SAI Equipment Development Initiative

CLIMATE MOONSHOT PORTFOLIO

Billions to save trillions

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

STRATOSPHERIC AEROSOL INJECTION (SAI)

AIRCRAFT • AUTOMATION • SULFUR SYSTEMS • MONITORING

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Developed with assistance from ChatGPT

OPEN SOURCE

Executive Summary

Purpose. This proposed $1 billion, five-year SAI Equipment Development Initiative is designed to turn the major hardware and operating-system questions behind stratospheric aerosol injection into testable engineering programs. It focuses on equipment development rather than authorizing climate deployment: a modified 777-class integration demonstrator, supervised flight and ground automation, a preliminary design for a purpose-built 65,000-foot aircraft, sulfur processing and loading equipment, monitoring instruments, integrated test systems, and the data and mission-control infrastructure needed to measure what the equipment actually does.

Technical architecture. The baseline program allocates $800 million to eight tightly connected baseline work packages and protects a $200 million central technical and schedule reserve. The aircraft demonstrator is intended to test storage, transfer, release, safety, automation and turnaround concepts under crew supervision; the purpose-built high-altitude aircraft stops at a credible preliminary-design package rather than a flying prototype. In parallel, a pilot sulfur/material facility tests receiving, processing, containment, rapid loading, purging and emergency isolation, while reusable monitoring hardware and release-metrology systems are calibrated and qualified for later scientific campaigns.

Program discipline. Major spending is stage-gated. Requirements and feasibility work comes first, followed by preliminary design, fabrication, integration, qualification and repeated end-to-end demonstrations. Independent organizations review airworthiness, software assurance, process safety, calibration, cost and readiness rather than allowing a prime contractor to accept its own work. Competitive procurement, measurable deliverables, retained final payments, open publication of failures as well as successes, and release of editable designs, source code, calibration records and measurement data are intended to maximize reusable climate benefit per dollar.

Success criterion. At the end of five years, success would not mean an operational SAI fleet or permission to inject material at climate-relevant scale. It would mean independently verified evidence about what can be built safely and economically: a crew-supervised automated demonstrator, a working sulfur-processing and aircraft-loading pilot, validated monitoring prototypes, a defensible 65,000-foot aircraft design, an integrated operating/data system, and substantially better estimates of Phase II cost, schedule, reliability and risk. Requirements that prove impractical should be revised or terminated rather than protected merely because they appeared in the initial concept.

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

This initiative develops and independently verifies the equipment needed for later controlled SAI research; it does not authorize climate intervention or atmospheric release.

Item	Program design
Funding / duration	$1.0B over five years: $800M baseline + $200M Funding-Source-controlled technical/schedule reserve.
Aircraft / material system	Crew-supervised modified 777 integration demonstrator; competing PDR-level high-altitude aircraft concepts; compare SO_2, sulfur-conversion and direct-H_2SO_4-compatible architectures before locking major hardware.
Automation / monitoring	Supervised flight and automated turnaround with human override; reusable release-metrology and atmospheric measurement hardware, interfaces, calibration and uncertainty records.
Evidence / gates	Competing concepts -> PDR -> build authorization -> qualification -> integrated ground/flight/endurance tests, with independent airworthiness, process-safety, software and metrology review.
Five-year decision	Proceed / redesign / stop recommendations plus Phase II development, fleet-sizing, lifecycle-cost, schedule and risk model.
Boundary	Equipment R&D only; deliberate atmospheric releases require separate SAI Experimental Research authorization.

System Architecture

The equipment program should be managed as one traceable system rather than as independent aircraft, sulfur, automation, and monitoring projects. A change in material form, payload, altitude, or cycle time can propagate through nearly every subsystem.

System element	Phase I function	Primary acceptance evidence
Mission / scientific requirements	Translate later research needs into payload, altitude, release-rate, timing, monitoring, and operating envelopes.	Configuration-controlled requirements and uncertainty ranges.
Material and ground system	Receive, process/condition, store, meter, load, purge, isolate, and account for candidate sulfur forms.	HAZOP/QRA, transfer rate, leak/containment tests, mass-balance closure.
Aircraft / payload	Carry a useful payload safely and provide tanks, plumbing, release interfaces, power, thermal control, and instrumentation.	Loads/weight evidence, qualification, ground/flight-test record.
Automation / turnaround	Automate mission functions, refueling/loading, inspection, dispatch, and fault handling under human command.	HIL tests, fault injection, human override, repeated cycles.
Release system	Meter and command a known release while preserving material compatibility and safe isolation.	Independent flow calibration, response time, leakage and shutdown evidence.
Monitoring / metrology	Verify loaded and released material and provide reusable calibrated sensor interfaces for scientific campaigns.	Traceable calibration, uncertainty budgets, intercomparison, data completeness.
Mission/data center	Maintain configuration, mission status, release records, equipment health, alarms, and open engineering data.	End-to-end data traceability, cyber tests, archive/recovery exercises.
Integration / assurance	Demonstrate the whole system safely across contractor boundaries.	Independent readiness reviews and repeated complete mission-cycle evidence.

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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:

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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
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What Exists Today and What This $1B Program Adds

The initiative should not be justified as if every component must be invented from scratch. Commercial widebody aircraft, modern flight-control systems, industrial sulfur and gas-processing equipment, research instrumentation, flight-test facilities, and digital operations systems already exist. The missing evidence is whether those capabilities can be integrated, qualified, automated, maintained, and economically scaled for the unusual SAI mission while preserving independent measurement and safe human authority.

Capability	What exists now	What the five-year initiative adds
Widebody aircraft / MRO	Mature commercial aircraft, modification, maintenance, and flight-test industries.	A hazardous-material integration demonstrator with mission-specific tanks, release systems, safety, metrology, and measured payload/turnaround evidence.
High-altitude aircraft	Specialized high-altitude aircraft experience and published SAI concept studies.	Competing configurations, physical risk tests, and an independently reviewed PDR-level aircraft design and cost/manufacturing plan.
Flight automation	Mature autopilot/avionics and emerging higher-autonomy demonstrations.	SAI-specific supervised mission automation, fault handling, cyber assurance, human override, and repeated integrated cycles.
Sulfur / industrial gas systems	Commercial receiving, storage, pumping/compression, process controls, and hazardous-material practice.	A replicable airport-side pilot integrating candidate material forms, rapid loading, purging, containment, emergency isolation, and aircraft interfaces.
Atmospheric instruments	Existing SO2, aerosol, ozone, water-vapor, radiation, lidar, balloon, and aircraft instruments.	Reusable calibrated interfaces, release metrology, ruggedization, synchronization, uncertainty budgets, and cross-platform intercomparison.
Data / mission systems	Commercial aviation operations software, telemetry, cloud/data platforms, and digital twins.	Configuration-controlled engineering mission center linking aircraft, ground, release, maintenance, metrology, alarms, and public technical records.
Independent assurance	Existing aerospace, process-safety, metrology, and test organizations.	Direct sponsor-side verification so no developer is the sole judge of its own critical performance claim.

Program Architecture and $1 Billion Budget

Prompt to AI: A 15-year Stratospheric Aerosol Injection (SAI) Plan is available here (https://www.ma2life.org/g/film/SAI_Reflectivity_Plan.pdf). This plan allocates $1B over 5 years to develop equipment needed for full-scale operations (i.e. design, prototype, test, debug). This includes an automated airplane that move SO_2 gas to the stratosphere (e.g. modify a Boeing 777 Airplane to move 100 tons of SO_2 every 5 hours where the flying, refueling and reloading are all automated). Also, a new airplane would be designed (yet not prototyped) that moves 100 tons of material to a high altitude (e.g. 65K feet) every 5 hours. Also, equipment that transports, stores, and processes sulfur would need to be designed/prototyped. Also, equipment would need to be designed/prototyped that monitors: (a) SAI operations, (b) impact and (c) side-effects. If $1B over 5 years was allocated for all of this activity, how might it be broken down in a budget?

Response From AI:

Recommended interpretation of the $1 billion

The linked document presently describes two separate Phase I budgets: approximately $1 billion for atmospheric experiments and another $1 billion for large-scale equipment development. The budget below instead assumes a single, constrained $1 billion equipment-development program, including prototype monitoring equipment but excluding a separate large atmospheric-science campaign.

All amounts are in constant 2026 dollars.

Five-year budget

Work package	Budget	%	Principal five-year deliverable
Area 1. Modified 777-class demonstrator	$230M	23.0%	One instrumented, crewed experimental aircraft with sulfur/SO_2 tank, transfer, release and safety systems
Area 2. Automated flight and ground turnaround	$110M	11.0%	Automated mission control, ground refueling, sulfur loading, dispatch, inspection and fault handling
Area 3. New 65,000-foot aircraft design	$105M	10.5%	Preliminary design review package, component tests and credible cost/manufacturing plan; no full aircraft
Area 4. Sulfur processing and logistics pilot	$85M	8.5%	One pilot facility for receiving, processing, storing, transferring and loading sulfur/SO_2
Area 5. Monitoring hardware, release metrology, and calibration systems	$110M	11.0%	Qualified reusable release-metrology and atmospheric instrument hardware, common interfaces, calibration and uncertainty package

Work package	Budget	%	Principal five-year deliverable
Area 6. Systems integration and testing	$65M	6.5%	Ground tests, crewed flight tests, automated turnaround demonstrations and reliability improvement
Area 7. Engineering digital twin, data platform and mission operations center	$45M	4.5%	Engineering digital twins, mission-control/data platform, configuration/maintenance tools and open engineering archive
Area 8. Program management, safety and independent assurance	$50M	5.0%	Owner's PMO, systems engineering, environmental review, airworthiness planning and open publication
Central technical and schedule reserve	$200M	20.0%	Funds released only for documented technical, integration or schedule risks
Total	**$1.000B**	**100%**	

The 20% reserve is deliberately large because the program combines a modified transport aircraft, toxic-material handling, flight automation, a novel high-altitude aircraft design and new atmospheric instrumentation. GAO does not prescribe a universal contingency percentage, but it recommends a complete technical baseline, risk analysis, independent cost estimates and estimates that can be updated as actual results become available.

Area 1. Modified 777-class demonstrator — $230 million

Subtask	Cost
Used aircraft acquisition, inspection and baseline overhaul	$25M
Structural modifications and tank-support structure	$55M
Sulfur/SO_2 tank, valves, piping, pressure and thermal controls	$45M
Tail delivery manifold, release pipe and nozzles	$25M
Leak detection, ventilation, fire protection and emergency isolation	$20M
Electrical power, avionics interfaces and test instrumentation	$20M
Fabrication, installation and ground qualification	$25M
Initial crewed flight-test preparation	$15M
Total	**$230M**

This aircraft should be treated as an integration demonstrator, not as the eventual 65,000-foot operational aircraft. A published SAI aircraft assessment concluded that no existing aircraft, even with extensive modification, combines the altitude and payload needed for the full mission.

There should also be an early requirement review of the “100 tons of SO_2” target. One hundred tons of material plus tanks, plumbing, safety systems and structural reinforcement may be too much for the selected aircraft configuration. The contract should therefore initially specify “maximum feasible payload, with a 100-ton objective” rather than guarantee 100 tons before the mass, balance and structural studies are complete.

Area 2. Automated flight and ground turnaround — $110 million

Subtask	Cost
Automated mission planning, taxi, takeoff, cruise, release and landing software	$35M
Automated ground refueling	$15M
Automated sulfur/SO_2 loading, coupling, purging and disconnection	$20M
Robotic inspection and turnaround equipment	$10M
Ground control, communications and cybersecurity	$10M
Hardware-in-the-loop simulation, fault injection and safety validation	$20M
Total	**$110M**

For five-year budget credibility, flight testing should remain optionally piloted: automation performs the mission while qualified pilots remain aboard to monitor and intervene. Attempting to obtain full certification for an unattended 777-class hazardous-material aircraft within this budget would probably consume much of the program.

The Phase I success criterion would be demonstration of the automated functions—not unrestricted permission to operate an uncrewed aircraft in normal civil airspace.

Area 3. New 65,000-foot aircraft design — $105 million

Subtask	Cost
Mission requirements and aircraft-configuration trade studies	$10M
Aerodynamics, structures, weight and stability design	$25M
High-altitude propulsion and engine-integration studies	$20M
Computational modeling, wind-tunnel and component tests	$20M
Manufacturing, maintenance and fleet-operating analysis	$10M
Preliminary design drawings and interface specifications	$10M
Independent preliminary design review	$10M

Subtask	Cost
Total	**$105M**

This work should deliver a design at roughly the preliminary-design-review level, sufficiently mature to estimate development cost, select suppliers and solicit proposals for a flying prototype.

It would not produce production drawings or a certified aircraft. NASA's readiness definitions require a high-fidelity prototype operating in a relevant environment for Technology Readiness Level 6, and an actual operational environment for Level 7. A paper design and component testing cannot legitimately claim those levels.

That distinction matters because Smith and Wagner estimated approximately $2 billion for development of a purpose-built SAI airframe plus $350 million for engine modification, with five years described as a best-case development period and roughly seven years through certification and entry into service. Those are 2018 estimates, but they illustrate why $105 million can fund design—not the aircraft itself.

Area 4. Sulfur processing and logistics pilot — $85 million

Subtask	Cost
Supply-chain, site and process selection	$7M
Sulfur receiving, unloading and storage equipment	$13M
Sulfur/SO_2 conversion and conditioning pilot skids	$20M
Compression, transfer and aircraft-loading equipment	$15M
Automated couplings, valves, purging and metering	$10M
Secondary containment, ventilation and emergency systems	$10M
Pilot-site construction, commissioning and testing	$10M
Total	**$85M**

The equipment should be modular enough to test alternatives such as transporting elemental sulfur and producing or conditioning SO_2 near the airport, versus transporting an already prepared material.

