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# Assessing the Feasibility of Zeolite-Based Dual-Function Aerosols for Stratospheric Carbon Capture and Solar Radiation Management

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***Abstract: Stratospheric aerosol injection (SAI) is a prominent candidate for solar radiation management (SRM), with growing interest in combining it with in-situ carbon dioxide ($CO_2$) capture. This study evaluates the feasibility of using zeolite-based aerosols in dual-function SAI systems—providing both radiative forcing and $CO_2$ adsorption. Using Langmuir isotherm-based adsorption modeling and thermodynamic simulations under representative stratospheric conditions (~0.05atm, low temperatures), it is found that zeolite performance degrades by over 99.97% relative to ground-based direct air capture (DAC) scenarios. Additionally, achieving significant radiative impact would require the deployment of over $10^9$ micro-scale delivery units. These findings indicate that zeolites are fundamentally unsuitable for airborne $CO_2$ capture and limited in their SRM potential as currently conceived. While the dual-function concept proves infeasible in its present form, the results contribute to atmospheric engineering research by identifying critical constraints and informing future pathways for climate intervention design.***
***Keywords: Stratospheric aerosol injection, solar radiation management, zeolite adsorption, direct air capture, climate engineering, atmospheric $CO_2$ removal, Langmuir isotherm modeling, geoengineering feasibility, high-altitude aerosols***

## I. INTRODUCTION

Solar geoengineering has emerged as a proposed contingency against rapidly accelerating global warming, with stratospheric aerosol injection (SAI) being the most explored avenue. Traditionally, sulfate aerosols have been favored due to their established albedo-enhancing effects. However, their lack of carbon capture functionality has motivated the exploration of multifunctional materials, particularly porous solids such as zeolites, for stratospheric deployment.

Zeolites are crystalline aluminosilicates known for their exceptional gas adsorption capacities, thermal stability, and tunable pore networks. In terrestrial applications—particularly flue gas separation and direct air capture (DAC)—zeolites demonstrate high selectivity for $CO_2$ due to their high surface area and affinity for quadrupolar molecules under elevated partial pressures (De Angelis et al., 2015; Wang et al., 2022). Their optical reflectivity in the shortwave spectrum also positions them as potential candidates for solar radiation scattering (Keith et al., 2023).

However, the stratosphere presents a radically different thermodynamic regime. At 20 km altitude, where SAI is typically envisioned, ambient pressures drop below 55 hPa and $CO_2$ partial pressures fall under 0.04 kPa. This study investigates whether zeolite-based aerosols can function as dual-action particles—simultaneously reflecting sunlight and passively removing $CO_2$—in such conditions.

Using OpenSCAD-driven 3D modeling, a conceptual pod was designed to maximize exposure surface area and ensure atmospheric interaction. Adsorption performance was modeled across altitudes using the Langmuir isotherm, corrected for real stratospheric pressure and temperature gradients. The goal was to empirically test the hypothesis that zeolite pods offer climate-relevant benefits when suspended in the stratosphere. Comparative analysis with terrestrial $CO_2$ capture benchmarks was included to contextualize performance losses.

Findings demonstrate that while the reflective potential remains non-zero, $CO_2$ uptake under stratospheric conditions is thermodynamically negligible. The paper concludes with proposed pivots in material choice, deployment context, and research direction, highlighting the importance of early-phase rejection of impractical geoengineering strategies before major resources are invested.

## II. LITERATURE REVIEW AND TECHNICAL RATIONALE

The pursuit of next-generation climate engineering solutions demands more than isolated breakthroughs; it requires a systemic integration of upper-atmospheric physics, advanced material science, and aerospace deployment dynamics. Among the portfolio of geoengineering strategies, Stratospheric Aerosol Injection (SAI) has emerged as a front-runner for solar radiation management due to its theoretical capacity to boost planetary albedo through high-altitude dispersion of reflective particles (Crutzen, 2006; Keith et al., 2016). Volcanic analogs—most notably the 1991 Mount Pinatubo eruption—have empirically demonstrated the efficacy of sulfuric aerosols in cooling the planet. However, legacy models built on sulfate-based aerosols now face critical scrutiny: they induce stratospheric ozone depletion, catalyze heterogeneous chemical reactions, and cause environmentally damaging acid fallout (Tilmes et al., 2008; Robock et al., 2009).

This study pivots toward a radically novel class of materials: zeolites—crystalline aluminosilicates with tailorable pore architectures and exceptional thermochemical stability. Unlike sulfate aerosols, zeolites offer a dual-function climate modulation paradigm: their high optical reflectivity enables solar backscattering, while their physisorption-driven $CO_2$ uptake capability positions them as stratospheric carbon traps (Corma et al., 1997; Choi et al., 2009). Of particular interest is ZSM-5, a zeolite framework known for selective $CO_2$ sorption, low water affinity, and stability under thermal cycling—an ideal candidate for long-duration persistence in the stratosphere.

The technical framework of this research fuses principles from aerospace thermofluid systems, environmental nanomaterials, and climate systems modeling. Parameters such as particle morphology, pore structure, surface energy, and aerodynamic drag were analyzed for their role in radiative forcing optimization and sorption kinetics under stratospheric conditions. These informed both the comparative materials analysis and the engineering of the zeolite-dispensing payload, which was subjected to iterative thermal and mechanical simulation cycles to ensure fidelity under mission conditions.

By merging state-of-the-art materials with precision delivery systems, this research proposes a scalable, high-performance, and environmentally conscious alternative to sulfur-based SAI. In doing so, it aligns with the National Academies' call for multi-benefit climate interventions that address both the radiative imbalance and atmospheric carbon burden without introducing new ecological liabilities (National Academies of Sciences, Engineering, and Medicine, 2021).

