

Proposed \$1B Stratospheric Aerosol Injection Equipment Development Fund

By ChatGPT 5.6

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What is Stratospheric Aerosol Injection (SAI)?

Prompt to AI: Summarize Stratospheric Aerosol Injection (SAI) in roughly 300 words.

ChatGPT Conversation

<https://chatgpt.com/share/6a67ccc7-e4dc-83ea-b763-490526b7f344>

Response From AI:

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, geopolitical misuse and whether reliance on SAI might weaken emissions-reduction efforts. 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.

SAI Equipment Development - \$1B Fund

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 SO₂ gas to the stratosphere (e.g. modify a Boeing 777 Airplane to move 100 tons of SO₂ 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	Share	Principal five-year deliverable
1. Modified 777-class demonstrator	\$230M	23.0%	One instrumented, crewed experimental aircraft with sulfur/SO ₂ tank, transfer, release and safety systems
2. Automated flight and ground turnaround	\$110M	11.0%	Automated mission control, ground refueling, sulfur loading, dispatch, inspection and fault handling
3. New 65,000-foot aircraft design	\$105M	10.5%	Preliminary design review package, component tests and credible cost/manufacturing plan; no full aircraft
4. Sulfur processing and logistics pilot	\$85M	8.5%	One pilot facility for receiving, processing, storing, transferring and loading sulfur/SO ₂
5. Monitoring and measurement systems	\$110M	11.0%	Prototype operational, atmospheric, radiative and side-effect monitoring network
6. Systems integration and testing	\$65M	6.5%	Ground tests, crewed flight tests, automated turnaround demonstrations and reliability improvement

7. Models, data and operating center	\$45M	4.5%	Digital twins, atmospheric models, control-center prototype and open-data platform
8. Program management, safety and independent review	\$50M	5.0%	Owner's PMO, systems engineering, environmental review, airworthiness planning and open publication
9. 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.

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

Subtask	Budget
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 SO₂” 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.

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

Subtask	Budget
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.

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

Subtask	Budget
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
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.

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

Subtask	Budget
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 SO₂ 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.

5. Monitoring systems — \$110 million

Monitoring function	Budget
Aircraft position, material flow, tank balance and release verification	\$20M
In-plume aerosol and gas instruments on aircraft	\$25M
Balloon, lidar and ground-station prototypes	\$20M
Aerosol optical depth and radiative-flux measurements	\$15M
Ozone, water vapor, sulfur chemistry and other side-effect indicators	\$15M
Satellite-data processing and assimilation	\$5M
Calibration laboratories and instrument intercomparison	\$10M
Total	\$110M

NOAA researchers emphasize that SAI assessment would require satellite observations validated by in-situ measurements, broader observations of atmospheric composition and climate variables, and measurements of species including ozone, aerosol composition, water vapor and sulfur dioxide.

Therefore, this \$110 million would build **prototype instruments and an initial distributed network**, not the complete global operational monitoring system required during deployment.

6–8. Integration, data and program oversight — \$160 million

The remaining baseline funding would be divided approximately as follows:

Activity	Budget
Systems-integration laboratory and test rigs	\$10M
Full-scale sulfur-handling ground tests	\$10M
Structural, taxi and aircraft ground tests	\$10M
Crewed flight-envelope expansion and release-system testing	\$15M
Automated loading and turnaround demonstrations	\$10M
End-to-end operating demonstrations and emergency exercises	\$10M
Atmospheric chemistry, dispersion and radiative models	\$15M
Aircraft and logistics digital twin	\$10M
Prototype operating center and mission-control software	\$8M
Open data repository, APIs, quality control and archival system	\$12M
Central program office and systems engineering	\$20M
Safety, environmental and airworthiness work	\$13M
Independent technical and cost reviews	\$7M
International engagement and governance studies	\$5M
Open-source CAD, software, reports, test data and documentation	\$5M
Total	\$160M

Contractor management, normal overhead and systems engineering within each technical work package would be included in those packages. The central \$50 million management line is for the government or foundation “owner’s team,” independent from the principal contractors.

The plan itself calls for rapid, broad sharing of monitoring results so independent scientists and governments can inspect the data and reproduce analyses.

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
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

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.

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.

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	Avionics interfaces; automatic taxi, takeoff, cruise, release and landing	\$25M

prototype	functions; redundant computers and communications	
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.

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
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.

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
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.

5. Monitoring and measurement systems — \$110 million

The plan requires monitoring of operations, atmospheric transport and transformation, climate effects and potential side effects. It also states that monitoring results should be shared broadly so independent researchers and governments can reproduce the analysis.

Subphase	Principal activities and deliverables	Cost
5A. Measurement requirements and error budgets	Define required variables, spatial coverage, time resolution, accuracy, calibration and detection thresholds	\$8M
5B. Monitoring-system architecture	Select aircraft, balloon, lidar, satellite and ground measurements; communication links; calibration standards; instrument interfaces	\$12M
5C. Prototype instrument	SO ₂ and aerosol instruments; particle-size measurement; release-flow	\$30M

fabrication	metering; radiometers; ozone and water-vapor instruments; tracking packages	
5D. Laboratory calibration and intercomparison	Calibration chambers; reference standards; environmental qualification; comparison of competing instruments	\$15M
5E. Field integration and validation	Install instruments on aircraft and ground systems; balloon and lidar trials; satellite comparisons; controlled non-SAI validation campaigns	\$30M
5F. Operational procedures and final network design	Calibration schedule; maintenance requirements; data-quality procedures; uncertainty reports; Phase II monitoring-network specification	\$15M
Total		\$110M

The \$110 million would not buy a permanent global monitoring network. It would establish the instrumentation, interfaces, calibration procedures and initial stations needed to design that network credibly.

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

Monitoring category	Approximate amount
Verification of aircraft operations and material release	\$20M
In-plume and downwind atmospheric measurements	\$30M
Radiative and optical measurements	\$20M
Ozone, water vapor, chemistry and side-effect indicators	\$20M
Ground, balloon, lidar and satellite integration	\$10M
Calibration, data quality and final documentation	\$10M

6. System 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	Repeated complete mission cycles; deficiency correction; performance	\$10M

readiness review	verification; final Phase II readiness assessment	
Total		\$65M

The final demonstration would begin with sulfur substitutes or inert gases. Actual SO₂ releases should occur only under the separate atmospheric-experiment program and its environmental authorization.

7. Models, data systems and operating center — \$45 million

Subphase	Principal activities and deliverables	Cost
7A. System and data requirements	Data ownership; formats; retention; access; latency; cybersecurity; interfaces with scientific institutions	\$5M
7B. Atmospheric and engineering digital twins	Aircraft and ground-system models; material-flow model; plume-transport tools; preliminary radiative calculations	\$12M
7C. Mission-control and data-platform construction	Operating-center software; mission displays; equipment status; flight tracking; release records; alert functions	\$10M
7D. Data ingestion and assimilation	Instrument streams; weather data; satellite products; calibration records; automated quality-control functions	\$8M
7E. Integrated simulation exercises	Simulated missions; equipment failures; abnormal atmospheric conditions; pause and termination exercises	\$6M
7F. Secure handoff and public archive	Documented software baseline; APIs; open-data portal; long-term storage; Phase II operating-center specification	\$4M
Total		\$45M

The operating 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. What atmospheric observations followed.

8. Program management, safety and independent review — \$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.

9. Central contingency and risk 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 and measurement systems	\$110M

System integration and testing	\$65M
Models, data and operating center	\$45M
Program management, safety and independent review	\$50M
Baseline technical program	\$800M
Central contingency and risk reserve	\$200M
Total	\$1.000B

Suggested program-level decision gates

Gate	Approximate date	Decision
Gate 1: Requirements review	Month 9	Are the payload, altitude, cycle time and material requirements plausible?
Gate 2: Preliminary design review	Month 20	Are the proposed aircraft, ground and monitoring designs technically credible?
Gate 3: Build authorization	Month 28	Should the program commit the largest fabrication expenditures?
Gate 4: Integrated test readiness	Month 40	Are the aircraft, sulfur facility, automation and monitoring systems safe enough to combine?
Gate 5: Flight-demonstration authorization	Month 48	Are supervised flight and release-system tests justified?
Gate 6: Phase II readiness review	Month 60	Has the program produced sufficiently safe, reliable and well-documented equipment to support controlled experimental operations?

The most important financial feature is that only about **\$200–250 million should be firmly committed before the preliminary design review**. Most fabrication spending and much of the reserve should remain conditional until the aircraft payload, sulfur form, automation architecture and monitoring requirements are substantially resolved.

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, in **millions of constant 2026 dollars**, and add to the previously proposed **\$1 billion** budget. Each PO should specify a deliverable, acceptance test, schedule, data rights, and payment milestones.

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

Phase	Illustrative purchase orders	Phase 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
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
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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.

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.

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	\$10M

	3A-4: Independent validation of the 100-ton/65,000-foot requirement — \$2M	
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.

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 —	\$15M

	\$4M; PO 4E-4: Operator training — \$2M; PO 4E-5: Independent facility acceptance testing — \$2M	
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 SO₂.

5. Monitoring and measurement systems — \$110 million

Phase	Illustrative purchase orders	Phase total
5A. Measurement requirements	PO 5A-1: Atmospheric and climate 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
5B. Monitoring architecture	PO 5B-1: Overall monitoring-network 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: Full-network 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.

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
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.

7. Models, data systems and operating center — \$45 million

Phase	Illustrative purchase orders	Phase total
7A. Data and system requirements	PO 7A-1: Data-governance and open-access plan — \$2M; PO 7A-2: Instrument and contractor interface requirements — \$1M; PO 7A-3: Cybersecurity and archival architecture — \$2M	\$5M
7B. Models and digital twins	PO 7B-1: Aircraft and ground-system digital twin — \$4M; PO 7B-2: Plume-dispersion and transport model — \$4M; PO 7B-3: Radiative and atmospheric-chemistry model — \$2M; PO 7B-4: Model validation and comparison — \$2M	\$12M
7C. Mission-control platform	PO 7C-1: Mission-control and fleet-management software — \$5M; PO 7C-2: Operator displays and visualization — \$2M; PO 7C-3: Equipment-status, alarm and pause-control system — \$3M	\$10M
7D. Data ingestion and assimilation	PO 7D-1: Data lake and real-time ingestion system — \$3M; PO 7D-2: Automated quality-control software — \$2M; PO 7D-3: Weather, satellite and external-data	\$8M

	interfaces — \$2M; PO 7D-4: Metadata catalog — \$1M	
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 archive and handoff	PO 7F-1: Public data portal and APIs — \$2M; PO 7F-2: Long-term scientific 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.

8. Program management, safety and independent review — \$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.

9. Central contingency and risk 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
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		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
Monitoring and measurement systems	\$110M
Systems integration and testing	\$65M
Models, data and operating center	\$45M
Program management and independent oversight	\$50M
Baseline procurements	\$800M
Contingent purchase orders and 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.