The principal deliverable would be one working pilot facility that demonstrates:

- Accurate material accounting from arrival through atmospheric release.
- Rapid loading compatible with the five-hour aircraft cycle.

- Automatic shutdown and isolation after leaks or equipment failures.
- Safe draining, purging, maintenance and emergency response.
- Designs capable of being replicated at future operating bases.

Area 5. Monitoring hardware, release metrology, and calibration systems — $110 million

Monitoring / metrology function	Cost
Release metrology and loaded-to-released material accounting	$25M
Reusable SO_2/H_2SO_4/aerosol instrument hardware and aircraft interfaces	$25M
Radiative/optical measurement prototypes and stabilized interfaces	$15M
Ozone, water-vapor and chemistry instrument prototypes	$15M
Balloon, lidar and ground-platform integration hardware	$15M
Calibration, intercomparison, spares and data-quality systems	$15M
Total	$110M

This work package develops reusable measurement hardware, release metrology, interfaces, calibration, and uncertainty control needed to verify what the equipment does. It does not replace the companion SAI Experimental Research Initiative, which defines atmospheric hypotheses, pays for scientific campaign operations, and interprets plume chemistry, aerosol microphysics, radiative response, ozone, and other atmospheric outcomes.

The $110 million therefore funds prototype instruments and integration evidence: loaded-to-released material accounting; SO2/H2SO4/aerosol measurement hardware; optical/radiative and ozone/water-vapor sensor prototypes; balloon/lidar/ground interfaces; calibration laboratories; and intercomparison procedures. A permanent global observing network remains outside this five-year equipment program.

Area 6. Systems integration and testing — $65 million

This work package pays for shared facilities and end-to-end tests that cross contractor boundaries: systems-integration laboratories, hazardous-material ground campaigns, aircraft/ground interfaces, supervised flight tests, automation/monitoring coordination, failure exercises, and repeated complete mission-cycle demonstrations. Ordinary component testing remains inside the subsystem work packages.

Area 7. Engineering digital twin, data platform, and mission operations center — $45 million

This area builds the engineering operating system: aircraft and ground-system digital twins, material-flow and logistics models, mission planning/status displays, release accounting, equipment-health alarms, configuration control, cybersecurity, synchronized data ingestion, and an open engineering archive. High-fidelity atmospheric chemistry, aerosol-microphysics, radiative, and climate-model development remains primarily in SAI Experimental Research and GCM.

Area 8. Program management, safety and independent assurance — $50 million

This is the sponsor-side owner function: program integration, requirements/configuration control, cost and schedule analysis, independent airworthiness and process-safety review, software assurance, test-readiness boards, environmental/airspace coordination for engineering tests, and independent lifecycle-cost/readiness evidence. It does not replace normal contractor project management included in each technical work package.

Area 9. Central technical and schedule reserve — $200 million

The reserve remains under Funding Source control and is not distributed to contractors at award. It may be released only through documented change control for real technical uncertainty, failed tests, redesign, competing concepts/second sources, replacement test articles, or schedule recovery. Unused reserve remains unspent or available only for a separately authorized next phase.

Suggested five-year funding profile

The $200 million reserve should be controlled centrally and not divided among contractors when contracts are awarded.

Year	Planned technical work	Reserve authority	Total
Year 1	$90M	$30M	$120M
Year 2	$150M	$30M	$180M
Year 3	$210M	$40M	$250M
Year 4	$220M	$50M	$270M
Year 5	$130M	$50M	$180M

Year	Planned technical work	Reserve authority	Total
Total	**$800M**	**$200M**	**$1.000B**

Year 1 would emphasize requirements, alternative designs, safety analysis and selection of the aircraft and pilot site. Years 2 and 3 would emphasize detailed design and fabrication. Year 4 would be the peak integration and flight-test year. Year 5 would focus on repeated demonstrations, correcting deficiencies, final design packages and the Phase II decision.

What $1 billion would—and would not—accomplish

At the end of five years, a successful program could reasonably have:

- One crew-supervised, highly automated 777-class sulfur-system demonstrator.
- One automated sulfur-processing, storage and aircraft-loading pilot facility.
- Prototype instruments for monitoring operations, atmospheric behavior and selected side effects.
- A preliminary design for the purpose-built 65,000-foot aircraft.
- An integrated modeling, data and mission-control system.
- Enough test results to estimate the cost and schedule of Reflectivity Plan Phase II with much greater confidence.

It would **not** provide a certified unmanned 777, a flying 65,000-foot purpose-built aircraft, a complete global monitoring network, multiple operational bases, an operational fleet, or the separate large atmospheric-experiment program contemplated in the linked plan.

Thus, **$1 billion is a plausible but tight design-and-demonstration budget**. It works only when "automation" means demonstrated under human supervision, the new high-altitude aircraft stops at preliminary design, and approximately $200 million remains protected against redesigns and failed tests

Program Crosswalk

This program crosswalk connects the approved $1 billion accounting structure to the engineering evidence needed for decisions. Purchase-order references later in the proposal are procurement mappings, not additional budget lines.

Area	Budget	Five-year product	Primary acceptance evidence	Gate
1. 777 demonstrator	$230M	Crew-supervised aircraft integration demonstrator.	Payload/loads, containment, release-system, ground and flight-test evidence.	G1-G6
2. Automation / turnaround	$110M	Supervised flight and automated ground-turnaround system.	HIL/fault injection, cyber assurance, human override, repeated cycles.	G2-G6
3. High-altitude aircraft design	$105M	Competing concepts + PDR-level preferred design.	Independent performance, propulsion, manufacturing and cost review.	G0-G7
4. Material / logistics pilot	$85M	Replicable processing/storage/loading pilot.	Material compatibility, HAZOP/QRA, transfer rate, containment, inventory closure.	G1-G6
5. Monitoring / metrology	$110M	Qualified reusable measurement hardware and interfaces.	Calibration, uncertainty, intercomparison, release-accounting closure.	G1-G6
6. Integration / testing	$65M	Cross-contractor qualification and end-to-end demonstrations.	Witnessed tests, deficiencies closed, complete mission-cycle evidence.	G4-G7
7. Engineering data / operations	$45M	Digital twin, mission center, engineering data platform.	Configuration/data traceability, cyber tests, archive/recovery.	G1-G7
8. Program assurance	$50M	Independent technical, safety, cost and readiness record.	Direct sponsor-side reviews and audits.	All
Central reserve	$200M	Controlled response to documented uncertainty.	Approved change-control evidence; no automatic contractor entitlement.	FS approval

Relationship to the SAI Experimental Research Initiative

The SAI Experimental Research initiative and the SAI Equipment Development initiative should use one asset registry and a clear lead-budget rule. Equipment Development builds, hardens, qualifies, automates, documents, and cost-models reusable engineering capability. Experimental Research determines whether an atmospheric release is scientifically justified, pays for campaign-specific operations and science adaptations, and interprets the atmospheric result.

Capability	Equipment Development	SAI Experimental Research
777 / delivery demonstrator	Aircraft modification, reusable tanks/transfer/release interfaces, automation, qualification and engineering test evidence.	Campaign-specific use, flight hours, experiment integration, and any actual atmospheric release authorization.
Purpose-built high-altitude aircraft	Mission trades, competing concepts, physical risk tests, PDR-level design and Phase II prototype estimate.	Provides scientific mission requirements and later campaign needs; does not duplicate aircraft development.
SO_2 / H_2SO_4 release hardware	Reusable engineering architectures, material compatibility, metrology, controls, maintainability and safe interfaces.	Experiment-specific source settings and campaign-grade variants needed to compare SO_2, H_2SO_4 and other research pathways.
Research aircraft / airborne instruments	Pays only for durable reusable interfaces or equipment-development increments not already owned elsewhere.	Normally pays flight hours, scientific payload operation, plume tracking and campaign-specific integration.
Monitoring systems	Ruggedized hardware, release accounting, calibration architecture, common interfaces, spares and maintainability.	Scientific variables, campaign sampling, plume/chemistry/radiative analysis and interpretation.
Models	Aircraft/ground digital twins, material-flow/logistics and limited engineering release-interface models.	Observability, plume chemistry/microphysics, data assimilation, radiative closure and experiment/model challenges.
Mission/data systems	Equipment health, configuration, dispatch, alarms, release records, maintenance and engineering archive.	Scientific targeting, plume-location/forecast products and experiment data analysis.
Shared assets	One capital owner; maintain custody, calibration, access and transfer records.	Pays incremental adaptation, consumables and operating time unless intentionally independent capacity is approved.

Top-Level Engineering Requirements, KPPs, and Traceability

Prompt to AI: What top-level engineering requirements and key performance parameters should be configuration-controlled before major SAI equipment spending?

Response From AI:

The program should maintain a living Requirements Traceability Matrix (RTM). Numerical thresholds should be frozen only when supported by the companion experimental program, physical feasibility studies, airworthiness/process-safety evidence, and lifecycle economics. The purpose is to prevent attractive round numbers from becoming expensive contractual assumptions before they are tested.

KPP / requirement	Initial Phase I treatment	Verification / evidence	Freeze point
Payload	Maximum useful demonstrated payload; 100 t is an objective, not a fixed minimum.	Weight/CG, structural loads, tank mass, flight-performance model and test.	G1-G3
Altitude / mission geography	Trade high-altitude tropical missions against lower-altitude/high-latitude cases required by science.	Performance/propulsion studies + mission-value input from Experimental Research.	G0-G2
Turnaround / cycle time	Five-hour cycle is an objective subject to reliability and lifecycle economics.	Timed loading, purge, refuel, inspection, maintenance and dispatch demonstrations.	G2-G6
Material architecture	Remain open among viable SO_2, elemental-sulfur conversion and direct-H_2SO_4-compatible approaches long enough to obtain discriminating evidence.	Material compatibility, mass/energy, release physics, safety, maintainability and cost.	G0-G2
Release rate / accuracy	Derived from experiment detectability and control needs; independently metered.	Traceable flow calibration, response time, uncertainty and mass-balance closure.	G1-G5
Airworthiness / containment	No unresolved critical structural, pressure, thermal, fire, leak or hazardous-material finding.	Independent analysis, qualification, conformity and flight-test evidence.	G3-G6
Automation / human authority	Phase I remains crew-supervised with immediate human override and defined safe states.	HIL, fault injection, communications loss, cyber red team and repeated supervised missions.	G2-G6

KPP / requirement	Initial Phase I treatment	Verification / evidence	Freeze point
Ground material handling	Safe, rapid, measured loading/unloading with purge, isolation and emergency response.	HAZOP/QRA, commissioning, leak/spill drills, transfer-rate and inventory reconciliation.	G2-G6
Monitoring / metrology	Uncertainty low enough to verify loaded/released material and support later scientific closure.	Independent calibration/intercomparison, inlet/interface characterization and data completeness.	G1-G6
Reliability / maintainability	Targets derived from Phase II fleet economics rather than assumed.	MTBF/MTTR, consecutive cycles, spare demand, inspection burden and reliability-growth record.	G3-G7
Lifecycle economics	Low/base/high model updated with measured Phase I data and independent estimate.	Aircraft/base/fleet model, supplier quotes where available, uncertainty and sensitivity analysis.	All; final at G7

Architecture commitment rule

No major aircraft tank, sulfur pilot, propulsion, or release-manifold commitment should be treated as irrevocable until the material form, payload/altitude envelope, release requirements, and monitoring interfaces are sufficiently bounded to avoid a fundamental redesign. Competing concepts should be carried long enough to obtain discriminating evidence, then down-selected explicitly.

Stage Gates and Go/No-Go Criteria

Prompt to AI: What program-level stage gates should control the $1 billion SAI equipment-development initiative?

Response From AI:

Passing a gate authorizes only the next engineering increment. It does not authorize an atmospheric experiment, climate intervention, or Phase II fleet. Failure should trigger redesign, additional evidence, scale reduction, competing concepts, or termination rather than automatic progression.

Gate	Timing	Required evidence	Decision enabled / if not met
G0 Mission / architecture baseline	~Month 6	Scientific mission envelope; candidate material forms; payload-altitude-cycle trade space; monitoring and data needs; initial lifecycle model.	Freeze initial design space / revise mission before expensive engineering.
G1 Requirements feasibility	Months 9-12	Payload, altitude, material, release, turnaround, monitoring, airworthiness and process requirements shown physically plausible.	Continue competing concepts / relax or replace infeasible requirements.
G2 Architecture down-selection	~Month 18	Aircraft/material/ground/automation alternatives compared with physical tests, safety evidence and lifecycle consequences.	Select architecture(s) for PDR / retain challengers or stop weak paths.
G3 Preliminary Design Review	Months 20-24	Integrated aircraft, ground, automation, metrology, interfaces, risks and independent cost estimate are credible.	Detailed design / redesign before long-lead commitments.
G4 Major build authorization	Months 28-30	Critical risks retired; safety and supplier plans acceptable; configuration sufficiently stable; independent review passed.	Commit major fabrication / defer or reduce build.
G5 Integrated test readiness	~Month 40	Qualified hardware/software; HAZOP/QRA; HIL/cyber evidence; calibration; emergency procedures; independent readiness review.	Integrated ground tests / correct deficiencies.
G6 Supervised flight / endurance authorization	~Month 48	Airworthiness and flight-safety evidence; safe-simulant release capability; monitoring ready; human override and recovery demonstrated.	Repeated supervised flight/turnaround cycles / remain at ground-test scale.
G7 Phase II decision	Month 60	Audited payload/altitude, reliability, turnaround, material handling, monitoring, manufacturing, cost, schedule and unresolved-risk evidence.	Proceed / redesign / targeted follow-on / stop.