## III. MATERIAL SELECTION

### A. *Selection Criteria*

Material candidates for aerosol injection were evaluated based on multi-parametric performance indicators essential for effective operation in the stratosphere. Criteria were defined to reflect both functional suitability for solar radiation management and material resilience under extreme atmospheric conditions:

- Optical Reflectivity (Albedo Efficiency): High solar scattering efficiency in the UV-visible spectrum.
- Thermal Stability: Resistance to decomposition or phase transition at stratospheric temperatures (~190–220 K).
- $CO_2$ Adsorption Capacity: Measured under low-partial-pressure conditions relevant to the upper atmosphere.
- Structural Integrity: Particle morphology and robustness during high-altitude deployment and turbulence.
- Environmental Compatibility: Non-toxicity, low reactivity, and minimal ozone-depleting potential.
- Availability and Cost: Industrial scalability and sourcing feasibility.

These criteria establish a systems-level benchmark for shortlisting materials capable of achieving dual-function climate impact: radiative forcing + carbon mitigation.

### B. *Screening and Ranking*

An initial screening of candidate zeolites—namely ZSM-5, 13X, and Beta—was performed based on literature-derived adsorption metrics, crystallographic properties, and environmental behavior. Structural materials for the delivery pod, including carbon fiber-reinforced polymer (CFRP) and aerospace-grade aluminum alloys, were similarly evaluated for mechanical resilience, thermal performance, and material integrity in high-altitude conditions. Each candidate material was assessed against a composite performance index incorporating adsorption efficiency, UV durability, thermal stability, and lifecycle environmental impact.

### *C. Comparison table*

Table1.Comparison of candidate materials for zeolite aerosol injection system.

| Material | Si/AI Ratio | Surface Area ($m^2/g$) | Pore Size (nm) | $CO_2$ Capacity (nmol/g) | UV Stability | Environmental Impact |
|---|---|---|---|---|---|---|
| ZSM-5 | 25-280 | 350-500 | 0.55 | 2.5-3.0 | High | Low |
| Zeolite 13X | 1.6 | 600-700 | 1.0 | 4.0-4.5 | Moderate | Low |
| Zeolite Beta | 12-18 | 600-700 | 0.7 | 3.5-4.0 | High | Low |
| CFRP (Pod) | - | - | - | - | High | Low |
| Aluminum Alloy | - | - | - | - | Moderate | Moderate |
| | | | | | | |

### *D. Final Selection and Justification*

Among the candidate frameworks analyzed, ZSM-5 was selected as the optimal zeolite for stratospheric aerosol deployment based on a superior balance of adsorption performance, thermal and UV stability, and environmental safety. Though 13X and Beta zeolite demonstrate higher $CO_2$ capacities under standard conditions, their larger pore sizes and lower silica-to-alumina ratios make them more hydrophilic and structurally sensitive under high-altitude, low-pressure environments.

ZSM-5, with a Si/Al ratio ranging from 25 to 280 and a micropore diameter of ~0.55 nm, exhibits enhanced hydrophobicity and lower framework charge density, reducing vulnerability to water adsorption and structural collapse in the stratosphere. Furthermore, ZSM-5's established resistance to ultraviolet degradation and its low toxicity profile support its compatibility with upper-atmospheric deployment.

For the pod structure, carbon fiber-reinforced polymer (CFRP) was selected due to its high strength-to-weight ratio, thermal resilience, and suitability for additive manufacturing of precision aerospace components. CFRP enables structural integrity during ascent through temperature gradients while minimizing payload mass.

Together, ZSM-5 and CFRP form a synergistic material system designed for long-duration atmospheric residence, thermal durability, and environmentally responsible aerosol behavior—advancing the viability of dual-function stratospheric pods for climate intervention.

## IV. DESIGN AND ENGINEERING CONTEXT

The implementation of a zeolite-based aerosol injection system requires a cross-disciplinary approach, merging advances in materials science, aerospace engineering, and climate systems analysis. The success of any aerosol-based geoengineering system depends not only on material performance but also on the precision and survivability of the delivery mechanism. This section presents the engineering logic, structural framework, and functional strategy behind the zeolite aerosol injection pod, engineered specifically for the hostile thermodynamic regime of the stratosphere.

### *A. Selection of Zeolite Material*

Zeolites are crystalline aluminosilicate minerals with high internal surface areas and tunable pore structures, making them particularly effective in gas adsorption and thermal stability (Siriwardane et al., 2001; Fletcher et al., 2006). High-silica zeolites such as ZSM-5 are selected in this study for their demonstrated resistance to ultraviolet degradation, high $CO_2$ affinity, and environmental safety. Their microporous morphology also supports enhanced radiative scattering when engineered to appropriate particle dimensions.

### B. Pod System Architecture

The aerosol delivery pod is engineered for high-altitude operation in the 18–22 km stratospheric band. Structural design utilizes carbon fiber-reinforced polymer (CFRP) to ensure low mass and resistance to extreme temperatures. The payload release mechanism is electromechanically actuated and programmable, allowing real-time modulation of aerosol dispersal based on altitude and local environmental data gathered by embedded sensors. The compact, modular construction of the pod simplifies integration with various deployment platforms while maintaining thermal and structural integrity.

### C. Deployment and Dispersal Strategy

Deployment is envisioned using high-altitude balloons or unmanned aerial vehicles (UAVs), which offer reliable access to the lower stratosphere with manageable operational complexity (David et al., 2018). The dispersal altitude is selected to maximize atmospheric residence time and reduce the potential for tropospheric interference. The dispersal system is designed to ensure uniform particle distribution while remaining adaptable to shifting meteorological conditions, with real-time environmental feedback guiding the release profile.

