SAI Experimental Research Initiative

CLIMATE MOONSHOT PORTFOLIO

Billions to save trillions

Proposed $1 Billion / Five-Year R&D Program

STRATOSPHERIC AEROSOL INJECTION (SAI)

SO_2 GAS • H_2SO_4 AEROSOL • ALTERNATIVE PARTICLES

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Developed with assistance from ChatGPT

OPEN SOURCE

Executive Summary

Purpose. This proposed $1 billion, five-year SAI Experimental Research Initiative is designed to produce decision-grade evidence about whether leading stratospheric aerosol injection pathways can be predicted, measured, controlled, and compared well enough to justify further research. It is an experimental research program, not a deployment program: it would not seek regional or global cooling and would not authorize a climate-scale intervention.

Experimental architecture. The portfolio is organized around three core pathways. C1 releases SO_2 and follows oxidation, sulfate formation, particle growth, transport, optics, heating, and ozone-relevant chemistry over days to weeks. C2 compares direct H_2SO_4 approaches—mechanical H_2SO_4/H_2O aerosol, jet engine exhaust-assisted vaporization, and a dedicated vaporizer—so the program can measure near-field nucleation, coagulation, particle size, energy demand, and radiative performance within seconds to hours. C3 screens alternative particles (e.g. calcium carbonate) through laboratory, chamber, toxicology, chemistry, and staged field gates before any larger test.

Measurement and governance. Each major outdoor experiment passes an observability and value-of-information gate that defines the uncertainty being reduced, the smallest release that can produce a usable signal, environmental consequences, preregistered predictions, and explicit stop criteria. Flagship closure campaigns separate the release aircraft from above-plume, through-plume, and below-plume measurements, supported by lidar, balloons, trajectory forecasting, plume reacquisition, and independent validation. Common metrics include radiative forcing per kilogram of sulfur, per aircraft-hour, and per total dollar.

Success criterion. The primary five-year deliverable is an open, validated predictive and technoeconomic system that links precursor, generation method, release geometry, plume evolution, chemistry, particle size, optics, climate-relevant forcing, side effects, aircraft requirements, and cost with quantified uncertainty. Results, including negative findings, are published on an open-science schedule. Success means reducing uncertainty, eliminating weak pathways, and defining what evidence would be required for any later decision—not proving that SAI should be deployed.

Climate Moonshot Portfolio. We define "Climate Moonshot" as conducting R&D to the extent required to solve the climate problem. This would require a portfolio of R&D initiatives, an example of which is at www.APlanToSaveThePlanet.org. The document you are reading is one initiative within that portfolio. It uses a Common Framework that establishes shared rules for governance, procurement, data rights, independent review, and oversight. All documents within this portfolio are open-source and may be freely viewed, used, and modified.

Program at a Glance

The program is summarized in the following table.

Item	SAI Experimental Research Initiative
Funding / duration	$1.0 billion over five years.
Mission	Determine which SAI pathways can be predicted, measured, controlled, and compared well enough to justify further research - or should be redirected or stopped.
C1 - SO_2	$270M core pathway: release SO_2 and measure oxidation, sulfate formation, particle evolution, optics, heating, transport, and ozone-relevant chemistry.
C2 - direct H_2SO_4	$220M core pathway: compete mechanical aerosol, exhaust-assisted vaporization, and dedicated-vaporizer architectures before major field spending.
C3 - alternative particles	$60M option-preserving tournament: laboratory optics/chemistry/toxicology first, then tightly staged field tests only for candidates that pass.
Supporting science / infrastructure	$400M for laboratory/chamber work, natural analogues, shared observing systems, modeling/observability, targeted baseline/detection, downstream effects, and program assurance.
Central reserve	$50M Funding-Source-controlled scientific and technical reserve; ordinary campaign weather/repair options remain inside approved campaign ceilings.
Experimental rule	Use the minimum atmospheric perturbation large enough to answer a defined decision question; no experiment is designed to produce detectable regional or global cooling.
Measurement architecture	Controlled release plus above-plume, through-plume, and below-plume measurements, supported by lidar, balloons, forecasting, plume reacquisition, and independent validation.
Primary metrics	Radiative forcing per kg-S, per aircraft-hour, and per total dollar; particle size/lifetime; heating; ozone-relevant chemistry; observability; reproducibility; side effects.
Five-year decision	Proceed / redesign / pause / stop separately for SO_2, each direct-H_2SO_4 architecture, and any surviving C3 candidate, with quantified uncertainty.
Boundary	Research only. Passing a scientific gate does not authorize an outdoor release, climate-scale intervention, or deployment.

Scientific Causal Chain and Measurement Architecture

The program should be managed around one quantitative source-to-forcing chain. A successful release is not a scientific result unless the input is independently known, the plume can be found, the chemistry and particle evolution are measured, the radiative effect closes within a stated uncertainty budget, and models are challenged against observations that were not used to tune them.

Chain element	What must be known	Primary evidence	Gate
Controlled source	Material, sulfur mass, mass flow, energy, release geometry, and generator settings.	Release-aircraft metrology, tank/source accounting, synchronized GPS/INS, and calibrated controls.	G1-G3
Near-field formation	Dilution, vaporization/atomization, nucleation, condensation, coagulation, and initial particle size.	Ground/exhaust plume facilities plus immediate in-air plume crossings.	G1-G4
Transport / reacquisition	Where the perturbation goes, its age, dilution, altitude, and sulfur mass through time.	Trajectory ensembles, lidar/imaging, balloons, in-situ plume hits, and data assimilation.	G0-G5
Microphysics / chemistry	Particle number, size, sulfate mass, composition, acidity, surface area, SO_2/H_2SO_4 conversion, and ozone-relevant chemistry.	Through-plume aircraft with gas, aerosol, optical, meteorological, and chemistry payloads.	G4-G5
Optics / radiation	Scattering, absorption, extinction, reflected sunlight, longwave effects, and net top-of-atmosphere forcing.	Above/below radiometry, lidar/polarimetry, in-situ optics, and radiative closure.	G4-G5
Prediction / economics	Whether preregistered models predict withheld observations and how measured physics changes system cost.	Independent model challenge plus equal-sulfur, equal-aircraft-time, and equal-dollar accounting.	G5-G6

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What is Stratospheric Aerosol Injection (SAI)?

Stratospheric Aerosol Injection (SAI) is a proposed form of solar radiation modification intended to cool Earth by increasing the amount of sunlight reflected back into space. The leading concept would use specialized high-altitude aircraft—potentially supplemented by balloons or other platforms—to release sulfur dioxide or aerosol particles into the lower stratosphere. Sulfur dioxide would react to form tiny sulfate droplets, producing a cooling effect broadly analogous to that observed after major volcanic eruptions.

Climate models indicate that sustained, carefully distributed injections could lower global average temperature relatively quickly and potentially reduce some heat-related climate damages. The cooling could be adjusted by changing the quantity, latitude, altitude and timing of injections. However, SAI would **not remove carbon dioxide**, stop ocean acidification or eliminate the need to reduce greenhouse-gas emissions.

The central concern is that SAI would create a different climate rather than precisely restoring the previous one. Possible effects include changes in regional precipitation and monsoons, heating of the stratosphere, ozone depletion, altered atmospheric circulation, whiter skies, and changes in the balance between direct and diffuse sunlight. Benefits and harms could also be distributed unevenly among countries and regions.

SAI would require continuous operation because aerosols eventually fall out of the stratosphere. If a large cooling program were suddenly stopped while greenhouse-gas concentrations remained high, temperatures could rise very rapidly—a danger known as **termination shock**.

SAI has not been demonstrated as a global climate intervention and remains scientifically, politically, ethically and legally controversial. Unresolved questions include environmental monitoring, international decision-making, compensation for damage, control over deployment, and geopolitical misuse. Major scientific assessments therefore describe SAI as a possible risk-reduction tool worth researching—not a substitute for emissions reductions or a technology ready for deployment.

For a summary of SAI, see the following videos:

Reflecting Sunlight [#9]
https://www.youtube.com/watch?v=AJ-ddFDiA4w

Can Air Pollution Save the Planet? [#10]
https://www.youtube.com/watch?v=p4O2hv9tSDA

Program Architecture and $1 Billion Budget

Prompt to AI: If a funding source wants to spend $1B on Stratospheric Aerosol Injection (SAI) experimental research over 5 years, what experiments should it fund? Assume the reader has not read any other atmospheric-experiments document. Organize the program around C1 (SO_2 gas), C2 (direct H_2SO_4/H_2O aerosol), and C3 (alternative candidate particles). Use release size based on observability and scientific value rather than an arbitrary low mass ceiling.

Response From AI:

A $1 billion, five-year SAI experimental research program should be designed to answer a practical question: can a specified injection pathway be predicted, measured, controlled, and evaluated well enough to inform a later decision about whether SAI research should continue, change direction, or stop? The program should not attempt to cool a region or the planet. Its purpose is to produce decision-grade knowledge about the physical chain from release to radiative effect and side effects.

The program should be built around three core experimental pathways: C1 for SO_2 gas; C2 for direct sulfuric-acid pathways, including mechanically generated H_2SO_4/H_2O aerosol and H_2SO_4 vapor generated from liquid acid using aircraft exhaust or a dedicated vaporizer; and C3 for alternative candidate particles. Laboratory work, near-field plume facilities, natural analogues, monitoring infrastructure, engineering-economic modeling, and global modeling should support these pathways rather than operate as separate research silos.

Design principle

To minimize harm, we intend to:

> Use the minimum atmospheric perturbation that is large enough to produce the measurement needed for a specific decision.

A release that is so small that the plume becomes unobservable before the important chemistry, microphysics, or radiative effect can be measured can waste aircraft time and money. Conversely, increasing release mass solely to create a larger signal can also distort plume microphysics. Release quantity therefore has to be chosen together with release geometry, duration, concentration, altitude, and the measurement objective.

Before each controlled release, the program should perform an observability and value-of-information analysis. That analysis should determine the release mass required to obtain a statistically useful signal and should show why the proposed experiment is preferable to existing observations, laboratory studies, modeling, or a natural volcanic analogue.

The three core SAI experiment families

C1 — Inject SO_2 gas and follow the complete sulfur pathway

C1 tests the simplest sulfur-based SAI pathway: release sulfur dioxide gas (SO_2) into the lower stratosphere and measure what the atmosphere actually produces. The physical chain is:

> SO_2 release -> dilution and transport -> oxidation -> H_2SO_4 vapor -> nucleation and/or condensation -> sulfate particle growth -> coagulation -> optical properties -> radiative effect -> heating and ozone-relevant chemistry

C1 is valuable because SO_2 is comparatively straightforward to store and release, and it is the sulfur form used in many climate-model studies. Its weakness as an experiment is time. The sulfate aerosol of greatest interest does not appear instantly. The plume stretches, folds, and dilutes while the chemistry proceeds, so C1 requires repeated plume interception over days and weeks.

- **Primary questions:** How rapidly does SO_2 convert? Does sulfur form new particles or condense onto existing particles? What particle-size distribution results? How does that distribution evolve? How much scattering is obtained per kilogram of sulfur?
- **Measurement window:** minutes and hours for near-field dilution; days to weeks for oxidation and particle growth; longer where detectability permits.
- **Core instruments:** SO_2 and H_2SO_4 gas measurements, nanoparticle and accumulation-mode sizing, aerosol composition, ozone and reactive chemistry, aerosol optics, lidar, radiometry, winds, water vapor, and trajectory data assimilation.
- **Success criterion:** the program can predict the evolving sulfur mass, particle distribution, optical properties, and chemistry within decision-relevant uncertainty bounds.

C2 — Engineer H_2SO_4 aerosol by competing direct-delivery architectures

C2 bypasses the slow SO_2 oxidation step, but it should no longer be treated as a single injection method. The program should compare at least three direct-acid architectures:

C2A Mechanically generated H_2SO_4/H_2O droplets.

C2B Concentrated liquid H_2SO_4 pumped into a hot aircraft-exhaust/vaporization region so that H_2SO_4 vapor nucleates and coagulates in the wake; and

C2C H_2SO_4 vapor produced by a dedicated heater or heat exchanger independent of the jet engine exhaust.

The objective is to learn which architecture produces the most useful, reproducible sulfate particle population after the first seconds and minutes of plume processing.

- **Primary questions:** Which generation mechanism produces the desired particle-size distribution after 1 second, 10 seconds, 1 minute, 10 minutes, 1 hour, and one day? How do mass flow, acid concentration, exhaust temperature, plume dilution, nozzle geometry, compressor or pump power, and ambient water vapor affect nucleation and coagulation? How much radiative forcing is obtained per kilogram of sulfur, per aircraft-hour, and per dollar of total system cost?
- **Measurement window:** milliseconds and seconds in ground/plume facilities; seconds to hours in atmospheric releases for near-field microphysics and optical closure; optional revisits over one to several days for aging, transport, and persistence.
- **Core instruments:** particle size and number from nucleation through accumulation mode, composition and acidity, H_2SO_4 vapor, exhaust temperature and dilution, mass-flow and energy measurements, optical scattering/absorption/extinction, lidar plume geometry, above/below radiometry and polarimetry, meteorology, and ozone-relevant chemistry.
- Success criterion: the program can predict delivered particle properties and radiative forcing from the generation mechanism and release conditions, and can rank C2A/C2B/C2C against C1 using standardized radiative-forcing-per-sulfur and radiative-forcing-per-dollar metrics.

C2 should begin earlier than the most expensive C1 campaigns because direct-acid signals are available immediately. Year 1 should emphasize ground and near-field plume experiments that compare C2A/C2B/C2C before large outdoor releases. This allows the program to validate instruments, plume models, radiative closure, and the measurement architecture while eliminating weak aerosol-generation approaches early.

C3 — Inject alternative candidate particles only after laboratory prequalification

C3 evaluates whether non-sulfate particles could provide useful sunlight reflection with lower ozone, heating, persistence, or other side effects. Candidate materials sometimes discussed in the literature include calcite, alumina, silica, and titanium-containing particles. The program should not assume that a material that looks attractive in a radiative model will behave safely or predictably in the real stratosphere.

- **Stage 1:** laboratory optical measurements, surface chemistry, aggregation, aging, toxicology, and ozone-relevant reaction studies.
- **Stage 2:** chamber and ground-dispersion tests to determine whether particles can be generated without uncontrolled agglomeration or contamination.
- **Stage 3:** kilogram-scale atmospheric tests only for candidates that pass predefined laboratory criteria.
- **Stage 4:** larger closure tests only if the material remains scientifically competitive and the observability analysis shows a clear need.

C3 should receive less early funding than C1 and C2 because sulfate has the strongest natural analogue in volcanic eruptions and the largest existing scientific base. C3 is an option-preserving program, not a reason to delay sulfate work.

Release-size framework

Release size should be selected from the measurement requirement, not from a universal ceiling. The following bands are useful for planning; they are not automatic approvals.

Experimental scale	Illustrative release mass	Primary purpose	Typical observation window
Process-scale	~1–100 kg	Near-field wake physics, nucleation, delivered particle distribution, instrument validation	Seconds to hours
Closure-scale	~100–10,000 kg (0.1–10 tonnes)	Measure plume optics, radiative flux, chemical evolution, and model closure with adequate signal	Hours to days
Pathway/transport campaign	Multi-ton campaign total when justified	Follow deployment-relevant plume evolution and reacquire material over days to weeks	Days to weeks

The upper end of a mass range should be used only when modeling shows that smaller releases will not produce the required signal. A multi-ton campaign does not imply a single concentrated dump. For many questions it is better to distribute material along a long flight path or among repeated sorties so that local plume concentration remains representative of a plausible SAI release geometry.

Illustrative $1 billion portfolio

These are planning estimates in 2026 dollars, not vendor quotations.