Outdoor atmospheric-release boundary

Engineering ground and flight tests should use safe simulants whenever possible. Any deliberate SO2, H2SO4, or other stratospheric release is a separate scientific activity and requires the SAI Experimental Research Initiative's observability/value-of-information, environmental, legal, governance, and release-authorization process. An equipment PO, reserve release, or engineering gate cannot substitute for that approval.

Program-level stop rule

The Funding Source should stop or redirect a workstream when its mission requirement proves unnecessary, the architecture cannot meet safety/performance/economic needs, repeated qualification fails, another approach provides better value, or the expected value of additional information is lower than competing uses of the funds. A documented NO is a successful R&D result.

Development Phases

Prompt to AI: With each budget item, what are the different phases, and how much might each cost?

Response From AI:

How the five-year development program could be phased

The 15-year Reflectivity Plan uses Phase I, Phase II and Phase III for research and development, experimental operations, and construction/scale-up. The "phases" below are therefore development subphases within the first five-year equipment-development program, not additional phases of the overall 15-year plan. The PDF describes approximately $1 billion for atmospheric experiments and a separate $1 billion for large-scale equipment development; the budget below follows our narrower assumption of one $1 billion equipment program, including prototype monitoring equipment but excluding a major atmospheric-release campaign.

These are preliminary, order-of-magnitude planning estimates in constant 2026 dollars—not contractor quotations.

Common five-year development sequence

Development stage	Approximate timing	General purpose
A. Requirements and feasibility	Months 0–12	Define what must be built and determine whether the requirements are physically credible
B. Preliminary design and risk reduction	Months 6–24	Compare alternatives and retire major technical risks
C. Detailed design and fabrication	Months 18–42	Produce drawings, software and prototype hardware
D. Integration and qualification	Months 30–54	Combine subsystems and test safety, performance and reliability
E. Operational demonstration and handoff	Months 45–60	Demonstrate complete operating cycles and produce Phase II design packages

The stages would overlap. Monitoring, modeling and safety work, for example, must begin before the aircraft is completed.

Area 1. Modified 777-class demonstrator — $230 million

The plan proposes modifying a large commercial aircraft with a sulfur tank and tail-delivery system to determine whether storage, transfer, release and automation can be safe, reliable and economical.

Subphase	Principal activities and deliverables	Cost
1A. Mission feasibility and requirements	Payload-versus-altitude study; material form; release rate; tank pressure and temperature; aircraft range; weight and balance; emergency scenarios	$10M
1B. Aircraft acquisition and baseline inspection	Purchase or lease aircraft; records review; structural inspection; maintenance baseline; engines and avionics assessment	$25M
1C. Preliminary aircraft design	Tank location; structural load paths; plumbing route; release-system configuration; preliminary safety analysis; preliminary design review	$25M
1D. Detailed design and hardware fabrication	Structural reinforcement; sulfur tank; pumps/compressors; valves; piping; tail manifold; thermal controls; ventilation; containment; leak detection; fire protection	$95M
1E. Installation and aircraft integration	Install equipment; modify electrical and avionics systems; instrument the aircraft; conduct mass-properties and interface tests	$35M
1F. Ground and flight qualification	Pressure and leak tests; loading trials; taxi tests; flight-envelope expansion; release-system tests using safe simulants; corrections and final configuration	$40M
Total		**$230M**

Major decision gates

At approximately Month 9, the program would decide whether a 777-class platform is suitable at all. At Month 18, it would freeze the prototype payload and material-handling configuration. At Month 30, it would decide whether to complete the physical modification.

The stated 100-ton payload should initially be treated as an **objective**, not a fixed contractual requirement. The feasibility study might conclude that the demonstrator can safely carry only 50–80 tons after accounting for tanks, piping, structural reinforcement and operating margins.

Area 2. Automated flight and ground turnaround — $110 million

This workstream covers automated flying, refueling, sulfur loading, dispatch and routine inspection. The plan identifies those functions as potentially necessary for economical large-scale operation.

Subphase	Principal activities and deliverables	Cost
2A. Concept of operations and safety architecture	Define which tasks are automatic, remotely supervised or human-controlled; establish abort modes and human authority	$8M
2B. Simulation and autonomy architecture	Digital aircraft environment; automated mission planning; routing; release control; weather avoidance; initial fault-management software	$17M
2C. Onboard flight-automation prototype	Avionics interfaces; automatic taxi, takeoff, cruise, release and landing functions; redundant computers and communications	$25M
2D. Automated ground-system prototypes	Robotic fuel connections; sulfur-loading couplings; purging; automatic metering; inspection sensors; dispatch software	$20M
2E. Hardware-in-the-loop and cybersecurity testing	Simulated component failures; communications loss; sensor faults; cyberattack exercises; independent software verification	$15M
2F. Supervised operating demonstrations	Repeated automated missions with pilots aboard; automatic reloading and refueling; reliability testing; operating manuals and final software baseline	$25M
Total		**$110M**

The five-year target should be **highly automated, crew-supervised operation**. Removing the flight crew completely would be a later certification and regulatory project.

A successful final demonstration might require 20–50 consecutive automated turnaround cycles with no safety-critical failures, followed by several complete flight-and-ground cycles.

Area 3. New 65,000-foot aircraft design — $105 million

This budget develops a credible preliminary design for the eventual high-altitude aircraft. It does **not** fabricate a complete airplane.

Subphase	Principal activities and deliverables	Cost
3A. Mission requirements and trade studies	Payload, altitude, cycle time, runway, range, fleet size, maintainability and automation requirements	$10M
3B. Aircraft-configuration concepts	Conventional twin-engine, four-engine, enlarged-wing and specialized high-altitude configurations; initial cost and risk comparisons	$15M
3C. Preliminary multidisciplinary design	Aerodynamics; wing sizing; structures; stability and control; pressurization; landing gear; tank integration; high-altitude performance	$25M
3D. Propulsion and physical risk testing	Engine studies; inlet performance; compressor margins; wind-tunnel models; structural coupons; tank and valve component tests	$20M
3E. Integrated preliminary design	Three-dimensional definition; weight statement; performance model; manufacturing plan; maintenance concept; operating-cost and fleet model	$20M

Subphase	Principal activities and deliverables	Cost
3F. Independent design review and Phase II package	Independent preliminary design review; revised configuration; prototype cost estimate; schedule; supplier strategy; request-for-proposals package	$15M
Total		**$105M**

Principal output

The final product would include enough design information to answer:

- Can 100 tons actually be carried to approximately 65,000 feet?
- What engine or engines would be required?
- What would one prototype probably cost?
- How many years would it take to build and test?
- What would an operational aircraft and fleet cost?
- Is a 100-ton aircraft better than a larger number of smaller aircraft?

A meaningful design competition might fund two or three teams through conceptual design and then select one or two for the preliminary design stage.

Area 4. Sulfur processing, storage and logistics pilot — $85 million

The plan calls for processing, transport, storage, transfer and loading systems, together with automated ground handling.

Subphase	Principal activities and deliverables	Cost
4A. Material and logistics trade study	Compare elemental sulfur, liquid SO_2 and other possible feed forms; transportation modes; airport siting; loading-cycle requirements	$7M
4B. Front-end engineering and hazard analysis	Process-flow diagrams; material balance; storage conditions; containment; ventilation; failure analysis; emergency-response concept	$10M
4C. Detailed engineering and approvals	Piping and instrumentation diagrams; civil work; electrical design; controls; supplier packages; environmental and safety documentation	$10M
4D. Pilot-plant fabrication and construction	Receiving equipment; tanks; processing skids; compressors or pumps; piping; loading stations; containment; control room	$33M
4E. Commissioning and process validation	Pressure testing; leak testing; material-quality tests; transfer-rate measurements; inventory reconciliation; initial operating cycles	$15M

Subphase	Principal activities and deliverables	Cost
4F. Automated turnaround and emergency demonstrations	Automated loading; connection and disconnection; purging; spill response; equipment failures; final replicable facility design	$10M
Total		**$85M**

The pilot plant should probably be sized to support the demonstrator, not a future 100-aircraft fleet. Its final engineering package would show how to replicate and enlarge the facility during later phases.

Area 5. Monitoring hardware, release metrology, and calibration systems — $110 million

This work package develops reusable release-metrology and atmospheric-measurement hardware needed by the equipment system and later scientific campaigns. It owns engineering requirements, interfaces, ruggedization, calibration, synchronization, maintainability and uncertainty control; SAI Experimental Research owns the atmospheric hypotheses, campaign operations and scientific interpretation.

Subphase	Principal activities and deliverables	Cost
5A. Measurement requirements and error budgets	Derive release-metrology and reusable sensor requirements from mission/science needs; accuracy, uncertainty, timing, synchronization, environmental and interface requirements	$8M
5B. Hardware and interface architecture	Select reusable aircraft/balloon/lidar/ground hardware; define racks, inlets, power, communications, calibration standards and common interfaces	$12M
5C. Prototype instrument fabrication	Release-flow/material-accounting hardware; acid-compatible SO_2/H_2SO_4/aerosol instruments; optical/radiative, ozone and water-vapor sensor prototypes	$30M
5D. Calibration and qualification	Calibration chambers/reference standards; environmental qualification; uncertainty documentation; independent instrument intercomparison	$15M
5E. Integration and non-SAI validation	Install reusable payloads on qualified platforms; balloon/lidar/ground trials; safe non-SAI campaigns; corrections after field integration	$30M
5F. Procedures and handoff	Calibration/maintenance/spares procedures; data-quality rules; interface control documents; Phase II and Experimental Research handoff package	$15M
Total		$110M

The $110 million does not buy a permanent global monitoring network. It qualifies reusable measurement capability and produces a Phase II interface/calibration package that the experimental program can use without duplicating capital development.

A reasonable internal allocation of the $110 million would be:

Monitoring / metrology category	Approximate amount
Release metrology and material accounting	$25M
Reusable gas/aerosol instrument hardware and interfaces	$25M
Radiative/optical measurement prototypes	$15M
Ozone, water-vapor and chemistry instrument prototypes	$15M
Balloon/lidar/ground-platform integration	$15M
Calibration, intercomparison, spares and data quality	$15M

Area 6. Systems integration and testing — $65 million

Subsystem contractors would pay for ordinary component testing within their own budgets. This separate allocation pays for **shared test facilities and end-to-end tests crossing contractor boundaries**.

Subphase	Principal activities and deliverables	Cost
6A. Integrated verification and test plan	Requirement-to-test matrix; acceptance criteria; test sequence; independent witnesses; configuration control	$5M
6B. Systems-integration laboratory	Representative avionics, valves, pumps, sensors, computers and communications; software and hardware simulation rigs	$10M
6C. Subsystem qualification	Vibration, temperature, pressure, compatibility, endurance and failure-mode testing using common standards	$10M
6D. Full-scale ground campaign	Sulfur loading, storage and transfer; aircraft interfaces; automated turnaround; shutdowns; emergency exercises	$15M
6E. Integrated flight campaign	Aircraft performance; release-system operation; monitoring-aircraft coordination; automation and ground-control tests	$15M
6F. End-to-end demonstration and readiness review	Repeated complete mission cycles; deficiency correction; performance verification; final Phase II readiness assessment	$10M
Total		**$65M**

The final demonstration would begin with sulfur substitutes or inert gases. Actual SO_2 releases should occur only under the separate atmospheric-experiment program and its environmental authorization.

Area 7. Engineering digital twin, data platform, and mission operations center — $45 million

Subphase	Principal activities and deliverables	Cost
7A. Engineering data and system requirements	Configuration ownership; engineering telemetry; retention/access; latency; cybersecurity; interfaces to external weather/science products	$5M
7B. Engineering digital twins	Aircraft, payload, ground facility, material-flow, logistics, power/thermal and maintenance models; bounded release-footprint interface model for operations only	$12M
7C. Mission-control and data platform	Mission displays; aircraft/ground equipment status; flight tracking; release accounting; alarms; pause controls; configuration status	$10M
7D. Engineering data ingestion and quality control	Telemetry, release metrology, maintenance events, calibration/configuration records and external weather/science-product interfaces; automated QC	$8M
7E. Integrated simulation exercises	Simulated missions, equipment failures, communication loss, abnormal weather inputs, pause/recovery and emergency exercises	$6M
7F. Secure handoff and open engineering archive	Documented software baseline, APIs, source code, configuration history, public engineering archive and Phase II operations-center specification	$4M
Total		$45M

This work package builds the engineering operating system, not a competing climate-science program. High-fidelity stratospheric chemistry, aerosol microphysics and radiative-response modeling remain with SAI Experimental Research/GCM; the equipment platform consumes their requirements and products through controlled interfaces. The mission center should be capable of showing, for every flight:

1. Where the aircraft went.
2. How much material was loaded.
3. How much was released.
4. Where and when it was released.
5. Whether independent instruments confirmed the release.
6. Which external scientific observations/products were linked to the engineering mission record.

Area 8. Program management, safety and independent assurance — $50 million

This is the owner's management function, separate from contractor management included within the technical work packages.