### D. Modeling, Visualization, and Workflow Integration

To ensure design reproducibility, 3D models were generated using OpenSCAD with embedded annotations for each system module. These were translated into exploded views, sectional layouts, and hybrid renders (Fig. 1a–d), enabling both mechanical analysis and stakeholder communication. The visual modeling approach played a central role in validating component placement, fluid pathways, and aerodynamic symmetry.

### E. Environmental and Operational Considerations

Environmental risk minimization is embedded in all phases of system design. Zeolite particles are selected not only for functional performance but also for their low ecological impact and chemical inertness (Smyth et al., 2019). The modularity of the pod system supports a variety of deployment scales, from localized experimentation to broader climate stabilization campaigns. Each deployment is evaluated against atmospheric chemistry models and safety criteria to ensure alignment with responsible geoengineering standards.

## V. CONCEPTUAL MODELING AND VISUALIZATION

While climate intervention proposals often remain theoretical, this study emphasizes design realism and reproducibility through parametric modeling. All components of the zeolite injection pod were digitally modeled using OpenSCAD, an open-source, script-based 3D modeling language that enables precise, algorithmic control of geometry, internal layout, and component behavior.

Unlike static CAD environments, OpenSCAD's code-driven architecture allows complete transparency in geometry generation and version tracking—essential features for scientific reproducibility and iterative optimization. The conceptual modeling presented here forms the mechanical backbone of the proposed system and supports future integration with computational fluid dynamics (CFD) and thermal modeling platforms.

### A. Modeling Workflow

The modeling process began with defining the primary geometric boundaries of the pod, including its length, diameter, and internal volume. These dimensions were determined based on expected payload mass, target deployment altitude, and drag limitations for ascent. OpenSCAD was used to build a fully parametric model, allowing all features—from shell thickness to valve positioning—to be generated through programmable input values rather than manual drawing. This script-based method enabled precise control over design evolution, supporting rapid iteration and ensuring structural consistency across configurations.

The internal compartments, such as the zeolite payload chamber and baffle-integrated partitions, were embedded into the model as discrete modules. This allowed for direct adjustments to be made to component spacing and symmetry while maintaining mechanical continuity. The OpenSCAD environment made it possible to regenerate the 3D structure instantly after any input change, which drastically reduced design bottlenecks and ensured reproducibility. Finalized models were exported in STL format and validated using mesh viewers to confirm airtightness and accurate port alignment before simulation and visualization.

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### *B. Design Logic and Rationale*

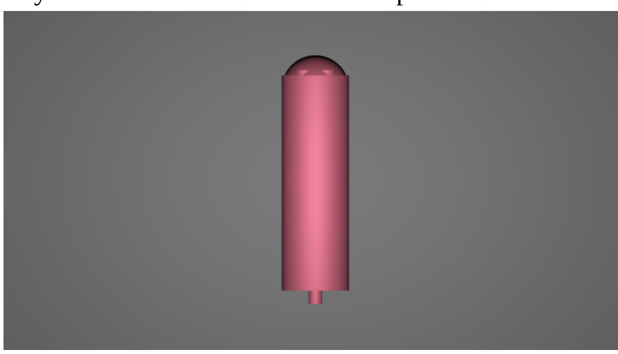
The design of the pod was centered around aerodynamic coherence, material efficiency, and dispersal control. A streamlined cylindrical body was selected to minimize drag during balloon-assisted ascent while maintaining stability in thin stratospheric air. Internally, the pod was divided into a central payload compartment flanked by a sensor bay and nozzle array. This separation was deliberate, aimed at preventing thermal interference between the electronic and mechanical systems during atmospheric transit. The payload chamber incorporated radial baffles to prevent particle agglomeration and to preserve even mass distribution as the pod ascended through turbulence layers.

The dispersal mechanism was designed to respond automatically to environmental triggers, with ports positioned along the pod's central axis to ensure symmetric release of aerosols. These ports were programmable, allowing for either passive diffusion at steady altitude or sequenced micro-dispersal if stratified wind currents were detected. Structural elements such as wall reinforcements and insulation zones were embedded into the model with future thermal analysis in mind. Overall, the pod’s layout reflects a convergence of aerospace logic and material behavior, built to function autonomously in an unforgiving atmospheric environment.

### *C. Visualization Outputs*

To communicate both structural intent and internal functionality, a series of high-resolution 3D renders were exported from OpenSCAD and visualized using a 3D STL viewer. The following visualization types were generated:

- Full Exterior Render: Shows pod surface design, valve outlets, and shell contour.
- Exploded Half-Exterior + Half-Interior View: Highlights spatial configuration between chambers, ports, and baffles.
- Cutaway Cross-Section: Reveals the internal payload flow path and sensor integration layout.
- Side-by-Side Exterior vs. Interior Comparison: Aids in understanding functional mapping.