Program	Five-year budget	Main purpose
C1 — SO_2 pathway experiments	$270M	Multi-day and multiweek experiments measuring conversion, particle growth, transport, radiative efficiency, heating, and ozone chemistry
C2 — H_2SO_4 delivery-architecture and aerosol experiments	$220M	Compete mechanical aerosol, exhaust-vaporized H_2SO_4, and dedicated-vaporizer approaches; measure near-field particle formation, optics, radiative forcing per kg-S, and radiative forcing per dollar
C3 — Alternative particle experiments	$60M	Laboratory-first screening followed by tightly staged field tests for promising non-sulfate candidates
Laboratory/chamber chemistry, microphysics and toxicology	$70M	Ozone kinetics, aerosol aging, surface chemistry, particle generation, and candidate-material screening
Volcanic/wildfire natural-analogue rapid response	$60M	Observe large natural stratospheric perturbations that deliberate experiments should not reproduce
Shared aircraft, instruments, lidar, balloons and monitoring infrastructure	$75M	Reusable monitoring capability for C1/C2/C3 and natural events
Modeling, observability, plume prediction and data assimilation	$75M	Predict detectability, guide flight targeting, reconstruct plumes, and convert observations into model improvements
Targeted baseline and SAI detection system	$25M	Measure only background quantities that materially limit interpretation; test detection of meaningful SAI-scale perturbations
Downstream deposition, ecology and cloud-interaction studies	$25M	Track descent/deposition and study relevant ecological and cloud pathways without pursuing climate-scale cooling
Program management, governance, international participation, open data and independent review	$70M	Fiduciary control, stage gates, environmental review, participation, data publication, audits, and independent evaluation
Central scientific and technical reserve	$50M	Funding-Source-controlled reserve for unexpected high-value follow-up, major redesign, independent replication, replacement of a failed major capability, or qualifying rapid-response opportunities. Ordinary weather/repair options remain inside approved campaign ceilings.

About $550 million is explicitly centered on C1, C2, and C3. Most of the remaining budget exists to make those experiments measurable, interpretable, and independently credible. Thus, roughly threequarters of the program is directly connected to the question: what happens when a candidate SAI material is actually released into the stratosphere, and can that outcome be predicted?

Budget accounting rule. The representative C1 and C2 campaign costs and the master-agreement ceilings later in this proposal are bottom-up planning and contracting views that draw from the program allocations above. They are not additional budgets and must not be multiplied by nominal campaign counts and added again to the $1 billion portfolio.

Detailed G0 — Observability and Value-of-Information Gate

No major outdoor release should be approved until an independent design review receives a written report answering the following questions:

1. What quantity or process is uncertain today?
2. What is the present best estimate and uncertainty range?
3. What later engineering, environmental, or policy decision depends on reducing that uncertainty?
4. Could existing data, a laboratory experiment, a chamber experiment, a volcanic plume, or additional modeling answer the question more cheaply?
5. What release mass and geometry are expected to produce a measurable signal?
6. What concentration and particle signal are expected after 1 minute, 1 hour, 1 day, 1 week, and other relevant times?
7. Which instruments can detect the signal and with what uncertainty?
8. What is the probability of finding the plume again at each planned revisit?
9. Would 100 kg work? Would 1 tonne work? Would 10 tonnes materially improve the answer?
10. At what point would additional material stop adding useful information or begin to distort the process being studied?
11. What environmental exposure and deposition are expected?
12. What result would cause the program to stop or abandon the pathway?
13. What result would justify replication or a larger follow-on experiment?
14. What independently testable predictions will be made before the data are collected?
15. What engineering decision will the result resolve—for example, whether to retain C2A, C2B, or C2C?

16. How will the result change the estimated radiative forcing per kilogram of sulfur, per aircraft-hour, and per dollar?
17. Could a ground engine/exhaust-plume experiment answer the question before any outdoor stratospheric release?

This gate directly addresses the risk of spending tens of millions of dollars on an exquisitely instrumented experiment whose plume is too weak to answer the stated scientific question.

Four-aircraft experimental and radiative-closure architecture

For the most important C1 and C2 closure experiments, separate four functional roles: a release aircraft that creates and precisely logs the perturbation, an above-plume aircraft, a through-plume aircraft, and a below-plume aircraft. The three monitoring aircraft provide complementary remote-sensing, in-situ, and radiative measurements; the release aircraft should normally remain separate so its hazardous-material systems and possible contamination do not compromise clean measurements.

Aircraft	Role	Purpose
Release/injector	Released mass and mass flow, feedstock state, particle-generation settings, exhaust/vaporizer conditions, aircraft position/attitude and ambient meteorology	Defines the controlled input and provides the source record needed for mass balance, plume modeling and reproducibility
Above plume	Up/down shortwave and longwave radiometry, spectral radiometry, polarimetry, lidar and multispectral imaging, with precision GPS/INS	Measures reflected/absorbed radiation, plume horizontal structure and vertical geometry from above
Through plume	SO_2/H_2SO_4, aerosol size and number, composition/acidity, scattering/absorption, ozone-relevant chemistry, water vapor, winds and turbulence	Provides direct physical and chemical measurements of the material being modeled and anchors remote-sensing retrievals
Below plume	Up/down radiometry, spectral attenuation, UV-visible spectroscopy/DOAS, upward-looking lidar, column optical depth and background context	Provides the second side of the radiative-flux difference and measures what radiation passes through the plume

Ground or mobile lidar, balloon profiles, targeted satellite observations and a real-time plume-location/navigation system should supplement this stack. Not every release requires all four roles simultaneously, but a campaign claiming radiative closure should explain any missing layer of observation. For multi-day C1 work, plume reacquisition should be treated as a core experimental capability rather than an informal flight-planning task.

Illustrative flagship C1 campaign

One useful C1 design is a high-latitude lower-stratospheric SO_2 campaign in a dynamically coherent late-winter air mass. An illustrative campaign might release about 10 tonnes of SO_2 total, distributed over multiple flight legs and sorties rather than concentrated at one point. For example, approximately 20 release sorties could each place about 500 kg along long flight tracks over roughly ten days. These numbers are illustrative; the Phase 0 calculation should determine the actual mass and geometry.

The scientific objective is not to create a surface-temperature signal. It is to generate a sulfur perturbation that can be reacquired often enough to measure the conversion from SO_2 to sulfate, particle-size evolution, optical efficiency, chemical surface area, and transport. Sampling might be concentrated on release day and then repeated around days 1, 2, 4, 7, 10, and 14, with later flights only when the plume remains measurable.

The principal products should be measured curves such as:

- SO_2 mass remaining versus time.
- Sulfate mass formed versus time.
- Particle number and size distribution versus time.
- Aerosol surface area versus time.
- Optical scattering and absorption per kilogram of sulfur versus time.
- Observed plume location and geometry versus pre-registered model forecasts.

If a 10-tonne campaign cannot be reacquired reliably, that is itself a major result: the program would know that multiweek C1 field measurements are less useful than expected and should redirect resources toward different designs, larger natural analogues, or different measurement methods.

Illustrative flagship C2 campaign

C2 can use a faster experimental rhythm, but the first major investment should be a competitive engineering down-selection rather than an immediate large atmospheric release. The program should first test C2A mechanical atomization, C2B exhaust-assisted vaporization, and C2C a dedicated vaporizer in laboratory and full-scale or near-full-scale exhaust/plume facilities. Atmospheric closure events should then use only the architectures that demonstrate reproducible particle generation and acceptable safety.

The strongest science occurs during the first milliseconds through hours. Ground and engine/plume tests should resolve vaporization, nucleation, initial coagulation, and energy demand. Airborne near-field passes should measure the particle distribution after seconds to minutes; mid-field passes should measure continued coagulation, dilution, and water equilibration; and long straight legs above and below the plume should measure radiative flux. A subset of cases should be revisited the following day to measure persistence and continued evolution.

Important Consideration

C2 should produce a map of generation mechanism + feedstock + energy source + mass flow + release geometry -> particle properties -> optical properties -> radiative effect -> radiative forcing per kg-S and per dollar. That map can then be compared directly with C1 (SO_2) to determine whether the theoretical controllability advantage of direct acid survives real aircraft-plume physics and total-system economics.

C3 candidate-material screening

C3 should proceed more conservatively because the atmosphere has far less experience with deliberate stratospheric releases of many proposed solids than it has with sulfate. Each candidate should pass laboratory gates for optical performance, heterogeneous ozone chemistry, aggregation, persistence, toxicology, and degradation products before an outdoor test is considered.

Initial C3 releases should normally remain kilogram-scale and focus on whether the material can be dispersed, identified, and measured without uncontrolled agglomeration. A larger experiment should require a positive scientific case that the candidate could materially outperform sulfate and that the larger release is necessary for optical or chemical closure.

Five-year sequence

Year	Priority	Illustrative activities
Year 1	Build and down-select generation systems	Phase 0 modeling; laboratory/chamber work; build near-field plume and exhaust test capability; compare C2A mechanical aerosol, C2B exhaust vaporization, and C2C dedicated vaporization; build the standardized sulfur/cost-efficiency model; instrument integration and natural-analogue readiness
Year 2	Small C2 closure first; first serious C1 test	Conduct small atmospheric C2 tests of the surviving generation systems with intensive seconds-to-hours measurements; validate radiative-closure geometry; conduct the first serious C1 release only after observability modeling and plume-reacquisition rehearsals
Year 3	Compare sulfur pathways	Major C1 campaign; matched C1/C2A/C2B or C2C experiments under similar conditions; equal-sulfur, equal-aircraft-time, and equal-cost comparisons; selected C3 laboratory-to-field transitions

Year	Priority	Illustrative activities
Year 4	Broaden conditions and scale	Test different H_2SO_4 flow rates, dilution geometries, altitude/latitude/season cases, and background aerosol conditions; second major C1 campaign; 777-class reference-scale mass/energy/cost validation; tightly screened C3 field work
Year 5	Replicate, challenge, and down-select	Independent model challenges and replication; integrated ranking of SO_2, mechanical H_2SO_4 aerosol, exhaust-vaporized H_2SO_4, dedicated-vaporizer H_2SO_4, and surviving C3 candidates; publish requirements for −1 W/m² scenarios without authorizing deployment

Program boundaries

The program should impose boundaries based on climate consequence, environmental review, and scientific necessity rather than a blanket prohibition on multi-ton experiments.

- No experiment should be designed to produce detectable regional or global climatic cooling.
- No deployment-scale fleet should be built under the experimental research fund.
- No C3 material should be released outdoors before laboratory toxicology, ozone-chemistry, and persistence review.
- No major release should proceed without the Phase 0 observability/value-of-information gate, environmental review, scientific approval, and independent governance approval.
- Release mass, geometry, and timing must be documented publicly in advance to the extent compatible with safety and regulatory requirements.
- All atmospheric data, model code, calibration records, and negative results should be released on a defined open-science schedule.
- Completion of the five-year program should create no presumption that deployment or larger experiments are authorized.

Primary program deliverable

The most valuable product of the $1 billion should be an open, validated predictive and technoeconomic system. Given a sulfur precursor, aerosol-generation architecture, release rate, particle specification, aircraft wake, altitude, latitude, season, and meteorological state, the system should predict plume dispersion, chemical conversion, particle evolution, radiative forcing, stratospheric heating, ozone-relevant effects, feedstock and energy requirements, aircraft utilization, and total cost—with quantified uncertainty. The field experiments are valuable to the extent that they make that system demonstrably better.

Program Crosswalk

The program crosswalk keeps the scientific pathways, supporting infrastructure, representative campaign budgets, and purchase orders tied to one approved $1 billion accounting structure. Purchase-order and campaign figures later in the proposal are mappings into these allocations, not extra money.

Program element	Budget	Primary five-year output	Primary acceptance quantity	Gate
C1 - SO_2	$270M	SO_2-to-sulfate pathway closure across minutes to weeks.	Sulfur mass, size, optics, chemistry, heating, transport, and forecast skill vs. time.	G1-G6
C2 - direct H_2SO_4	$220M	Down-selected direct-acid architecture(s) with measured near-field and radiative performance.	Particle distribution, energy, RF/kg-S, RF/aircraft-hour, RF/$, and side-effect constraints.	G1-G6
C3 - alternatives	$60M	Laboratory-first tournament; only qualified candidates reach the atmosphere.	Optics, chemistry, toxicology, aggregation, persistence, and advantage vs. sulfate.	G1-G6
Lab + natural analogues	$130M	Mechanistic constraints, prequalification, and observations of large natural perturbations.	Reproducible chemistry/microphysics plus model-observation closure for transport and removal.	G0-G6
Observing + modeling + baseline/downstream	$200M	Reusable observations, plume prediction/reconstruction, and targeted background/downstream evidence.	Calibration/detectability, held-out prediction, signal/background discrimination, relevant deposition/ecology.	G0-G6
Program assurance	$70M	Independent scientific, environmental, international, data, and fiduciary evidence.	Accepted reviews, audit trail, public records, and release-authorization documentation.	All
Central reserve	$50M	Controlled response to genuinely unplanned high-value need.	Formal reserve/change-control approval; no automatic contractor entitlement.	FS
Total	**$1.000B**	**One integrated five-year decision program.**	**Proceed / redesign / pause / stop evidence by pathway.**	**G6**

Relationship to the SAI Equipment Development Initiative

The SAI Experimental Research initiative and the SAI Equipment Development initiative should use one asset registry and a clear lead-budget rule. Experimental Research specifies the scientific performance needed and pays for campaign-specific operations and interpretation. Equipment Development hardens, qualifies, automates, scales, and lifecycle-costs reusable engineering capability. The same capital asset should not be purchased at full cost by both programs.

Capability	SAI Experimental Research owns	SAI Equipment Development owns
Scientific requirements	The experiment question, required release characteristics, detectability, sampling, uncertainty, and decision endpoint.	Translates stable requirements into reusable, reliable, scalable engineering specifications.
Release systems	Campaign-grade variants/settings needed to compare SO_2, C2A/C2B/C2C, and later C3 candidates.	Long-life source hardware, material compatibility, airworthiness, automation, maintainability, metrology, and scale-up evidence.
Aircraft	Campaign access, release/sampling flight hours, and science-specific integration.	777-class engineering demonstrator, future high-altitude aircraft design, reusable aircraft modifications, and engineering qualification.
Monitoring hardware	Scientific payload operation, calibration during campaigns, sampling design, and interpretation.	Ruggedized reusable interfaces, release metrology, calibration architecture, common racks, spares, and maintainability.
Atmospheric models	Observability, plume chemistry/microphysics, data assimilation, radiative closure, and prediction challenges.	Aircraft/ground digital twins, material-flow/logistics, mission operations, and limited engineering release-interface models.
Shared assets	Pays incremental adaptation, consumables, and operating time unless independent duplicate capacity is explicitly justified.	One designated capital owner where appropriate, with asset registry, custody, configuration, and transfer records.

Scientific Requirements, Traceability, and Acceptance

Every major campaign should maintain a configuration-controlled Scientific Traceability Matrix. The experiment succeeds when it resolves a stated decision with accepted evidence and uncertainty - not simply because a flight occurred or a statistically significant signal was found.

Traceability element	Required record	Example for a C2 closure experiment	Gate
Decision question	State the later research/engineering decision that depends on the result.	Whether C2B exhaust-assisted vaporization should remain in the program.	G0
Hypothesis / prediction	Preregister the expected signal and uncertainty before seeing outcome data.	Particle-size distribution and optics at specified plume ages for a defined acid flow and exhaust condition.	G0-G3
Controlled input	Measure the actual source, not merely commanded settings.	H_2SO_4 mass flow, temperature, vaporization fraction, energy, geometry, aircraft state, and ambient conditions.	G1-G4
Primary endpoint	Choose the smallest set of quantities that can answer the decision question.	Particle distribution plus RF/kg-S and RF/$ with heating/chemistry constraints.	G0-G4
Controls / comparators	Predefine matched background, alternative architecture, and/or equal-S/equal-time/equal-dollar comparisons.	C2B versus C2A/C2C and, where possible, matched C1 conditions.	G2-G5
Uncertainty / detectability	Propagate source, sampling, calibration, plume-location, model, and cost uncertainty.	Minimum detectable particle/flux change and reacquisition probability.	G0-G5
Acceptance / decision	Predefine pass, redesign, replicate, or stop conditions; negative results are accepted outputs.	Continue C2B only if measured performance remains competitive after uncertainty and side effects.	G4-G6

C1, C2 and C3 Experimental Pathways

Prompt to AI: How should the $1B program divide effort among C1, C2, and C3? Explain the experiments from first principles, including why C2 should generally be tested before the most expensive C1 campaigns and how paired C1/C2 experiments should be used.