Subphase	Principal activities and deliverables	Cost
8A. Program formation	Establish management organization; contracts; accounting; systems-engineering plan; scientific and safety panels	$8M
8B. Requirements and preliminary-design oversight	Requirements reviews; architecture review; cost analysis; schedule review; independent preliminary design reviews	$8M
8C. Detailed-design and procurement oversight	Contractor surveillance; configuration control; safety cases; supply-chain review; cost and schedule updates	$10M
8D. Test and regulatory oversight	Test-readiness reviews; flight-safety work; environmental review; airspace coordination; emergency-response review	$12M
8E. Final readiness and Phase II planning	Independent operational review; updated lifecycle cost; performance audit; open publication; Phase II procurement plan	$12M
Total		**$50M**

A portion of this money should finance independent reviewers who do not report to the aircraft or sulfur-system contractors.

Area 9. Central technical and schedule reserve — $200 million

The reserve should not be distributed to contractors at the beginning. It should be held by the sponsoring organization and released only after documented review.

Reserve release stage	Types of problems covered	Maximum release
9A. Requirements and feasibility reserve	Additional trade studies; material changes; aircraft-selection changes; unexpected regulatory work	$20M
9B. Preliminary-design risk reserve	Tank or structural redesign; propulsion studies; new safety requirements; competing prototype concepts	$35M
9C. Fabrication and construction reserve	Supplier failures; long-lead components; manufacturing rework; facility changes; material-price escalation	$60M
9D. Integration and test reserve	Failed qualification tests; damaged hardware; aircraft downtime; software rework; additional flight-test hours	$65M
9E. Final schedule and demonstration reserve	Additional reliability cycles; unresolved deficiencies; documentation and schedule recovery	$20M
Total reserve		**$200M**

This table shows release authority, not a commitment to spend all $200 million. Any unused balance would remain unspent or move into the next authorized phase.

Complete budget summary

Work package	Baseline budget
Modified 777-class demonstrator	$230M
Automated flight and ground turnaround	$110M
New 65,000-foot aircraft preliminary design	$105M
Sulfur processing and logistics pilot	$85M
Monitoring hardware / release metrology / calibration	$110M
Systems integration and testing	$65M
Engineering digital twin / data / mission operations	$45M
Program management, safety and independent assurance	$50M
Baseline technical program	**$800M**
Central technical and schedule reserve	$200M
Total	**$1.000B**

Parametric Phase II Fleet-Sizing and Lifecycle-Cost Model

Prompt to AI: What parametric model should convert Phase I equipment evidence into a Phase II aircraft, base, fleet, schedule, and lifecycle-cost decision?

Response From AI:

This is a decision model, not a deployment plan. Atmospheric efficacy enters as an uncertain external requirement from SAI Experimental Research/GCM; Equipment Development calculates the aircraft, bases, material system, availability and cost required to satisfy a specified delivery scenario.

Input family	Examples
Scientific mission requirement	Required annual sulfur/material delivery or forcing scenario; latitude/altitude/season envelope and uncertainty supplied externally by the scientific programs.
Aircraft performance	Payload vs altitude, range/block time, fuel, runway/base constraints and reserve margins.
Availability / reliability	Turnaround, weather and technical availability, MTBF/MTTR, inspection/overhaul intervals, spare ratio and service life.
Material / ground system	Feed form, conversion/conditioning energy, storage, transfer rate/losses, base footprint and safety staffing.
Manufacturing / cost	Prototype/nonrecurring engineering, production learning, supplier capacity, development schedule, constant-dollar CAPEX/OPEX and low/base/high ranges.
Monitoring / operations	Release metrology, mission center, required monitoring hardware, calibration, communications and data-system costs.

Outputs: aircraft and sorties/year; bases; material throughput; production rate; acquisition and annual operating cost; cost per delivered tonne; sensitivity to payload, altitude and availability; and a low/base/high Phase II development schedule. No climate benefit is assumed inside the equipment accounting.

Purchase Orders

Prompt to AI: With each phase of each budget item, what are the different purchases orders that might be issued?

Response From AI:

Below, **"purchase order" means a procurement package**. Depending on the sponsoring organization, a package might legally be issued as a contract, subcontract, grant, cooperative agreement, or task order under a master contract.

Amounts are illustrative planning allocations in millions of constant 2026 dollars and map to the approved $1 billion work-package budget; they are not a second budget. Each procurement package should specify a deliverable, acceptance test, schedule, data rights, and payment milestones.

Area 1. Modified 777-class demonstrator — $230 million

Phase	Illustrative purchase orders	Total
1A. Mission feasibility and requirements	PO 1A-1: Mission and operating requirements — $3M; PO 1A-2: Payload, altitude, range, weight-and-balance feasibility study — $4M; PO 1A-3: Preliminary hazardous-material and airworthiness assessment — $3M	$10M
1B. Aircraft acquisition and inspection	PO 1B-1: Purchase used 777-class aircraft — $18M; PO 1B-2: Heavy inspection, records review and maintenance baseline — $5M; PO 1B-3: Initial spare parts, ground-support equipment and technical data — $2M	$25M
1C. Preliminary aircraft design	PO 1C-1: Structural modification and load-path design — $9M; PO 1C-2: Tank, transfer and material-conditioning design — $8M; PO 1C-3: Release-system and safety architecture — $5M; PO 1C-4: Independent preliminary design review — $3M	$25M
1D. Detailed design and fabrication	PO 1D-1: Structural reinforcement kits — $22M; PO 1D-2: Flight-qualified storage tank fabrication — $20M; PO 1D-3: Pumps, compressors, valves and pressure controls — $14M; PO 1D-4: Piping, tail manifold and release nozzles — $12M; PO 1D-5: Heating, cooling, ventilation, leak detection and fire protection — $12M; PO 1D-6: Electrical, avionics and test-instrumentation equipment — $10M; PO 1D-7: Manufacturing inspection and nondestructive testing — $5M	$95M
1E. Aircraft installation and integration	PO 1E-1: Airframe modification labor and hangar services — $16M; PO 1E-2: Tank, piping and release-system installation — $8M; PO 1E-3: Avionics, controls and software integration — $6M; PO 1E-4: Weight-and-balance, conformity inspection and documentation — $5M	$35M

Phase	Illustrative purchase orders	Total
1F. Ground and flight qualification	PO 1F-1: Pressure, leak, loading and structural ground tests — $10M; PO 1F-2: Pilots, engineers, fuel, maintenance and flight-test operations — $15M; PO 1F-3: Safe-simulant release trials and measurement support — $7M; PO 1F-4: Post-test redesign and hardware corrections — $5M; PO 1F-5: Final qualification reports and configuration baseline — $3M	$40M
	Work-package total	**$230M**

The aircraft-purchase PO should probably be delayed until the $10 million feasibility phase confirms that the selected aircraft can safely carry a useful payload.

Area 2. Automated flight and ground turnaround — $110 million

Phase	Illustrative purchase orders	Phase total
2A. Operating concept and safety architecture	PO 2A-1: Automated mission concept of operations — $3M; PO 2A-2: Autonomy and fault-management architecture — $3M; PO 2A-3: Regulatory and certification-path analysis — $2M	$8M
2B. Simulation and software architecture	PO 2B-1: High-fidelity aircraft and airport simulation environment — $6M; PO 2B-2: Mission planning, routing and release-control software — $7M; PO 2B-3: Weather avoidance, abnormal-event and fault-management software — $4M	$17M
2C. Onboard automation prototype	PO 2C-1: Flight-control and avionics interface hardware — $8M; PO 2C-2: Redundant computers, communications and navigation equipment — $7M; PO 2C-3: Automated taxi, takeoff, cruise, release and landing software — $7M; PO 2C-4: Software assurance and certification documentation — $3M	$25M
2D. Automated ground systems	PO 2D-1: Automated aircraft refueling demonstrator — $5M; PO 2D-2: Automated sulfur/SO_2 loading and purging system — $8M; PO 2D-3: Robotic inspection and leak-detection equipment — $3M; PO 2D-4: Ground-turnaround orchestration software — $4M	$20M
2E. Hardware-in-the-loop and cybersecurity testing	PO 2E-1: Hardware-in-the-loop test laboratory — $6M; PO 2E-2: Independent software verification and validation — $4M; PO 2E-3: Cybersecurity penetration and red-team testing — $3M; PO 2E-4: Independent automation safety assessment — $2M	$15M
2F. Supervised operating demonstration	PO 2F-1: Crew-supervised automated flight campaign — $10M; PO 2F-2: Automated refueling and reloading demonstrations — $5M; PO 2F-3: Reliability-growth testing and software corrections — $6M; PO 2F-4: Operator manuals, training and final software release — $4M	$25M
	Work-package total	$110M

A useful contracting distinction is that the flight-automation developer should not be the only organization responsible for safety verification. Independent verification should have its own PO and reporting line.

Area 3. New 65,000-foot aircraft design — $105 million

Phase	Illustrative purchase orders	Phase total
3A. Mission requirements	PO 3A-1: Aircraft mission and performance requirements — $3M; PO 3A-2: Fleet, base and maintenance concept — $3M; PO 3A-3: Preliminary certification basis — $2M; PO 3A-4: Independent validation of the 100-ton/65,000-foot requirement — $2M	$10M
3B. Competing aircraft concepts	PO 3B-1: Conceptual design, Team A — $3M; PO 3B-2: Conceptual design, Team B — $3M; PO 3B-3: Conceptual design, Team C — $3M; PO 3B-4: Independent propulsion concept study — $3M; PO 3B-5: Concept evaluation and down-selection — $3M	$15M
3C. Preliminary multidisciplinary design	PO 3C-1: Aerodynamics and wing design — $7M; PO 3C-2: Structural design and loads analysis — $6M; PO 3C-3: Flight controls, stability and aircraft systems — $5M; PO 3C-4: Payload-tank and release-system integration — $4M; PO 3C-5: Overall configuration integration — $3M	$25M
3D. Component and physical testing	PO 3D-1: Engine and high-altitude inlet studies — $7M; PO 3D-2: Wind-tunnel models and tests — $5M; PO 3D-3: Structural material and joint testing — $3M; PO 3D-4: Tank, valve and plumbing high-altitude tests — $3M; PO 3D-5: Environmental and material-compatibility tests — $2M	$20M
3E. Integrated preliminary design	PO 3E-1: Integrated three-dimensional aircraft definition — $7M; PO 3E-2: Final preliminary weight and performance model — $4M; PO 3E-3: Manufacturing and maintainability plan — $4M; PO 3E-4: Fleet lifecycle and operating-cost model — $3M; PO 3E-5: Supplier and manufacturing-readiness assessment — $2M	$20M
3F. Design review and Phase II package	PO 3F-1: Independent preliminary design review — $4M; PO 3F-2: Design corrections following review — $3M; PO 3F-3: Prototype cost and schedule estimate — $4M; PO 3F-4: Phase II prototype request-for-proposals package — $2M; PO 3F-5: Final technical-data archive — $2M	$15M
	Work-package total	$105M

The three conceptual-design POs would intentionally fund competing approaches. The sponsor would not need to select a single configuration before seeing the competing results.

Area 4. Sulfur processing, storage and logistics pilot — $85 million

Phase	Illustrative purchase orders	Phase total
4A. Material and logistics trade study	PO 4A-1: Feedstock and material-form comparison — $2M; PO 4A-2: Rail, truck, ship and airport logistics study — $2M; PO 4A-3: Process simulation and material-balance model — $2M; PO 4A-4: Independent trade-study review — $1M	$7M
4B. Front-end engineering and hazard analysis	PO 4B-1: Front-end engineering design — $4M; PO 4B-2: HAZOP and quantitative risk assessment — $3M; PO 4B-3: Environmental and permitting analysis — $2M; PO 4B-4: Emergency-response plan — $1M	$10M
4C. Detailed engineering	PO 4C-1: Detailed process and mechanical engineering — $5M; PO 4C-2: Electrical, instrumentation and controls engineering — $2M; PO 4C-3: Civil and site engineering — $2M; PO 4C-4: Equipment procurement specifications — $1M	$10M
4D. Pilot-facility fabrication and construction	PO 4D-1: Receiving and storage tanks — $8M; PO 4D-2: Sulfur-processing or SO_2-conditioning skids — $8M; PO 4D-3: Pumps, compressors, piping and valves — $6M; PO 4D-4: Aircraft-loading gantry and automated couplings — $4M; PO 4D-5: Containment, ventilation and fire-protection systems — $4M; PO 4D-6: Site construction and equipment installation — $3M	$33M
4E. Commissioning and validation	PO 4E-1: Facility commissioning services — $4M; PO 4E-2: Flow-meter calibration and inventory-accounting system — $3M; PO 4E-3: Process-performance validation — $4M; PO 4E-4: Operator training — $2M; PO 4E-5: Independent facility acceptance testing — $2M	$15M
4F. Turnaround and emergency demonstrations	PO 4F-1: Ground-automation integration — $3M; PO 4F-2: Spill, leak and emergency exercises — $2M; PO 4F-3: Repeated aircraft-turnaround demonstration — $3M; PO 4F-4: Replicable full-scale facility design package — $2M	$10M
	Work-package total	$85M

The construction POs should be issued only after the material form is selected. A facility optimized for elemental sulfur could be substantially different from one receiving and storing liquid SO_2.