Purchase Order Recipients

Prompt to AI: With each purchase order, who might they be issued to?

Response From AI:

The recipients below are **illustrative candidates, not endorsements or prequalified bidders**. For most technically novel POs, I would solicit proposals from two to four teams and select on technical merit, cost, openness, and conflict-of-interest controls.

A few procurement distinctions matter:

- Companies can receive ordinary contracts or task orders.
- NASA and NOAA work would normally require a reimbursable agreement, cooperative agreement, interagency agreement, or similar instrument—not a conventional commercial PO.
- NSF NCAR work would generally be contracted through UCAR.
- Universities would usually receive grants, cooperative agreements, or research subcontracts.
- Independent reviewers must not report through the prime contractor whose work they are reviewing.

Boeing Global Services, ST Engineering, Lufthansa Technik, AAR, and Calspan have relevant aircraft-modification, engineering, MRO, or flight-test capabilities. Aurora, Northrop Grumman, and Lockheed Martin have advanced or high-altitude aircraft experience; Honeywell, Reliable Robotics, Collins Aerospace, and Aurora have relevant autonomy or avionics capabilities.

1. Modified 777-class demonstrator

I would probably appoint **Boeing Global Services as aircraft design authority and prime integrator**. The modification could be physically performed by Boeing, ST Engineering, Lufthansa Technik, AAR, or Calspan, depending on hangar capacity, certification strategy, location, and price.

1A. Feasibility and requirements

PO	Likely recipient	Other team members or alternatives
1A-1 Mission and operating requirements	Boeing Global Services	Aurora Flight Sciences; MITRE for independent requirements review
1A-2 Payload, altitude, range, and weight feasibility	Boeing Global Services	Aurora; Calspan; GE Aerospace for engine-performance inputs
1A-3 Hazardous-material and airworthiness assessment	Exponent	MITRE; Boeing; an FAA-authorized certification consultancy

MITRE would be especially useful for operating concepts, aviation-system safety, and regulator coordination, while Exponent could independently examine hazardous-material, structural, thermal, and failure risks.

1B. Aircraft acquisition and inspection

PO	Likely recipient	Other team members or alternatives
1B-1 Purchase used 777	AerCap or Altavair, depending on available aircraft	Avolon; another airline or lessor disposing of a suitable aircraft
1B-2 Heavy inspection and maintenance baseline	Boeing Global Services or ST Engineering	Lufthansa Technik; AAR
1B-3 Spares, ground equipment, and technical data	Boeing Global Services	AAR parts and supply-chain organization

AerCap and Altavair both handle widebody aircraft and have transacted Boeing 777 aircraft, making them plausible sources—not guarantees that a suitable airframe would be available when needed.

1C. Preliminary aircraft design

PO	Likely recipient	Other team members or alternatives
1C-1 Structural modification and load-path design	Boeing Global Services	Calspan; ST Engineering
1C-2 Tank, transfer, and conditioning design	Boeing, with Parker Aerospace or Eaton	Air Liquide Engineering; Linde Engineering
1C-3 Release system and safety architecture	Boeing, with Parker Aerospace	Eaton; Curtiss-Wright; Exponent as safety reviewer
1C-4 Independent preliminary design review	The Aerospace Corporation	MITRE; Exponent

Parker and Eaton have aerospace fluid-control, pump, tubing, coupling, valve, and integration capabilities, although compatibility with concentrated SO₂ would require a dedicated materials-testing program.

1D. Detailed design and fabrication

PO	Likely recipient	Other team members or alternatives
1D-1 Structural reinforcement kits	Boeing Global Services	ST Engineering or Calspan for fabrication
1D-2 Flight-qualified storage tank	Boeing-led specialty tank team	Qualified AS9100 pressure-vessel fabricator selected after material tests
1D-3 Pumps, compressors, valves, and pressure controls	Parker Aerospace	Eaton; Curtiss-Wright
1D-4 Piping, tail manifold, and nozzles	Parker Aerospace	Eaton; Boeing fabrication organization
1D-5 Thermal controls, ventilation, leak and fire protection	Honeywell Aerospace	Parker; Collins Aerospace; Boeing

1D-6 Electrical, avionics, and test instrumentation	Collins Aerospace	Honeywell; Curtiss-Wright
1D-7 Manufacturing inspection and nondestructive testing	Southwest Research Institute	Exponent; an accredited independent NDT laboratory

I would not award the tank PO as a simple build-to-print order until material compatibility, thermal behavior, pressure cycling, crash loading, and emergency venting have been experimentally established.

1E. Installation and integration

PO	Likely recipient	Other team members or alternatives
1E-1 Airframe modification labor and hangar services	ST Engineering	Lufthansa Technik; AAR; Boeing
1E-2 Tank, piping, and release-system installation	ST Engineering under Boeing design authority	Calspan; Lufthansa Technik
1E-3 Avionics, controls, and software integration	Collins Aerospace and Boeing	Honeywell
1E-4 Weight, balance, conformity, and documentation	Boeing Global Services	Independent conformity support from Exponent or an authorized certification organization

ST Engineering operates widebody-capable maintenance facilities and extensive commercial aircraft modification operations; Lufthansa Technik has broad design-organization authority for major commercial-aircraft changes.

1F. Ground and flight qualification

PO	Likely recipient	Other team members or alternatives
1F-1 Pressure, leak, loading, and structural tests	Southwest Research Institute	Calspan; Boeing
1F-2 Pilots, engineers, maintenance, and flight-test operations	NASA Armstrong or Calspan	Boeing flight-test organization
1F-3 Safe-simulant release trials	NASA Armstrong/Calspan team	NASA Langley and NOAA CSL for measurements
1F-4 Post-test redesign and corrections	Boeing Global Services	Original subsystem suppliers
1F-5 Final qualification and configuration baseline	Boeing	The Aerospace Corporation as independent reviewer

NASA Armstrong specializes in high-risk atmospheric flight research, modified research aircraft, simulation, instrumentation, data reduction, and remotely operated aircraft. Calspan performs one-off aircraft modifications and autonomy-related flight testing.

2. Automated flight and ground turnaround

For the 777 demonstrator, I would favor a **Boeing–Aurora–Honeywell or Boeing–Collins team**, with Reliable Robotics or Near Earth Autonomy assigned bounded prototype tasks rather than responsibility for the complete widebody-aircraft autonomy system.

2A. Operating concept and safety architecture

PO	Likely recipient	Other team members or alternatives
2A-1 Automated mission concept of operations	MITRE	Boeing; Aurora; prospective operators
2A-2 Autonomy and fault-management architecture	Aurora Flight Sciences	Honeywell; Reliable Robotics; Near Earth Autonomy
2A-3 Regulatory and certification-path analysis	MITRE	Boeing certification group; Exponent

Reliable Robotics says its system automates taxi, takeoff, en-route flight, and landing on smaller cargo aircraft; Honeywell and Near Earth have demonstrated autonomy on an existing helicopter. Scaling that to a 777 would be a much larger and more demanding program.

2B. Simulation and architecture

PO	Likely recipient	Other team members or alternatives
2B-1 High-fidelity aircraft and airport simulation	Calspan	Aurora; Collins; Boeing
2B-2 Mission planning, routing, and release software	Aurora Flight Sciences	Boeing; Reliable Robotics
2B-3 Weather avoidance and abnormal-event software	Honeywell Aerospace	Aurora; MITRE

2C. Onboard automation prototype

PO	Likely recipient	Other team members or alternatives
2C-1 Flight-control and avionics interfaces	Collins Aerospace	Honeywell; Boeing
2C-2 Redundant computers, communications, and navigation	Collins Aerospace	Honeywell
2C-3 Automated flight-phase software	Aurora Flight Sciences	Honeywell; Reliable Robotics
2C-4 Software-assurance and certification documentation	Collins or Honeywell	MITRE as independent assessor

Collins provides avionics integration, certification services, ground-based systems-integration laboratories, and UAS autopilot technology.

2D. Automated ground systems

PO	Likely recipient	Other team members or alternatives
2D-1 Automated aircraft refueling demonstrator	Boeing/ST Engineering team	Parker; Eaton; specialist airport-fueling supplier
2D-2 Automated SO ₂ loading and purging	Air Liquide Engineering	Linde Engineering; Parker; Eaton
2D-3 Robotic inspection and leak detection	ST Engineering or AAR	Honeywell sensors; specialist industrial-robotics integrator
2D-4 Turnaround orchestration software	Boeing Digital Aviation	AAR's Trax organization; Collins

2E. Hardware-in-the-loop and cybersecurity

PO	Likely recipient	Other team members or alternatives
2E-1 Hardware-in-the-loop laboratory	Collins Aerospace or Calspan	Southwest Research Institute
2E-2 Independent software verification	MITRE	The Aerospace Corporation
2E-3 Cybersecurity red team	Battelle	MITRE; an accredited aviation-cybersecurity firm
2E-4 Independent automation safety assessment	The Aerospace Corporation	Exponent; MITRE

MITRE's aviation FFRDC focuses on aviation safety and transportation systems, while Aerospace performs independent technical reviews, design assurance, software assessments, and testbed-based evaluation.

2F. Supervised demonstrations

PO	Likely recipient	Other team members or alternatives
2F-1 Crew-supervised automated flight campaign	NASA Armstrong or Calspan	Boeing; Aurora; Honeywell
2F-2 Automated refueling and loading campaign	ST Engineering with Air Liquide or Linde	Parker; Eaton
2F-3 Reliability-growth and software corrections	Aurora/Honeywell team	Boeing; Collins
2F-4 Manuals, training, and final software release	Boeing Global Services	Collins; AAR Trax

3. New 65,000-foot aircraft design

For this work package, I would deliberately finance a **three-team design competition**:

1. **Aurora Flight Sciences/Boeing**
2. **Northrop Grumman**
3. **Lockheed Martin Skunk Works**

Northrop operates high-altitude, long-endurance autonomous aircraft; Lockheed developed and sustains the U-2 high-altitude aircraft; Aurora was founded around high-altitude, long-endurance aircraft and currently designs, builds, and flies advanced aircraft.

3A. Mission requirements

PO	Likely recipient	Other team members or alternatives
3A-1 Mission and performance requirements	MITRE	All three design teams provide inputs
3A-2 Fleet, base, and maintenance concept	Boeing Global Services	Northrop; Lockheed; Lufthansa Technik
3A-3 Preliminary certification basis	MITRE	Boeing; specialist FAA certification consultancy
3A-4 Independent validation of 100-ton/65,000-foot requirement	The Aerospace Corporation	Exponent; NASA Langley

3B. Competing concepts

PO	Likely recipient	Other team members or alternatives
3B-1 Conceptual design Team A	Aurora Flight Sciences/Boeing	GE Aerospace; Collins
3B-2 Conceptual design Team B	Northrop Grumman	GE Aerospace or Rolls-Royce
3B-3 Conceptual design Team C	Lockheed Martin Skunk Works	Pratt & Whitney or Rolls-Royce
3B-4 Independent propulsion study	NASA Glenn	GE Aerospace; Pratt & Whitney; Rolls-Royce
3B-5 Concept evaluation and down-selection	The Aerospace Corporation	MITRE; NASA subject-matter experts

NASA Glenn's Propulsion Systems Laboratory can simulate altitudes to 90,000 feet and test complete engines or propulsion components. GE, Pratt & Whitney, and Rolls-Royce are plausible engine-study participants.