Response From AI:

C1, C2, and C3 are complementary pathways, but C2 should now be treated as an engineering competition rather than one fixed aerosol-release method. C1 asks what the atmosphere makes from SO_2. C2 asks whether engineers can make a more useful sulfate aerosol directly—and which of several physical methods for doing so is best. C3 asks whether a non-sulfate material can outperform sulfur pathways without introducing worse problems.

The core-pathway budget is: $270 million for C1, $220 million for C2, and $60 million for C3 ($550M total). Shared aircraft, instruments, laboratory work, plume modeling, and governance add substantial support beyond those line items.

Pathway	Five-year core budget	Field emphasis	Why this share
C1 — SO_2	$270M	Fewer, longer and more expensive multi-day/multiweek campaigns	Most deployment-relevant simple sulfur pathway; expensive because the plume must be found repeatedly while chemistry evolves
C2 — direct H_2SO_4 pathways	$220M	Ground-heavy architecture competition followed by repeatable same-day/short-duration closure campaigns and selected aging revisits	Fast signal; tests mechanical aerosol, exhaust vaporization, and dedicated vaporization; directly measures the cost-versus-particle-size tradeoff
C3 — Alternative particles	$60M	Laboratory-heavy screening; limited staged outdoor tests	Preserves options but should not delay sulfate research; chemistry and toxicology are less established

C1 and C2 test different parts of the same sulfur problem

Feature	C1 — SO_2 gas	C2 — engineered H_2SO_4 aerosol
Starting material	SO_2 gas	Concentrated liquid H_2SO_4 and/or H_2SO_4/H_2O solution; final aerosol may be mechanically atomized or formed after vaporization

What must happen before strong sulfate optics appear	Oxidation to H_2SO_4, then nucleation/condensation and growth	Depends on architecture: preformed droplets equilibrate and mix; vaporized H_2SO_4 nucleates and coagulates in the wake before aging and transport
Strongest experimental window	Minutes to weeks	Milliseconds to hours; optional days
Main uncertainty	Conversion, nucleation, condensation, growth and long-range plume evolution	Generation mechanism, vaporization/atomization, wake dilution, nucleation, coagulation, energy demand, persistence, and cost-normalized radiative efficiency
Operational difficulty	High: repeated plume search and reacquisition	Moderate-to-high: corrosive feedstock plus specialized aerosol-generation hardware; same-day closure is possible
Potential deployment advantage	Simple storage and release hardware	Potentially higher radiative efficiency and particle-size control, if useful size distributions can be produced at practical mass flow and cost

Why begin with C2 engineering and ground tests

C2 gives the program immediate feedback and can answer many of its most important questions on the ground. Mechanical atomization, exhaust-assisted vaporization, dedicated vaporization, corrosion, pumping, heat transfer, and the first milliseconds-to-seconds of particle formation should be challenged in instrumented plume facilities before expensive field campaigns. The surviving systems can then be tested in the atmosphere, where the aerosol can be measured almost at once.

C2 also isolates a central uncertainty in the global-model literature. Models that show an advantage for accumulation-mode H_2SO_4 generally prescribe a post-plume particle distribution; they do not resolve whether a real aircraft can create that distribution at economically useful mass flow. The program should therefore treat generation method and mass flow as primary experimental variables, not merely assume that an ideal particle population leaves the aircraft.

Accordingly, Years 1–2 should emphasize C2 process and closure experiments. C1 modeling, engineering, and rehearsals proceed in parallel, but the first expensive multiweek C1 campaign should use lessons learned from C2.

Illustrative campaign counts

Campaign counts are less important than information value. The following is a reasonable planning architecture if major monitoring hardware is reusable:

Pathway	Illustrative five-year campaign architecture	Illustrative release scale
C2 (H_2SO_4 architectures)	Ground/plume screening of C2A/C2B/C2C; then 6–10 major atmospheric campaigns using only surviving approaches, with paired and replication cases	Ground tests from gram/s to multi-kg/s equivalent flow; 1–100 kg atmospheric process tests; ~0.1–10 t closure events only when needed
C1 (SO_2)	4–6 major campaigns, including at least two multiweek pathway campaigns and several smaller process/paired experiments	1–100 kg process tests; ~0.1–10 t closure events; multi-ton campaign totals when needed for repeated tracking
C3	Laboratory screening of many candidates; perhaps 4–8 outdoor experiments across only the best candidates	Usually kg-scale at first; larger only after explicit material-specific review

Matched C1/C2A/C2B/C2C experiments

The highest-value sulfur experiments should compare C1 with the best surviving C2 architectures under closely matched atmospheric conditions. A campaign can release comparable sulfur mass on nearby flight tracks as SO_2, mechanically generated H_2SO_4 aerosol, and/or H_2SO_4 vapor formed with exhaust or a dedicated vaporizer, using the same monitoring system to compare them.

A paired campaign should compare at least:

- Delivered and newly formed particle-number distributions during the first hour.
- Particle size and sulfate mass after one day.
- Optical scattering and absorption per kilogram of sulfur.
- Aerosol surface area relevant to heterogeneous ozone chemistry.
- Stratospheric heating per unit radiative forcing.
- Fraction of sulfur remaining in the target altitude range.
- Predictability of dispersion and reacquisition.
- Aircraft payload and operational complexity per unit of useful radiative effect.

The comparison should not ask simply which method leaves more aerosol aloft. It should report three standardized comparisons: equal sulfur, equal aircraft time, and equal total cost. The final metric is cooling-relevant radiative forcing per kilogram of sulfur and per dollar, adjusted for aerosol lifetime, stratospheric heating, ozone-relevant surface area, sulfur deposition, safety, and controllability.

C1 (SO_2) release design: increase total signal without creating an unrealistic local plume

If plume dilution is the problem, increasing total released mass is a rational response. But total mass and local plume concentration should be treated as separate control variables. A campaign can increase total detectable sulfur by lengthening the flight track, extending release duration, or using repeated sorties instead of injecting the entire mass into a short, highly concentrated segment.

This distinction matters because high local concentrations can increase nucleation and coagulation and thereby change the particle distribution the experiment is trying to study. A good C1 design therefore asks two questions at once: How much total sulfur is needed for reacquisition, and what release rate per unit length best represents the pathway being tested?

C2 aerosol-generation experimental matrix

C2 can exploit controlled variation much more aggressively than C1. A campaign can divide a release into distinct segments and vary:

- Aerosol-generation mechanism: mechanical atomization, exhaust-assisted vaporization, or dedicated vaporization.
- Energy source and measured parasitic energy: compressor, pump, electrical/hydraulic power, engine-exhaust heat, or dedicated heater.
- H_2SO_4 vaporization fraction and unevaporated droplet/residue fraction.
- Near-field dilution rate and plume residence time before mixing with background air.
- Initial particle-size distribution.
- Acid/water concentration at release.
- Mass flow per second.
- Release duration and geometry.
- Altitude.
- Ambient temperature and water vapor.
- Background aerosol loading.
- Continuous versus segmented release.

Each segment should be linked to a pre-registered prediction for particle size, number, sulfur mass, radiative properties, energy use, and cost. That makes C2 a calibration laboratory in the actual stratosphere: the program can determine which combinations of generation architecture, engineering settings, and atmospheric conditions produce stable and efficient particle populations, and whether the optimum in forcing per kg-S is also competitive in forcing per dollar.

C3 down-selection

C3 should use a tournament structure. Many candidates can be studied in the laboratory, fewer should reach chamber testing, and only the best should reach the atmosphere. A candidate should be dropped when it fails a major criterion rather than kept alive simply because money was budgeted for it.

Gate	Minimum evidence before advancing
Laboratory optics	Measured spectral scattering/absorption and realistic particle-size assumptions
Chemistry	Acceptable heterogeneous reaction behavior under stratospheric temperature, pressure, humidity and trace-gas conditions
Toxicology / environment	Characterized toxicity and plausible degradation/deposition products
Engineering	Demonstrated generation and de-agglomeration with a known size distribution
Small field test	Measured plume dispersion, particle integrity, composition, and detectability consistent with predictions
Larger closure test	A credible case that the candidate materially improves a decision-relevant metric relative to sulfate

End-of-program decision

At the end of five years, the program should be able to state, with quantified uncertainty, whether SO_2, mechanically generated H_2SO_4 aerosol, exhaust-vaporized H_2SO_4, a dedicated H_2SO_4 vaporizer, or any C3 candidate remains scientifically and economically credible. It is completely acceptable for one or more pathways to be abandoned. The program succeeds by reducing uncertainty and eliminating bad options, not by proving that SAI must advance.

Stage Gates and Go/No-Go Criteria

Prompt to AI: What program-level stage gates should control the $1 billion SAI Experimental Research Initiative?

Response From AI:

The stage-gate system should answer one question repeatedly: what evidence justifies the next increment of perturbation, cost, and complexity? The gates below consolidate the existing Phase 0 and campaign gate logic into one authoritative program sequence.

Gate	Approx. timing	Required evidence	Decision enabled
G0 - Observability / value of information	Before major field commitment	Decision question, present uncertainty, alternatives to field release, predicted signal, smallest informative perturbation, detection limits, reacquisition probability, environmental consequence, and preregistered predictions.	Lab/model/natural analogue, redesign, field preparation, or stop.
G1 - Source and measurement readiness	Year 1 / before field integration	Controlled source output; material compatibility; calibrated instruments; source accounting; plume forecast; uncertainty budget; safe handling and preliminary airworthiness.	Proceed to integrated source/measurement preparation.
G2 - Architecture down-selection	~Months 12-24	C2A/C2B/C2C ground/exhaust evidence; C1 release design; C3 laboratory screens; cost/energy/safety comparison.	Select surviving architectures. Major C2 atmospheric spending is conditional on this gate.
G3 - Field experiment readiness	Before each major campaign	Final protocol, preregistration, aircraft/payload readiness, source metrology, baseline/rehearsal, independent environmental/safety review, and explicit stop rules.	Experiment becomes eligible for separate outdoor Release Authorization (RA).
G4 - Scientific closure	After each major campaign	Accepted source-to-microphysics-to-optics/radiation evidence, complete uncertainty budget, deviations, negative findings, and open archive.	Repeat, redesign, expand, or stop that pathway.
G5 - Replication / predictive transfer	Years 3-5	Independent replication and/or another regime; models predict held-out observations without post-hoc tuning; side-effect constraints remain acceptable.	Broaden evidence base or terminate/redirect pathway.
G6 - Five-year pathway decision	Month 60	Integrated evidence for physics, observability, reproducibility, side effects, RF/kg-S, RF/aircraft-hour, RF/$, cost, unresolved risks, and remaining uncertainty.	Proceed, redirect, pause, or stop each pathway; no presumption of deployment.

Outdoor Release Authorization (RA). Passing a scientific gate never authorizes an atmospheric release by itself. Before every deliberate outdoor perturbation and every material increase in scale, the separate RA overlay must confirm the applicable aviation, hazardous-material, environmental, legal/transboundary, public-disclosure, emergency-response, and independent-governance conditions. Scientific readiness and permission to release are distinct decisions.

Program stop rule. A pathway should stop or be redesigned when its signal cannot be measured reliably, the source cannot be generated reproducibly, a lower-perturbation method answers the question, adverse evidence dominates its prospective value, or the expected result no longer changes a decision. Unspent funds should move only through the Common Framework change-control process.

SO_2 versus Direct H_2SO_4 Aerosol

Prompt to AI: One SAI option is to inject SO_2 and then let it oxidize into H_2SO_4 aerosol over several weeks. Another option is for an airplane to emit an H_2SO_4 aerosol directly. If one creates an H_2SO_4 aerosol with an airplane, is that the same as what you get from SO_2 that has naturally converted to an H_2SO_4 aerosol over many weeks? If not, how do these differ? What are the advantages and disadvantages of each option?

Response From AI:

No. The mature aerosol can have similar basic chemical composition—sulfuric acid and water—but the aerosol population is not determined by chemistry alone. Particle number, size distribution, spatial concentration, mixing with background aerosol, and the history of nucleation, condensation, and coagulation determine radiative efficiency and chemical surface area. Two sulfate populations with the same total sulfur mass can therefore behave quite differently.

For C1, SO_2 is released as a gas and is dispersed while oxidation proceeds. The pathway is SO_2 -> oxidation -> H_2SO_4 vapor -> nucleation and/or condensation -> particle growth -> coagulation -> mature sulfate aerosol. Because oxidation and transport occur over days to weeks, much of the sulfate can condense on existing particles or form new particles after the original aircraft wake has diluted.

For direct H_2SO_4, there are at least two physically distinct possibilities. One is to create droplets mechanically and inject an H_2SO_4/H_2O aerosol. Another is to carry liquid H_2SO_4, vaporize it near the aircraft, and let the H_2SO_4 vapor nucleate and coagulate in the rapidly expanding wake. Pierce et al. (2010) proposed the vapor route; Weisenstein et al. (2022) then tested the global consequences of injecting a prescribed accumulation-mode H_2SO_4 distribution, while explicitly noting that the first plume-scale seconds are unresolved and uncertain.

Feature	SO_2 -> atmospheric sulfate	Direct engineered H_2SO_4
Initial material	SO_2 gas after release	Preformed droplets or H_2SO_4 vapor generated from liquid acid
Time to sulfate aerosol	Days to weeks for oxidation and growth	Essentially immediate for preformed aerosol; seconds for vapor nucleation and early coagulation
Particle-size control	Indirect; strongly controlled by atmospheric chemistry and background aerosol	Potentially higher, but only if wake microphysics preserves the intended size distribution
Spatial control	SO_2 can travel and dilute before conversion	Aerosol formation begins close to the release path

Near-field coagulation risk	Lower before oxidation because the precursor is gaseous	Potentially high if direct particles or H_2SO_4 vapor are too concentrated in the wake
Natural analogue	Strong volcanic analogue	Much weaker natural analogue; requires engineering validation
Operational complexity	Relatively simple release hardware, but chilled/liquefied handling may be needed	Corrosive liquid handling plus atomizer, vaporizer, exhaust interface, or other generation hardware
Potential radiative efficacy per kg-S	Lower in current multi-model comparisons at the same sulfur injection	Higher in current models if accumulation-mode particles can actually be produced

At 5 Tg-S/year, the Weisenstein et al. (2022) three-model intercomparison found net top-of-atmosphere forcing of about −0.9 to −2.5 W/m² for SO_2 and −1.6 to −3.8 W/m² for prescribed accumulation-mode H_2SO_4. The corresponding radiative-efficacy ranges are approximately 0.18–0.50 and 0.32–0.76 W/m² per Tg-S/year. The models also produced smaller effective particle radii for accumulation-mode H_2SO_4 than for SO_2 at the same sulfur injection.

The important qualification is that these global models prescribe the H_2SO_4 particle population after plume processing. They do not demonstrate that a real aircraft can create it at the required mass flow. This is why C2 should focus heavily on the first milliseconds, seconds, and minutes after release.

If two pathways somehow produced exactly the same particle number, size distribution, composition, altitude, spatial distribution, and mixing state, the atmosphere would have little reason to care how the H_2SO_4 molecules were produced. The practical difference is that SO_2 and direct-acid architectures usually do not arrive at that same aerosol state.

Key references: Pierce et al. (2010), Geophysical Research Letters, DOI 10.1029/2010GL043975; Weisenstein et al. (2022), Atmospheric Chemistry and Physics, DOI 10.5194/acp-22-2955-2022; Yu et al. (2024), Environmental Science & Technology, DOI 10.1021/acs.est.3c08408.