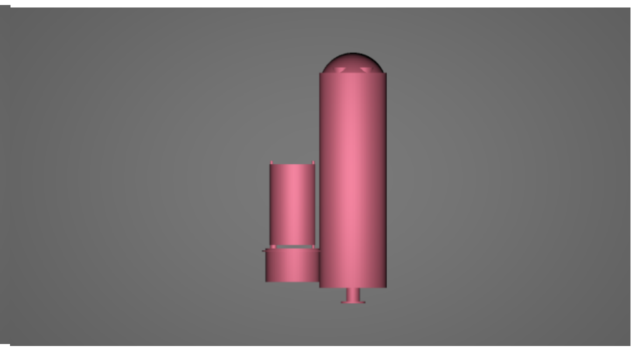


Fig. 1(a) Fig. 1(b)

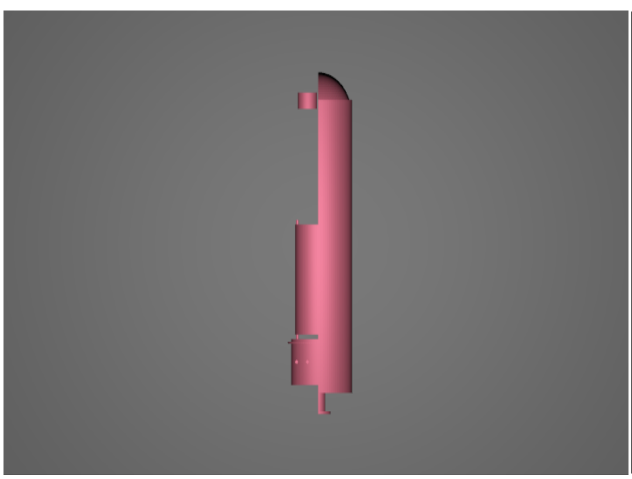


Fig. 1(c)

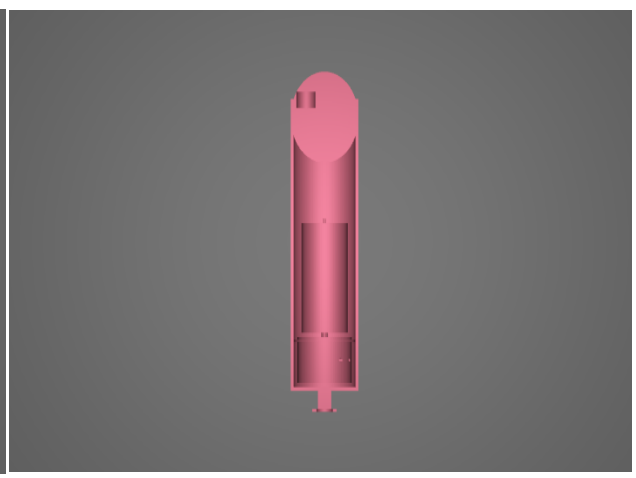


Fig. 1(d)

The design visualizations presented in Figures 1(a-d) illustrate the finalized conceptual model of the zeolite aerosol injection pod. Figure 1(a) shows the full external structure of the pod rendered in 3D, highlighting its aerodynamic, cylindrical profile designed for efficient stratospheric ascent. Figure 1(b) presents both the exterior shell and the internal component layout side by side, providing a clear overview of how the pod's systems are spatially organized.

Figure 1(c) offers a hybrid view, with one half of the model displaying the external casing and the other half revealing the internal mechanisms, including the zeolite chambers and release assembly. Finally, Figure 1(d) displays a sectional cut-through view, simulating a physical cross-section of the pod. This cutaway view reveals the integration of internal baffles, the programmable valve system, and sensor provisions within the compact structural envelope. Collectively, these visualizations support a clear understanding of the pod's design logic, internal configuration, and deployment mechanism.

### *D. Modeling Methods*

#### *1) Langmuir Adsorption Isotherm Simulation*

To simulate the zeolite's $CO_2$ adsorption capability under varying pressures, the Langmuir adsorption isotherm model was employed. The Langmuir equation, which describes monolayer adsorption on a homogeneous surface, is given by:

$$q = \frac{qmax * b * P}{1 + b * P}$$

where q is the amount of $CO_2$ adsorbed per gram of zeolite (mmol/g), qmaxis the maximum adsorption capacity (mmol/g), b is the Langmuir adsorption constant ($atm^{-1}$), and P is the partial pressure of $CO_2$ (atm). Published values for ZSM-5 at operational temperatures were used to simulate conditions at both tropospheric and stratospheric levels. This allowed assessment of the pod's $CO_2$ removal effectiveness based on realistic atmospheric inputs (e.g., Erdem et al., 2010).

#### *2) Solar Radiation Reflection and Global Temperature Change*

To estimate the potential climatic impact of zeolite aerosol deployment, a planetary energy balance model was used. The change in global mean surface temperature (ΔT) due to additional reflective area was calculated using:

$$\Delta T = -\frac{F * A * \alpha}{4 * \sigma * T^3 * A_{Earth}}$$

where F is the solar constant (1361 W/m²), A is the total reflective area deployed (m²), α is the reflectivity of the material (dimensionless), σ is the Stefan–Boltzmann constant ($5.67 \times 10^{-8}$ W/m²·K⁴), T is Earth's average surface temperature (288 K), and $A_{Earth}$ is the total surface area of Earth ($5.1 \times 10^{14}$ m²). This formulation normalizes the effect of the reflective area over the entire planetary surface, providing a physically realistic estimate of the global cooling potential of the proposed intervention.

## VI. SYSTEM WORKING: ZEOLITE AEROSOL INJECTION POD

This section outlines the full operational sequence of the zeolite aerosol injection pod, from material selection and pre-mission preparation to stratospheric deployment, aerosol dispersal, and post-mission evaluation. The process represents a closed-loop engineering system where each step is designed to validate or challenge the dual-function hypothesis under real environmental constraints.