3C. Preliminary multidisciplinary design

These POs should normally go to the **winning airframe team**, with owner-direct specialty contracts where independence or technology competition is important.

PO	Likely recipient	Other team members or alternatives
3C-1 Aerodynamics and wing design	Winning team: Aurora/Boeing, Northrop, or Lockheed	NASA Langley; university aerodynamics group
3C-2 Structural design and loads	Winning airframe team	Southwest Research Institute for independent analysis
3C-3 Flight controls, stability, and aircraft systems	Winning team with Collins or Honeywell	Aurora autonomy group
3C-4 Payload tank and release integration	Winning team with Boeing, Parker, and Eaton	Air Liquide or Linde
3C-5 Overall configuration integration	Winning airframe prime	The Aerospace Corporation as design-assurance reviewer

3D. Physical risk testing

PO	Likely recipient	Other team members or alternatives
3D-1 Engine and high-altitude inlet studies	NASA Glenn plus engine OEM	GE; Pratt & Whitney; Rolls-Royce
3D-2 Wind-tunnel models and testing	NASA Langley or Calspan	University wind-tunnel facility
3D-3 Structural material and joint testing	Southwest Research Institute	NIAR/Wichita State; airframe prime
3D-4 Tank, valve, and plumbing altitude tests	Southwest Research Institute	Parker; Eaton; NASA Glenn facility support
3D-5 Environmental and material compatibility	Exponent	SwRI; independent chemical laboratory

3E. Integrated preliminary design

PO	Likely recipient	Other team members or alternatives
3E-1 Integrated 3-D aircraft definition	Winning airframe prime	Major subsystem suppliers
3E-2 Weight and performance model	Winning airframe prime	NASA Langley independent check
3E-3 Manufacturing and maintainability plan	Winning prime	Boeing Global Services; ST Engineering
3E-4 Fleet lifecycle and operating-cost model	MITRE	Boeing; airline operations consultancy
3E-5 Supplier and manufacturing-readiness assessment	The Aerospace Corporation	Battelle; specialist aerospace supply-chain consultancy

3F. Review and Phase II package

PO	Likely recipient	Other team members or alternatives
3F-1 Independent preliminary design review	The Aerospace Corporation	NASA; MITRE; outside experts
3F-2 Design corrections	Winning airframe prime	Subsystem suppliers
3F-3 Prototype cost and schedule estimate	Independent cost-estimating team led by MITRE	Aerospace Corporation; airframe-prime estimate submitted separately
3F-4 Phase II prototype solicitation package	MITRE/procurement-law team	Sponsor's contracting organization
3F-5 Final technical-data archive	Winning airframe prime	Independent configuration-management contractor

4. Sulfur processing, storage, and logistics

The strongest plausible primes are **Air Liquide Engineering & Construction, Linde Engineering, and Worley**. Air Liquide and Linde have extensive industrial-gas, process-plant, storage, purification, and sulfur-related experience; Worley works across the complete lifecycle of chemical and energy infrastructure and has sulfur-processing expertise.

I would run a competitive front-end engineering phase before choosing the pilot-plant EPC contractor.

4A. Material and logistics study

PO	Likely recipient	Other team members or alternatives
4A-1 Feedstock and material-form comparison	Air Liquide Engineering	Linde; Worley; independent university chemical-engineering team
4A-2 Transportation and airport logistics	Worley	Boeing Global Services; specialist hazardous-material logistics firm
4A-3 Process simulation and material balance	Linde Engineering	Air Liquide; Worley
4A-4 Independent trade-study review	Exponent	MITRE; independent process-safety consultant

4B. Front-end engineering and hazards

PO	Likely recipient	Other team members or alternatives
4B-1 Front-end engineering design	Worley or Air Liquide	Linde
4B-2 HAZOP and quantitative risk assessment	Exponent	Independent process-safety consultancy
4B-3 Environmental and permitting analysis	Worley	AECOM or another environmental engineering firm

4B-4 Emergency-response plan	Exponent	Local fire/hazmat authority; airport emergency-management organization
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The HAZOP reviewer should be contractually independent from the EPC designer.

4C. Detailed engineering

PO	Likely recipient	Other team members or alternatives
4C-1 Process and mechanical engineering	Selected EPC prime: Air Liquide, Linde, or Worley	Parker and Eaton for aircraft interface
4C-2 Electrical, instrumentation, and controls	EPC prime with major industrial-controls supplier	Honeywell Process Solutions; Emerson or Siemens as alternatives
4C-3 Civil and site engineering	Worley	Local licensed engineering firm
4C-4 Equipment procurement specifications	Selected EPC prime	Boeing reviews aircraft-interface specifications

4D. Fabrication and construction

PO	Likely recipient	Other team members or alternatives
4D-1 Receiving and storage tanks	Selected EPC prime	Qualified chemical-storage tank manufacturer
4D-2 Processing or conditioning skids	Air Liquide or Linde	Modular process-equipment fabricator
4D-3 Pumps, compressors, piping, and valves	EPC prime	Parker; Eaton; industrial process-equipment manufacturers
4D-4 Aircraft-loading gantry and couplings	Air Liquide/Boeing team	Linde; Parker; Eaton
4D-5 Containment, ventilation, and fire protection	EPC prime	Honeywell; specialist industrial fire-protection contractor
4D-6 Construction and installation	Worley-managed local EPC contractor	Air Liquide or Linde construction organization

4E. Commissioning

PO	Likely recipient	Other team members or alternatives
4E-1 Facility commissioning	EPC prime	Independent owner's commissioning agent
4E-2 Flow calibration and inventory accounting	Emerson or Honeywell Process Solutions team	Independent metrology laboratory
4E-3 Process-performance validation	Air Liquide or Linde	Independent verification by SwRI
4E-4 Operator training	EPC prime	Equipment manufacturers
4E-5 Independent facility acceptance	Southwest Research Institute or Exponent	Separate process-safety auditor

4F. Operational demonstrations

PO	Likely recipient	Other team members or alternatives
4F-1 Ground-automation integration	Air Liquide/Honeywell team	Linde; Boeing; Parker
4F-2 Spill, leak, and emergency exercises	Independent safety contractor led by Exponent	Airport fire department and local emergency authorities
4F-3 Repeated aircraft-turnaround demonstration	ST Engineering plus EPC prime	Boeing; Calspan
4F-4 Replicable full-scale facility design	Selected EPC prime	Independent cost review by MITRE

5. Monitoring and measurement systems

The monitoring program should be scientifically led by a consortium involving **NOAA Chemical Sciences Laboratory, NASA Langley, NASA atmospheric research programs, and NSF NCAR/UCAR**. Commercial instrument suppliers could include Aerodyne Research, TSI, Droplet Measurement Technologies, Vaisala, and Teledyne API.

NOAA CSL already operates aircraft-ready SO₂ instruments and a range of high-altitude aerosol and chemistry instruments. NASA Langley operates airborne lidar systems for aerosol optical and microphysical properties. NSF NCAR develops atmospheric-chemistry observations and models. TSI, Droplet Measurement Technologies, Vaisala, and Teledyne API offer particle, aerosol, lidar, radiosonde, and SO₂ instruments.

5A. Measurement requirements

PO	Likely recipient	Other team members or alternatives
5A-1 Atmospheric and climate measurement requirements	NOAA CSL/NSF NCAR consortium	NASA Langley; university scientists
5A-2 Instrument accuracy and uncertainty budgets	National Institute of Standards and Technology-supported metrology team	NOAA; NASA; instrument manufacturers
5A-3 Operational release-verification requirements	NASA Langley and Boeing	NOAA CSL; MITRE
5A-4 Independent scientific review	National Academies	International external reviewers

The National Academies would be most appropriate for a balanced, independently reviewed scientific assessment rather than detailed engineering execution.

5B. Monitoring architecture

PO	Likely recipient	Other team members or alternatives
5B-1 Overall monitoring architecture	NSF NCAR/UCAR	NOAA CSL; NASA Langley
5B-2 Aircraft, balloon, lidar, and ground trade study	NASA Langley	NOAA; NCAR; Vaisala; DMT
5B-3 Communications and data interfaces	MITRE	NASA; NOAA; cloud-platform integrator
5B-4 Calibration and reference-standard plan	NOAA/NIST team	Instrument manufacturers
5B-5 Full-network lifecycle cost estimate	MITRE	Aerospace Corporation; NCAR technical inputs

5C. Prototype instruments

PO	Likely recipient	Other team members or alternatives
5C-1 SO ₂ instruments	NOAA CSL and Aerodyne Research	Teledyne API for ground systems
5C-2 Aerosol concentration, size, and composition	TSI and Aerodyne	Droplet Measurement Technologies; NOAA CSL
5C-3 Radiometers and optical-depth instruments	NASA Langley	University radiative-transfer group; specialist optical-instrument firm
5C-4 Ozone, water vapor, and chemistry instruments	NOAA CSL	NASA; Aerodyne
5C-5 Release-flow and operations verification	Boeing with Parker/Eaton	Independent metrology contractor
5C-6 Balloon and ground packages	Vaisala and Droplet Measurement Technologies	NOAA; NCAR

Teledyne's commercial SO₂ analyzers would be better suited to ground or facility monitoring than the lowest-concentration stratospheric measurements; NOAA's aircraft SO₂-LIF instrument would be more relevant aloft.

5D. Calibration and qualification

PO	Likely recipient	Other team members or alternatives
5D-1 Atmospheric calibration chamber	NOAA CSL or a university laboratory consortium	TSI; Aerodyne; DMT
5D-2 Reference gases, particles, and standards	NIST-linked calibration supplier	NOAA CSL
5D-3 Environmental qualification	Southwest Research Institute	Calspan; instrument manufacturers
5D-4 Instrument intercomparison campaign	NOAA CSL/NCAR	NASA; all instrument vendors
5D-5 Uncertainty and calibration	Independent metrology team	NOAA/NIST reviewers

documentation		
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5E. Field integration and validation

PO	Likely recipient	Other team members or alternatives
5E-1 Aircraft instrument installation	NASA Armstrong or Calspan	NOAA instrument teams; Boeing
5E-2 Balloon and lidar trials	NASA Langley and Vaisala	DMT; NOAA
5E-3 Initial ground stations	UCAR/NCAR	Vaisala; DMT; Teledyne API
5E-4 Satellite-data cross-validation	NASA and NOAA	NCAR
5E-5 Field-campaign operations	UCAR/NCAR campaign-management team	NASA; NOAA; Calspan
5E-6 Instrument corrections	Original instrument manufacturers	NOAA/NASA scientific oversight

5F. Operational procedures and network design

PO	Likely recipient	Other team members or alternatives
5F-1 Calibration and operating procedures	NOAA CSL	NASA; instrument manufacturers
5F-2 Maintenance and spares plan	UCAR/NCAR	Manufacturers
5F-3 Data quality and anomaly detection	NCAR	NOAA; MITRE; cloud integrator
5F-4 Phase II network design	NCAR/NOAA/NASA consortium	International meteorological institutions
5F-5 Independent monitoring-readiness review	National Academies or Aerospace Corporation	Independent international scientists
5F-6 Instrument-operator training	Instrument manufacturers coordinated by UCAR	NOAA and NASA instructors

6. Systems integration and testing

A good structure would appoint **Southwest Research Institute or Battelle as ground-system integration lead**, while NASA Armstrong or Calspan runs flight testing. SwRI provides aircraft systems engineering, integration laboratories, structural testing, hazardous-material testing, avionics work, and flight-test data systems.