Reference-Aircraft Feedstock, Energy, and Cost Model

Prompt to AI: Using a Boeing 777F as one reference case rather than a fixed program baseline, build a parametric feedstock, energy, payload, and sortie-cost model for SO_2 and direct-H_2SO_4 architectures. What assumptions should vary?

Response From AI:

The 777F should remain an illustrative reference point, not the economic baseline. The working model should expose low/base/high inputs for chemical payload, tank/release-system mass, mission duration, altitude, fuel burn, fuel price, nonfuel aircraft cost, release-system power or heat, maintenance, H_2SO_4 flow rate, and turnaround. Any purpose-built-aircraft case should use the same accounting so pathways can be compared without changing definitions.

The preferred C2 research architecture should not assume that a very large compressor mechanically manufactures the final submicron aerosol. The fund should compare mechanical atomization against a vapor route in which concentrated liquid H_2SO_4 is pumped into a hot exhaust or vaporizer region and then forms particles by nucleation and coagulation in the wake. Franke et al. (2026) finds that pump and power mass are negligible in its purpose-built-aircraft cases, while injection rate and cruise time dominate lofting economics.

A Boeing 777F is useful as a reference-scale mass, energy, and cost model because Boeing lists a 107-tonne gross structural payload. A conventional 777, however, has a maximum operating altitude of about 13.14 km, so it should not be assumed to be a 20-km tropical deployment aircraft. The fund should use the 777 as a scale reference and test platform where scientifically appropriate, while separately extrapolating to purpose-built high-altitude aircraft.

For an illustrative 95-tonne chemical payload—leaving roughly 12 tonnes of the 107-tonne structural payload for tanks and release equipment—95 tonnes of SO_2 contains about 47.5 tonnes of sulfur. Ninety-five tonnes of 98 wt% H_2SO_4 contains about 30.4 tonnes of sulfur. Using the large-scale material-cost assumptions in Franke et al. (2026), approximately \$150/t-S for SO_2 and \$300/t-S for H_2SO_4, the chemical cost is only about \$7,100 for the SO_2 payload and \$9,100 for the H_2SO_4 payload. These are planning values, not vendor quotations.

Architecture	Airborne feedstock	Primary energy source	Research question
C2A mechanical aerosol	Concentrated H_2SO_4 and/or H_2SO_4/H_2O solution	Aircraft electrical/hydraulic power and possibly compressed air	Can atomizers produce sufficiently small droplets at multi-kg/s equivalent flow

			without excessive compressor mass or unevaporated droplets?
C2B exhaust-assisted vaporization	Concentrated liquid H_2SO_4; normally little or no separately carried water	Waste heat in engine exhaust plus small pump/metering power	Can exhaust heat vaporize the acid at useful flow while producing a controlled 200–300 nm-class particle population after wake processing?
C2C dedicated vaporizer	Concentrated liquid H_2SO_4	Dedicated heater/heat exchanger, potentially Jet A or electrical/thermal power	Does independent control of temperature and vaporization justify the added fuel, mass, complexity, and maintenance?

Franke et al. reports a latent heat of vaporization for H_2SO_4 of 67.6 kJ/mol, about 0.69 MJ/kg, and assumes H_2SO_4 can be carried as a liquid near ambient surface temperature. For approximately 95 tonnes of H_2SO_4, latent heat alone is roughly 65 GJ. If otherwise-wasted engine exhaust supplies that heat, incremental fuel for vaporization could be small, although engine integration, pressure loss, heat transfer, corrosion, and maintenance penalties still have to be measured. A dedicated burner would instead consume several tonnes of Jet A in a 95-tonne example once sensible heating and realistic heat-transfer efficiency are included.

For a fuel-cost sensitivity example, this chat used a 5-hour 777 mission burning about 40 tonnes of Jet A. At the U.S. Gulf Coast spot price of $3.506/gal on August 3, 2026 and a standard reporting density of 0.8 kg/L, 40 tonnes corresponds to roughly $46,000 of fuel. Actual 777 mission fuel must be obtained from a certified flight-performance model and should be varied with altitude, payload, route, loiter time, and release rate.

The feedstock should not automatically include enough water to make a finished ~75/25 H_2SO_4/H_2O droplet solution. Carrying water consumes payload, while H_2SO_4 aerosol can take up water from exhaust and ambient air. C2 experiments should therefore vary acid concentration and measure water uptake directly rather than assuming that the aircraft must lift all final aerosol water.

Key reference: Franke et al. (2026), “Trade-Offs between Sulfuric Acid Aerosol Precursors for Stratospheric Aerosol Geoengineering,” Environmental Science & Technology, DOI 10.1021/acs.est.5c15172.

Reflectivity per Dollar and per Kilogram of Sulfur

Prompt to AI: Compare SO_2 and direct-H_2SO_4 pathways using radiative forcing per kilogram of sulfur, per aircraft-hour, and per total dollar. Use the 777F only as an illustrative reference case and keep the cost model parametric enough to substitute other aircraft and operating assumptions.

Response From AI:

The fund should report "reflectivity" primarily as global-mean top-of-atmosphere radiative forcing, because that is the quantity used by the SAI model literature. Two primary figures of merit should be mandatory: radiative forcing per unit sulfur injected and radiative forcing per total lifecycle dollar. The first captures atmospheric/material efficiency; the second captures whether a more sophisticated aerosol is actually worth the extra aircraft time and hardware.

Metric	SO_2	Accumulation-mode H_2SO_4 in 2022 global models	Interpretation
Net forcing at 5 Tg-S/year	−0.9 to −2.5 W/m²	−1.6 to −3.8 W/m²	Model spread is large; direct H_2SO_4 is systematically more efficacious within each model
Radiative efficacy	0.18–0.50 W/m² per Tg-S/year	0.32–0.76 W/m² per Tg-S/year	A midpoint comparison is about 1.6× more forcing per kg-S for idealized AM-H_2SO_4
Effective wet radius at 5 Tg-S/year	0.40–0.52 µm	0.27–0.39 µm	Smaller H_2SO_4-derived particles are closer to efficient scattering sizes in these simulations

A simple 777 payload calculation reveals why the per-kilogram advantage does not automatically become a per-sortie advantage. SO_2 is about 50% sulfur by mass, while 98% H_2SO_4 is about 32% sulfur by payload mass. In the illustrative 95-tonne chemical-load case, SO_2 carries about 47.5 tonnes S and 98% H_2SO_4 about 30.4 tonnes S—a 1.56× sulfur-payload advantage for SO_2. That is close to the ~1.6× midpoint radiative-efficacy advantage of idealized accumulation-mode H_2SO_4, so the two effects can roughly cancel at equal chemical payload.

Illustrative 777F reference case	SO_2	Idealized direct H_2SO_4
Chemical payload	95 t	95 t of 98 wt% H_2SO_4
Sulfur payload	47.5 t-S	30.4 t-S
Approx. material cost using Franke et al. assumptions	$7.1k	$9.1k
Illustrative fuel cost used in this chat	~$46k for a 40-t Jet A mission	~$46k before any dedicated-heater penalty
Illustrative nonfuel aircraft/O&M allowance used in this chat	$45k/sortie planning placeholder	$45k/sortie planning placeholder
Approx. total before detailed release-system O&M	~$100k/sortie	~$104k/sortie
Modeled forcing per kg-S	Lower	Higher if the desired accumulation-mode distribution is actually achieved
Primary unknown	Long-term conversion, size growth, reacquisition	Whether practical generation rate preserves the modeled particle-size advantage

Using those deliberately simplified chat assumptions, $1 billion/year would deliver about 0.475 Tg-S/year as SO_2 or about 0.293 Tg-S/year as H_2SO_4. Combining those sulfur delivery rates with the 2022 model ranges gives approximately 0.086–0.238 W/m² for SO_2 and 0.094–0.222 W/m² for idealized accumulation-mode H_2SO_4. Their midpoints are therefore almost identical. This is an illustrative sensitivity calculation, not a deployment estimate: the 777 altitude, actual flight fuel, release-system O&M, and especially the delivered H_2SO_4 particle distribution are unresolved.

A second benchmark comes from Franke et al. (2026), which uses a purpose-built 20-km aircraft rather than a 777. Their central total costs are about $2,280/t-S for SO_2, $5,150/t-S for H_2SO_4 at a 4.8 kg/s material injection rate, and about $70,300/t-S for H_2SO_4 at 0.1 kg/s. The 0.1 kg/s case is intended to produce roughly 0.1 µm-diameter aerosols in the Yu et al. engine/plume configuration; Franke et al. estimates it is about 14× more expensive per kg-S and about 4× more expensive per watt of forcing than the high-rate H_2SO_4 case. They also note that a larger engine could permit higher useful injection rates.

The conclusion for the research fund is not that one option already wins. It is that forcing per kg-S and forcing per dollar can rank technologies differently. The optimum may be an intermediate H_2SO_4 vaporization rate rather than either the slowest "perfect particle" rate or the maximum throughput rate. The experiment should therefore map H_2SO_4 flow over a wide range—roughly 0.1, 0.25, 0.5, 1, 2, and several kg/s equivalent rates—against plume dilution, particle size, optical properties, aircraft time, energy use, and total cost.

The standardized final comparison should include three scenarios: equal sulfur mass, equal aircraft-hour, and equal dollar. A fourth systems analysis should ask what fleet, sulfur mass, energy, annual cost, ozone-relevant surface area, and stratospheric heating would be required to produce a specified forcing such as $-1\ W/m^2$.

Key references: Weisenstein et al. (2022), DOI 10.5194/acp-22-2955-2022; Yu et al. (2024), DOI 10.1021/acs.est.3c08408; Franke et al. (2026), DOI 10.1021/acs.est.5c15172.

Campaign Development and Execution Phases

Prompt to AI: With the C1/C2/C3 experimental program, what are the phases of each experiment, what happens first, and how much might a representative campaign cost? Include an observability/value-of-information phase before outdoor releases.

Response From AI:

Each major field campaign should be treated as a complete decision cycle rather than merely a release flight. The program should pay for design, modeling, environmental review, engineering, monitoring, analysis, and independent evaluation as parts of one experiment.

Campaign accounting. The $31M C2 and $53M C1 examples below are bottom-up planning models that draw from the approved $1 billion portfolio. Their campaign operating contingency covers foreseeable weather loss, repairs, replacement sorties, and schedule recovery within that campaign ceiling. It is distinct from the $50M central scientific and technical reserve, which remains under Funding Source control for genuinely unplanned program-level needs.

Campaign G0 package: observability and value of information

Phase 0 occurs before expensive engineering or flight commitments. It produces an independent go/redesign/stop recommendation based on detection limits, predicted plume evolution, scientific decision value, alternatives, and environmental consequence. A campaign that cannot show a credible path to a useful measurement should stop at Phase 0.

Phase 0 work package	Deliverable	Typical planning cost
Current-knowledge review	Best estimate, uncertainty range, and decision that depends on the result	$0.2M–$0.5M
Forward plume/chemistry/optics ensemble	Predicted signal versus release mass, geometry, altitude, and time	$0.3M–$0.8M
Instrument detectability analysis	Detection limits, signal-to-background, sampling statistics and reacquisition probability	$0.2M–$0.5M
Alternative-method comparison	Why field work is superior to lab, chamber, natural analogues or existing data	$0.1M–$0.3M
Independent review	Published go/redesign/stop recommendation and release-size range	$0.2M–$0.5M

Engineering/economic decision model	How the experiment changes RF/kg-S, RF/aircraft-hour and RF/$; whether a ground test is sufficient	$0.2M–$0.6M

Representative C2 campaign — competing direct H_2SO_4 architectures

A repeat C2 closure campaign is assumed to use one dedicated release aircraft and up to three monitoring roles, with multiple controlled release segments over approximately two to three weeks of field operations. The release quantity might range from process-scale kilograms to closure-scale tonnes depending on the Phase 0 observability result.

Phase	Central estimate	Principal work
0. Observability / value-of-information	$1.2M	Signal prediction, architecture comparison, mass/geometry selection, detectability, and decision analysis
1. Scientific and engineering design	$1.3M	Hypotheses, generation-method matrix, uncertainty budget, pre-registered particle and cost predictions
2. Ground/plume architecture down-selection	$4.5M	Mechanical atomization, exhaust vaporization, dedicated vaporizer, corrosion, heat transfer, and near-field microphysics
3. Governance/environmental review	$1.2M	Permits, environmental assessment, public disclosure, independent approval
4. Release-system preparation	$4.5M	Corrosion-resistant storage, metering, atomizers/vaporizers, exhaust interfaces, controls, and acceptance tests
5. Instrument preparation	$3.0M	Particle sizing, H_2SO_4 vapor, composition, optics, energy/mass flow, radiometry, lidar, and calibration
6. Aircraft integration / certification	$3.0M	Release and monitoring payload integration, airworthiness, hazardous-material and engine-interface safety
7. Baseline / rehearsal	$1.5M	Background measurement, plume-search rehearsal, timing, communications, and formation practice
8. Release operations	$3.5M	Multiple architectures/flow segments and coordinated above/through/below measurements
9. Hours-to-days follow-up	$1.5M	Revisits for aging, transport, coagulation, persistence, and water equilibration
10. Radiative, microphysical and economic closure	$3.5M	Particle evolution, forcing/kg-S, forcing/$, heating, chemistry, energy use, and uncertainty analysis
11. Independent evaluation / open archive	$1.0M	Quality audit, blinded model comparison, technoeconomic audit, and complete public data package
12. Campaign operating contingency	$1.3M	Weather losses, repairs, replacement sorties and schedule extension

Representative C2 repeat campaign total: approximately $31 million. The first year should also make a shared investment in near-field plume and exhaust testing so that each field campaign does not pay to rediscover basic generation physics. A first-of-a-kind architecture can cost substantially more; once the capability is mature, a new release segment can be much cheaper than starting a new campaign from scratch.

Representative C1 campaign — SO_2 gas

A major C1 campaign is assumed to create a sufficiently detectable sulfur perturbation for repeated sampling over approximately two to six weeks. One illustrative design is a multi-ton total release distributed across flight legs and multiple sorties. The expensive part is not the SO_2 itself; it is repeatedly finding and measuring an evolving three-dimensional plume.

Phase	Central estimate	Principal work
0. Observability / value-of-information	$1.5M	Release mass/geometry, oxidation and dispersion ensemble, detectability and reacquisition probabilities
1. Scientific design	$1.5M	Sampling schedule, tracer plan, chemistry targets, uncertainty budget
2. Laboratory / chamber support	$2.0M	SO_2 oxidation/particle-formation tests, instrument validation and chemistry checks
3. Governance / environmental review	$2.0M	Permits, transboundary planning, environmental assessment and independent approval
4. SO_2 release system	$3.0M	Storage, metering, controls, tracer, safety systems and ground validation
5. Chemical instrument preparation	$5.0M	SO_2, H_2SO_4, nanoparticles, sulfate, ozone/reactive chemistry and aerosol optics
6. Aircraft / balloon / lidar integration	$3.5M	Release platform, sampling aircraft, remote sensing and communications
7. Background / rehearsal	$2.0M	Baseline flights, lidar background, trajectory rehearsal and search practice
8. Release-day experiment	$3.0M	Release and intensive near-field sampling
9. Days 1–7 sampling	$7.0M	Repeated plume-interception sorties, balloons, lidar and twice-daily forecasts
10. Weeks 2–6 sampling	$10.0M	Long-range reacquisition, repositioning, distributed observations and contingency opportunities
11. Plume reconstruction / data assimilation	$3.0M	Three-dimensional sulfur mass balance, source inversion and trajectory evaluation
12. Chemistry / microphysics / radiative analysis	$4.0M	Oxidation, growth, coagulation, optics, ozone and heating assessment

13. Independent evaluation / open archive	$1.0M	Quality audit, blinded forecast challenge and public repository
14. Campaign operating contingency	$4.5M	Weather, missed plume, instrument repair, repositioning and schedule extension

Representative major C1 campaign total: approximately $53 million. Smaller process-focused C1 experiments could be much cheaper. A polar-vortex or other coherent-air-mass campaign with extensive reacquisition may be more expensive, especially if several high-altitude aircraft are required.