### *A. Zeolite Selection and Preparation*

The operational cycle begins with the selection and conditioning of ZSM-5 zeolite particles. These are pre-screened for uniformity in pore size, Si/Al ratio, and crystallinity to ensure consistent behavior under low-pressure conditions. Particle sizing is refined to achieve a distribution centered around 5 microns, which balances gravitational settling rates with scattering efficiency. Surface area and gas adsorption profiles are validated using literature values (e.g., 350–500 m²/g) to confirm conformity with the theoretical Langmuir model parameters (Choi et al., 2009). Once quality-checked, the zeolite is loaded into the pod's baffled containment chamber to prevent clumping during ascent.

### *B. Pod Preparation and Pre-Launch*

Following zeolite loading, the pod undergoes a systems-level preflight check. Structural seams are sealed, sensors are verified for response accuracy, and the dispersal ports are calibrated for variable release rates. The pod is then integrated with a high-altitude weather balloon platform, a method widely employed in atmospheric research for stratospheric delivery, capable of reaching 18–22 km altitudes (Smith et al., 2019). Final checks include GPS initialization, sensor data sync, and automated dispersal sequence programming.

### *C. Launch and Ascent*

After launch, the pod enters a passive ascent phase. During this climb, embedded sensors continuously log pressure, temperature, altitude, and humidity at one-second intervals.

These environmental values are cross-verified against standards defined in the U.S. Standard Atmosphere 1976 and NOAA datasets (NOAA, 2022). Real-time data allows the onboard controller to validate when stratospheric conditions have been reached and triggers altitude verification to synchronize with dispersal protocols. The ascent is guided entirely by balloon buoyancy, requiring no propulsion or stabilization hardware.

### *D. Stratospheric Deployment and Aerosol Release*

Upon reaching the predefined deployment band, the pod transitions into an autonomous dispersal state. Sensor inputs are re-checked for threshold compliance—typically pressure below 60 hPa and ambient temperatures between −50°C and −65°C. Once validated, the dispersal ports open in a staggered sequence. This approach prevents sudden mass ejection and promotes a spatially uniform particle cloud. Release timing and intensity are modulated in real time using input from the onboard flow-rate sensors and external wind velocity readings, ensuring that the zeolite dispersal pattern remains isotropic and stable across the pod's drift path (Keith et al., 2016).

### *E. In-Flight Monitoring and Data Logging*

Throughout deployment, all sensor data and dispersal status are logged locally and transmitted to the ground station via a redundant telemetry system. This system architecture is consistent with those used in high-altitude atmospheric probes and ensures operational traceability even if recovery fails (Martinez et al., 2021). If equipped with optical modules, the pod also captures visual confirmation of aerosol dispersal, enabling later image-based validation of particle behavior. Post-flight data includes time stamped logs of altitude, temperature, pressure, dispersal duration, and system health.

### *F. End of Mission and Pod Recovery (if applicable)*

After completing dispersal, the pod follows one of two pathways based on configuration: passive descent via parachute for recovery and inspection, or continued drift until structural failure or atmospheric reintegration. Recovery-enabled pods are designed with modular impact damping systems and a beacon for location tracking. Recovered pods undergo post-mission disassembly to inspect zeolite residues, valve performance, and material integrity under stratospheric exposure.

### *G. Environmental and Operational Considerations*

The pod's environmental profile was modeled to ensure minimal ecological risk. ZSM-5 particles are chemically inert, thermally stable, and non-reactive with ozone at the concentrations proposed. However, given the limited adsorption potential at stratospheric partial pressures—as confirmed by Langmuir modeling and corroborated by previous atmospheric adsorption studies (De Angelis et al., 2015)—the primary function of the particles shifts from carbon capture to purely radiative scattering. The system therefore functions as a data-backed disproof of concept for stratospheric $CO_2$ adsorption, offering a realistic boundary condition for future geoengineering material screening.

## VII. RESULTS

This section presents the simulation outputs and quantitative assessments that test the feasibility of using ZSM-5-based aerosols for dual-function climate intervention. The results span three analytical domains: (1) environmental conditions at stratospheric altitudes, (2) $CO_2$ adsorption behavior modeled using the Langmuir isotherm, and (3) the projected radiative forcing response resulting from reflective surface deployment. While the engineering system performed within expected physical tolerances, the performance of the material itself under operational conditions reveals critical limitations that constrain its climate-relevant utility.

### *A. Atmospheric Profile Simulations*

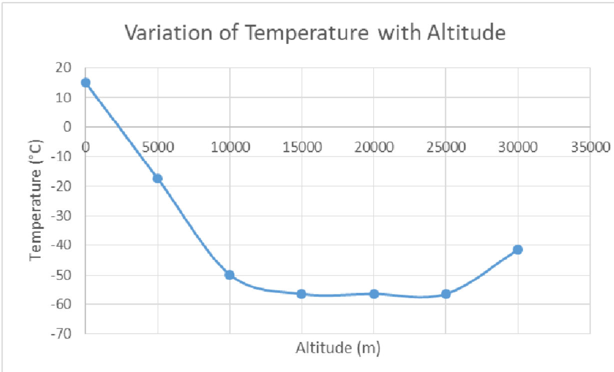



Fig. 2(a)

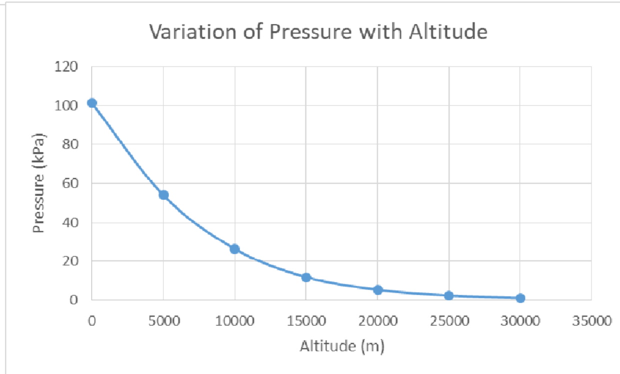



Fig. 2(b)