6A. Verification planning

PO	Likely recipient	Other team members or alternatives
6A-1 Master verification plan	The Aerospace Corporation	MITRE; SwRI
6A-2 Requirements and configuration system	MITRE	Aerospace Corporation
6A-3 Acceptance criteria and test standards	SwRI	NASA Armstrong; Aerospace Corporation

6B. Systems-integration laboratory

PO	Likely recipient	Other team members or alternatives
6B-1 Laboratory buildout	Southwest Research Institute	Battelle
6B-2 Hardware-in-the-loop equipment	Collins Aerospace	Honeywell; Calspan; SwRI
6B-3 Software and communications bench	MITRE/SwRI team	Collins
6B-4 Laboratory commissioning	Independent Aerospace Corporation team	Exponent

6C. Subsystem qualification

PO	Likely recipient	Other team members or alternatives
6C-1 Environmental and vibration testing	SwRI	Calspan
6C-2 Chemical compatibility testing	Exponent or SwRI	University materials laboratory
6C-3 Endurance and deliberate-failure tests	SwRI	Battelle
6C-4 Qualification reports	Test contractor	Aerospace Corporation audit

6D. Full-scale ground campaign

PO	Likely recipient	Other team members or alternatives
6D-1 Aircraft-to-ground integration tests	SwRI/ST Engineering team	Boeing
6D-2 Hazardous-material safety support	Exponent	EPC process-safety organization
6D-3 Emergency-response exercises	Independent emergency-management contractor	Airport fire and hazmat departments
6D-4 Test instrumentation and data collection	SwRI	Collins; National Instruments integrator
6D-5 Independent witnessing	The Aerospace Corporation	MITRE

6E. Integrated flight campaign

PO	Likely recipient	Other team members or alternatives
6E-1 Flight aircraft, pilots, and engineers	NASA Armstrong or Calspan	Boeing
6E-2 Airspace, telemetry, and range services	NASA Armstrong Dryden Aeronautical Test Range	Other authorized flight-test range
6E-3 Chase and monitoring aircraft	NASA or Calspan	NOAA research aircraft subject to availability
6E-4 Flight-data reduction	NASA Armstrong/SwRI	Boeing
6E-5 Independent flight-safety review	The Aerospace Corporation	MITRE; Exponent

6F. End-to-end demonstration

PO	Likely recipient	Other team members or alternatives
6F-1 Complete mission-cycle demonstration	NASA Armstrong-led consortium	Boeing; EPC prime; monitoring consortium
6F-2 Reliability growth and corrections	Boeing as system prime	All affected subsystem suppliers
6F-3 Final readiness review	The Aerospace Corporation	National Academies scientific observers; MITRE
6F-4 System-acceptance report	Sponsor's independent systems engineer	Aerospace Corporation or MITRE

7. Models, data systems, and operating center

I would separate this into:

- Scientific models: **NSF NCAR, NOAA, NASA**
- Aircraft and logistics digital twins: **Boeing, Aurora, SwRI**
- Secure data infrastructure: **AWS Professional Services, Microsoft Azure Government, or Google Public Sector**
- Geospatial display: **Esri**
- Independent cyber and architecture review: **MITRE**

These cloud and geospatial providers currently offer government/public-sector data, analytics, security, and mapping platforms.

7A. Requirements and governance

PO	Likely recipient	Other team members or alternatives
7A-1 Data governance and open-access plan	UCAR/NCAR	NOAA; National Academies; open-science specialists
7A-2 Instrument and contractor interfaces	MITRE	Boeing; NASA; NOAA
7A-3 Cybersecurity and archival architecture	MITRE	Battelle; selected cloud provider

7B. Models and digital twins

PO	Likely recipient	Other team members or alternatives
7B-1 Aircraft and ground-system digital twin	Boeing/Aurora team	SwRI
7B-2 Plume dispersion and transport model	NSF NCAR	NOAA CSL; university modeling groups
7B-3 Radiative and chemistry model	NCAR/NOAA consortium	NASA
7B-4 Model validation and comparison	Independent multi-university consortium	National Academies review

7C. Mission-control platform

PO	Likely recipient	Other team members or alternatives
7C-1 Mission and fleet-management software	Boeing Digital Aviation	Collins; Aurora
7C-2 Operator displays and visualization	Collins Aerospace plus Esri	Honeywell
7C-3 Status, alarms, and pause controls	Honeywell/Collins team	MITRE safety oversight

7D. Data ingestion and assimilation

PO	Likely recipient	Other team members or alternatives
7D-1 Data lake and real-time ingestion	AWS, Microsoft, or Google Public Sector integrator	MITRE architecture oversight
7D-2 Automated quality-control software	NCAR	NOAA; commercial data-engineering contractor
7D-3 Weather, satellite, and external interfaces	NOAA/NCAR team	NASA
7D-4 Metadata catalog	UCAR/NCAR	NASA/NOAA archive specialists

7E. Simulation exercises

PO	Likely recipient	Other team members or alternatives
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7E-1 Mission and emergency simulations	MITRE	Boeing; Calspan
7E-2 Failure-scenario library	The Aerospace Corporation	Exponent; MITRE
7E-3 Exercise analysis and corrections	MITRE	Software primes

7F. Public archive

PO	Likely recipient	Other team members or alternatives
7F-1 Public data portal and APIs	UCAR with selected cloud provider	Esri for mapping
7F-2 Long-term scientific archive	NASA or NOAA data center	UCAR
7F-3 Software documentation and open-source release	UCAR/NCAR	Linux Foundation-style open-source program manager or university software center

8. Program management, safety, and independent review

For the sponsor's owner organization, my strongest candidate would be **MITRE**, provided the sponsor and work structure permit it. Other possibilities include **Battelle, RTI, or a specially formed nonprofit management organization**. The Aerospace Corporation would be particularly valuable as independent technical-design and readiness reviewer, although its strongest institutional history is in space systems rather than commercial aviation.

8A. Program formation

PO	Likely recipient	Other team members or alternatives
8A-1 Program-management-office support	MITRE	Battelle; RTI
8A-2 Lead systems engineering	MITRE	Aerospace Corporation
8A-3 Contracting, accounting, and controls	Experienced federal or major R&D contracting-services firm	Independent audit firm
8A-4 Scientific and safety panels	National Academies for scientific panel design	Separate aviation/process-safety panel managed by MITRE

8B. Requirements and preliminary-design oversight

PO	Likely recipient	Other team members or alternatives
8B-1 Independent requirements review	MITRE	Aerospace Corporation
8B-2 Independent cost estimate	Specialist aerospace cost-estimating contractor	MITRE; Aerospace Corporation
8B-3 Integrated schedule and risk	MITRE	Independent project-controls firm

analysis		
8B-4 Independent preliminary design reviews	Aerospace Corporation	NASA, Exponent, and outside experts

8C. Design and procurement oversight

PO	Likely recipient	Other team members or alternatives
8C-1 Resident contractor surveillance	Sponsor's PMO/MITRE	Independent quality-assurance contractor
8C-2 Configuration and technical-data management	MITRE	Aerospace Corporation
8C-3 Manufacturing and quality audits	Aerospace Corporation or SwRI	Independent AS9100 audit firm
8C-4 Supply-chain and vendor-risk review	Battelle or specialist aerospace supply-chain consultancy	MITRE
8C-5 Cost and schedule monitoring	Independent project-controls contractor reporting to sponsor	MITRE

8D. Test and regulatory oversight

PO	Likely recipient	Other team members or alternatives
8D-1 Independent flight-safety organization	Aerospace Corporation	MITRE; Exponent
8D-2 Environmental review and public documentation	Independent environmental consultancy	National Academies workshop support
8D-3 Aviation and airspace coordination	MITRE	Boeing regulatory group; test-range representatives
8D-4 Emergency-response oversight	Exponent	Airport and local authorities
8D-5 Independent test-readiness boards	Aerospace Corporation	NASA, MITRE, NOAA experts as appropriate

8E. Final readiness and Phase II planning

PO	Likely recipient	Other team members or alternatives
8E-1 Updated lifecycle cost estimate	Independent cost-estimating firm	MITRE
8E-2 Operational-readiness review	Aerospace Corporation	MITRE; NASA; Exponent
8E-3 Financial, scientific, and open-data audit	Major independent audit firm plus scientific-data auditors	National Academies observer
8E-4 Phase II procurement plan	MITRE and sponsor contracting office	Procurement-law counsel
8E-5 Program closeout and	MITRE	National Academies workshop or

lessons learned		independent evaluation team
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9. Contingency POs

Contingency awards should generally go to the organization best positioned to correct the specific problem, but no contractor should be allowed to approve its own reserve release.