Representative C3 candidate-particle pathway

C3 is best budgeted by candidate and gate rather than as a fixed-size flight campaign. Most candidates should be eliminated before they ever reach an aircraft.

Stage	Typical cost per candidate	Purpose
1. Laboratory optical/chemical/toxicology screen	$0.5M–$2M	Determine whether the material deserves further work
2. Chamber and generation engineering	$1M–$4M	Measure aggregation, aging, surface chemistry and achievable size distribution
3. Small atmospheric test	$3M–$8M	Kilogram-scale dispersion, detectability, composition and microphysics
4. Closure-scale follow-on	$8M–$20M	Only for top candidates; radiative/chemical closure at a signal large enough to be useful

The $60 million C3 portfolio is therefore enough to screen many materials in the laboratory but should support only a small number of atmospheric tests. If no candidate beats sulfate on the predefined scorecard, unused C3 funds should be redirected or returned rather than spent to complete a quota.

Shared capability should be built once and reused

Shared capability	Five-year planning investment	Use
High-altitude aerosol/trace-gas/radiation instrument suite	$25M	Reusable C1/C2/C3 payloads, calibration and spares
Modular sulfur-generation and near-field test capability	$15M	SO_2 release plus mechanical H_2SO_4 aerosol, exhaust-assisted H_2SO_4 vaporization, dedicated

		vaporization, controls, corrosion testing, and ground validation
Plume location, imaging and navigation system	$10M	Real-time 3-D plume location and geometry using lidar, optical/polarimetric imaging, UV-visible SO_2 information, trajectory forecasts and in-situ plume hits
Forecasting, trajectory and data-assimilation center	$10M	Observability studies, mission targeting, plume uncertainty envelopes, flight guidance and post-flight reconstruction
Balloon and distributed observation capability	$8M	Profiles and extended spatial coverage
Common mission communications and data system	$4M	Time synchronization, common GPS/INS, telemetry, live aircraft/plume displays and quick-look products
Common calibration/QA reserve	$3M	Cross-campaign calibration and independent checks

These values total the $75 million shared-infrastructure line in the portfolio. Laboratory and governance capabilities are budgeted separately in their own program lines.

Relationship to the Program Stage Gates

Campaign subphases remain conditional on the program-level G0-G6 gates. Within an approved campaign, the project team may sequence ordinary work, but an outdoor release still requires the separate RA overlay. A failed observability, source, readiness, closure, or replication test is a reason to redesign or stop rather than spend the next planned increment automatically.

Purchase Orders

Prompt to AI: For the C1/C2/C3 program, what purchase orders, task orders, grants, or subawards might the Managing Organization issue? Keep the contracting structure practical and tie payments to measurable scientific deliverables.

Response From AI:

The program should not issue hundreds of unrelated purchase orders. It should establish a limited number of master agreements and then issue experiment-specific task orders. Universities and laboratories performing research would often receive subawards or sponsored-research agreements; commercial engineering, aircraft services, instruments, calibration, and consulting are more conventional procurements.

Recommended master agreements

Master agreement	Typical task orders covered	Illustrative five-year ceiling
Aircraft and flight operations	Baseline, rehearsal, release, plume-interception, long-range search and standby sorties	\$140M
Payload integration and airworthiness	Mechanical/electrical integration, inlets, racks, certification, hazardous-material review	\$45M
Release-system engineering	SO_2 systems; mechanical H_2SO_4 aerosol; exhaust-assisted and dedicated H_2SO_4 vaporization; controls; near-field plume rigs; C3 dispersal prototypes	\$45M
Atmospheric instrumentation and calibration	Gas, aerosol, optics, radiation, lidar, spares, calibration and field operation	\$80M
Modeling, observability and mission forecasting	Phase 0 studies, plume forecasts, data assimilation, inversion and model challenges	\$75M
Balloon, lidar and distributed observing	Balloon launches, mobile lidar, remote sites and rapid-response deployments	\$35M
Scientific analysis consortium	University/laboratory subawards for chemistry, microphysics, radiation and downstream effects	\$105M
Governance, environmental review and independent evaluation	Environmental assessment, engagement, audit, safety review and open-data oversight	\$70M

The ceilings above overlap the portfolio categories and should not be summed as a second budget. They illustrate how money can be packaged contractually while remaining tied to the approved annual operating plan.

Common Phase 0 and cross-program orders

Code	Procurement package	Deliverable	Illustrative amount
G0-01	Observability ensemble	Release-mass/geometry versus signal and reacquisition probability for each proposed field campaign	\$0.3M–\$0.8M/campaign
G0-02	Independent value-of-information review	Written decision analysis and go/redesign/stop recommendation	\$0.2M–\$0.5M/campaign
G0-03	Instrument detectability audit	Detection limits, background variability, uncertainty budget and required sampling density	\$0.2M–\$0.5M/campaign
G0-04	Environmental consequence model	Expected transport, exposure, deposition and cumulative-release assessment	\$0.2M–\$0.6M/campaign
G0-05	Open data and reproducibility service	Repository, metadata schema, code archive, DOIs and release-deadline monitoring	\$2M–\$4M/year

C2 — direct H_2SO_4 delivery-architecture task orders

Code	Package	Required deliverable	Illustrative amount
C2-01	Science-design subaward	Architecture matrix, hypotheses, closure metrics, equal-S/equal-time/equal-cost comparisons, and pre-registered predictions	\$1.2M
C2-02A	Mechanical aerosol-generator task order	Acid-compatible atomizer/compressor system; measured droplet distribution, flow, power, and unevaporated fraction	\$3.0M
C2-02B	Exhaust-vaporization task order	Metered H_2SO_4 injection into representative hot exhaust; vaporization fraction, corrosion, heat-transfer and engine-interface report	\$4.0M
C2-02C	Dedicated-vaporizer task order	Independent heater/heat-exchanger architecture; energy, mass, temperature-control and aerosol-generation performance	\$3.0M
C2-03	Near-field plume facility	Milliseconds-to-minutes measurements of nucleation, coagulation, dilution and particle-size evolution across flow rates	\$4.0M

Code	Package	Required deliverable	Illustrative amount
C2-04	777/reference-scale mass-energy-cost model	Open model of payload, tank/system mass, sulfur density, fuel, aircraft time, feedstock, maintenance and forcing/$	$1.0M
C2-05	Aerosol microphysics instrument package	Nanometre-to-micrometre size, number, H_2SO_4 vapor, composition and inlet-loss characterization	$1.4M
C2-06	Optics/radiation package	Scattering, absorption, extinction, lidar, polarimetry and above/below flux measurements	$1.6M
C2-07	Release-aircraft mission order	Approved release sorties with certified material mass, flow, energy, time and location records	$1.3M
C2-08	In-plume sampling-aircraft order	Immediate and repeated plume crossings with synchronized chemistry/microphysics and plume-age data	$1.2M
C2-09	Above/below closure aircraft orders	Radiative legs and mapped plume geometry	$1.5M
C2-10	Plume-location, forecasting and real-time guidance	Fused trajectory, lidar/imaging and in-situ information; live plume map, uncertainty envelope, quick-look data and updated aircraft targeting	$0.5M
C2-11	Hours-to-days follow-up option	Additional sorties, lidar or balloons when plume aging remains measurable	$1.2M
C2-12	Radiative/microphysical/economic closure	Measured-versus-predicted forcing/kg-S, forcing/$, particle evolution, heating, chemistry and lifecycle cost	$2.5M
C2-13	Independent data/model challenge	Withheld-observation predictions, calibration/QA audit, cost-model audit and final public report	$0.8M

These line items show the major scientific procurements; campaign logistics, governance, integration, field personnel, and contingency are funded through the associated master agreements and annual plan. The key acceptance test is not that a flight occurred. It is that the specified measurement was delivered with the required uncertainty and documentation.

C1 — SO_2 pathway campaign task orders

Code	Package	Required deliverable	Illustrative amount
C1-01	Integrated science and observability design	Release mass/geometry, chemistry targets, sampling calendar and detectability envelope	$1.5M

Code	Package	Required deliverable	Illustrative amount
C1-02	SO_2 release-system task order	Storage, metering, tracer, controls, leak detection, safety and ground validation	$3.0M
C1-03	SO_2/H_2SO_4 gas measurement package	Fast-response calibrated gas measurements with spares and field support	$1.3M
C1-04	Nanoparticle/sulfate package	New-particle formation, size growth, composition and sulfur mass measurements	$1.6M
C1-05	Ozone/reactive chemistry and optics package	Ozone-relevant gases, aerosol surface area, scattering/absorption and heating diagnostics	$1.4M
C1-06	Release-day aircraft block	Release aircraft plus immediate chase sampling and remote sensing	$2.5M
C1-07	Days 1–7 sampling block	Approximately four to eight primary plume-interception sorties plus search support	$5M–$7M
C1-08	Weeks 2–6 high-altitude follow-up	Periodic direct sampling, long-range search and repositioning	$7M–$10M
C1-09	Distributed balloons/lidar	Profiles and aerosol-layer searches along predicted transport corridors	$1M–$2M
C1-10	Plume-location/forecast/data-assimilation center	Twice-daily and on-demand 3-D plume estimate, uncertainty envelope, lidar/imaging assimilation and aircraft flight recommendations	$1.5M–$2.5M
C1-11	Sulfur mass-balance reconstruction	3-D SO_2, gaseous products and sulfate mass through time	$0.8M
C1-12	Chemistry/microphysics/radiative closure	Oxidation, nucleation, condensation, coagulation, optics and ozone assessment	$2M–$3M
C1-13	Independent trajectory/model challenge	Firewalled predictions and comparison against withheld observations	$0.6M
C1-14	Open archive/final technical report	Calibrated dataset, code, uncertainty package, negative results and synthesis	$0.4M

C3 — alternative-particle procurement packages

Code	Package	Required deliverable	Illustrative amount
C3-01	Candidate optical characterization	Spectral refractive index, scattering/absorption and particle-size sensitivity	$0.3M–$0.8M/candidate
C3-02	Stratospheric chemistry screen	Surface reactions, aging and ozone-relevant chemistry under controlled conditions	$0.5M–$1.5M/candidate

Code	Package	Required deliverable	Illustrative amount
C3-03	Toxicology/environmental screen	Hazard, degradation products, deposition and exposure assessment	$0.3M–$1.0M/candidate
C3-04	Particle-generation engineering	Generate and de-agglomerate a known size distribution; publish test data	$0.5M–$2M/candidate
C3-05	Small field-test package	Kilogram-scale controlled release with composition confirmation, plume mapping and microphysics	$3M–$8M/test
C3-06	Optional closure-scale follow-on	Only after board approval; optics, chemistry and radiative closure at a decision-useful signal	$8M–$20M/test

Other portfolio-level purchase orders and subawards

Portfolio activity	Example contracting package	Five-year program budget
Laboratory/chamber research	Multi-institution cooperative awards for ozone kinetics, aerosol aging, microphysics and toxicology	$70M
Natural-analogue rapid response	Standing aircraft/balloon/instrument options activated by qualifying volcanic or wildfire events	$60M
Targeted baseline/detection	Measurement campaigns only where model interpretation is limited; detection tests for meaningful perturbations	$25M
Downstream effects	Deposition modeling/measurement, cirrus interaction, ecological and solar-resource studies	$25M
Central scientific and technical reserve	Funding-Source-controlled reserve for unexpected high-value follow-up, major redesign, independent replication, failed major capability replacement, or qualifying rapid-response opportunities; ordinary campaign recovery options are budgeted inside campaign ceilings.	$50M

Contract acceptance and payment rules

- Every major task order must state the uncertainty being reduced and the decision the result will inform.
- The final payment should depend on accepted data, calibration, metadata, source files, and documentation—not merely completion of field operations.
- Release quantity, material, major subcontractors, data rights, or acceptance criteria may not be changed by informal email; a formal change order is required.

- Negative or inconclusive results are deliverables and must be published.
- Fixed-price milestones are appropriate for defined engineering work; uncertain aircraft/research operations may require cost-reimbursement or time-and-materials structures with ceilings.
- Replacement-flight options should be pre-priced but exercised only when the scientific value remains high.
- The organization that performs the experiment should not be the sole organization auditing its calibration, environmental compliance, or model performance.

Recipients of Purchase Orders

Prompt to AI: For the C1/C2/C3 purchase orders and subawards, who might receive them? Identify plausible organizations by function, while preserving independent review and avoiding concentration of authority.

Response From AI:

The program should use a consortium model. No single institution has all of the required capabilities in high-altitude aircraft, stratospheric chemistry, aerosol microphysics, plume modeling, environmental review, data systems, and independent evaluation. The organizations listed below are plausible candidates based on the capabilities identified in the prior program analysis; actual participation would require competition, willingness, legal authority, and conflict review.

Program-wide functional leads

Function	Plausible lead or recipient	Possible partners
Managing Organization / fiduciary prime	RTI International; UCAR or Battelle as alternatives	Independent Agreement Oversight Board
Atmospheric-science integrator	UCAR/NSF NCAR	NOAA CSL/CIRES, Cornell, universities, international partners
Stratospheric measurements and chemistry	NOAA Chemical Sciences Laboratory / CIRES	Harvard, NASA instrument teams, university laboratories
High-altitude aircraft operations	NASA JSC WB-57 Program; NASA Armstrong ER-2 Program	NSF NCAR Gulfstream V or other research aircraft where altitude permits
Field-campaign logistics	NASA Earth Science Project Office or UCAR Earth Observing Laboratory	Aircraft operators, local logistics providers
Release-system engineering	Southwest Research Institute, Creare, or Battelle	Specialist valves, pumps, nozzle, gas and materials suppliers
Modeling and mission forecasting	NSF NCAR/UCAR and NOAA CSL	Cornell, NASA Ames, independent university teams
Environmental review	AECOM, Ramboll, or RTI unit independent of technical release leadership	Aviation/environmental law counsel
Public and jurisdictional engagement	Consensus Building Institute or Keystone Policy Center	Regional and international partners
Independent scientific review	National Academies or a separately appointed international panel	External aerosol, ozone, climate, ecology and aviation experts

C1 — SO_2 pathway recipients

C1 package	Likely recipient type / example	Key reason
C1-01 science/observability design	CIRES/CU Boulder + NOAA CSL; Cornell/NCAR as independent model partners	Combines stratospheric measurement, chemistry and plume modeling
C1-02 SO_2 release system	SwRI or Creare; industrial gas suppliers such as Airgas/Linde for certified gases	Aircraft systems engineering plus qualified gas handling
C1-03 SO_2/H_2SO_4 instruments	NOAA CSL instrument teams and atmospheric-chemistry collaborators	Direct relevance to sulfur conversion measurements
C1-04 nanoparticle/sulfate package	NOAA CSL, NASA/academic aerosol teams; commercial aerosol instrument OEMs	Nanometre-to-micrometre sizing and composition
C1-05 ozone/optics	NOAA CSL, NASA Langley, Harvard atmospheric chemistry	Reactive chemistry, aerosol optics and radiation
C1-06 through C1-08 aircraft	NASA WB-57/ER-2; NCAR GV for complementary long-range work where altitude allows	High-altitude in-situ sampling, overflight and search
C1-09 balloons/lidar	NOAA balloon teams, Aerostar, NASA/NOAA/university lidar groups	Distributed plume profiles and tracking
C1-10 forecast/assimilation center	NOAA CSL + NCAR	Operational trajectories, chemistry and data assimilation
C1-11/C1-12 analysis	NOAA CSL, NCAR, Cornell, Harvard, NASA Langley and selected international groups	Independent expertise across mass balance, microphysics, chemistry and radiation
C1-13 independent model challenge	A firewalled Cornell/NCAR/NASA team separate from the primary prediction team	Prevents the operating team from grading its own forecast