Area 5. Monitoring hardware, release metrology, and calibration systems — $110 million

Phase	Illustrative purchase orders	Phase total
5A. Measurement requirements	PO 5A-1: Release-metrology and reusable measurement requirements — $3M; PO 5A-2: Instrument accuracy and uncertainty budgets — $2M; PO 5A-3: Operational release-verification requirements — $1M; PO 5A-4: Independent scientific review — $2M	$8M

Phase	Illustrative purchase orders	Phase total
5B. Monitoring architecture	PO 5B-1: Reusable monitoring hardware and interface architecture — $4M; PO 5B-2: Aircraft, balloon, lidar and ground-platform trade study — $3M; PO 5B-3: Communications and data-interface design — $2M; PO 5B-4: Calibration and reference-standard plan — $2M; PO 5B-5: Monitoring-hardware lifecycle cost estimate — $1M	$12M
5C. Instrument prototype fabrication	PO 5C-1: SO_2 measurement instruments — $6M; PO 5C-2: Aerosol concentration, size and composition instruments — $7M; PO 5C-3: Radiometers and optical-depth instruments — $4M; PO 5C-4: Ozone, water-vapor and atmospheric-chemistry instruments — $5M; PO 5C-5: Aircraft release-flow and operations-verification instruments — $4M; PO 5C-6: Balloon and ground-station prototype packages — $4M	$30M
5D. Calibration and qualification	PO 5D-1: Atmospheric calibration chamber — $5M; PO 5D-2: Reference gases, particles and standards — $2M; PO 5D-3: Temperature, pressure, vibration and environmental qualification — $3M; PO 5D-4: Instrument intercomparison campaign — $3M; PO 5D-5: Formal uncertainty and calibration documentation — $2M	$15M
5E. Field integration and validation	PO 5E-1: Aircraft instrument installation — $6M; PO 5E-2: Balloon and lidar validation trials — $6M; PO 5E-3: Initial ground-monitoring stations — $5M; PO 5E-4: Satellite-data cross-validation — $4M; PO 5E-5: Field-campaign personnel and operations — $6M; PO 5E-6: Instrument corrections after field testing — $3M	$30M
5F. Operational procedures and final network design	PO 5F-1: Calibration and operating procedures — $3M; PO 5F-2: Maintenance and spare-instrument plan — $2M; PO 5F-3: Data-quality and anomaly-detection system — $3M; PO 5F-4: Phase II monitoring-network design — $4M; PO 5F-5: Independent monitoring-readiness review — $2M; PO 5F-6: Instrument-operator training — $1M	$15M
	Work-package total	$110M

Several competing instrument developers could receive small prototype POs, with the best instruments selected after intercomparison testing.

Area 6. Systems integration and testing — $65 million

Phase	Illustrative purchase orders	Phase total
6A. Verification planning	PO 6A-1: Master verification and validation plan — $2M; PO 6A-2: Requirements-traceability and configuration system — $1M; PO 6A-3: Test standards and acceptance criteria — $2M	$5M
6B. Systems-integration laboratory	PO 6B-1: Laboratory buildout — $3M; PO 6B-2: Hardware-in-the-loop equipment — $4M; PO 6B-3: Software and communications integration bench — $2M; PO 6B-4: Laboratory commissioning — $1M	$10M

Phase	Illustrative purchase orders	Phase total
6C. Subsystem qualification	PO 6C-1: Environmental and vibration testing — $4M; PO 6C-2: Chemical and material-compatibility tests — $2M; PO 6C-3: Endurance and deliberate-failure testing — $3M; PO 6C-4: Qualification reports — $1M	$10M
6D. Full-scale ground campaign	PO 6D-1: Aircraft-to-ground-system integrated tests — $6M; PO 6D-2: Hazardous-material safety support — $3M; PO 6D-3: Emergency-response exercises — $2M; PO 6D-4: Test instrumentation and data collection — $3M; PO 6D-5: Independent test witnessing — $1M	$15M
6E. Integrated flight campaign	PO 6E-1: Flight-test aircraft, pilots and engineering crew — $7M; PO 6E-2: Airspace, telemetry and flight-range services — $3M; PO 6E-3: Chase and monitoring-aircraft services — $2M; PO 6E-4: Flight-data reduction — $2M; PO 6E-5: Independent flight-safety review — $1M	$15M
6F. End-to-end demonstration	PO 6F-1: Complete mission-cycle demonstrations — $4M; PO 6F-2: Reliability-growth and deficiency correction — $3M; PO 6F-3: Final readiness review — $2M; PO 6F-4: System-acceptance report — $1M	$10M
	Work-package total	$65M

This integration budget should not duplicate ordinary contractor testing. It pays for tests involving multiple systems and multiple contractors.

Area 7. Engineering digital twin, data platform, and mission operations center — $45 million

Phase	Illustrative purchase orders	Phase total
7A. Engineering data and system requirements	PO 7A-1: Engineering data/open-access plan — $2M; PO 7A-2: Contractor/instrument interface requirements — $1M; PO 7A-3: Cybersecurity and archival architecture — $2M	$5M
7B. Engineering digital twins	PO 7B-1: Aircraft/payload digital twin — $4M; PO 7B-2: Ground/material-flow/logistics digital twin — $4M; PO 7B-3: Maintenance/availability model — $2M; PO 7B-4: External scientific-model interface emulator/validation — $2M	$12M
7C. Mission-control platform	PO 7C-1: Mission/fleet-management software — $5M; PO 7C-2: Operator displays and visualization — $2M; PO 7C-3: Equipment status, alarms and pause controls — $3M	$10M
7D. Engineering data ingestion / QC	PO 7D-1: Real-time engineering-data ingestion — $3M; PO 7D-2: Automated data-quality/configuration checks — $2M; PO 7D-3: External weather/science-product interfaces — $2M; PO 7D-4: Metadata/configuration catalog — $1M	$8M

Phase	Illustrative purchase orders	Phase total
7E. Integrated simulation exercises	PO 7E-1: Mission and emergency simulations — $3M; PO 7E-2: Failure-scenario library — $1M; PO 7E-3: Exercise analysis and software correction — $2M	$6M
7F. Public engineering archive / handoff	PO 7F-1: Public engineering portal and APIs — $2M; PO 7F-2: Long-term engineering/configuration archive — $1M; PO 7F-3: Software documentation and open-source release — $1M	$4M
	Work-package total	$45M

The public portal should show both raw and processed data, calibration information, uncertainty estimates, software versions, and changes made after data release.

Area 8. Program management, safety and independent assurance — $50 million

Phase	Illustrative purchase orders	Phase total
8A. Program formation	PO 8A-1: Program-management-office support — $3M; PO 8A-2: Lead systems-engineering support — $2M; PO 8A-3: Contracting, accounting and financial controls — $2M; PO 8A-4: Scientific, safety and public-interest panel formation — $1M	$8M
8B. Requirements and preliminary-design oversight	PO 8B-1: Independent requirements review — $2M; PO 8B-2: Independent cost estimate — $2M; PO 8B-3: Integrated schedule and risk analysis — $2M; PO 8B-4: Independent preliminary design reviews — $2M	$8M
8C. Detailed-design and procurement oversight	PO 8C-1: Resident contractor surveillance — $3M; PO 8C-2: Configuration and technical-data management — $2M; PO 8C-3: Manufacturing and quality audits — $2M; PO 8C-4: Supply-chain and vendor-risk review — $1M; PO 8C-5: Cost and schedule performance monitoring — $2M	$10M
8D. Test and regulatory oversight	PO 8D-1: Independent flight-safety organization — $3M; PO 8D-2: Environmental review and public documentation — $3M; PO 8D-3: Aviation and airspace coordination — $2M; PO 8D-4: Emergency-response oversight — $2M; PO 8D-5: Independent test-readiness boards — $2M	$12M
8E. Final readiness and Phase II planning	PO 8E-1: Updated lifecycle cost estimate — $3M; PO 8E-2: Independent operational-readiness review — $3M; PO 8E-3: Financial, scientific and open-data audit — $2M; PO 8E-4: Phase II contracting and procurement plan — $3M; PO 8E-5: Program closeout and lessons-learned report — $1M	$12M
	Work-package total	$50M

The independent safety, cost and readiness reviewers should be hired directly by the funding sponsor, not through the principal aircraft contractor.

Area 9. Central technical and schedule reserve — $200 million

These POs would **not be issued initially**. They would be preplanned contingent task orders activated only when a documented problem occurs.

Reserve phase	Possible contingent purchase orders	Maximum reserve
9A. Requirements and feasibility reserve	PO 9A-1: Additional payload or aircraft studies — up to $6M; PO 9A-2: Early subsystem redesign — up to $6M; PO 9A-3: Additional environmental or regulatory analysis — up to $4M; PO 9A-4: Early schedule-recovery support — up to $4M	$20M
9B. Preliminary-design reserve	PO 9B-1: Structural or tank redesign — up to $10M; PO 9B-2: Additional propulsion testing — up to $8M; PO 9B-3: Safety-system redesign — up to $7M; PO 9B-4: Competing or second-source prototypes — up to $6M; PO 9B-5: Independent technical red team — up to $4M	$35M
9C. Fabrication and construction reserve	PO 9C-1: Replacement of failed supplier — up to $15M; PO 9C-2: Unexpected long-lead components — up to $15M; PO 9C-3: Manufacturing rework — up to $15M; PO 9C-4: Facility or site modifications — up to $10M; PO 9C-5: Exceptional logistics or price escalation — up to $5M	$60M
9D. Integration and test reserve	PO 9D-1: Replacement test articles — up to $15M; PO 9D-2: Additional flight-test hours — up to $15M; PO 9D-3: Major software corrections — up to $10M; PO 9D-4: Hardware redesign after failed tests — up to $15M; PO 9D-5: Failure investigation and repairs — up to $10M	$65M
9E. Final schedule and demonstration reserve	PO 9E-1: Additional reliability cycles — up to $8M; PO 9E-2: Final deficiency correction — up to $6M; PO 9E-3: Additional documentation or regulatory work — up to $3M; PO 9E-4: Final schedule-recovery support — up to $3M	$20M
	Maximum reserve	$200M

Consolidated totals

Procurement area	Planned POs
Modified 777-class demonstrator	$230M
Automated flight and ground turnaround	$110M
New 65,000-foot aircraft design	$105M
Sulfur processing and logistics pilot	$85M

Procurement area	Planned POs
Monitoring hardware / release metrology / calibration	$110M
Systems integration and testing	$65M
Engineering digital twin / data / mission operations	$45M
Program management, safety and independent assurance	$50M
Baseline procurements	**$800M**
Central technical and schedule reserve	$200M
Total authorization	**$1.000B**

Recommended contracting structure

Rather than issuing hundreds of unrelated purchase orders, the sponsor could establish approximately **eight prime contract vehicles**, one for each main work package. The detailed POs above would then become subcontracts or task orders under those vehicles.

Three contract types would probably be needed:

- **Fixed-price milestone contracts** for well-defined studies, standard equipment, aircraft acquisition, calibration services and final reports.
- **Cost-plus or cost-reimbursement contracts** for novel aircraft modifications, autonomy development, prototype instrumentation and flight testing, where requirements will change as problems are discovered.
- **Indefinite-delivery task-order contracts** for flight hours, engineering support, testing services and contingent reserve work.

Payments for major hardware should generally be tied to tangible milestones—for example, 10% at design approval, 20% at procurement of long-lead materials, 30% after fabrication, 20% after installation, and 20% after passing acceptance tests—rather than being paid entirely on the basis of contractor labor hours.

Potential Performers and Facilities

Prompt to AI: Which types of organizations and facilities might competitively perform the major SAI equipment-development work?

Response From AI:

The organizations below are illustrative capability examples drawn from the existing proposal, not endorsements, prequalified bidders, or selections. Current capability, availability, conflicts, export/regulatory constraints, and price should be reverified at procurement. Early concept work should be competed wherever practical, and independent reviewers should report outside the performer whose work they evaluate.

Capability	Illustrative organizations / facilities	Likely role
Commercial-aircraft design authority / modification	Boeing Global Services; ST Engineering; Lufthansa Technik; AAR; Calspan.	777 feasibility, airframe modification, integration, hangar/MRO, conformity and flight-test support.
High-altitude aircraft concepts	Aurora/Boeing; Northrop Grumman; Lockheed Martin Skunk Works.	Competing 65,000-ft-class concepts and preliminary design.
High-altitude propulsion / aero testing	NASA Glenn; NASA Langley; engine OEMs; Calspan; qualified wind-tunnel facilities.	Propulsion/inlet studies, wind tunnel, component and altitude testing.
Automation / avionics / cyber	Honeywell; Collins Aerospace; Aurora; Reliable Robotics; MITRE; Battelle.	Supervised automation, avionics interfaces, HIL, software assurance and cyber red-team work.
Sulfur / industrial process EPC	Air Liquide Engineering; Linde Engineering; Worley; specialist pump/valve/control suppliers.	Material-form studies, FEED/EPC, storage/conditioning/loading, commissioning and replicable base design.
Process / hazardous-material assurance	Exponent; Southwest Research Institute; independent process-safety firms.	Materials compatibility, HAZOP/QRA, failure analysis, emergency systems and independent acceptance.
Atmospheric instrumentation / metrology	NOAA CSL; NASA Langley; NSF NCAR/UCAR; NIST-linked metrology; Aerodyne; TSI; Droplet Measurement Technologies; Vaisala.	Prototype instruments, calibration, intercomparison, interfaces and uncertainty certification.
Systems integration / qualification	Southwest Research Institute; Battelle; NASA Armstrong; Calspan; The Aerospace Corporation.	Integration laboratories, qualification, flight test, independent readiness and acceptance.

