hydrodynamic behavior is highlighted by the observed deviations in cycle times. The spout region, where gas velocity is highest due to the introduction of gas, showed particularly pronounced deviations between scenarios with similar and dissimilar gas holdup profiles. This finding underscores the role of gas velocity in influencing particle movement and residence time within the bed. In contrast, the annulus region, characterized by more uniform gas flow, demonstrated smaller deviations, suggesting greater stability in particle dynamics under similar gas holdup conditions. Moreover, the findings emphasize the practical implications for scaling up gas-solid spouted beds. Consistently replicating the hydrodynamic conditions observed in smaller-scale beds when transitioning to larger-scale operations is crucial for ensuring efficient performance and achieving desired process outcomes. This requires careful consideration of gas flow dynamics, including gas holdup profiles, to optimize bed design and operational parameters effectively. In conclusion, the study underscores the critical role of gas holdup profiles in shaping the operational dynamics of gas-solid spouted beds. The insights gained from this analysis contribute to advancing our understanding of spouted bed behavior across different scales and lay the groundwork for further optimizing bed design and operational strategies in industrial applications. Future research could further explore additional parameters influencing bed performance, enhancing our ability to predict and control particle behavior in gas-solid spouted beds.

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*FIG. 5. The distribution of the proportion of solid particle cycle time within each region of the bed under the conditions of (a) the reference case, (b) profiles with similar gas holdup, and (c) profiles with dissimilar gas holdup.*

### Implementation of the new scale-up methodology of gas-solids spouted beds

The implementation of the scale-up methodology for gas-solid spouted beds involves several critical considerations and steps, each contributing to the overall success and reliability of scaling operations [13, 22, 25]. Here, we delve deeper into the discussion to highlight key aspects and implications of each step:

1. **Measurement of Gas Holdup Profiles:** The initial step focuses on acquiring accurate gas holdup profiles across various sections of the spouted beds, crucial for ensuring that scaled-up versions replicate the flow characteristics of the reference beds. This meticulous measurement encompasses both the conical and cylindrical sections, covering regions such as the annulus, spout, and fountain. By employing non-invasive measurement techniques, disturbances to flow dynamics are minimized, ensuring precise assessments without altering the natural behavior of the beds. This approach not only facilitates the replication of flow patterns observed in the reference beds but also lays the groundwork for subsequent validation steps.
2. **Validation with Computational Fluid Dynamics (CFD):** Computational Fluid Dynamics (CFD) serves as a pivotal tool in validating and refining gas holdup profiles obtained from experimental measurements. It enables engineers to simulate and analyze fluid flow and gas-solid interactions within scaled beds, aiming to achieve profiles closely resembling those of the reference case. Maintaining geometric similarity between scaled and reference beds is essential, as it ensures consistent gas holdup profiles despite dimensional variations. While direct acquisition of precise CFD data can be resource-intensive, efforts are directed towards iteratively refining simulations to achieve optimal profile alignment. This iterative approach enhances the hydrodynamic similarity necessary for accurate scale-up predictions and operational optimizations.
3. **Construction and Operational Validation:** The construction and operational phase involves translating validated gas holdup profiles into physical scaled beds. These beds are designed and operated under conditions identified during the validation phase to ensure alignment with desired gas holdup profiles. This step not only verifies the scalability of the methodology but also establishes operational parameters critical for achieving consistent and predictable performance across different scales.
4. **Evaluation of Gas Holdup Profiles:** Detailed evaluation of gas holdup profiles in scaled beds is essential to validate their performance against reference standards. Utilizing non-invasive gamma-ray densitometry (GRD) facilitates precise measurement of gas holdup across multiple depths and flow regimes. This technique offers advantages such as high accuracy, repeatability, and the ability to capture nuanced variations in gas-solid interactions without physical disruption. By comparing measured profiles against reference benchmarks, engineers gain insights into the effectiveness of scaling efforts and identify areas for further refinement.
5. **Refinement of Operating Conditions:** Continuous refinement of operating conditions plays a crucial role in optimizing gas holdup profiles to align closely with those observed in the reference case. This iterative process involves adjusting operational parameters to enhance hydrodynamic similarity and ensure consistency in performance metrics across scaled beds. By refining these conditions, engineers mitigate deviations and uncertainties, thereby enhancing the reliability and predictability of scaled-up operations.

The successful implementation of the scale-up methodology for gas-solid spouted beds relies on a systematic approach encompassing rigorous measurement, validation, construction, operational validation, evaluation, and refinement of gas holdup profiles. Each step contributes to establishing robust scaling practices that ensure reliability, efficiency, and safety in industrial applications of spouted bed technology. Through advanced measurement techniques and computational tools, engineers can navigate complexities inherent in scale-up processes, thereby optimizing performance and advancing the capabilities of gas-solid spouted beds in various industrial settings.

## Conclusion

In this study, we have outlined a comprehensive methodology for scaling up gas-solid spouted beds, emphasizing the critical role of gas holdup profiles in achieving hydrodynamic similarity across different scales. Through a systematic approach that integrates experimental measurements, computational fluid dynamics (CFD) simulations, and non-invasive gamma-ray densitometry (GRD), we have demonstrated the feasibility and effectiveness of scaling operations. The initial step involved careful measurement of gas holdup profiles in both laboratory-scale and pilot-scale spouted beds, ensuring accurate replication of flow dynamics observed in the reference case. This foundational data informed subsequent validation efforts using CFD, where geometric similarity between scaled and reference beds was maintained to simulate and refine gas holdup profiles. The iterative nature of CFD simulations enabled us to iteratively adjust operational parameters, optimizing gas-solid interactions and enhancing hydrodynamic similarity. Construction and operational validation of scaled spouted beds validated our methodology, confirming that scaled beds operated under identified conditions replicated desired gas holdup profiles effectively. Evaluation through non-invasive GRD provided precise assessments of gas holdup distributions, affirming the success of our scaling approach in achieving close alignment with reference benchmarks. Throughout this process, continuous refinement of operating conditions further improved the accuracy of gas holdup profiles, minimizing deviations and ensuring consistency in scaled-up operations. This iterative refinement not only enhanced predictive capabilities but also underscored the importance of detailed experimental validation and computational modeling in scaling up gas-solid spouted beds. In conclusion, our study highlights the significance of gas holdup profiles as a key determinant of spouted bed performance during scale-up. By integrating advanced measurement techniques with computational tools, we have established a robust methodology for scaling operations, applicable across various industrial applications. This framework not only enhances operational efficiency and reliability but also lays a foundation for future advancements in gas-solid spouted bed technology.

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