Contingency PO	Likely recipient
9A-1 Additional aircraft or payload studies	Boeing, Aurora, NASA, or independent airframe-design team
9A-2 Early subsystem redesign	Original subsystem designer, after independent review
9A-3 Additional environmental or regulatory analysis	Independent environmental consultant or MITRE
9A-4 Early schedule recovery	Independent project-controls firm
9B-1 Structural or tank redesign	Boeing plus specialist tank team
9B-2 Additional propulsion testing	NASA Glenn plus selected engine OEM
9B-3 Safety-system redesign	Original designer with Exponent/Aerospace review
9B-4 Competing prototypes or second sources	A supplier not already dependent on the incumbent design
9B-5 Independent technical red team	Aerospace Corporation, MITRE, or National Academies-selected experts
9C-1 Failed-supplier replacement	Competitively selected second source
9C-2 Long-lead components	OEM or authorized distributor
9C-3 Manufacturing rework	Original prime unless responsibility or performance argues for another firm
9C-4 Facility modifications	EPC prime or local construction contractor
9C-5 Exceptional logistics or escalation	Specific supplier or logistics provider after cost audit
9D-1 Replacement test articles	Original qualified manufacturer or second source
9D-2 Additional flight-test hours	NASA Armstrong, Calspan, or Boeing
9D-3 Major software corrections	Original software developer, with independent verification
9D-4 Hardware redesign after failure	Original design team plus independent failure-analysis firm
9D-5 Failure investigation and repairs	Exponent or SwRI for investigation; prime contractor for repair
9E-1 Additional reliability cycles	NASA Armstrong, Calspan, SwRI, or applicable test contractor
9E-2 Final deficiency correction	Responsible hardware or software prime
9E-3 Additional documentation or regulatory work	Boeing, MITRE, or certification consultancy
9E-4 Final schedule-recovery support	Independent project-controls contractor

Recommended prime-contract structure

Rather than treating all of these as unrelated purchases, I would establish approximately **nine major contract vehicles**:

Prime vehicle	Most plausible lead candidates
777 demonstrator	Boeing Global Services
Aircraft modification and installation	ST Engineering, Lufthansa Technik, AAR, or Boeing
Flight and ground automation	Aurora/Honeywell/Collins team, under Boeing integration
65,000-foot aircraft concepts	Separate awards to Aurora/Boeing, Northrop, and Lockheed
Sulfur facility	Air Liquide, Linde, or Worley
Monitoring science and instruments	UCAR/NCAR-led consortium with NOAA and NASA agreements
Integration and qualification	SwRI or Battelle, with NASA Armstrong/Calspan for flight work
Models and data platform	UCAR/MITRE/cloud-provider team
Owner's PMO and independent assurance	MITRE as PMO; Aerospace Corporation and Exponent as independent reviewers

Most important conflict-of-interest separations

Five functions should be independently contracted:

1. **The aircraft prime should not approve its own airworthiness or flight-readiness conclusions.**
2. **The autonomy developer should not perform the final independent software verification.**
3. **The sulfur-facility EPC contractor should not conduct the final HAZOP or facility acceptance alone.**
4. **The instrument manufacturers should not be solely responsible for calibration and uncertainty certification.**
5. **The program manager should not control the independent scientific panel's findings.**

A particularly credible overall organization would therefore look like:

- **Boeing:** 777 design authority and system integration.
- **ST Engineering or another MRO:** physical aircraft modification.
- **Aurora/Honeywell/Collins:** automation.
- **Air Liquide, Linde, or Worley:** sulfur processing and ground infrastructure.
- **NASA/NOAA/NCAR consortium:** measurement science and atmospheric modeling.
- **NASA Armstrong/Calspan:** flight testing.
- **MITRE:** sponsor-side systems engineering and program coordination.
- **Aerospace Corporation, Exponent, and National Academies:** independent technical, safety, and scientific review.

Project Management

Prompt to AI: In theory, a Project Manager (PM) would need to issue a Purchase Order (PO). The PO would specify the recipient, amount of money, and deliverable. The PM would be employed by a “Managing Organization” (MO) that receives money from the Funding Source (FS). Who is the MO? Is the MO a foundation (e.g. gates foundation), lab, university, non-profit, or company? What do you suggest and why? The MO would need to be trusted by the FS since the MO would be spending their money.

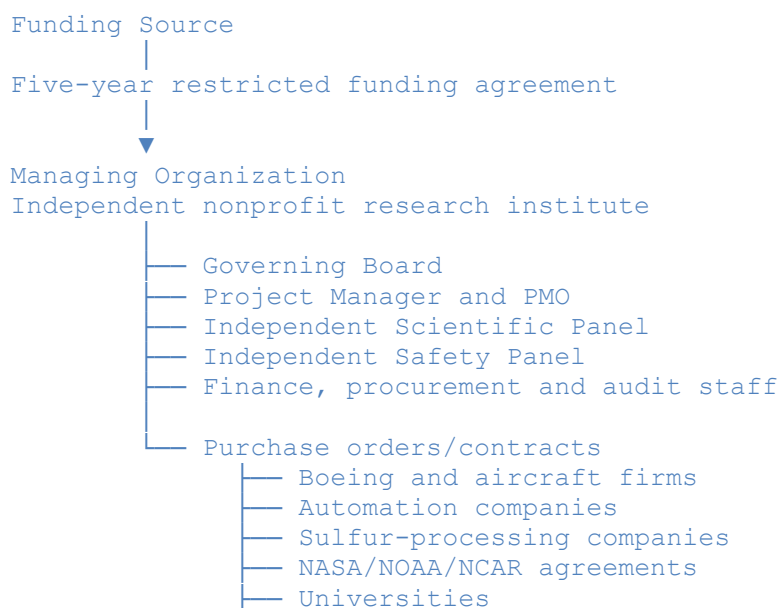
Response From AI:

Recommendation

The **Managing Organization should be an established, independent nonprofit applied-research organization**, not a university, ordinary foundation, national laboratory, or commercial aircraft company.

My leading candidate would be **Battelle Memorial Institute**, subject to due diligence and its willingness to establish a legally and financially separated SAI program office. A second strong possibility would be **RTI International**, perhaps paired with a more engineering-oriented organization such as Draper, SRI, or MITRE.

The proposed arrangement would be:



Best organizational form

Candidate form	Suitability as MO	Assessment
Established nonprofit applied-R&D institute	Excellent	Best combination of public-purpose mission, engineering competence, contracting systems and institutional credibility
Newly created nonprofit	Fair initially	Can be tailored perfectly, but has no track record, staff, systems or audited performance
Private foundation	Fair as funder; weak as operator	Should establish objectives, fund the program and enforce milestones rather than operate an aircraft-development organization
University	Fair to poor	Excellent for individual research POs, but usually not structured for centrally managed, safety-critical industrial development
National laboratory	Poor as the overall MO	Valuable technical participant, but generally government-owned, contractor-operated and tied to federal missions and approval systems
Commercial company	Poor to fair	Strong at execution, but has a financial incentive to direct work toward itself and its affiliates
Government agency	Potentially excellent	Appropriate if Congress and the executive branch establish the program, but much more difficult for a private funding source to control

1. Why an established nonprofit R&D institute is preferable

This program is unusual because the MO would need to behave partly like:

- A government R&D program office.
- An aerospace customer.
- A construction owner.
- A scientific funding agency.
- A safety regulator.
- A grant-making organization.
- A data steward.
- A financial fiduciary.

A nonprofit applied-research organization is more likely than the other organizational types to combine these functions without having a shareholder obligation to maximize profit.

The MO would not need to possess every technical capability internally. Its central job would be to:

1. Hire a highly qualified PM and program staff.
2. Translate the overall plan into requirements and POs.

3. Select competent vendors.
4. Inspect and accept deliverables.
5. Control costs, schedules and technical changes.
6. Maintain safety and scientific independence.
7. Protect the FS against waste, conflicts and unjustified scope expansion.
8. Preserve and publish the resulting knowledge.

My first choice: Battelle

Battelle describes itself as the world's largest independent nonprofit applied-science and technology organization. It also says that it manages eight U.S. national laboratories for the Departments of Energy and Homeland Security. That history is especially relevant because operating national laboratories requires procurement, safety, project controls, scientific management and oversight of very large, technically complex programs.

Why Battelle might fit

Battelle has institutional experience with:

- Large multidisciplinary R&D programs.
- Government-grade procurement and accounting.
- Laboratory and facility management.
- Chemical, materials, environmental and engineering work.
- Managing other scientists rather than relying only on its own staff.
- Safety, security and quality-assurance systems.
- Long-term programs whose benefits are primarily public rather than commercial.

Most importantly, it is capable of being the **buyer and manager**, rather than merely one of the technical vendors.

Principal concern

Battelle also performs technical work. That produces a potential conflict:

Would Battelle issue work competitively, or direct attractive assignments to itself and its affiliates?

The solution would be to make Battelle's MO role contractually separate from any technical role. Battelle should ordinarily be prohibited from receiving the POs it administers. An exception could be made only after:

- Public or documented competitive analysis.
- Independent board approval.
- FS approval.

- A finding that Battelle offers unique value.
- Separate accounting and management teams.

My second choice: RTI International

RTI describes itself as an independent nonprofit scientific research institute with multidisciplinary scientific, engineering, environmental and international-program capabilities.

RTI might be particularly strong in:

- Program administration.
- Scientific review.
- Environmental and health effects.
- Data collection and statistics.
- International engagement.
- Transparent reporting.
- Managing grants and research consortia.

RTI probably has less internal experience than Battelle with large aircraft modifications and major industrial test facilities. That does not disqualify it, but it suggests a consortium such as:

[RTI as MO + Draper or SRI as owner's engineering organization + MITRE as independent systems adviser](#)

Draper describes itself as an independent nonprofit engineering organization providing applied engineering to government, industry and academia. SRI is also an independent nonprofit R&D institute serving government and industry.

Another possible candidate: SRI International

SRI could be considered alongside Battelle and RTI. It is an independent nonprofit R&D institute with experience creating and delivering technology for government and industry.

SRI's advantages include:

- Advanced technology development.
- Systems and multidisciplinary research.
- Experience working with government, industry and foundations.
- Greater technological-development orientation than a conventional grant-making nonprofit.

Its possible weakness is that it does not appear to have Battelle's scale of national-laboratory management experience. That should be tested during due diligence rather than assumed.

2. Why the Funding Source should not itself be the MO

A Gates-type foundation would normally be better positioned as the **Funding Source**, not as the day-to-day Managing Organization.

The Gates Foundation states that its primary funding mechanisms are grants and strategic investments. Its grant process uses agreements containing intended results, targets, measurement and reporting milestones, delivery schedules and payment schedules. That is a useful model for the FS-to-MO agreement.

A foundation could hire several technical program officers, but directly operating a \$1 billion aircraft, sulfur-processing and atmospheric-monitoring program would require a major new organization involving:

- Aerospace engineering.
- Aviation certification.
- Hazardous-material processing.
- Industrial procurement.
- Flight testing.
- Quality assurance.
- Configuration management.
- Scientific monitoring.
- Environmental review.
- International governance.

It would be inefficient for a foundation to build all of that internally for one program.

Better division of responsibilities

The FS should:

- Define the charitable or strategic purpose.
- Select the MO.
- Approve the overall budget and major requirements.
- Appoint some governing-board members.
- Approve releases of large funding tranches.
- Receive independent audits and progress reports.
- Retain suspension and termination authority.

The MO should:

- Employ the PM.

- Hire the PMO.
- Issue POs.
- Review bids.
- Monitor contractor work.
- Inspect deliverables.
- Authorize ordinary payments.
- Maintain records and data.
- Report performance to the FS.

This allows the FS to exercise control without trying to operate an aerospace program.

3. Why a university should not be the principal MO

MIT, Stanford, Caltech or another major university could contribute enormously to the program, but I would not place the entire \$1 billion program under a university.

Universities are particularly good at:

- Fundamental science.
- Atmospheric modeling.
- Instrument invention.
- Independent analysis.
- Student and faculty research.
- Peer-reviewed publication.
- Convening scientific experts.