Capability	Illustrative organizations / facilities	Likely role
Engineering data / mission operations	MITRE; UCAR/NCAR; Boeing/Collins/Honeywell digital teams; selected government/public-sector cloud and geospatial providers.	Configuration, mission-control, data integration, cyber architecture and open technical archive.
Sponsor-side assurance / cost review	MITRE; The Aerospace Corporation; Exponent; independent aerospace cost/schedule and audit firms.	Requirements, cost, schedule, safety, readiness, reserve and Phase II evidence independent of technical primes.

Recommended contracting structure

Use a limited number of competed prime or master vehicles with task orders/subcontracts for defined packages. The high-altitude aircraft concept phase should intentionally fund multiple teams. The sulfur pilot should use competitive front-end engineering before selecting an EPC path. Monitoring hardware should permit competing prototype instruments followed by intercomparison/down-selection. Flight-safety, software verification, process-safety acceptance, calibration certification, and independent cost/readiness reviews should remain structurally independent.

Most important conflict-of-interest separations

- The aircraft prime should not approve its own airworthiness or flight-readiness conclusions.
- The autonomy developer should not perform the final independent software verification.
- The sulfur/process EPC contractor should not conduct the final HAZOP or facility acceptance alone.
- Instrument manufacturers should not be solely responsible for calibration and uncertainty certification.
- The Managing Organization and major recipients should not control the independent panel findings or reserve-release decision.

Project Management

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

Response From AI:

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

Initiative-specific management requirements

The Managing Organization must be capable of safety-critical aerospace and industrial development: commercial-aircraft modification, high-altitude aircraft concept/design competition, automated flight and ground operations, hazardous sulfur/SO_2 processing and loading, atmospheric instrumentation, systems integration, qualification, flight test, environmental review, and acceptance of hardware/software deliverables.

Maintain one configuration-controlled system baseline across the eight baseline work packages plus the central reserve: modified 777-class demonstrator; flight and ground automation; 65,000-foot aircraft preliminary design; sulfur processing/logistics; monitoring hardware/release metrology/calibration; systems integration/testing; engineering digital twin/data/mission operations; owner-side program assurance; and the central technical/schedule reserve.

Assign accountable leads for aircraft/airworthiness and requirements traceability, autonomy/software assurance and cybersecurity, sulfur/process safety, monitoring/metrology/data, lifecycle economics, and cross-contractor integration/test. A developer may not be the sole organization accepting its own critical safety, performance, calibration, or cost claim.

Coordinate formally with the companion SAI Experimental Research Initiative. Equipment Development builds and qualifies reusable delivery, sulfur-handling, monitoring, and operating capability; Experimental Research determines whether and how any atmospheric release is scientifically justified and interprets the atmospheric results. Shared aircraft, instruments, data systems, and other assets must have one lead budget and an auditable usage/transfer rule so the same asset is not funded twice.

Equipment ground and flight tests should use safe simulants whenever possible. Actual SO_2, sulfuric-acid, or other stratospheric releases require the separate scientific, environmental, legal, and governance authorization applicable to atmospheric experiments; an engineering PO or change order cannot authorize climate-relevant release.

Completion of the five-year equipment program ends with independently reviewed demonstrator evidence, a sulfur-facility/monitoring capability package, a credible 65,000-foot aircraft preliminary design, updated lifecycle cost and risk estimates, and a Phase II decision package. It creates no entitlement to an operational fleet or deployment.

Funding Source Requirements

Prompt to AI: Which Funding Source requirements are specific to the SAI Equipment Development Initiative beyond the portfolio-wide requirements in the common framework?

Response From AI:

The portfolio-wide Funding Source requirements are specified in the Moonshot Common Framework. The additions below address the program's equipment-development boundary, aircraft and process safety, autonomy, sulfur handling, monitoring/metrology, shared assets, lifecycle economics, and Phase II decision package.

Program-specific additions

Keep the five-year authorization limited to R&D, design competition, prototypes, engineering qualification, monitoring capability, supervised flight/ground demonstrations, and decision support. It does not authorize an operational SAI fleet or climate-scale atmospheric intervention.

Require a configuration-controlled Requirements Traceability Matrix linking scientific/mission needs to measurable engineering requirements for payload, altitude, cycle time, material form, aircraft configuration, sulfur processing/loading, automation, monitoring, interfaces, verification methods, uncertainty, and the recorded acceptance or redesign decision.

Require independent verification of airworthiness and structural margins, hazardous-material/process safety, automation/software assurance and cybersecurity, release-flow metrology, atmospheric-instrument calibration, test evidence, reliability/maintainability, and lifecycle cost before the program claims readiness.

Require the final technical record to include native CAD and interface specifications, mass/loads assumptions, bills of material, source code, configuration history, calibration, raw and processed test data, failures/corrective actions, operating and maintenance evidence, supplier/manufacturing assumptions, and lifecycle-cost/emissions calculations under the common open-source/data policy.

Apply the common shared-asset rule to the companion SAI Experimental Research Initiative: purchase each reusable aircraft modification, instrument suite, data system, test facility, or other physical/digital asset once; the other initiative pays only incremental adaptation, operating time, consumables, or intentionally independent capacity.

Keep the $200 million central technical and schedule reserve outside contractor entitlement. Release it only for documented redesign, competing concepts/second sources, replacement test articles, failed qualification or flight tests, integration/schedule recovery, or other initiative-specific needs that pass the common reserve/change-control process.

Program-specific success metric

Measure success by reproducible engineering evidence: payload/altitude and turnaround feasibility, safe sulfur/SO_2 handling, automation reliability and human override, release metrology, monitoring closure, airworthiness/test evidence, lifecycle cost and maintainability, and a credible low/base/high Phase II development and fleet-sizing model. Climate efficacy and any decision to deploy remain separate scientific and policy conclusions with stated uncertainty.

Top SAI Engineering and Equipment References

Prompt to AI: Summarize the top papers that related to our proposed research fund

Response From AI:

How I selected the papers

"Top" is not a strict citation ranking. This chapter emphasizes references that change equipment requirements or architecture: aircraft and sulfur-delivery feasibility; precursor/material form; aerosol generation and wake behavior; monitoring and detectability; injection altitude/location flexibility; infrastructure and cost; and equipment-relevant safety or continuity requirements. Broader climate-impact literature belongs primarily in SAI Experimental Research and GCM unless it directly establishes an engineering requirement.

- Aircraft and sulfur-delivery feasibility.
- Aerosol formation, precursor choice, particle size, wake behavior, and delivery efficiency.
- Release metrology, monitoring hardware, detectability, and field-test interfaces.
- Injection altitude/location flexibility and control requirements that affect aircraft and base design.
- Ozone, heating, continuity, and other risks only where they create explicit monitoring or reliability requirements.

A central conclusion is that the literature **does not yet validate a 777 carrying 100 metric tons to approximately 65,000 feet every five hours**. Existing engineering studies generally point toward specialized aircraft, smaller payloads, and major propulsion and high-altitude design challenges. The fund should therefore treat the 100-ton requirement as a research question, not a predetermined specification.

A. Foundational and engineering papers

Crutzen, 2006 — "Albedo Enhancement by Stratospheric Sulfur Injections"

This paper reopened serious scientific discussion of injecting sulfur into the stratosphere to increase planetary reflectivity. Crutzen argued that sulfur injection might provide temporary cooling if emissions reductions remained inadequate, while emphasizing that it was not a substitute for reducing greenhouse gases.

Fund relevance: It establishes the basic sulfur-based concept and identifies ozone chemistry, atmospheric lifetime, quantity required, and environmental consequences as essential research questions.

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 examined delivery methods, aerosol behavior, climate-model results, and important uncertainties. It concluded that sulfate aerosol could offset much global-average warming, but would not reproduce the original climate exactly.

Fund relevance: This is a useful starting framework for dividing the program into delivery, aerosol microphysics, climate modeling, monitoring, and side-effect workstreams.

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

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

The simulations found that both tropical and Arctic sulfur injection could cool the planet, but could also alter regional precipitation. In particular, the modeled interventions disrupted Asian and African summer monsoons.

Fund relevance: It shows why optimizing only global-average temperature is inadequate. The monitoring and modeling programs must evaluate precipitation and regional climate, especially in heavily populated monsoon regions.

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

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

This paper examined practical aircraft deployment, bases, flight numbers, payload delivery, and costs. It estimated that a hypothetical program would require thousands of flights annually and likely a purpose-built high-altitude aircraft rather than an existing commercial aircraft.

Fund relevance: This is the principal paper against which the proposed aircraft program should be compared. It suggests that aircraft design, engine performance, fleet manufacturing, bases, and turnaround operations—not sulfur purchase—would dominate implementation complexity.

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

Janssens, 2020 — “A Specialised Delivery System for Stratospheric Sulphate Aerosols: Design and Operation”

The authors developed a detailed conceptual unmanned aircraft designed for approximately 20-kilometer operation. Their configuration required an unusually large strut-braced wing and four custom high-altitude turbofan engines; they found aircraft performance highly sensitive to delivery altitude and propulsion.

Fund relevance: This paper provides a much better starting point for the new 65,000-foot aircraft than a modified 777. It also indicates that custom engines, aerodynamic limits, aerosol-dispersion rate, and operation near the aircraft’s “coffin corner” deserve early physical testing.

https://doi.org/10.1007/s10584-020-02740-3

Smith, 2018 — “Production of Sulfates Onboard an Aircraft”

This preliminary engineering assessment considered carrying elemental sulfur and converting it onboard into SO_2, SO_3, or sulfuric acid. Because elemental sulfur contains more sulfur per unit mass than SO_2 or sulfuric acid solution, onboard conversion might reduce the material mass that must be lifted, although it adds chemical equipment, heat, and safety challenges.

Fund relevance: The proposed sulfur-processing workstream should compare at least three architectures: ground-produced SO_2, onboard sulfur conversion, and direct sulfuric-acid aerosol production.

https://doi.org/10.1002/2018EA000370

Smith, 2024 — “An Assessment of the Infrastructural and Temporal Barriers Constraining a Near-Term Implementation of a Global SAI Program”

This paper argues that starting a global SAI program would take much longer than is implied by “emergency response” scenarios. Aircraft development, engine development, factory construction, fleet production, bases, sulfur infrastructure, testing, and authorization could take many years or decades.

Fund relevance: It supports beginning equipment development well before any possible decision to deploy. It also means that the five-year fund should deliver validated designs and prototypes—not promise an operational global system.

https://doi.org/10.1088/2515-7620/ad4f5c

Duffey, 2025 — "Low-Altitude High-Latitude Stratospheric Aerosol Injection Is Feasible with Existing Aircraft"

This study explored injecting at relatively low stratospheric altitudes in high latitudes, where the tropopause is lower. It concluded that some climate-relevant injections might be technically possible with existing aircraft, although the resulting aerosol distribution, seasonality, efficiency, and climate effects differ from tropical high-altitude injection.

Fund relevance: The fund should not assume that 65,000 feet is always optimal. It should compare high-altitude tropical injection against lower-altitude, high-latitude approaches that could be demonstrated sooner with modified aircraft.

https://doi.org/10.1029/2024EF005567

B. Aerosol formation, chemistry, and efficiency

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

The authors modeled the release of sulfuric-acid vapor rather than SO_2. Rapid nucleation and dilution in an aircraft wake might create smaller particles closer to the size that efficiently scatters sunlight.

Fund relevance: This paper motivates aircraft-wake experiments measuring dilution, nucleation, coagulation, particle size, and plume evolution over seconds to hours.

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

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

This work compared SO_2, sulfuric-acid vapor, and direct aerosol injection using a three-dimensional aerosol model. It found that the injected form and resulting particle-size distribution substantially influence aerosol burden and optical depth.

Fund relevance: The sulfur-handling system should not be designed before the program decides what chemical and physical form should leave the aircraft. The decision changes tanks, pumps, nozzles, thermal controls, and required payload.

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

Niemeier, 2015 — "What Is the Limit of Stratospheric Sulfur Climate Engineering?"

This study examined the diminishing effectiveness of increasing SO_2 injection. Higher injection rates generate larger particles, which scatter less sunlight per unit mass and settle faster.

Fund relevance: Cooling is not proportional to sulfur mass. The fund needs experiments and models establishing the relationship among injection rate, particle growth, lifetime, optical depth, and radiative forcing before sizing an operational fleet.

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

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

The authors compared injecting SO_2 with injecting sulfuric-acid particles of a controlled initial size. Their model found that accumulation-mode sulfuric-acid aerosol could provide greater radiative efficacy than SO_2 under the assumptions studied.

Fund relevance: Controlled-particle injection could reduce the annual mass and aircraft flights required. It would, however, require difficult equipment for manufacturing, transporting, preventing coagulation, and dispersing corrosive aerosol.

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

Weisenstein, 2022 — "An Interactive Stratospheric Aerosol Model Intercomparison…"

Multiple interactive aerosol models compared SO_2 and accumulation-mode sulfuric-acid injection. The study found meaningful intermodel differences in aerosol size, spatial distribution, lifetime, and radiative forcing.

Fund relevance: The research program should fund multiple modeling groups using common cases and common released input data. Relying on one model could create unjustified confidence in aircraft requirements or expected cooling.

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

Kremser, 2016 — "Stratospheric Aerosol—Observations, Processes, and Impact on Climate"

This major review synthesized knowledge about natural and volcanic stratospheric aerosols, including sources, transport, microphysics, observations, radiative effects, and climate impacts. It also documented important limitations in existing measurement systems.

Fund relevance: It should guide the design of the monitoring network and the use of volcanic eruptions as natural validation cases for instruments and models.

https://doi.org/10.1002/2015RG000511

Golja, 2021 — "Aerosol Dynamics in the Near Field of the SCoPEx Stratospheric Balloon Experiment"

This paper modeled how released material would mix, dilute, and evolve in the turbulent near field of a small stratospheric experiment. It demonstrated that the initial plume and platform-generated turbulence strongly affect what instruments would encounter.