C2 — direct H_2SO_4 architecture recipients

C2 package	Likely recipient type / example	Key reason
C2-01 science design	CIRES/CU Boulder, NOAA CSL, Cornell, UChicago and aerosol specialists	Links particle-delivery settings and engineering alternatives to measurable closure questions
C2-02A mechanical aerosol	SwRI, Creare, Battelle or other aerosol-generation engineering groups; acid-compatible component suppliers	Atomization, compressor/pump design, corrosion-resistant storage and metering
C2-02B exhaust vaporization	SwRI/Creare/Battelle with a qualified engine OEM or propulsion research partner where required	Heat transfer, engine/exhaust integration, vaporization, materials and airworthiness

C2 package	Likely recipient type / example	Key reason
C2-02C dedicated vaporizer	Thermal-systems engineering firms, SwRI/Creare/Battelle, specialist heat-exchanger suppliers	Independent temperature and vaporization control with measured mass and energy penalty
C2-03 near-field plume	SUNY Albany/Yu collaborators, Harvard/Keutsch, UChicago, NOAA and plume/CFD laboratories	Nucleation and coagulation in the first milliseconds to minutes
C2-04 scale/economic model	UChicago climate-systems engineering, Cornell, independent aircraft-cost analysts	Translates measured particle performance into payload, aircraft-hour, fleet and forcing/$ metrics
C2-05/C2-06 instruments	NOAA aerosol teams, NASA Langley, commercial aerosol instrument OEMs and academic groups	Fast particle sizing, vapor/composition, optics and radiative closure
C2-07 release aircraft	Certified operator selected for the approved release system	Dedicated emitter kept separate from measurement aircraft
C2-08/C2-09 monitoring aircraft	NASA WB-57/ER-2 and other qualified research aircraft	In-plume sampling and above/below radiometry
C2-10 forecasting	NOAA CSL and NCAR	Real-time plume targeting and post-flight reconstruction
C2-12 closure analysis	NOAA CSL, NASA Langley, NCAR, Cornell/UChicago and independent universities	Compare measured particles/optics/flux/cost to preregistered predictions
C2-13 independent evaluation	RTI or independent metrology/statistics/economics team plus a separate modeling group	Data quality, blind prediction testing and independent cost audit

C3 — alternative-particle recipients

C3 activity	Plausible recipients	Selection rule
Optical characterization	University/national-lab aerosol optics groups; NIST-traceable laboratories where appropriate	Capability to measure spectral optical properties of realistic particle distributions
Stratospheric chemistry	Harvard, NOAA CSL, other atmospheric-chemistry laboratories and international ozone experts	Demonstrated heterogeneous-chemistry capability
Toxicology/environment	Independent toxicology laboratories, environmental-health researchers and risk-assessment contractors	Must be organizationally separate from teams advocating the candidate
Particle-generation engineering	SwRI, Creare, Battelle or other qualified aerosol-generation engineering groups	Demonstrate controlled size and de-agglomeration before flight

C3 activity	Plausible recipients	Selection rule
Small field tests	Selected release-system contractor + NASA/NOAA/NCAR measurement stack as appropriate	Only candidates passing lab gates reach atmosphere
Closure follow-on	Same measurement stack plus independent external review	Requires evidence of material advantage and explicit board approval

Natural-analogue and shared-infrastructure recipients

Activity	Plausible recipients
Volcanic/wildfire rapid response	NOAA CSL, NASA airborne science, NCAR/UCAR, university and international volcanic-aerosol groups
Shared high-altitude instrument suite	NOAA/NASA instrument teams plus commercial OEMs and university laboratories
Mobile/airborne lidar	NASA Langley, NOAA/university lidar groups, qualified commercial lidar integrators
Balloon observations	NOAA stratospheric balloon teams, Aerostar and international meteorological partners
Open data and campaign archive	UCAR EOL, NOAA or NASA data systems; independent reproducibility support
Downstream/ecological studies	Rutgers, atmospheric/environmental universities, agriculture/ecology groups and selected Global South partners

Independence and conflict rules

The most important procurement rule is separation of roles. The organization designing or operating a release should not control the environmental approval, data-quality audit, public-engagement record, or final determination that a larger experiment should proceed.

- At least two qualified bidders should normally be sought for commercial engineering work.
- A scientific panel member must recuse from an award benefiting that member's institution or close collaborators.
- Major model predictions should be challenged by at least one separate team that does not see withheld observations.
- Environmental and toxicology contractors should report to independent oversight, not to the candidate-material developer.

- Aircraft operators retain flight-safety and airworthiness authority regardless of program schedule pressure.
- The Managing Organization should retain final payment until required open data, calibration, code, and documentation are accepted.

Project Management

Prompt to AI: What project-management provisions are specific to the SAI Experimental Research Initiative after incorporating the Climate Moonshot Portfolio Common Framework?

Response From AI:

Portfolio-wide Managing Organization selection, fiduciary controls, procurement, financial controls, reserve governance, independent review, audit, conflicts, open-source/data rights, management oversight, and transition rules are specified in the Moonshot Common Framework. This chapter states additional technical-management structure required by the SAI experimental program.

Initiative-specific management requirements

- The Managing Organization must be able to coordinate high-altitude atmospheric research, aircraft and balloon operations, hazardous SO_2/H_2SO_4 handling, environmental review, international participation, and rapid open-data publication across universities, government laboratories, research aircraft operators, and specialized vendors.
- Maintain controlled C1, C2, and C3 experimental baselines. Each major campaign must identify the decision question, observability/value-of-information analysis, release mass and geometry, preregistered predictions, measurement uncertainty, plume-reacquisition plan, environmental consequences, and explicit stop/advance criteria.
- No Project Manager or principal investigator may authorize a significant outdoor release alone. Applicable scientific, safety/environmental, regulatory, and independent governance approvals must be satisfied before release authorization.
- Separate release operations from independent measurement and final evaluation where practical. Flagship closure campaigns should preserve source records, calibration, chain of custody, model forecasts, held-out or blinded comparisons, failures, and a complete reproducibility archive.
- Program continuation among SO_2, mechanical H_2SO_4 aerosol, exhaust-assisted H_2SO_4 vaporization, dedicated-vaporizer H_2SO_4, and C3 candidates should follow measured information value, forcing per kilogram of sulfur, forcing per dollar, side effects, observability, safety, and reproducibility rather than an obligation to spend equally across pathways.

Funding Source Requirements

We assume the Funding Source aims to maximize climate benefit per dollar spent, as opposed to maximize financial return on an investment. This is sometimes referred to as "climate money", and it differs from the traditional investment portfolio. Sources of climate money include high-net-worth individuals, foundations, and governments.

The portfolio-wide Funding Source requirements are specified in the Moonshot Common Framework. The additions below address controlled atmospheric perturbations, observability, preregistration, environmental review, international/transboundary issues, and the need to compare SAI pathways using common scientific and economic metrics.

Program-specific additions

- Require an observability and value-of-information gate before every major outdoor release. The experiment must state why existing observations, laboratory or chamber work, modeling, or a natural analogue cannot answer the question more cheaply or with less perturbation.
- Use the minimum atmospheric perturbation that is large enough to produce the measurement needed for the stated decision. No experiment may be designed to produce detectable regional or global climatic cooling.
- For C3 materials, require material-specific laboratory optics, ozone-relevant chemistry, aggregation, persistence, toxicology, and environmental review before outdoor testing, followed by staged field gates.
- Require preregistered predictions, instrument detection limits, calibration and uncertainty budgets, release/source records, plume-reacquisition probability, independent replication or challenge where practical, and prompt release of data, code, calibration records, negative results, and deviations.
- For significant releases, require the applicable aviation, environmental, legal, international, transboundary, public-engagement, emergency-response, and incident-reporting processes in addition to the common safety and stop-work rules.

Climate-benefit metric

Do not measure success by flights completed, sulfur released, papers published, or dollars spent. Report decision-relevant uncertainty reduction and the ability to distinguish or eliminate pathways, including radiative forcing per kilogram of sulfur, per aircraft-hour, and per total dollar; aerosol lifetime and size; stratospheric heating; ozone-relevant chemistry; deposition and other side effects; observability; reproducibility; and the cost and evidence required for any later research decision.

Top SAI Science Papers

Prompt to AI: Summarize the top SAI papers, including recent work most relevant to the revised C1/C2/C3 program.

Response From AI:

"Top" is necessarily subjective. I ranked these roughly by historical influence, scientific importance, and usefulness for designing an SAI research program, rather than by citation count alone. The list emphasizes sulfur-based SAI, including SO_2 and H_2SO_4 injection, climate effects, ozone, field experiments, costs, and termination risk.

Foundations and early risk identification

Crutzen, 2006 — "Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma?"

The modern starting point for SAI research. Crutzen argued that persistent failure to reduce greenhouse-gas emissions justified serious study of stratospheric sulfur injection as a temporary emergency measure. The paper emphasized that SAI would not solve the underlying CO_2 problem and could damage ozone, but it made the subject scientifically discussable again.

https://doi.org/10.1007/s10584-006-9101-y

Rasch, 2008 — "An Overview of Geoengineering of Climate Using Stratospheric Sulphate Aerosols"

This early comprehensive review explains volcanic analogues, sulfate chemistry, particle microphysics, radiative forcing, climatic effects, and possible delivery systems. It concludes that sulfate could offset much global-mean warming, but not reproduce the original climate region by region. It remains an excellent introduction to the entire physical chain.

https://doi.org/10.1098/rsta.2008.0131

Robock, 2008 — "Regional Climate Responses to Geoengineering with Tropical and Arctic SO_2 Injections"

One of the first influential global-model studies of explicit SO_2 injection. It found that both tropical and Arctic injections produced global effects and could weaken Asian and African summer monsoons. The paper helped shift attention from "Can SAI cool Earth?" to "Where would the residual climate damages occur?"

https://doi.org/10.1029/2008JD010050

Tilmes, 2008 — "The Sensitivity of Polar Ozone Depletion to Proposed Geoengineering Schemes"

This paper showed that sulfate aerosol provides surfaces on which ozone-destroying chemistry can occur. It projected increased Arctic ozone loss during cold winters and delayed recovery of the Antarctic ozone hole under large sulfate interventions. It established ozone as a primary constraint on sulfur-based SAI.

https://doi.org/10.1126/science.1153966

Robock, 2009 — "Benefits, Risks, and Costs of Stratospheric Geoengineering"

A concise synthesis of potential benefits and adverse effects. The paper covers cooling, sea ice, glaciers, precipitation, ozone, diffuse light, astronomy, solar electricity, ocean acidification, termination, and governance. Although some quantitative assumptions are now dated, its checklist of risks remains influential.

https://doi.org/10.1029/2009GL039209

Aerosol formation, chemistry, and efficiency

Heckendorn, 2009 — "The Impact of Geoengineering Aerosols on Stratospheric Temperature and Ozone"

This study integrated sulfate aerosol microphysics with atmospheric chemistry and radiation. It showed that particle growth, stratospheric heating, and ozone response are coupled, so one cannot estimate SAI effects from injected sulfur mass alone. Particle size and aerosol surface area are critical state variables.

https://doi.org/10.1088/1748-9326/4/4/045108

Pierce, 2010 — "Efficient Formation of Stratospheric Aerosol for Climate Engineering by Emission of Condensible Vapor from Aircraft"

Especially relevant to the proposed H_2SO_4 experiments. The authors modeled releasing H_2SO_4 vapor from an aircraft so that nucleation and coagulation in the expanding plume create accumulation-mode particles. They concluded this could provide better particle-size control and greater radiative efficiency than releasing SO_2, although the near-field plume assumptions require experimental validation.

https://doi.org/10.1029/2010GL043975

Kravitz, 2011 — "The Geoengineering Model Intercomparison Project (GeoMIP)"

GeoMIP established standardized experiments that different climate-model groups could run and compare. Before GeoMIP, differences between studies often reflected both differing models and differing scenarios. The framework made it possible to identify results that were robust across models and those that were not.

https://doi.org/10.1002/asl.316

English, 2012 — "Microphysical Simulations of Sulfur Burdens from Stratospheric Sulfur Geoengineering"

This paper compared SO_2 gas, gaseous H_2SO_4, and particle injection in a three-dimensional model with sectional aerosol microphysics. It showed that increasing sulfur injection can produce disproportionately larger particles, which scatter less efficiently per unit mass and fall faster. Injection material, particle size, altitude, and spatial distribution all strongly influence performance.

https://doi.org/10.5194/acp-12-4775-2012

Schmidt, 2012 — "Solar Irradiance Reduction to Counteract Radiative Forcing from a Quadrupling of CO_2"

The first major analysis of GeoMIP's idealized G1 experiment. Reducing solar irradiance could largely restore global-mean temperature after quadrupling CO_2, but it could not restore all regional temperature and precipitation patterns. The paper clearly demonstrates why equal and opposite global radiative forcings do not create an unchanged climate.

https://doi.org/10.5194/esd-3-63-2012

Hydrology, termination, and field experiments

Tilmes, 2013 — "The Hydrological Impact of Geoengineering in the Geoengineering Model Intercomparison Project"

Using 12 Earth-system models, this paper found that solar reduction generally suppresses the global hydrological cycle relative to a climate with the same global temperature but lower CO_2. Precipitation and evaporation therefore cannot be simultaneously restored by selecting a global cooling target. It is a central paper on SAI's precipitation tradeoffs.

https://doi.org/10.1002/jgrd.50868

Jones, 2013 — "The Impact of Abrupt Suspension of Solar Radiation Management—Termination Effect—in GeoMIP Experiment G2"

Eleven models simulated stopping solar geoengineering after decades of offsetting increasing CO_2. All produced rapid global warming, increased precipitation, and declining sea ice after termination. This paper established the physical basis of "termination shock" and the importance of preventing abrupt interruption.

https://doi.org/10.1002/jgrd.50762

Dykema, 2014 — "Stratospheric Controlled Perturbation Experiment: A Small-Scale Experiment to Improve Understanding of the Risks of Solar Geoengineering"

This is the most important conceptual paper on an actual small stratospheric perturbation experiment. It outlines a balloon platform, plume creation, in-situ sampling, aerosol and ozone chemistry, instrumentation, and external oversight. Its central argument is that laboratory work and global models cannot completely replace small, controlled atmospheric measurements.

https://doi.org/10.1098/rsta.2014.0059

Niemeier, 2015 — "What Is the Limit of Climate Engineering by Stratospheric Injection of SO_2?"

The authors modeled injection rates up to 100 teragrams of sulfur per year. Radiative forcing increased much less than proportionally because higher aerosol loading produced larger particles, faster sedimentation, and altered circulation. This established that SO_2 injection has strong diminishing returns and cannot be scaled linearly.

https://doi.org/10.5194/acp-15-9129-2015

Keith, 2016 — "Stratospheric Solar Geoengineering Without Ozone Loss"

This paper proposed alkaline solid particles, particularly calcite, that might neutralize acidic chlorine and nitrogen compounds and potentially reduce ozone loss. It broadened SAI research beyond sulfate, but the favorable result depends on uncertain particle-surface chemistry, aggregation, aging, toxicity, and manufacturability. It should be read as a research hypothesis, not proof that calcite is safe.

https://doi.org/10.1073/pnas.1615572113

Injection design and climate control

Visioni, 2017 — "Sulfate Geoengineering: A Review of the Factors Controlling the Needed Injection of Sulfur Dioxide"

A valuable technical review of how injection rate, altitude, latitude, season, transport, microphysics, particle size, and stratospheric heating determine the quantity of SO_2 required. It explains why estimates from different models vary substantially. For planning a research program, it provides a good map of the largest physical uncertainties.

https://doi.org/10.5194/acp-17-3879-2017

MacMartin, 2017 — "The Climate Response to Stratospheric Aerosol Geoengineering Can Be Tailored Using Multiple Injection Locations"

The authors showed that injecting at several latitudes provides more control than injecting only at the equator. Different injection locations influence global mean temperature, interhemispheric temperature balance, and the equator-to-pole temperature gradient differently. This paper introduced the idea of SAI as a multivariable control problem rather than a single global thermostat.

https://doi.org/10.1002/2017JD026868

Kravitz, 2017 — "First Simulations of Designing Stratospheric Sulfate Aerosol Geoengineering to Meet Multiple Simultaneous Climate Objectives"

This study used feedback control to adjust injections at four latitudes while pursuing three temperature objectives. It demonstrated that a climate model could approximately maintain global mean temperature and two broad temperature gradients despite rising greenhouse gases.