They are less naturally structured for:

- Centralized command by a single PM.
- Five-hour aircraft turnaround requirements.
- Commercial aircraft modification.
- Industrial chemical construction.
- Supplier performance enforcement.
- Rapid termination of failing projects.
- Warranty and liability management.
- Controlling hundreds of industrial subcontracts.

Academic principal investigators also value research independence. That is an advantage for science, but it can conflict with a highly integrated engineering program in which all teams must meet common interfaces, dates and acceptance tests.

Universities should therefore receive **individual monitoring, modeling, materials and scientific-analysis POs or grants**, rather than control the whole program.

4. Why a national laboratory should not normally be the MO

National laboratories could provide excellent technical work, modeling, testing and scientific advice. However, most DOE laboratories are government-owned, contractor-operated institutions overseen through federal Management and Operating contracts and focused on federal missions.

A private FS could potentially fund work at a lab through an appropriate agreement, but the lab would generally need to:

- Obtain government approval.
- Remain within its federal mission.
- Follow laboratory and federal contracting rules.
- Recover its full costs.
- Accommodate federal priorities and facility schedules.

That makes a national laboratory a useful **PO recipient or technical partner**, but not the cleanest fiduciary MO for privately supplied money.

There is an important distinction:

[Battelle itself could be the MO, but a Battelle-managed national laboratory probably should not be the MO.](#)

Battelle is an independent nonprofit institution. A national laboratory that Battelle manages is a federally sponsored facility with additional government constraints.

5. Why MITRE is better as adviser than MO

MITRE is a respected not-for-profit organization that operates six federally funded research and development centers. It emphasizes objective public-interest work and freedom from ordinary commercial conflicts.

MITRE could be excellent at:

- Requirements.
- Systems architecture.
- Aviation safety.
- Acquisition strategy.
- Program risk analysis.

- Independent cost estimates.
- Verification planning.
- Cybersecurity.
- Airspace and regulatory coordination.

However, MITRE states that FFRDCs cannot manufacture products or compete directly with industry. Its principal institutional structure is designed around federal agency sponsorship.

I would therefore give MITRE one of two roles:

1. **Owner's systems engineer reporting to the MO, or**
2. **Independent technical adviser reporting directly to the FS.**

It could help ensure that the MO and contractors are following a coherent technical plan without becoming the organization responsible for constructing sulfur plants or modifying aircraft.

6. Why a commercial company should not control the whole program

A commercial aerospace or engineering company could theoretically serve as MO. Boeing, Bechtel, Jacobs, Worley or another large prime contractor could manage substantial portions of the program.

The difficulty is incentive alignment.

For example, if Boeing were the MO, it might have authority to decide:

- Whether Boeing should modify the demonstrator.
- Whether a Boeing subsidiary should design the new aircraft.
- Whether competing aircraft concepts deserve funding.
- Whether Boeing had completed its own deliverables.
- Whether additional money should be issued for redesign.

Even if all decisions were made honestly, the structure would reasonably be perceived as conflicted.

Commercial companies should therefore be **PO recipients and work-package primes**, but should not normally control the overall allocation of the FS's \$1 billion.

7. Recommended specific arrangement

Preferred model

The FS awards a five-year, restricted program-management grant or contract to Battelle Memorial Institute. Battelle creates a separately governed Reflectivity Research Program Office.

The program office would have:

- A dedicated executive director.
- A program manager.
- Approximately 25–40 permanent PMO employees.
- Independent contracting and finance staff.
- Systems engineers.
- Aircraft, chemical-processing and monitoring leads.
- Quality and safety personnel.
- A dedicated restricted bank or accounting fund.
- An independent governing board.
- Independent scientific, safety and public-interest panels.

Possible alternative

RTI becomes the MO, with Draper or SRI serving as the owner’s engineering partner and MITRE performing independent systems assurance.

This might provide stronger organizational separation between program management and technical execution, but it creates more interfaces for the FS to supervise.

8. The MO should be selected competitively

The FS should not simply approach Battelle and transfer \$1 billion. It should issue a **Managing Organization competition**.

A reasonable first procurement might be:

Item	Proposed amount
Four-month MO proposal and due-diligence process	\$2M–\$4M
Transition and program-design phase	\$10M–\$15M
Initial one-year authorization	Approximately \$75M–\$120M
Remaining funds	Released annually and at technical gates

The FS might invite:

- Battelle.
- RTI International.
- SRI International.
- Draper.
- A consortium assembled specifically for the competition.
- Potentially a university-affiliated nonprofit with major industrial partners.

Each bidder would submit:

- Proposed PM and senior staff.
- Governance design.
- Procurement system.
- Conflict-of-interest plan.
- Five-year management cost.
- Technical-management approach.
- Safety architecture.
- Open-data and intellectual-property policy.
- Examples of comparably complex programs.
- Audited financial statements.
- Insurance and liability strategy.
- Proposed controls over reserve funding.

9. How the Funding Source protects its money

Trust should not rest solely on the reputation of the MO. The agreement itself should make misuse, drift and poor performance difficult.

A. Do not transfer the full \$1 billion initially

The FS might legally commit up to \$1 billion, but release funds in tranches:

Funding point	Illustrative cumulative release
MO transition and requirements phase	\$15M
After approved program plan	\$100M
After requirements review	\$225M
After preliminary design review	\$450M
After build authorization	\$700M
After test-readiness review	\$900M
Final demonstration and closeout	\$1.000B

The exact amounts would depend on the work schedule. The important principle is that the MO should not hold five years of unused funding without a reason.

B. Establish a restricted account

The money should:

- Be legally restricted to the approved program.

- Be kept in a separately identifiable account or cost center.
- Generate monthly cash and obligation reports.
- Be inaccessible for unrelated MO activities.
- Require FS approval before transfers between major work packages.

C. Require competitive procurement

A reasonable rule would be:

- Competitive bidding normally required above \$250,000.
- At least three qualified bids sought above \$1 million.
- Sole-source awards require written technical justification.
- Awards above \$10 million require an independent procurement review.
- Awards above \$25 million require governing-board approval.
- Awards above perhaps \$50 million require FS concurrence.

Dollar thresholds could be adjusted after the MO is selected.

D. Use deliverable-based payments

A PO should not merely say:

Pay Company X \$10 million to work on aircraft design.

It should say:

Pay Company X up to \$10 million to deliver specified models, drawings, test results, risk registers and a preliminary design review package that satisfies stated acceptance criteria.

Payments might be divided:

- 10% at contract initiation.
- 20% after requirements approval.
- 25% after preliminary design.
- 25% after delivery and testing.
- 20% after acceptance and delivery of complete data.

E. Maintain an independent audit chain

The FS should directly appoint:

- Financial auditor.

- Procurement auditor.
- Technical-cost estimator.
- Safety reviewer.
- Scientific-review panel.
- Data and open-source auditor.

These reviewers should report to the FS or an independent board committee, not exclusively to the PM.

10. Governance of the MO program office

I suggest a **nine-member governing board**:

Seat	Background
1–2	Representatives appointed by the FS
3	Large aerospace-program management
4	Atmospheric science
5	Industrial chemical-process safety
6	Aviation safety and certification
7	Public finance, audit and procurement
8	International governance or public policy
9	Independent public-interest or environmental representative

No current Boeing, sulfur supplier, instrument vendor or other likely PO recipient should sit as a voting board member.

The board should not micromanage ordinary POs. It should:

- Hire and evaluate the PM.
- Approve the annual operating plan.
- Approve major requirement changes.
- Release contingency above a threshold.
- Address conflicts.
- Review safety and scientific findings.
- Recommend continuation, redirection or termination to the FS.

11. Management cost

The previously proposed program allocated **\$50 million over five years** to program management, safety and independent review. That is about 5% of the \$1 billion authorization.

A possible division would be:

Management function	Five-year amount
MO PMO salaries and program operations	\$22M
Procurement, finance and contract administration	\$8M
Systems engineering and configuration control	\$7M
Independent technical and cost reviews	\$5M
Financial, procurement and data audits	\$3M
Scientific and safety panels	\$3M
FS reporting and public transparency	\$2M
Total	\$50M

The MO should not automatically charge its standard institutional overhead to every dollar passing through it. The FS should negotiate:

- A fixed management fee.
- Actual approved PMO costs.
- A low pass-through rate on large subcontracts.
- No overhead on contingency until it is used.
- Caps on executive and central administrative allocations.

Otherwise, a nominal 10%–20% institutional charge on \$1 billion could consume \$100 million–\$200 million without producing aircraft, instruments or facilities.

Bottom line

The strongest model is an established nonprofit applied-R&D institute acting as a fiduciary program manager.

My preferred structure is:

Battelle as the Managing Organization; MITRE or Aerospace Corporation as independent systems adviser; a National Academies-style scientific panel; Exponent or another independent organization for safety; and commercial, government-lab and university organizations receiving specific POs.

Battelle's nonprofit status, applied engineering orientation and experience managing eight national laboratories make it the most plausible single candidate among the organizations discussed.

The FS should nevertheless trust the **governance and control system**, not merely Battelle's name. The FS should retain milestone-based funding authority, independent audit rights, board representation, conflict controls, and the right to suspend or replace the MO.

Funding Source Requirements

Prompt to AI: What requirements might be demanded by the Funding Source (FS) to maximize climate benefit per dollar spent (i.e. reduce risk of wasted time and money)? Might they require all produced materials and measurement data be placed on the internet and marked open-source (i.e. available to others for free), for maximum benefit?

Response From AI:

Yes. I would make **open access and broad reuse a central condition of the funding**, not an optional aspiration. The objective is that the \$1 billion produces not merely one aircraft demonstrator or one sulfur facility, but a **global body of usable engineering and scientific knowledge** that other governments, universities, laboratories, and companies can build upon without paying the original contractors again.

However, openness alone will not prevent waste. The Funding Source should combine it with **stage-gated funding, competitive procurement, independent verification, measurable deliverables, and authority to stop weak projects**.

1. An “open by default” requirement

The FS-to-MO agreement could state:

All publications, data, software, models, engineering designs, test results, operating procedures, calibration records, cost analyses, and other developments substantially funded by the program shall be made publicly accessible and reusable under approved open licenses, except for narrowly defined legal, privacy, cybersecurity, export-control, or physical-security restrictions.

This would be consistent with established philanthropic and government research practices. The Gates Foundation requires unrestricted access and reuse of funded research, including underlying datasets, and its “Global Access” framework can cover technologies, materials, software, data, intellectual property, manufacturing, and distribution. NASA requires funded publications, supporting data, and software to be public at publication, with other scientifically useful data and software released by the end of the award.

The National Academies specifically recommends that solar-geoengineering governance include data sharing, intellectual-property rules, a research registry, assessments, permitting, stakeholder engagement, and international cooperation. It also recommends that funders require public disclosure of research activities, funding sources, and results.

2. What should be made public

The term “**open source**” is most precise for software and hardware. For other outputs, the better terms are open access, open data, or open documentation.