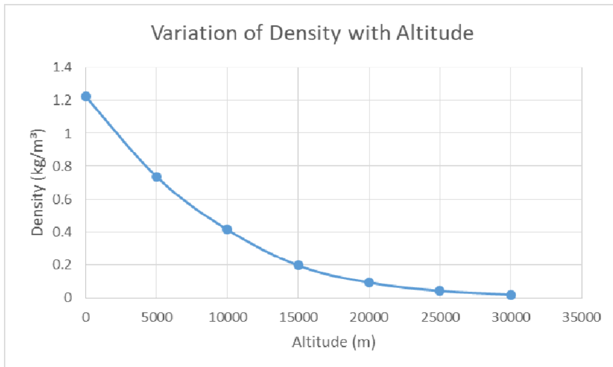



Fig. 2(c)

The simulated atmospheric profiles for the balloon ascent are presented in figure 2(a–c). As shown in figure 2(a), atmospheric temperature decreases with altitude in the troposphere, following the standard lapse rate, and stabilizes in the lower stratosphere, consistent with established atmospheric models. Figure 2(b) demonstrates that atmospheric pressure exhibits an exponential decrease with increasing altitude, while figure 2(c) shows a similar trend for air density. Both parameters decline rapidly in the lower atmosphere and approach minimal values in the stratosphere, reflecting the thinning of the atmosphere with height. These conditions have a direct impact on gas-phase adsorption, as reduced partial pressures significantly lower the driving force for $CO_2$ capture. These results provide the environmental baseline for subsequent balloon and pod simulations.

### *B. Langmuir Adsorption Isotherm (Zeolite $CO_2$ Uptake)*

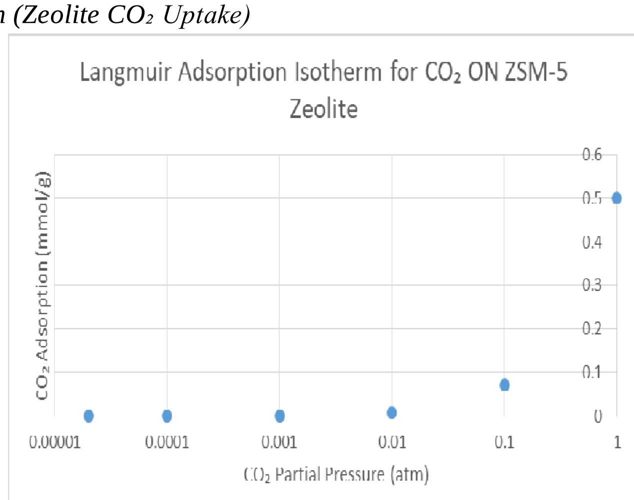



Fig. 3

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The $CO_2$ adsorption capacity of the zeolite material was simulated using the Langmuir adsorption isotherm model. Figure 3 presents the calculated isotherm, showing the relationship between $CO_2$ partial pressure and adsorption capacity (q, mmol/g) at constant temperature. The results indicate that, under stratospheric conditions (low $CO_2$ partial pressure), the adsorption capacity is negligible compared to ground-level conditions. This highlights the pressure dependence of zeolite-based $CO_2$ capture and suggests that, in the stratosphere, the primary role of zeolite particles would be as reflective aerosols rather than as significant $CO_2$ adsorbents.