Fund relevance: A small experiment cannot simply release material and sample "downwind." The release mechanism, vehicle wake, turbulence, flight path, sampling geometry, and elapsed time must be jointly designed.

https://doi.org/10.1029/2020JD033438

Lange, 2025 — "Investigating the Ability of Satellite Occultation Instruments to Monitor Possible Geoengineering Experiments"

This study assessed whether current satellite occultation instruments could detect aerosol resulting from relatively small continuous sulfur injections. It found that steady-state injections at the modeled scale could be detectable, but early-stage changes—particularly during the first month—could be difficult to distinguish from background variability.

Fund relevance: Satellites alone will not provide complete early verification. The monitoring design needs in-situ aircraft, balloons, lidar, ground observations, and satellite measurements working together.

https://doi.org/10.5194/acp-25-11673-2025

C. Injection strategy, control, and experiment design

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

This study used injections at several latitudes and a feedback-control strategy to pursue several temperature objectives simultaneously, rather than controlling only the global mean. It demonstrated that injection location and quantity could be adjusted to influence temperature gradients.

Fund relevance: Aircraft and operating-center designs should support variable injection latitude, altitude, season, and rate. A system optimized for only one fixed route could prevent later control strategies.

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

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

The GLENS project produced a large ensemble of simulations using interactive stratospheric chemistry, aerosols, atmospheric dynamics, oceans, and land. Multiple injections were adjusted to maintain global temperature and temperature-gradient objectives.

Fund relevance: GLENS is an important baseline dataset for defining which climate variables, geographic regions, and side effects the monitoring program must examine. It also illustrates why ensembles are necessary to distinguish forced responses from ordinary climate variability.

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

Laakso, 2022 — "Dependency of the Impacts of Geoengineering on the Stratospheric Sulfur Injection Strategy"

This modeling study showed that estimated aerosol behavior and climate consequences depend strongly on injection strategy and aerosol-model formulation. Differences in latitude, altitude, season, and model microphysics can alter the outcome.

Fund relevance: The program should compare alternative injection patterns before locking the aircraft, bases, and loading facilities into a single operating concept.

https://doi.org/10.5194/acp-22-93-2022

Keith, 2014 — "Field Experiments on Solar Geoengineering"

This paper laid out a portfolio of possible field experiments ranging from small atmospheric-process studies to larger measurements. It emphasized designing experiments around specific uncertainties that cannot be resolved adequately through laboratories, observations, or models alone.

Fund relevance: This should be a central reference for the proposed experiment-selection process. Each release experiment should identify the decision it enables and demonstrate why a smaller or non-release experiment cannot answer the question.

https://doi.org/10.1098/rsta.2014.0175

MacMartin, 2019 — "Mission-Driven Research for Stratospheric Aerosol Geoengineering"

The authors argued that research should be organized backward from the information policymakers would need to make decisions, rather than as an open-ended collection of interesting scientific studies. They proposed a clear boundary between research-scale activities and deployment.

Fund relevance: This paper strongly supports the proposed PM/PO model. Every PO should identify the deployment or policy uncertainty it reduces, the required evidence, and the decision that follows from the result.

https://doi.org/10.1073/pnas.1811022116

D. Side effects and failure risks

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

Using knowledge from volcanic aerosol and polar ozone chemistry, this paper found that sustained sulfate enhancement could increase heterogeneous chemical reactions that destroy ozone, particularly while significant chlorine remains in the stratosphere.

Fund relevance: Ozone-related instruments, chemistry models, laboratory reaction studies, and UV monitoring are mandatory—not secondary additions to the monitoring program.

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

Ferraro, 2011 — "Stratospheric Heating by Potential Geoengineering Aerosols"

The authors calculated that candidate aerosols absorb some solar and terrestrial radiation and therefore heat the stratosphere. Heating varies with aerosol material and particle size and can alter temperature gradients and atmospheric circulation.

Fund relevance: Selecting an aerosol based only on visible-light scattering would be a mistake. Measurements must cover full spectral optical properties, infrared absorption, stratospheric temperature, water vapor, and circulation.

https://doi.org/10.1029/2011GL049761

Eastham, 2018 — "Quantifying the Impact of Sulfate Geoengineering on Mortality from Air Quality and UV-B Exposure"

This study modeled changes in surface particulate matter, ozone, and ultraviolet exposure. It showed that health effects arise through several competing pathways, including settling sulfate, climate-mediated air-quality changes, and ozone-layer effects.

Fund relevance: A credible side-effects program needs atmospheric chemistry linked to population exposure and health-impact modeling. Measuring only sulfate deposition would miss potentially larger indirect effects.

https://doi.org/10.1016/j.atmosenv.2018.05.047

Jones, 2013 — "The Impact of Abrupt Suspension of Solar Radiation Management"

GeoMIP models were used to examine sudden termination after decades of offsetting greenhouse warming. The models showed rapid warming, precipitation changes, and sea-ice loss following termination.

Fund relevance: Reliability and continuity are climate-safety requirements. Aircraft redundancy, reserve sulfur capacity, multiple bases, spare equipment, cybersecurity, political continuity, and gradual phase-down plans should be included in system design from the beginning.

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

What these papers imply for the research fund

The literature suggests six priorities.

Research priority	Approximate implication
Aircraft architecture competition	Compare modified commercial aircraft, lower-altitude existing-aircraft operation, and purpose-built 20-kilometer aircraft before committing to one design
Aerosol-form competition	Compare SO_2, onboard sulfur conversion, sulfuric-acid vapor, and controlled-size aerosol
Near-field experiments	Measure aircraft-wake dilution, nucleation, coagulation, dispersion, and nozzle performance
Integrated monitoring	Combine aircraft, balloons, lidar, ground instruments, and satellites; do not rely on one platform
Multi-objective modeling	Optimize regional temperature, precipitation, ozone, and circulation—not only global-average cooling
Reliability and termination planning	Design for interruptions, failed bases, grounded aircraft, supplier failures, and orderly phase-down

The most important unanswered engineering questions

Based on these papers, the first major POs should answer:

1. Can a modified 777 safely carry a meaningful sulfur payload, and to what altitude?
2. Is 100 tons at 65,000 feet physically and economically preferable to 15–25-ton purpose-built aircraft?
3. Should the aircraft carry SO_2, elemental sulfur, sulfuric-acid vapor, or premanufactured particles?
4. What nozzle and wake conditions produce the desired particle-size distribution?
5. How does radiative forcing per ton change as injection increases?
6. What monitoring system can independently verify material released, aerosol formed, forcing produced, and side effects?
7. Which observations would reveal unacceptable ozone, precipitation, circulation, or health impacts early enough to stop?

The papers support the general concept of a large research effort, but they also suggest that prematurely building one specific 100-ton aircraft would be risky. A better first stage would fund competing aircraft and aerosol concepts, physical plume experiments, multiple atmospheric models, and independent measurement systems before selecting the final operating architecture.

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 of SAI researchers. The list below emphasizes people whose work is most directly relevant to the proposed **$1 billion equipment, experiments, modeling, and monitoring program**, rather than simply ranking publication counts.

Most relevant researchers

Core scientific and systems leaders

Researcher	Current base	Why especially relevant to the fund
David Keith	University of Chicago	Probably the broadest single expert across SAI science, technology, costs, experiments, and public policy. He founded UChicago's Climate Systems Engineering initiative after previously leading Harvard's solar-geoengineering program.
Frank Keutsch	Harvard University	Leading atmospheric chemist studying aerosol reactions, alternative particles, laboratory experiments, and measurement methods. He led the proposed SCoPEx stratospheric experiment.
Douglas MacMartin	Cornell University	Applies systems engineering and feedback-control theory to injection locations, quantities, climate targets, and operational strategy. Particularly useful for converting climate objectives into aircraft and monitoring requirements.
Daniele Visioni	Cornell University	One of the leading younger SAI climate and aerosol modelers; studies uncertainties, regional effects, injection designs, and aerosol behavior. He is a co-leader of GeoMIP.
Ben Kravitz	Indiana University	Co-founder and coordinator of the Geoengineering Model Intercomparison Project, which organizes standardized simulations across many climate-modeling centers.
Simone Tilmes	NSF National Center for Atmospheric Research	Leading researcher on stratospheric chemistry, ozone, aerosol injection altitude, atmospheric circulation, and whole-Earth-system impacts. She has led major GLENS and ARISE-SAI work.
Alan Robock	Rutgers University	Senior authority on volcanic analogues, regional climate impacts, precipitation, agriculture, termination effects, and the risks and limitations of SAI.
Jim Haywood	University of Exeter and UK Met Office	Major aerosol–radiation and climate-modeling expert and a long-standing participant in GeoMIP. His group studies SAI, marine cloud brightening, aerosol observations, and climate effects.

Ulrike Niemeier	Max Planck Institute for Meteorology	Important researcher on aerosol microphysics, injection strategies, particle growth, radiative efficiency, and climate-model responses.

Equipment, aerosol, and experimental specialists

Researcher	Current base	Relevant specialty
Wake Smith	Yale School of the Environment	Probably the most directly relevant researcher on aircraft requirements, fleet size, deployment logistics, infrastructure, and program cost. He also has senior commercial-aviation management experience.
Jim Franke	University of Chicago	Professional control-systems engineer now working on practical SAI implementation, sulfur precursor choices, aircraft systems, and engineering constraints.
Mingyi Wang	University of Chicago	Atmospheric chemist specializing in aerosol microphysics, nucleation, precursor chemistry, and predicting how injected gases form reflective particles.
Dan Cziczo	University of Chicago	Experimental aerosol and cloud physicist whose group develops high-altitude aircraft instruments and laboratory chambers that reproduce atmospheric conditions.
Sandro Vattioni	ETH Zurich	Leading researcher on alternatives to sulfate, including solid particles, and their effects on ozone chemistry, stratospheric heating, circulation, and climate.
Michael Mills	NSF NCAR	Developer and user of detailed stratospheric aerosol microphysics within the Community Earth System Model; important for predicting particle size, lifetime, transport, and chemistry.
Jadwiga Richter	NSF NCAR	Key leader in GLENS and ARISE-SAI simulations involving feedback-controlled injection strategies and coupled atmospheric responses.
Pete Irvine	University of Chicago	Studies regional and global climate consequences, partial cooling, polar strategies, hydrology, and how deployment choices alter benefits and risks.

Economics and governance

Researcher	Current base	Relevant specialty
Gernot Wagner	Columbia University	Economics, risk, public policy, moral hazard, and program costs; founding executive director of Harvard's Solar Geoengineering Research Program.
Jesse Reynolds	Degrees Initiative; UCLA affiliation	International law, governance of research and deployment, intellectual property, transparency, and participation by developing countries.

Researchers most important for your particular equipment program

For the proposed fund, I would place these people near the top of the initial consultation list:

1. **David Keith** — overall scientific and technical architecture.

2. **Douglas MacMartin** — systems requirements and control strategy.
3. **Wake Smith** — aircraft, fleet, logistics, and cost assumptions.
4. **Frank Keutsch** — aerosol chemistry, experiments, and instrumentation.
5. **Simone Tilmes** — ozone, chemistry-climate modeling, and monitoring requirements.
6. **Daniele Visioni** — injection strategies, aerosol modeling, and uncertainty analysis.
7. **Jim Franke** — practical implementation engineering.
8. **Mingyi Wang** — aerosol formation and sulfur-precursor selection.
9. **Jim Haywood** — aerosol radiative effects and model validation.
10. **Alan Robock** — independent scrutiny of side effects and failure risks.

I would not place the whole program under one of these researchers. The fund needs separate scientific, engineering, safety, and governance leadership, with researchers holding different views about SAI.

Leading organizations

1. University of Chicago Climate Systems Engineering initiative

UChicago is probably the **strongest emerging integrated SAI engineering center**. Its work now encompasses aircraft concepts, sulfur precursors, aerosol chemistry, monitoring, regional impacts, and policy. It is building a multidisciplinary faculty and research program rather than supporting only one or two researchers.

Best prospective roles:

- Overall architecture studies.
- Aircraft and sulfur-delivery trade studies.
- Aerosol precursor research.
- Monitoring-system concepts.
- Climate-risk and implementation modeling.
- Engineering-oriented research POs.

UChicago itself states that it is presently developing research and designs rather than constructing a deployment fleet.

2. NSF National Center for Atmospheric Research and UCAR

NSF NCAR is arguably the **most important SAI Earth-system modeling organization**. Its Community Earth System Model and Whole Atmosphere Community Climate Model represent aerosol microphysics, atmospheric chemistry, ozone, circulation, ocean, land, and climate feedbacks. NCAR led the GLENS and ARISE-SAI simulation efforts.

Best roles:

- Whole-Earth-system simulations.
- Aerosol and ozone modeling.
- Injection optimization.
- Regional impact analysis.
- Model–measurement comparisons.
- Design of operational monitoring requirements.

The contractual organization would generally be **UCAR**, which operates NCAR for the National Science Foundation.

3. Cornell Climate Engineering group

Cornell has an unusually strong combination of **mechanical and aerospace systems engineering and detailed atmospheric modeling**, centered around Douglas MacMartin and Daniele Visioni.

Best roles:

- Convert climate objectives into injection requirements.
- Optimize latitude, altitude, season, and release quantity.
- Develop feedback-control algorithms.
- Quantify uncertainty.
- Compare operational strategies.
- Establish measurable system-level requirements.