It also showed that meeting temperature objectives does not automatically eliminate precipitation, ozone, circulation, or regional impacts.

https://doi.org/10.1002/2017JD026874

Mills, 2017 — "Radiative and Chemical Response to Interactive Stratospheric Sulfate Aerosols in Fully Coupled CESM1(WACCM)"

This paper describes and evaluates a model that interactively calculates sulfate formation, particle evolution, radiation, atmospheric dynamics, and chemistry. Validation against volcanic aerosol observations made it an important foundation for subsequent SAI simulations. It helped replace prescribed aerosol layers with more physically complete sulfur-injection modeling.

https://doi.org/10.1002/2017JD027006

Tilmes, 2018 — "CESM1(WACCM) Stratospheric Aerosol Geoengineering Large Ensemble Project"

The GLENS project produced a large ensemble of century-scale simulations using four injection locations and feedback control. Multiple realizations allow researchers to distinguish forced SAI responses from ordinary climate variability. GLENS became one of the principal datasets for studying regional climate, extremes, circulation, agriculture, water, and ecosystems under SAI.

https://doi.org/10.1175/BAMS-D-17-0267.1

Deployment, societal impacts, and newer model comparisons

Smith, 2018 — "Stratospheric Aerosol Injection Tactics and Costs in the First 15 Years of Deployment"

This engineering-economic study examined aircraft requirements, payload, altitude, fleet size, flights, and operating costs. It estimated average direct deployment costs of roughly $2.25 billion per year over an illustrative first 15 years, while requiring thousands and eventually tens of thousands of annual flights. Its key message is that SAI might be financially inexpensive relative to climate damages but operationally large and difficult to conceal.

https://doi.org/10.1088/1748-9326/aae98d

Proctor, 2018 — "Estimating Global Agricultural Effects of Geoengineering Using Volcanic Eruptions"

Using volcanic eruptions as natural experiments, the paper estimated how cooling and altered sunlight affect major crops. The modeled benefits of lower temperature were approximately offset by yield losses associated with reduced direct sunlight. Volcanic eruptions are imperfect analogues for sustained SAI, but this paper demonstrates why diffuse and direct radiation must be included in impact studies.

https://doi.org/10.1038/s41586-018-0417-3

Vattioni, 2019 — "Exploring Accumulation-Mode H_2SO_4 Versus SO_2 Stratospheric Sulfate Geoengineering"

This directly compares the two pathways discussed in your proposed experiments. Spatially distributed injection of accumulation-mode H_2SO_4 generally produced greater radiative forcing per unit sulfur than SO_2, but concentrated point or pulse injections caused enhanced coagulation and could lose much of that advantage. The paper shows that release geometry is almost as important as injected chemical form.

https://doi.org/10.5194/acp-19-4877-2019

Visioni, 2021 — "Identifying the Sources of Uncertainty in Climate Model Simulations … with the G6sulfur and G6solar GeoMIP Simulations"

This study separates uncertainty caused by the underlying climate models from uncertainty caused by how models represent sulfate aerosol and its transport. Models broadly agree that SAI could reduce temperature increases, but disagree more on aerosol distribution, required sulfur, stratospheric effects, and precipitation. It cautions against presenting one model's injection requirement as a reliable engineering specification.

https://doi.org/10.5194/acp-21-10039-2021

Weisenstein, 2022 — "An Interactive Stratospheric Aerosol Model Intercomparison … by Injection of SO_2 or Accumulation-Mode Sulfuric Acid Aerosols"

Three interactive aerosol models ran coordinated SO_2 and accumulation-mode H_2SO_4 scenarios. All found greater radiative efficacy for direct accumulation-mode aerosol, but they differed in particle distributions, transport, and quantitative performance. Crucially, the study acknowledges that it prescribes the particles after near-field plume processing rather than modeling the first seconds and minutes—precisely the uncertainty that controlled C2 field experiments could address.

https://doi.org/10.5194/acp-22-2955-2022

Yu, 2024 — "On Nucleation Pathways and Particle Size Distribution Evolutions in Stratospheric Aircraft Exhaust Plumes with H_2SO_4 Enhancement"

This study models the first moments of H_2SO_4-enhanced aircraft exhaust. Under modeled conditions that produce desirable roughly 200–300 nm diameter particles, nucleation occurs in the nascent hot, dry plume and subsequent coagulation governs evolution toward a relatively narrow size distribution. It gives the revised C2 program a concrete near-field mechanism and makes flow rate, exhaust conditions, dilution and plume age explicit experimental variables.

https://doi.org/10.1021/acs.est.3c08408

Franke, 2026 — "Trade-Offs between Sulfuric Acid Aerosol Precursors for Stratospheric Aerosol Geoengineering"

This engineering-economic study compares sulfur precursors, liquid handling, vaporization, safety, injection rate, material cost and aircraft lofting cost for a purpose-built 20-km aircraft. For H_2SO_4 it analyzes both a high 4.8 kg/s material rate and a 0.1 kg/s case intended to produce smaller particles, finding a strong particle-size-versus-aircraft-cost tradeoff and noting that larger engines could shift the optimum. It directly motivates C2A/C2B/C2C down-selection and mandatory forcing-per-dollar metrics.

https://doi.org/10.1021/acs.est.5c15172

Recommended Reading

The twelve papers I would have experiment-design teams read first are: *Pierce 2010; English 2012; Dykema 2014; Niemeier and Timmreck 2015; Visioni 2017; Mills 2017; Smith and Wagner 2018; Vattioni 2019; Visioni 2021; Weisenstein 2022; Yu 2024; and Franke 2026.*

Taken together, they define important experimental questions: can a real aircraft-generation system produce a known and reproducible sulfate particle-size distribution at economically useful mass flow, and can models predict its evolution from the first milliseconds through global dispersion?

Top Researchers

Prompt to AI: Who are the top researchers in this field? What are the top organizations working in this field?

Response From AI:

There is no authoritative ranking. This chapter is a landscape of researchers and organizations whose work may be useful to the initiative; it is not an appointment list for the Scientific Advisory Panel and does not imply preferred funding recipients. The assessment below emphasizes influence on SAI science, current activity, leadership of major datasets or programs, and relevance to the field experiments under consideration.

Leading SAI researchers

Central technical leaders

Researcher	Current base	Principal contribution
David Keith	University of Chicago	Probably the field's best-known interdisciplinary leader. Works across SAI physics, engineering, risk analysis, policy and governance; founded UChicago's Climate Systems Engineering initiative.
Simone Tilmes	NSF NCAR	One of the strongest chemistry–climate modelers in SAI. Led GLENS-related work and recent efforts to establish scientific criteria for assessing SAI scenarios.
Ben Kravitz	Indiana University	Co-founder and coordinator of the Geoengineering Model Intercomparison Project, or GeoMIP; especially important for model comparison and climate-control design.
Douglas MacMartin	Cornell University	Leading expert on SAI system design, feedback control, injection-location optimization, uncertainty and research strategy.
Daniele Visioni	Cornell University	Major current researcher on sulfate-aerosol microphysics, injection strategies, climate effects and multi-model uncertainty.
Karen Rosenlof	NOAA Chemical Sciences Laboratory	Particularly important for stratospheric observations, aerosol budgets, intervention detection, field measurements and connecting observations to models.
Frank Keutsch	Harvard University	Atmospheric chemist and instrument developer; led the proposed SCoPEx field experiment. SCoPEx was discontinued in 2024, but Keutsch remains highly relevant to plume chemistry and small-field-experiment design.

Researcher	Current base	Principal contribution
Alan Robock	Rutgers University	Foundational researcher on volcanic analogues, regional climate effects, monsoons, risks and termination; also an influential critical voice within the field.
Claudia Timmreck	Max Planck Institute for Meteorology	Leads work on stratospheric forcing and climate, especially volcanic aerosols, aerosol transport and climate-model evaluation.
Jim Haywood	University of Exeter and UK Met Office community	Leading aerosol–radiation and climate-modeling expert; prominent in the expanding UK SRM research program.

Important specialists

Researcher	Particularly valuable for
Jadwiga Richter, NSF NCAR	Stratospheric dynamics, climate control and leadership of the ARISE-SAI simulation program.
Michael Mills, NSF NCAR	Interactive sulfate microphysics, chemistry, ozone and WACCM modeling.
Lili Xia, Rutgers	Agriculture, vegetation, food-system and regional-impact analysis under SAI.
Govindasamy Bala, Indian Institute of Science	Hydrological cycles, Indian monsoons, regional impacts and Global South scientific leadership.
Peter Irvine, University of Chicago	Earth-system impacts, risk comparisons, tipping elements and decision-oriented analysis.
Wake Smith, Yale	Aircraft, logistics, deployment architecture, costs and institutional organization.
Gernot Wagner, Columbia	Economics, risk, public policy and SAI deployment costs.
Jesse Reynolds, Degrees Initiative	International law, research governance and institutional arrangements.
Inés Camilloni, University of Buenos Aires/CONICET	South American hydroclimate impacts, equity and Global South participation in SRM decisions.
James Franke, University of Chicago	Sulfur-precursor engineering tradeoffs, aircraft lofting economics, feedstock and injection-rate cost comparisons
Fangqun Yu, University at Albany/SUNY	Near-field H_2SO_4 nucleation, aircraft-exhaust plume microphysics and particle-size evolution

For the revised C2 engineering competition and C1 SO_2 pathway experiments, the most directly relevant initial group would probably include Rosenlof, Keutsch, Tilmes, Visioni, MacMartin, Mills, Richter, Keith, Yu and Franke. Wake Smith would be useful for aircraft and operational design, while Robock and Timmreck would provide strong independent scientific challenge.

Top organizations

1. NOAA Chemical Sciences Laboratory

NOAA CSL is probably the most important U.S. organization for the **actual measurement side** of SAI. Its strengths include:

- Stratospheric SO_2, aerosol, ozone, water-vapor and trace-gas measurements.
- High-altitude aircraft instrumentation.
- The SABRE stratospheric aircraft campaigns.
- Earth’s Radiation Budget research.
- Aerosol detection, attribution and model validation.

For a controlled SO_2-release experiment, NOAA CSL would be difficult to replace.

2. NSF NCAR and UCAR

NCAR is probably the strongest single center for **integrated chemistry–climate modeling** of SAI. It operates CESM/WACCM and led major datasets including GLENS and ARISE-SAI. It also has field-campaign, aircraft, data-management and supercomputing infrastructure through the wider UCAR system.

3. Cornell Climate Engineering group

Cornell has one of the most concentrated academic teams devoted specifically to SAI. Its distinctive strength is integrating:

- Aerosol and climate modeling.
- Injection strategy.
- Engineering control.
- Scenario design.
- Uncertainty analysis.
- Regional and extreme-event impacts.

MacMartin and Visioni make Cornell particularly important for converting scientific questions into a structured experimental program.

4. University of Chicago Climate Systems Engineering initiative

UChicago is building a broad program around sunlight reflection, carbon removal and related climate interventions under David Keith. It is particularly promising for combining atmospheric science with engineering, risk analysis, economics, governance and public policy. It is newer than NCAR or NOAA but may become one of the field's dominant centers.

5. Harvard Solar Geoengineering Research Program and Keutsch laboratory

Harvard has produced influential work on atmospheric chemistry, materials, governance and public policy. The proposed SCoPEx experiment gave Harvard substantial experience with the scientific and governance challenges surrounding outdoor research, even though the experiment was ultimately discontinued.

6. Geoengineering Model Intercomparison Project

GeoMIP is a research network rather than a single institution, but it is one of the field's most important scientific structures. It specifies common experiments for multiple climate models, allowing researchers to distinguish robust results from behavior specific to one model. It is essential for independent replication.

7. Max Planck Institute for Meteorology

MPI-M is especially strong in volcanic forcing, stratospheric aerosol evolution, circulation and Earth-system modeling. Claudia Timmreck's group would be a valuable independent European modeling and natural-analogue partner.

8. University of Exeter and the UK Met Office

Together, these organizations provide substantial expertise in aerosol–radiation interactions, SAI climate modeling, regional impacts and atmospheric observations. Exeter is also expanding interdisciplinary work on responsible climate intervention.

9. Rutgers University

Rutgers is particularly important for independent assessment of adverse effects, regional climate, agriculture, ecosystems and termination risk. Its team includes Alan Robock and Lili Xia and has long-standing involvement in GeoMIP.

10. Indian Institute of Science

IISc is a leading technical center for examining how SAI could affect India and its monsoon-dependent population. It would be an important partner for avoiding a research program dominated solely by U.S. and European perspectives.

Important funders and network builders

The **Simons Foundation** operates an international SRM collaboration focused on fundamental scientific gaps. The UK's **ARIA Exploring Climate Cooling program** is funding laboratory, modeling and carefully governed real-world work, while **NERC** funds complementary impact modeling. The **Degrees Initiative** is the leading organization building the capacity of Global South research teams to independently evaluate SRM.

Best consortium for the proposed $1 billion program

I would build the scientific core around:

Function	Suggested lead
Stratospheric observations and instruments	**NOAA CSL**
Integrated global modeling	**NSF NCAR/UCAR**
Experiment and injection-strategy design	**Cornell**
Systems engineering and cross-disciplinary assessment	**University of Chicago**
Laboratory aerosol chemistry	**Harvard/Keutsch group**
Independent European modeling	**Max Planck and Exeter/Met Office**
Regional and agricultural impacts	**Rutgers, IISc and Global South university teams**
Multi-model replication	**GeoMIP**
Global participation and capacity building	**Degrees Initiative**

No single laboratory presently has all the capabilities required. The strongest program would deliberately distribute authority among **measurement teams, modelers, experiment designers, regional-impact researchers and independent critics**, rather than allowing one group to design, perform and evaluate its own experiments.

Scientific Advisory Panel

Prompt to AI: What technology-specific expertise should the SAI Experimental Research Scientific Advisory Panel contain after generic governance and conflict rules are incorporated from the Common Framework?

Response From AI:

The proposal should specify the expertise needed rather than depend on particular individuals being available. The panel reviews scientific merit, observability, pathway down-selection, measurement closure, replication, and the evidence supporting proceed / redesign / pause / stop recommendations. Generic appointment, conflict, recusal, audit, and transparency rules are supplied by the Moonshot Common Framework.

Seat / expertise	Required contribution	Illustrative candidates
Independent chair	Broad atmospheric-science leadership; no active program award; protects independent technical judgment.	Susan Solomon or a comparably independent former senior scientific leader.
Stratospheric observations	Aircraft/balloon observations, transport, ozone, water vapor, aerosol budgets, measurement strategy.	Karen Rosenlof or equivalent.
Aerosol chemistry / field experiments	H_2SO_4/SO_2 chemistry, instruments, heterogeneous reactions, controlled perturbation design.	Frank Keutsch or equivalent.
Chemistry-climate / ozone	Interactive aerosol, ozone, circulation, heating, and whole-atmosphere consequences.	Simone Tilmes or equivalent.
Injection strategy / control	Translate decision questions into release geometry, observability, controls, and experiment requirements.	Douglas MacMartin or equivalent.
Aerosol microphysics	Nucleation, condensation, coagulation, size distributions, plume-to-global scale transfer.	Daniele Visioni, Fangqun Yu, or equivalent.
Independent model evaluation	Multi-model comparisons, held-out tests, uncertainty, and reproducibility.	Ben Kravitz or equivalent.
Volcanic analogues / critical review	Natural perturbations, termination/risk context, and independent challenge of optimistic assumptions.	Claudia Timmreck, Alan Robock, or equivalent.