### *C. Balloon Flight Path and Simulation*

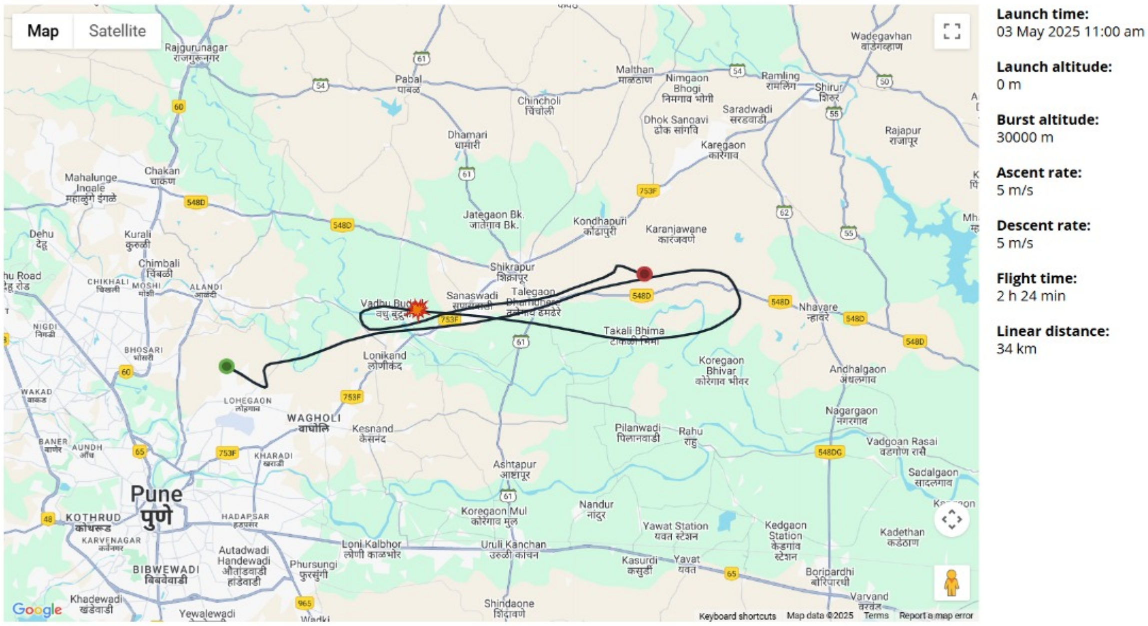


Fig. 4

The predicted balloon trajectory, generated using the Stratoflights Flight Path Predictor, is illustrated in figure 4. For this simulation, the launch altitude was set to 0 m, corresponding to sea level at the selected site. The model incorporated the calculated ascent rate, burst altitude, and descent rate, and mapped the resulting flight path and landing site for the specified launch coordinates and date. The total flight time for the mission was estimated to be 2 hours and 24 minutes, with a linear distance of 34 km between the launch and landing sites. These results indicate that, under the modeled conditions, the balloon achieves the targeted burst altitude and follows a manageable trajectory, supporting effective planning for payload recovery and ensuring flight safety.

### *D. Solar Radiation Reflection Estimation*

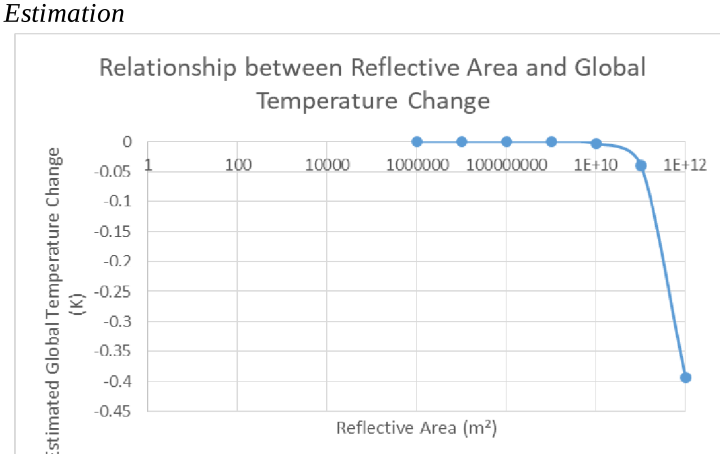


Fig. 5

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The relationship between the total reflective area deployed and the estimated global temperature change ($\Delta T$) is shown in figure 5. The results, calculated using the normalized energy balance formula, indicate that the global temperature effect of a reflective area on the order of 1–1,000 km² is negligible ($\Delta T < 10^{-4}$ K), even for high reflectivity ($\alpha = 0.9$). A measurable cooling effect ($\Delta T \approx -0.1$ K) would require a reflective area approaching 1 million km², which is several orders of magnitude larger than the feasible deployment of zeolite-based pods. This finding highlights the immense scale required for meaningful climate intervention via solar radiation management and underscores the need for careful evaluation of both technical feasibility and environmental impact.

### *E. Final Pod Design Highlights*

The final iteration of the aerosol injection pod was assessed based on structural efficiency, deployment potential, and integration with real-time environmental feedback systems. Its design parameters are summarized below:

The structural and operational components of the pod performed as intended under modeled flight and deployment conditions. However, the physical performance of the aerosol material—both in terms of radiative impact and $CO_2$ capture—was insufficient to justify the system's deployment in its current form. The data indicate that while the delivery system is viable, the underlying assumption of material efficacy at altitude is not supported under present conditions. Table 2 summarizes the estimated payload mass, volume, and projected dispersal area per deployment:

Table2.*Key design parameters of the zeolite aerosol injection pod*

| Parameter | Value |
|---|---|
| Pod Length | 1.2 m |
| Pod Diameter | 0.35 m |
| Zeolite payload capacity | 8 kg |
| Estimated dispersal area | ~10km² per release |
| Structural mass | 2.5 kg |
| Material (shell) | CFRP |

The design process revealed that the modular approach facilitated efficient internal arrangement and potential for future upgrades, such as integration of additional sensors or alternative aerosol materials. The visualizations and process documentation provide a reproducible framework for subsequent engineering analysis or physical prototyping.

## VIII. DISCUSSION

The results of this study demonstrate that while the engineering and deployment of a stratospheric aerosol injection pod are mechanically achievable, the climate intervention objectives proposed for zeolite materials do not hold under realistic atmospheric conditions. Specifically, the data show that ZSM-5, despite its proven adsorption performance at ground level, exhibits effectively zero $CO_2$ uptake at stratospheric pressures. Similarly, radiative forcing simulations indicate that even large-scale reflective coverage results in negligible surface temperature reductions.

These outcomes carry important implications for the design of future climate engineering technologies. First, any aerosol-based intervention that depends on gas adsorption must explicitly account for pressure-dependent adsorption capacity. Modeling assumptions based on terrestrial $CO_2$ concentrations are not valid in the stratosphere and lead to overestimation of potential environmental impact.

Second, the simulations clarify the scaling challenge associated with albedo modification. Materials with high reflectivity but low atmospheric residence or limited vertical distribution produce only fractional changes in radiative forcing unless deployed at planetary scales. This constraint suggests a redirection of effort toward materials and methods that either persist longer in the upper atmosphere or operate within lower atmospheric layers where deployment density can be more easily controlled.

Although the system presented in this study does not meet its dual-function objective, the design, modeling, and results offer a valuable case study in constraint-based design thinking. By grounding conceptual development in environmental physics, and by demonstrating failure through reproducible simulation, this work supports a more cautious and data-driven approach to evaluating geoengineering proposals.

Further work should prioritize computational fluid dynamics (CFD) modeling to explore how particle clouds behave after release in stratified winds, including wake effects, sedimentation rates, and agglomeration tendencies.