Funded output	Required public deliverables
Scientific studies	Manuscripts, technical reports, methods, assumptions, references and peer-review responses
Measurement data	Raw data, calibrated data, processed data, metadata, quality flags, uncertainty estimates and calibration records
Models	Source code, equations, parameter values, input files, output files, workflows and validation cases
Software	Human-readable source code, build instructions, dependencies, test suites, version history and issue tracker
Aircraft engineering	Native CAD files, drawings, specifications, interface documents, mass estimates, loads, design assumptions and test results
Sulfur equipment	Process-flow diagrams, piping and instrumentation diagrams, equipment specifications, control logic, hazard analyses and operating procedures
Monitoring equipment	Schematics, CAD, bills of materials, firmware, calibration methods, test fixtures and uncertainty budgets
Experiments	Protocols, preregistered hypotheses, unsuccessful trials, anomalies, deviations and complete final results
Economics	Capital and operating-cost models, labor assumptions, maintenance assumptions, supplier quotations where releasable and sensitivity analyses
Program management	PO recipient, amount, deliverable, selection method, schedule, status, amendments, accepted outputs and reasons for cancellation
Governance and safety	Risk registers, environmental assessments, safety cases, incident reports, public comments and responses

An open-hardware release must include the **modifiable native design**, not just a PDF picture or flattened drawing. The Open Source Hardware Association’s definition calls for design files in the preferred form for modification, sufficient to allow others to study, modify, manufacture, distribute and use the hardware.

3. Recommended licenses

The PO should name the license rather than merely saying “available online.”

Output	Suggested license
Reports, manuals, images and documentation	CC BY 4.0
Scientific datasets and metadata	CC0 , where legally possible; otherwise CC BY 4.0
Software and model code	Apache License 2.0 or another OSI-approved permissive license
Hardware designs	CERN-OHL-P or CERN-OHL-W

Standards and interface specifications	CC BY 4.0, with an irrevocable royalty-free implementation permission
Patents resulting from the program	Royalty-free open license, patent non-assert covenant, or defensively held patent with universal climate-use rights

CC BY 4.0 permits copying, adaptation, redistribution and commercial use with attribution. CERN’s open-hardware licenses are expressly intended to support use, study, modification, sharing, distribution and construction from hardware designs.

I would **not** generally use a “noncommercial” restriction. It could prevent manufacturers from building and selling improved equipment, which would work against broad adoption. Companies should be allowed to manufacture the open design commercially; competition among manufacturers is one mechanism for lowering future costs.

4. Release schedule

“Public eventually” is insufficient. Every PO should include release deadlines.

Material	Suggested deadline
PO title, recipient, value and deliverable	Within 10 business days after award
Project plan and requirements	Within 30 days after approval
Periodic progress report	Quarterly
Preliminary and critical design packages	Within 30–60 days after review
Raw measurement data	Rapid provisional release, perhaps within 7–30 days
Quality-controlled data	Within 90 days
Calibration and metadata	Released with the corresponding data
Test report, including failures	Within 60 days after completion
Publication-related code and data	No later than publication
Remaining useful data and software	No later than PO completion
Final engineering archive	Before final payment
Final cost and lessons-learned report	Within 90 days after PO completion

NASA’s current practice offers a useful model: publication-related data and software are released at publication, while other scientifically useful data and software are released by the end of the award. Gates requires data necessary to reproduce published findings to be publicly available when the results are published, with persistent identifiers and sufficient metadata and documentation.

Final payment—perhaps the last **10% to 20% of each PO**—should depend on successful delivery of the complete public archive.

5. Narrow exceptions to openness

The FS should not promise that literally every file will be posted immediately. Legitimate exceptions could include:

- Personal information.
- Employee medical or employment records.
- Live cybersecurity credentials and encryption keys.
- Detailed vulnerabilities in airport or critical infrastructure.
- Information legally controlled by export restrictions.
- Third-party intellectual property that existed before the project.
- Procurement-sensitive bidder information during an active competition.
- Material temporarily withheld to permit a patent filing.
- Data whose release would create a clearly documented safety or security threat.

DOE's public-access approach similarly applies to unrestricted research data while recognizing confidentiality, privacy, business-sensitive information, security and intellectual-property limitations. Gates also permits restrictions where public sharing would be legally or ethically improper, but requires disclosure of the restriction and a method of obtaining controlled access where possible.

Safeguards against abusing the exception

A contractor should not be able to label everything "proprietary." I recommend:

1. **Background intellectual property must be identified before award.**
2. Anything developed with program money is presumed to be a **Funded Development**.
3. Each withheld item must appear in a public exception register.
4. The contractor must identify the exact reason, reviewing authority and anticipated release date.
5. An independent information-release panel—not the contractor alone—approves withholding.
6. A public redacted version must be released whenever possible.
7. Results may not be suppressed merely because they are unfavorable or embarrassing.

Any patent-filing delay should normally be limited to perhaps **90–180 days**. A contractor should not receive years of secrecy after public-benefit funding.

6. Protect the program from proprietary lock-in

Before issuing a PO, the MO should require a **Background IP and Dependency Schedule** identifying:

- Existing patents needed to use the design.

- Proprietary software libraries.
- Proprietary CAD formats.
- Closed avionics or control components.
- Third-party datasets.
- Supplier-only manufacturing processes.
- Restrictions on maintenance or modification.

The FS should reject a proposed design when one company would be the only organization legally or practically able to build, repair or operate it—unless no reasonable alternative exists.

Where closed commercial components are unavoidable, the PO should require:

- Open, fully documented interfaces.
- Data export in nonproprietary formats.
- Rights to replace the component.
- Source-code escrow for essential software.
- Long-term availability commitments.
- A second-source or substitution plan.
- A royalty-free license sufficient to operate and maintain the complete system.

The Gates Global Access framework provides a useful precedent: it calls for identification of necessary background IP, reporting of funded developments, data-sharing strategies, appropriate licensing structures and rights sufficient to ensure continued access to the funded product.

Requirements beyond open access

7. Each PO must identify the decision it is intended to enable

A weak PO says:

Study high-altitude aircraft for \$5 million.

A stronger PO says:

Determine whether an aircraft carrying at least 100 metric tons to approximately 65,000 feet at a five-hour cycle is physically and economically credible. Deliver independently reviewable aerodynamic, propulsion, structural, weight, cost and uncertainty models sufficient for a go/no-go decision.

Every PO should state:

- What uncertainty is being reduced.
- What future decision depends on the result.
- What would constitute success.
- What would constitute failure.
- What evidence could cause the workstream to stop.
- Why the information is not already available.
- Why the PO is the least-expensive reasonable way to obtain it.
- How the output can be reused by other workstreams.

For R&D, the immediate “climate benefit” is not tons of cooling. It is **decision-relevant knowledge, risk retired and useful capability created**.

8. Stage-gated funding

The FS should not irrevocably commit the entire \$1 billion. Funding should be released only after independent evidence at major gates:

Gate	Evidence required
Requirements gate	Mission need, alternatives and measurable requirements established
Feasibility gate	Critical physics, payload, altitude, materials and operating assumptions shown credible
Preliminary design gate	Integrated design appears capable of satisfying cost, schedule, safety and performance requirements
Build gate	Major technologies sufficiently mature; interfaces frozen; independent cost estimate complete
Test-readiness gate	Safety case, test plan, instrumentation and abort criteria approved
Demonstration gate	Prototype passes agreed performance and reliability tests
Phase II gate	Results justify further investment relative to competing climate-research opportunities

GAO recommends evaluating technology maturity before integration because immature technologies are associated with delays and cost increases. Its knowledge-based approach calls for requirements and resources to match before development, stable design before major build commitments, and demonstrated manufacturing maturity before production.

A failed gate should have four possible outcomes:

1. Proceed.
2. Proceed with reduced scope.
3. Redesign and return to the gate.
4. Terminate.

Termination should be considered a legitimate R&D result, not automatically a management failure.

9. Independent verification and replication

At least **5% to 8% of the technical budget** could be reserved for independent testing, replication and red-team analysis.

The organization that designs a system should not be the only organization that:

- Calculates its performance.
- Tests it.
- Certifies safety.
- Estimates lifecycle cost.
- Determines whether the deliverable passed.
- Decides whether more funding is justified.

Examples:

- Boeing produces an aircraft design; NASA, Calspan, SwRI or another organization independently examines flight-test results.
- An instrument company calibrates its sensor; NOAA, NIST or another laboratory independently verifies calibration.
- An EPC company designs the sulfur facility; a separate process-safety organization performs HAZOP and acceptance review.
- A modeling group predicts aerosol behavior; another group reruns the cases using the released inputs and code.

10. Publish negative results

Every PO should require disclosure of:

- Failed tests.
- Abandoned designs.
- Unexpected maintenance requirements.
- Software defects.
- Instrument drift.
- Data rejected during processing.
- Unfavorable cost results.
- Assumptions that proved incorrect.
- Differences between forecast and measured performance.

A failed \$10 million prototype that prevents five organizations from repeating the same error may create more global value than a seemingly successful project whose limitations remain secret.

The FS should explicitly prohibit publication incentives that reward only favorable conclusions.

11. Competitive procurement and anti-self-dealing

Suggested rules include:

Procurement value	Requirement
Below \$250,000	Documented price reasonableness
\$250,000–\$1 million	Multiple quotations where practical
\$1 million–\$10 million	Formal competition, normally at least three qualified bidders solicited
Above \$10 million	Independent procurement review
Above \$25 million	MO board approval
Above \$50 million	FS concurrence
Sole-source award	Public written justification and independent approval

Each public award record should show:

- Recipient.
- Amount.
- Deliverable.
- Competing bidders or procurement method.
- Selection criteria.
- Reason for selection.
- Conflicts disclosed.
- Major amendments.
- Final accepted output.

The MO should be prohibited from steering technical work to itself or affiliates without competition and explicit FS approval.

12. Payments tied to acceptance, not effort alone

A PO might pay:

Milestone	Payment
Approved requirements and project plan	10%
Preliminary design accepted	20%
Prototype delivered	25%
Independent test completed	25%
Deficiencies corrected	10%

Complete open archive accepted	10%
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Novel R&D sometimes requires cost-reimbursement contracting, but even then, payment and continuation can be tied to evidence and review gates.

The PO should also include:

- A not-to-exceed ceiling.
- Monthly cost and schedule reporting.
- Advance approval for major scope changes.
- Rights to audit direct and indirect costs.
- Recovery of unsupported charges.
- Ownership or control of unfinished work if the contractor defaults.
- Transition assistance to a replacement contractor.

13. Require lifecycle economics, not merely prototype success

A technically successful prototype could still be useless if operations are unaffordable.