Cornell would be especially useful as the fund's independent **systems-analysis and design-optimization center**.

4. Harvard Solar Geoengineering Research Program and Keutsch laboratory

Harvard remains an important center for atmospheric chemistry, particle composition, alternative aerosols, governance, and policy. The proposed SCoPEx field project was discontinued in 2024, but the

Keutsch laboratory and Harvard Solar Geoengineering Research Program continue related laboratory, modeling, and policy research.

Best roles:

- Laboratory aerosol chemistry.
- Alternative-material evaluation.
- Stratospheric reaction measurements.
- Small-experiment design.
- Instrument development.
- Governance and public-policy studies.

5. NOAA Chemical Sciences Laboratory

NOAA CSL has directly relevant capabilities in stratospheric aerosol and gas measurements, aircraft instrumentation, atmospheric chemistry, remote sensing, and modeling. It has an ongoing project studying uncertainty in the atmospheric response to SAI.

Best roles:

- SO_2 and aerosol instruments.
- Ozone and water-vapor monitoring.
- Airborne field campaigns.
- Instrument calibration.
- Satellite validation.
- Independent measurement of experimental releases.

NOAA could be one of the most important partners for ensuring that the equipment program does not design a release system before designing a credible method of measuring what it produces.

6. University of Exeter and UK Met Office

The Exeter–Met Office community has major expertise in aerosols, radiation, climate modeling, volcanic analogues, SAI, marine cloud brightening, and regional impacts.

Best roles:

- Independent climate-model runs.
- Aerosol radiative forcing.
- Volcanic validation cases.
- Regional precipitation and circulation.

- Comparison of SAI with other sunlight-reflection methods.

7. Max Planck Institute for Meteorology

The Max Planck Institute has conducted long-running modeling of sulfate aerosol formation, injection strategy, particle growth, atmospheric transport, precipitation effects, and termination risk.

Best roles:

- Independent aerosol-model simulations.
- Injection-altitude and latitude comparisons.
- Particle-size optimization.
- Identification of diminishing efficiency at high injection rates.
- European independent review.

8. ETH Zurich Institute for Atmospheric and Climate Science

ETH has strong capabilities in aerosol microphysics, chemistry-climate modeling, ozone reactions, sulfate aerosols, and proposed solid-particle alternatives.

Best roles:

- Sulfate versus solid-particle comparisons.
- Surface chemistry and ozone effects.
- Particle optical properties.
- Laboratory-to-global-model integration.
- Independent assessment of alternative materials.

9. Rutgers University

Rutgers is important for climate-impact analysis, volcanic analogues, agriculture, ecosystems, regional precipitation, termination risk, and critical evaluation of SAI’s limitations.

Best roles:

- Independent risk analysis.
- Agriculture and ecosystem effects.
- Termination scenarios.
- Volcanic comparisons.
- Red-team review of optimistic projections.

10. Indiana University and GeoMIP

Indiana University is Ben Kravitz's base, while **GeoMIP is an international modeling collaboration rather than a conventional organization**. GeoMIP establishes standard experiments that many independent climate centers can run, allowing researchers to distinguish model-specific results from more robust conclusions.

Best roles:

- Coordinate independent model teams.
- Define common scenarios.
- Publish open simulation protocols.
- Compare model uncertainty.
- Prevent the fund from relying on one climate model.

11. World Climate Research Programme

WCRP has established a Climate Intervention Research Lighthouse Activity covering both carbon removal and sunlight-reflection approaches. It is intended to coordinate research needed for informed decisions.

Best roles:

- International scientific coordination.
- Research-gap assessment.
- Common terminology and protocols.
- Links to WMO, UNEP, and global climate institutions.
- Independent international review.

WCRP would not normally build equipment, but it could help ensure that the research program is internationally useful and scientifically credible.

12. Degrees Initiative

The Degrees Initiative funds and supports researchers in developing countries so that those countries can conduct their own regional modeling and governance analysis rather than relying entirely on North American and European institutions. Its funded researchers have produced more than 50 papers.

Best roles:

- Regional climate-impact studies in the Global South.
- Training and computing support.
- Independent African, Asian, and Latin American research.
- Social and political analysis.
- International participation in research governance.

A $1 billion fund should probably reserve a meaningful amount—perhaps **$25 million to $50 million**—for independently managed Global South research rather than merely asking researchers there to comment on work designed elsewhere.

13. NASA

NASA is not presently a single dedicated SAI research center, but several NASA facilities have capabilities the equipment program would need:

- **NASA Armstrong:** experimental aircraft, flight research, remotely operated systems, telemetry, and high-risk flight testing.
- **NASA Glenn:** high-altitude propulsion and engine testing.
- **NASA Langley:** atmospheric instruments, lidar, aerodynamics, remote sensing, and wind tunnels.

NASA should be viewed as a **critical technical partner**, not as the organization that decides whether SAI should be developed or used.

Recommended research consortium

For the proposed fund, I would assemble the following structure:

Function	Suggested lead or co-leads
Program scientific architecture	UChicago CSEi, with independent NCAR participation
System requirements and control	Cornell
Aerosol chemistry and laboratory experiments	Harvard, UChicago, and ETH Zurich
Global climate, chemistry, and ozone modeling	NSF NCAR
Independent model intercomparison	GeoMIP, Exeter, Max Planck, Rutgers

Function	Suggested lead or co-leads
Measurement and monitoring	NOAA CSL, NASA, NCAR
Aircraft and deployment engineering	UChicago engineering team, Wake Smith, Cornell, NASA, and competitively selected aerospace companies
Regional impacts in developing countries	Degrees Initiative-supported research teams
International scientific coordination	WCRP
Economics and governance	Columbia, Degrees Initiative, Harvard policy researchers, and independent legal experts
Critical risk review	Rutgers, Exeter, Max Planck, outside health and ecology experts

My overall assessment

The leading centers have different strengths:

- **UChicago:** strongest developing center for integrated practical engineering.
- **NCAR:** strongest comprehensive chemistry-climate modeling capability.
- **Cornell:** strongest systems, control, and deployment-strategy group.
- **Harvard:** strongest established aerosol-chemistry and experimental legacy.
- **NOAA:** strongest prospective monitoring and atmospheric-measurement partner.
- **GeoMIP/WCRP:** strongest mechanisms for international model coordination.
- **Degrees Initiative:** strongest organization for broadening the research beyond wealthy-country institutions.

No existing organization appears able to conduct the complete $1 billion program alone. The Managing Organization should therefore issue work to a **deliberately distributed consortium**, with multiple independent modeling teams, separate equipment and safety contractors, and open publication of all assumptions, designs, software, and measurements.

Scientific and Engineering Advisory Panel

Prompt to AI: What technical expertise should a scientific and engineering panel provide for this SAI equipment-development initiative?

Response From AI:

The initiative should use a compact working panel focused on technology-specific judgment. Portfolio-wide independence, conflicts, recusal, appointment, audit access, and management-oversight rules are governed by the Common Framework. The panel does not manage contractors, approve its own members' awards, authorize an atmospheric release, or authorize deployment.

Seat / expertise	Why it is needed
Independent chair	Integrates evidence across disciplines and protects the mission from capture by one architecture or contractor.
SAI systems / mission engineering	Translates scientific mission needs into payload, altitude, material, timing, monitoring and fleet requirements.
Aircraft configuration / structures	Reviews widebody modification, loads, tank integration, weight, stability and future high-altitude concepts.
High-altitude propulsion / aerodynamics	Reviews engine/inlet feasibility, wing/configuration tradeoffs and altitude-performance evidence.
Aviation operations / certification	Reviews supervised autonomy, airworthiness basis, maintenance, turnaround, flight-test and operational constraints.
Safety-critical software / cyber	Reviews fault management, human authority, HIL evidence, communications loss and independent V&V.
Sulfur / chemical-process safety	Reviews material form, storage/transfer/loading, compatibility, HAZOP/QRA, containment and emergency systems.
Aerosol / release engineering	Connects precursor and nozzle/release architecture to the scientific source requirements without conducting the atmospheric efficacy decision.
Atmospheric instrumentation / metrology	Reviews release accounting, inlets/interfaces, calibration, uncertainty, synchronization and data quality.
Reliability / maintainability / manufacturing	Reviews endurance, MTBF/MTTR, spares, production readiness, base replication and supplier capacity.
Lifecycle economics / cost estimating	Independently challenges prototype, certification, fleet, base and operating-cost assumptions.
Independent climate-risk liaison	Ensures equipment flexibility and monitoring requirements remain compatible with SAI Experimental Research/GCM findings without turning this panel into a climate-deployment authority.

Panel powers and procedures

- Review the RTM, competing architectures, design reviews, major test plans, acceptance evidence, and G0-G7 readiness recommendations.
- Recommend proceed, proceed with conditions, redesign, repeat/replicate, pause, terminate, or release/withhold centrally controlled reserve subject to Funding Source authority.
- Require direct access to test data and contractors; permit minority technical reports; use outside specialists for design reviews when the standing panel lacks depth.
- Recuse members from awards or acceptance decisions involving their own institutions or financial interests under the Common Framework.
- Coordinate with separate flight/process safety authorities and with the SAI Experimental Research release-governance process; a positive engineering recommendation is never an atmospheric-release authorization.

Management Advisory Panel

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

Response From AI:

The Moonshot Common Framework governs the panel charter, independence, fiduciary oversight, audit access, conflicts, procurement escalation, reserve review, corrective action, and Managing Organization succession. This initiative adds aerospace, hazardous-process, automation, and monitoring capabilities needed to oversee a large safety-critical prototype and flight-test program.

Initiative-specific oversight capabilities

Aerospace acquisition and flight test: commercial-aircraft modification, high-altitude aircraft design, propulsion, airworthiness/certification strategy, configuration control, flight-test readiness, reliability growth, maintenance, and lifecycle execution.

Hazardous sulfur/SO_2 processing: chemical-process design, HAZOP/quantitative risk, storage/transfer/loading, containment, emergency isolation, industrial construction, commissioning, and independent facility acceptance.

Autonomy and safety-critical software: human command authority, fault management, communications loss, cybersecurity, hardware-in-the-loop testing, independent software verification/validation, and supervised operating demonstrations.

Atmospheric monitoring and metrology: release accounting, aerosol/gas instrumentation, calibration, uncertainty, data integrity, satellite/airborne/ground integration, and separation of instrument development from independent calibration/acceptance.

Cross-contractor systems integration: aircraft-ground interfaces, sulfur facility, monitoring, operating center, shared test assets, independent witnessing, schedule/long-lead risks, and readiness evidence before large fabrication or flight-test commitments.

Environmental, regulatory, and international boundaries: aviation/airspace coordination, hazardous-material rules, environmental review, public documentation, incident response, and strict separation between equipment testing and authorization of any atmospheric release.

All other management-panel seats and authorities are supplied by the common framework. Technology-specific scientific and engineering judgment remains with the Scientific and Engineering 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 hazardous-material rules, government partners, environmental requirements, and the actual procurement instrument.

Program-Specific Schedules to the Common Agreements

Aircraft requirements, configuration, and airworthiness schedule

Attach the approved mission/Requirements Traceability Matrix, payload-altitude-cycle assumptions, aircraft configuration and interfaces, mass/loads baseline, verification methods, configuration identifiers, design/change authority, certification or experimental-flight basis, independent witnesses, success/failure criteria, and evidence required for acceptance at each aircraft gate.

Automation, cybersecurity, and flight-test schedule

Specify which functions are automatic, remotely supervised, or crew-controlled; human override; fault and communications-loss behavior; software assurance; cyber testing; hardware-in-the-loop evidence; test envelope; safe simulants; flight-readiness authority; telemetry; abort/emergency procedures; reliability goals; and independent flight-safety/test witnessing.

Sulfur processing, storage, loading, and process-safety schedule

Specify permitted feed/material forms, receiving and storage conditions, process-flow and P&ID baselines, material compatibility, transfer/loading rates, metering and inventory reconciliation, containment/ventilation, HAZOP and quantitative risk, automated isolation and purging, maintenance, emergency response, commissioning, and independent facility acceptance.

Monitoring, metrology, data, and open-engineering schedule

Specify release-flow verification, SO_2/aerosol and side-effect measurements, calibration and uncertainty, instrument interfaces, validation trials, repositories and release dates for native CAD, bills of material, firmware/source code, models, raw/processed test data, failure records, operating logs, cost assumptions, and the reproducibility package required for an unaffiliated team to inspect or continue the work.

Outdoor atmospheric-release boundary schedule

No equipment agreement itself authorizes SAI experimentation or deployment. Any approved atmospheric release must separately identify material, quantity/rate, altitude/location/time, expected dispersion, monitoring, environmental/legal approvals, public disclosure, stop conditions, incident response, and the boundary between Equipment Development and the companion SAI Experimental Research Initiative.

Shared-asset and Phase II transition schedule

Identify ownership, custody, maintenance, insurance, data rights, and scheduling responsibility for shared aircraft, instruments, test facilities, software/data systems, and other capital assets; prevent duplicate full-cost charging to Experimental Research; and define the final asset, records, suppliers, software credentials, open designs, cost models, and unresolved risks transferred into a separate Phase II decision.

No duplicate master terms

General competition, pricing, milestone payment, retainage, audit, conflicts, open-source/data rights, background/foreground IP, reserve, changes/claims, remedies, termination, step-in, succession, insurance, and routine reporting are governed by the common framework unless an approved SAI-specific schedule expressly adds or overrides a term.