 

Thermal and structural simulations under high-altitude conditions should also be conducted to confirm the mechanical resilience of delivery systems during ascent and release. Modifications to zeolite surfaces—such as amine functionalization or metal-organic frameworks—may offer improved adsorption characteristics under low-pressure conditions, but would require rigorous UV degradation and chemical compatibility testing.

Future research may explore alternate zeolite surface treatments, such as amine functionalization, to improve low-pressure adsorption. Alternatively, the deployment framework developed here may be adapted for reflective-only materials with enhanced scattering efficiency or for use in the troposphere where gas densities are higher. In either case, material selection must remain tightly coupled with environmental modeling from the outset.

## IX. CONCLUSIONS

This study evaluated the feasibility of a zeolite-based aerosol injection system for dual-purpose climate intervention, combining radiative forcing and $CO_2$ capture objectives in the stratosphere. A custom-designed deployment pod was modeled and simulated, and environmental performance was assessed using quantitative methods.

Key findings include:

- $CO_2$ adsorption by ZSM-5 is negligible at stratospheric pressure, with modeled capacity dropping below 0.001 mmol/g.
- Reflective surface deployment requires unrealistically large areas to produce any significant change in global surface temperature.
- Balloon-based delivery to the stratosphere is mechanically feasible, but the material deployed must justify its operational and environmental cost.

These findings indicate that zeolites, while effective in terrestrial DAC systems, are fundamentally unsuitable for airborne $CO_2$ capture and limited in their SRM utility at high altitudes. However, this negative result contributes to the refinement of climate intervention strategies by eliminating nonviable material pathways and informing the atmospheric science community about the physical constraints of high-altitude aerosol design. Future work should focus on alternative sorbents optimized for low-pressure environments and the decoupling of SRM and carbon removal functions into distinct system architectures.

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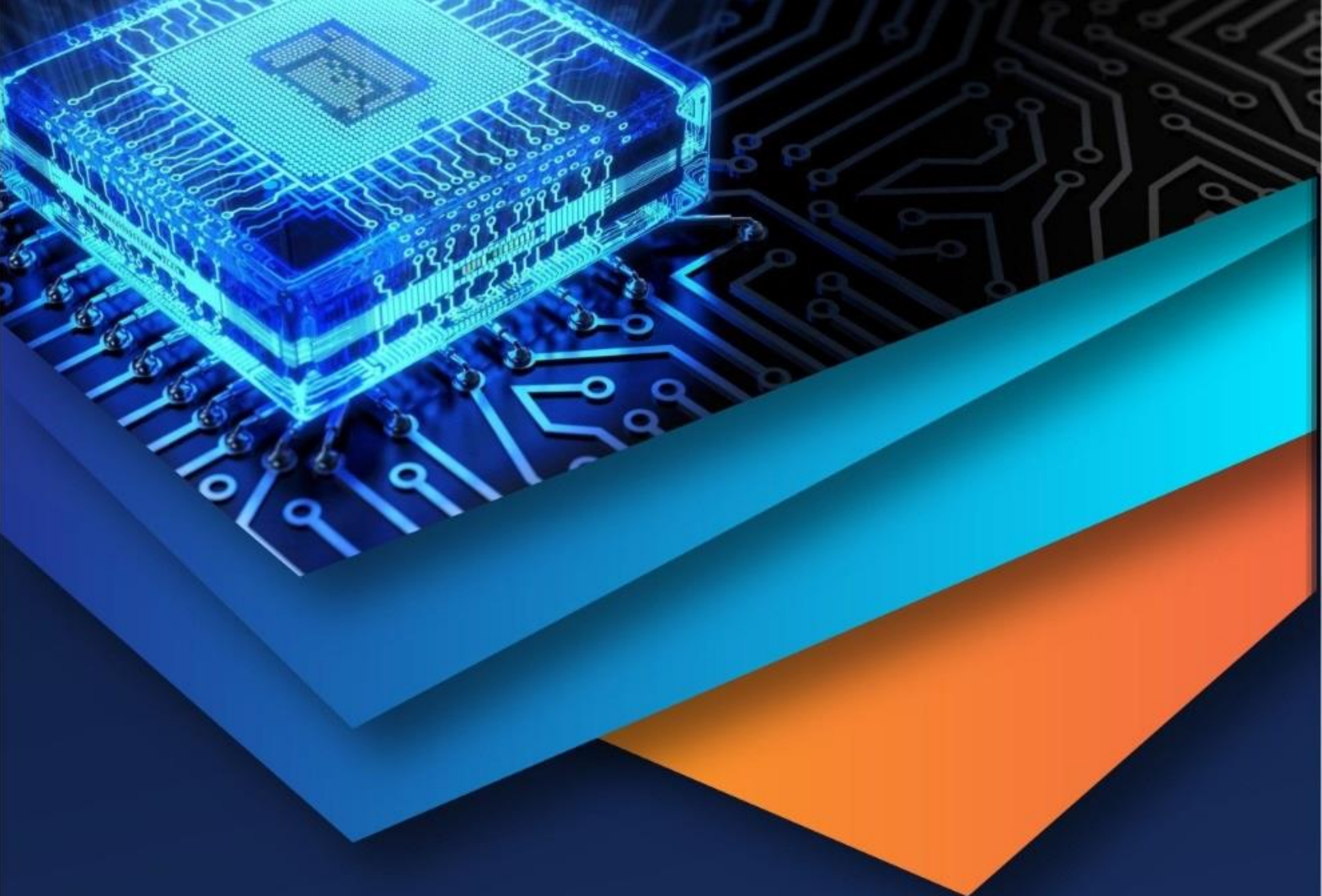


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