Regional / Global South climate	Hydrology, monsoons, regional impacts, and research priorities beyond North America/Europe.	Govindasamy Bala, Inés Camilloni, or equivalent.
Health / environment	Surface exposure, toxicology/ecology, air quality, and downstream consequences.	Tracey Holloway plus material-specific experts as needed.
Statistics / UQ / causal inference	Preregistration, detection, power, blinded comparisons, uncertainty propagation, and stopping rules.	Independent statistician/UQ specialist.
Aviation / field operations adviser	High-altitude flight operations, payload integration, airworthiness, and test readiness; may be non-voting.	NASA/FAA or equivalent independent specialist.

Panel boundary

The Scientific Advisory Panel determines whether a proposed experiment is scientifically worth doing and whether the resulting evidence closes the stated question. It does not manage contractors and does not possess unilateral authority to approve an outdoor release. Every deliberate atmospheric perturbation must separately satisfy the Release Authorization overlay and the applicable safety, environmental, legal, aviation, transboundary, and public-governance requirements.

Conflicts and independence

Because many leading experts work at institutions that may seek program funding, the Common Framework conflict and recusal rules apply in full. For SAI specifically, a panelist should not participate in the award, acceptance, or scale-up decision for work from that panelist's institution or close collaborators, and the organization that performs a release should not be the sole organization judging calibration, environmental compliance, model performance, or whether the next release should be larger.

Management Advisory Panel

Prompt to AI: What management-oversight expertise is uniquely needed for the SAI Experimental Research Initiative beyond the common Management Advisory Panel charter?

Response From AI:

The Moonshot Common Framework governs the panel charter, independence, audit access, conflicts, escalation rights, reserve review, corrective action, and Managing Organization oversight. This initiative adds several seats or equivalent capabilities because it combines controlled atmospheric releases, high-altitude field campaigns, hazardous materials, international participation, and unusually sensitive public-governance questions.

- High-altitude aircraft and complex field-campaign management, including aviation safety, test readiness, weather loss, plume reacquisition, and schedule risk.
- Environmental, atmospheric-release, and hazardous-material governance, including independent hold/stop authority and incident review.
- International/transboundary research governance, public engagement, transparency, and participation by regions potentially affected by future SAI decisions.

All other management-panel seats and responsibilities are supplied by the common framework. Technology-specific scientific review remains with the Scientific Advisory Panel in this proposal.

Agreements

Prompt to AI: Which agreement provisions should remain inside this proposal after the portfolio-wide Funding Source-to-Managing Organization and Managing Organization-to-Recipient master terms are moved to the common framework?

Response From AI:

The generic master agreement terms are specified in the Moonshot Common Framework and are not repeated here. Final agreements would use those common terms plus the SAI-specific schedules below, adapted by counsel to the parties, jurisdictions, aviation and environmental requirements, hazardous-material rules, and the actual grant, contract, cooperative agreement, reimbursable agreement, or task order.

Program-Specific Schedules to the Common Agreements

Outdoor release and experiment schedule

For each outdoor release, attach the decision question, observability/value-of-information analysis, release material, mass, rate, geometry, altitude, timing, expected plume evolution, monitoring plan, preregistered predictions, uncertainty budget, environmental and transboundary analysis, required approvals, abort/stop conditions, emergency procedures, and post-release follow-up obligations.

Aircraft, hazardous materials, and instrumentation

Schedules should identify release-aircraft and monitoring-aircraft responsibilities, airworthiness and flight-readiness evidence, SO_2/H_2SO_4 storage and handling controls, corrosion/material compatibility, calibration, instrument configuration, time synchronization, source accounting, plume-location systems, maintenance, contamination control, and independent acceptance.

Data, preregistration, and scientific independence

Require public preregistration where feasible, raw and calibrated measurement data, source records, model inputs and forecasts, code, calibration and uncertainty records, negative results, protocol deviations, and final reproducibility packages. The release team, instrument vendors, and principal modeling team should not have unilateral authority to exclude adverse data or certify final scientific closure.

No duplicate master terms

Procurement, milestone-payment logic, audit, conflicts, open-source/data rights, background-IP disclosure, reserve, changes/claims, remedies, termination, step-in, succession, insurance, general reporting, and transition provisions are governed by the common framework unless a written SAI-specific schedule expressly adds or overrides a term.

Termination Shock — SAI-Specific Considerations

Prompt to AI: What termination-shock evidence is specific to SAI Experimental Research, and what should instead remain in the Global Climate Model Experimental Research Initiative?

Response From AI:

Termination shock is primarily a coupled climate-system response to removing a sustained radiative forcing while greenhouse-gas concentrations remain high. The definitive portfolio-wide analysis therefore belongs in the Global Climate Model Experimental Research Initiative. This proposal should retain only the SAI-specific empirical and operational inputs needed to make those simulations more realistic.

SAI-Specific Empirical Inputs

SAI-specific input	What this initiative should measure or bound
Aerosol / forcing decay	How quickly optical depth and radiative forcing decline after injection is reduced or stopped, including dependence on particle size, altitude, latitude, season, and circulation.
Release-to-forcing response	The dynamic relationship between changes in injection rate/geometry and changes in measured forcing, with uncertainty and lag.
Operational ramp rates	How quickly real aircraft, source systems, bases, and monitoring can increase, decrease, pause, restart, or redistribute research-scale injection.
Monitoring latency / failure detection	How quickly an unintended reduction in source output or forcing can be independently detected and distinguished from normal atmospheric variability.
Continuity failure modes	Aircraft grounding, base loss, feedstock interruption, release-system failure, cyber/communications loss, and monitoring outages that matter to later continuity planning.

Operational continuity evidence

SAI aerosol does not disappear the instant aircraft stop flying; the existing stratospheric aerosol layer decays over time. That buffer is relevant but does not eliminate continuity risk. This five-year research program should therefore measure forcing decay and monitoring latency and document operational failure/recovery behavior, while avoiding claims about the long-term warming trajectory that cannot be established by these small experiments.

Boundary with the GCM initiative

The GCM initiative should calculate the global and regional temperature, precipitation, monsoon, sea-ice, ocean-heat, AMOC, ecosystem, greenhouse-gas, abrupt-versus-gradual phaseout, and carbon-removal consequences of stopping SAI or MCB. SAI Experimental Research supplies aerosol lifetime, forcing decay, release-response, monitoring, and operational-rate inputs with uncertainty. The simplified 10-year and 1,200-ppm arithmetic previously shown here is intentionally omitted from the proposal-level evidence requirements.

SAI Aircraft, Instrumentation and Plume Tracking

Prompt to AI: The "sai_experiments_research_fund_ai, v1o.docx" file refers to four types of airplanes: (a) inject material, (b) fly above plume, (c) fly through plume, (d) fly below plume. Tell me more about these airplanes. What parameters does each measure? What instrumentation is needed to measure each parameter? Do we need to develop aircraft or modify existing aircraft? Do we need to develop instrumentation or equipment that is added to aircraft? What do we need to develop? Notice we are looking at a plume that moves about in the wind and disperses. Do we need an image (e.g. 1000 x 1000 pixels) or is one pixel sufficient? Do we need the imager (IR, UV, visible) on a gimbal to keep it steady as the airplane rocks back and forth? How do we see the plume? Are existing atmospheric research airplanes suited for this kind of work? They tend to look at other things. Might a phased-array microwave receiver be helpful?

Response From AI:

The monitoring problem should be treated as an instrument-and-mission-system problem more than an aircraft-development problem. Existing research aircraft are generally suitable as sensor buses. The largest new engineering efforts are the SAI release package, real-time plume finding and navigation, acid-compatible sampling/integration, and common radiative-closure payloads. A purpose-built high-altitude aircraft becomes relevant only if later work requires a combination of altitude and payload that the research fleet cannot provide.

Four aircraft roles

Aircraft role	Primary job and parameters	Representative instrumentation	Development need
Release / injector	Release a precisely known perturbation. Measure total mass and mass flow, feedstock pressure/temperature, aerosol-generator settings, exhaust or vaporizer conditions, position/attitude, ambient temperature/pressure/water vapor and release timing.	Precision mass-flow and tank metrology; pressure/temperature sensors; aerosol-generation diagnostics; GPS/INS; meteorological sensors; leak detection and safety controls.	High for the release module. Modify an existing aircraft initially; develop a modular, certifiable SO_2/H_2SO_4/C3 release system rather than a new airframe.
Above plume	Measure reflected and absorbed radiation plus plume geometry: up/down SW and LW flux, spectral reflectance, polarization, layer height, width/length and optical-depth heterogeneity.	Broadband SW/LW radiometers; spectral radiometer; multi-angle polarimeter/imager; HSRL/CPL-class lidar; precision GPS/INS.	Low-to-moderate. Existing aircraft and most sensors are suitable; improve stabilization, common calibration and real-time processing.

Through plume	Measure what the released material becomes: SO_2/H_2SO_4, particle number and size, sulfate mass/composition/acidity, surface area, scattering/absorption/extinction, ozone-relevant chemistry, H_2O, winds and turbulence.	SO_2 detector; CIMS for H_2SO_4/trace gases; nanoparticle-to-micrometre sizing; aerosol composition instruments; nephelometer/absorption optics; ozone/NOy/H_2O; gust/turbulence package.	Low-to-moderate. Use existing stratospheric chemistry aircraft; emphasize low-loss/acid-compatible inlets, calibration, synchronized racks and plume-targeting displays.
Below plume	Measure radiation transmitted through the plume and the lower boundary for closure: SW/LW flux, spectral attenuation, column AOD, SO_2 column early in C1, plume-base altitude and background aerosol/cloud state.	Up/down radiometers; spectral radiometer; UV-visible spectrometer/DOAS; upward-looking lidar; optional polarimeter; GPS/INS and meteorology.	Low-to-moderate. Existing aircraft are suitable; integrate matched radiation sensors and attitude correction.

Do we need to develop new aircraft?

For the five-year experimental fund, usually no. Existing high-altitude atmospheric research aircraft can perform the above-plume and through-plume roles, while Gulfstream-, C-130-, King-Air- or Twin-Otter-class research aircraft can perform many below-plume and lower-altitude roles. The program should develop removable payloads and certified interfaces so the same instrument packages can migrate among qualified aircraft.

The injector is the exception. For C1, the new equipment is a corrosion-resistant SO_2 storage, metering and safety package. For C2, the aircraft also becomes part of the aerosol-generation experiment: mechanical atomization, exhaust-assisted H_2SO_4 vaporization and dedicated-vaporizer architectures require tanks, pumps, heat exchangers or vaporizers, exhaust interfaces, controls, leak detection, acceptance testing and airworthiness approval.

Finding a moving and dispersing plume

For multi-day C1 work, plume reacquisition may be as important as individual instrument accuracy. The program should develop a Plume Location, Imaging and Navigation System that fuses trajectory forecasts, measured winds, lidar curtains, multispectral/polarimetric imagery, UV-visible SO_2 information and confirmed in-situ plume hits into a continuously updated three-dimensional plume estimate with an uncertainty envelope.

The operations display should function conceptually like weather radar for the science mission: predicted plume volume, latest confirmed detection, estimated plume age, uncertainty, and recommended cross-plume or along-plume flight legs. The same data system should guide the above, through and below aircraft and feed post-flight data assimilation.

One pixel versus an image

Measurement need	One-pixel / integrated measurement	Imaging requirement
Radiative forcing / flux closure	Often appropriate. A broadband or spectral flux radiometer deliberately integrates radiation over a defined field of view or hemisphere; this directly measures the quantity needed for the radiation budget.	An image is not required to obtain the flux number, but imaging helps establish whether the radiometer sampled plume center, edge, gaps or clean background.
Plume location and geometry	Insufficient by itself. A single signal cannot determine the two-dimensional plume boundary or heterogeneous optical depth.	Use a multi-pixel imager/polarimeter plus lidar. Specify ground sampling distance, swath, spectral bands, signal-to-noise and viewing geometry rather than an arbitrary 1000 x 1000 pixel count.
Practical spatial-resolution rule	N/A	Aim for roughly 20-50 independent samples across the narrowest plume width that must be resolved, then bin pixels when higher signal-to-noise is more valuable than native spatial resolution.

Stabilization and gimbals

Precision radiometry should use either a stabilized platform or sufficiently accurate, high-rate inertial measurements to correct for aircraft pitch and roll. A gimbaled imager is useful when the instrument must hold the plume in view or acquire multiple viewing angles. A lidar can often remain fixed nadir- or zenith-looking if its beam direction is accurately referenced to the aircraft INS; scanning lidar can be added when cross-track geometry is scientifically valuable.

How the plume is seen

C1 and C2 are different. Immediately after a C1 SO_2 release, much of the perturbation is an optically weak gas plume. Early plume finding therefore relies heavily on the source trajectory, winds, trajectory models, UV-visible/SO_2 detection and direct SO_2 measurements when an aircraft crosses the plume. As sulfate forms, lidar, polarimetric imaging and aerosol optical measurements become progressively more useful.

For C2 direct H_2SO_4 aerosol, particles exist immediately, so lidar and optical imaging can map the layer almost at once. The combined observing logic is: lidar provides the vertical skeleton, imaging/polarimetry maps horizontal structure, the through-plume aircraft supplies physical and chemical truth, and above/below radiometers measure the energy-budget effect.

Are existing atmospheric research aircraft suited?

Yes. They already carry many of the required instrument families, even though current campaigns study volcanoes, ozone, air pollution, clouds, convection or satellite validation rather than deliberate SAI plumes. The SAI-specific work is mainly mission integration: acid-compatible and low-loss inlets, source-record synchronization, standardized instrument racks, real-time plume targeting, common calibration and coordinated multi-aircraft operations.

Illustrative platform assignment

Role	Illustrative existing platform class	Why it fits
Above plume	ER-2-class high-altitude remote-sensing aircraft	Very high altitude with optical ports and heritage carrying radiometers, lidar and imaging instruments.
Through plume	WB-57-class high-altitude in-situ aircraft	High altitude plus substantial payload for aerosol, gas chemistry and meteorological instruments.
Below plume	NSF/NCAR Gulfstream V or comparable high-performance research jet; smaller aircraft where altitude permits	Good payload/endurance for radiation, lidar, cloud/aerosol context and stacked flight legs.
Boundary-layer/context	C-130, King Air or Twin Otter class	Useful for lower-altitude radiation, aerosol/cloud context and remote sensing; not a substitute for stratospheric sampling.
Release	Modified existing jet initially	Keeps new development concentrated on the release module rather than the entire airframe.

Would a phased-array microwave receiver help?

It is not a priority instrument for directly detecting submicron sulfate aerosol. The particle size is far smaller than microwave wavelengths, so direct microwave backscatter is weak. Microwave radar/radiometry can still provide useful cloud, precipitation, temperature/humidity or dynamical context. If additional plume-detection money is available, the SAI program should prioritize lidar, UV-visible SO_2 detection, multi-angle optical/polarimetric imaging and real-time data fusion before a phased-array microwave receiver.

What the SAI fund should develop

- Modular SAI release-aircraft payloads for C1, C2A, C2B, C2C and later C3, including precision release metrology and corrosion/safety systems.

- A real-time three-dimensional plume finder and flight-guidance system combining forecasts, winds, lidar, imagery and in-situ detections.
- A stabilized radiative-closure payload with matched above/below SW and LW sensors, spectral radiometry, high-rate INS and common calibration.
- A standardized through-plume chemistry/microphysics payload assembled largely from existing instrument families but optimized for acid compatibility, inlet losses, rapid changes and synchronized data.
- A multispectral/polarimetric plume-mapping package adapting existing imaging-polarimetry and lidar technology rather than creating a new camera solely around an arbitrary pixel count.

The main conclusion is that the airplanes should be treated primarily as reusable buses. The unique new technology is the release hardware and the integrated measurement, plume-tracking and mission-navigation system.