Each major hardware PO should continuously update:

- Dollars per kilogram delivered to target altitude.
- Payload delivered per aircraft-hour.
- Fuel consumed per ton delivered.
- Five-hour turnaround feasibility.
- Aircraft availability.
- Maintenance labor per flight-hour.
- Expected equipment life.
- Fleet size.
- Base and sulfur-facility costs.
- Monitoring cost.
- Lifecycle emissions.
- Cost of redundancy and spare aircraft.
- Cost under pessimistic rather than only optimistic assumptions.

For the new aircraft, success should not mean only “it may fly.” It should mean something closer to:

The independently reviewed design has a plausible pathway to delivering the required material at an acceptable lifecycle cost and reliability.

14. Maintain a dynamically allocated competition fund

The full five-year budget should not be permanently assigned on Day 1. The existing **\$200 million reserve** could function partly as a competitive opportunity fund.

It could pay for:

- Alternative aircraft concepts.
- A better sulfur material or delivery method discovered in Year 2.
- Replacement of an underperforming contractor.
- Independent replication.
- Unanticipated monitoring requirements.
- Small-business or university innovations.
- Problems identified during integration.

The National Academies recommends that a substantial portion of solar-geoengineering research funding remain dynamically allocated so that the program can adapt as knowledge develops, and that governance and public engagement receive explicit funding.

15. Safety and experiment governance

Equipment development must not automatically authorize atmospheric release.

The FS should require a separately approved experiment plan showing:

- Why laboratory work, modeling and observations of opportunity are insufficient.
- Quantity and composition of material.
- Expected dispersion.
- Detection thresholds.
- Environmental and health assessment.
- Independent scientific review.
- Government permits.
- Public notice and engagement.
- Monitoring plan.
- Abort conditions.
- Incident-response plan.
- Public release of all resulting data.

The National Academies recommends that outdoor atmospheric-release experiments proceed only when they provide critical observations unavailable through less intrusive means, and that they be subject to permitting, impact assessment and public engagement.

16. Require a public program registry

The MO should maintain a website containing, for every work package:

- PO number and title.
- Recipient and major subcontractors.
- Funding source and amount.
- Project dates.
- PM and technical lead.
- Research question.
- Deliverables.
- Current status.
- Gate results.
- Spending to date.
- Reports and datasets.
- Software and hardware repositories.
- Conflicts of interest.
- Exceptions to public release.
- Safety or environmental incidents.
- Reasons for cancellation.

The website should permit bulk download—not merely human-readable pages—so outsiders can analyze the complete portfolio.

17. Independent annual “value for money” review

An external review team should annually classify every workstream:

Classification	Meaning
Accelerate	Results are strong and additional spending has high expected value
Continue	Performance is satisfactory
Modify	Objective remains valuable but technical approach or recipient should change
Pause	Important unresolved question prevents further spending
Terminate	Expected benefit no longer justifies cost
Replicate	Claim is important enough to require independent confirmation

The review should address:

- Money obligated and spent.
- Deliverables accepted.
- Technical risks retired.

- New risks discovered.
- Cost estimate changes.
- Schedule performance.
- Public reuse of outputs.
- Independent reproductions.
- Safety performance.
- Remaining expected value.

The reviewers should report directly to the FS or an independent board committee—not only to the PM.

A possible “climate benefit per dollar” scorecard

A single dollar-per-degree figure would create false precision. I would use a weighted scorecard when comparing proposed POs:

Criterion	Illustrative weight
Importance of the decision or uncertainty addressed	25%
Probability the PO will produce a conclusive answer	15%
Reduction in major technical or safety risk	15%
Potential reduction in eventual lifecycle cost	15%
Reusability and open public value	15%
Time required to obtain the answer	5%
Ability to stop or redirect based on intermediate results	5%
Leverage of outside money, facilities or prior work	5%
Total	100%

A project should receive a low score when it:

- Duplicates existing work.
- Produces only proprietary knowledge.
- Has no measurable acceptance criterion.
- Cannot influence a future decision.
- Requires a huge follow-on commitment before providing useful evidence.
- Is managed by a recipient with unresolved conflicts.
- Has no credible path to independent verification.

Recommended core FS requirements

The ten most important requirements would be:

1. **Open by default**, with explicit licenses and narrow exceptions.
2. **All requirements flow down** from the MO into every subcontract and PO.
3. **Stage-gated release of money**, with genuine stop authority.
4. **Competitive selection** and public sole-source justifications.
5. **Deliverable-based payment**, including a retained final payment.
6. **Independent testing, cost estimates and safety review.**
7. **Disclosure of failures and negative results.**
8. **No proprietary lock-in** without explicit FS approval.
9. **Public registry of recipients, spending, deliverables and results.**
10. **Annual portfolio reallocation toward the highest-value opportunities.**

The FS should therefore require openness, but define it as more than posting final reports. The contractors should deliver the **raw evidence, editable designs, source code, models, calibration records, cost assumptions and legal reuse rights** needed for an independent organization to reproduce, improve and eventually manufacture the work. That is what converts a \$1 billion private R&D program into a much larger global public asset.

Top 25 Papers

Prompt to AI: Summarize the top 25 papers that related to our proposed research fund

[Response From AI:](#)

How I selected the papers

“Top” is not a strict citation ranking. I prioritized papers that would most directly affect decisions by the proposed **\$1 billion, five-year SAI research fund**, especially:

- Aircraft and sulfur-delivery feasibility.
- Aerosol formation, size, residence time, and radiative efficiency.
- Monitoring and field experiments.
- Injection-location and control strategies.
- Ozone, precipitation, health, and termination risks.

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

1. 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.

2. Rasch et al., 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.

3. Robock, Oman, and Stenchikov, 2008 — “Regional Climate Responses to Geoengineering with Tropical and Arctic SO₂ 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.

4. Smith and Wagner, 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.

5. Janssens et al., 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.

6. Smith et al., 2018 — “Production of Sulfates Onboard an Aircraft”

This preliminary engineering assessment considered carrying elemental sulfur and converting it onboard into SO₂, SO₃, or sulfuric acid. Because elemental sulfur contains more sulfur per unit mass than SO₂ 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 SO₂, onboard sulfur conversion, and direct sulfuric-acid aerosol production.

7. 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.

8. Duffey et al., 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.

B. Aerosol formation, chemistry, and efficiency

9. Pierce et al., 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 SO₂. 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.

10. English, Toon, and Mills, 2012 — “Microphysical Simulations of Sulfur Burdens from Stratospheric Sulfur Geoengineering”

This work compared SO₂, 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.

11. Niemeier and Timmreck, 2015 — “What Is the Limit of Stratospheric Sulfur Climate Engineering?”

This study examined the diminishing effectiveness of increasing SO₂ 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.

12. Vattioni et al., 2019 — “Exploring Accumulation-Mode H₂SO₄ versus SO₂ Stratospheric Sulfate Geoengineering”

The authors compared injecting SO₂ 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 SO₂ 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.

13. Weisenstein et al., 2022 — “An Interactive Stratospheric Aerosol Model Intercomparison...”

Multiple interactive aerosol models compared SO₂ 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.

14. Kremser et al., 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.

15. Golja et al., 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.

16. Lange et al., 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.

C. Injection strategy, control, and experiment design

17. Kravitz et al., 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.

18. Tilmes et al., 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.

19. Laakso et al., 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.

20. Keith, Duren, and MacMartin, 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.

21. MacMartin and Kravitz, 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.

D. Side effects and failure risks

22. Tilmes, Müller, and Salawitch, 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.

23. Ferraro, Highwood, and Charlton-Perez, 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.

24. Eastham et al., 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.

25. Jones et al., 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.

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 SO₂, 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 Vioni	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 Visoni.

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:

- SO₂ 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
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 Advisory Panel

Prompt to AI: If a scientific/engineering panel was set up to oversee the development, who might you suggest be on that panel?

Response From AI:

Recommended panel

I would establish a **12-member Scientific and Engineering Oversight Panel**. It should be technically strong but not dominated by people who have already advocated for, designed, or criticized SAI. It needs aircraft, chemical-process, measurement, health, and regional-climate expertise—not only atmospheric modelers.

The panel should oversee:

- Technical requirements.
- Competing design selections.
- Preliminary and critical design reviews.
- Major test plans.
- Release of contingency funding.
- Independent verification.
- Go, modify, pause, or terminate recommendations.

It should **not** manage contractors or issue POs; that remains the PM’s responsibility. It should also not possess unilateral authority to approve outdoor atmospheric releases or deployment. Those decisions require separate environmental, regulatory, governance, and public-review processes. The National Academies recommends multidisciplinary solar-geoengineering research coupled with explicit research governance.

Proposed voting members

Proposed member	Proposed panel role	Why selected
Marcia McNutt — chair	Independent scientific chair and institutional leadership	McNutt is a geophysicist and president of the National Academy of Sciences, with previous leadership at the USGS and experience overseeing scientific responses to major disasters. She is not identified principally with the pro- or anti-SAI camps. Availability would be uncertain, so a former NASA, NOAA, USGS, or National Academies leader of comparable independence could substitute.

David Keith	Overall climate-systems engineering and technology strategy	Keith is founding faculty director of the University of Chicago's Climate Systems Engineering initiative and has worked across atmospheric science, engineering, economics, experiments, and public policy. He should not chair the panel because of his major intellectual role in developing the field.
Douglas MacMartin	Systems engineering, control strategy, and requirements	MacMartin works at the intersection of feedback-control engineering and climate dynamics. He could help translate objectives such as temperature, latitude, and seasonal outcomes into aircraft, injection, measurement, and control-system requirements.
Frank Keutsch	Aerosol chemistry, experimental design, and materials	Keutsch is Harvard's Stonington Professor of Engineering and Atmospheric Science and a professor of chemistry. His work is particularly relevant to aerosol formation, atmospheric reactions, particle materials, and small, controlled experiments.
Simone Tilmes	Chemistry-climate modeling, ozone, and side effects	Tilmes is a major NSF NCAR researcher on aerosols, chemistry, ozone, and SAI impacts and is associated with whole-atmosphere modeling. She would help ensure that aerosol performance is evaluated together with ozone, stratospheric heating, circulation, and regional climate effects.
David Fahey	Stratospheric observations, ozone science, and monitoring architecture	Fahey directs NOAA's Chemical Sciences Laboratory and participates in leadership of the international scientific assessment of ozone depletion. NOAA CSL develops and operates instruments for stratospheric gases, particles, ozone, water vapor, and aerosol properties.
Wake Smith	Aircraft concepts, fleet logistics, bases, and cost	Smith is a Yale School of the Environment lecturer and UChicago affiliated scholar who has published extensively on SAI aircraft, costs, infrastructure, and operational feasibility. He has examined both specialized high-altitude aircraft and modified existing-aircraft concepts.
R. John Hansman	Aviation operations, automation, reliability, and certification	Hansman is MIT's T. Wilson Professor of Aeronautics and Astronautics and directs the MIT International Center for Air Transportation. His aviation-systems perspective would help prevent the program from treating aircraft design as merely a payload-and-altitude calculation.
Faisal Khan	Sulfur-processing safety, storage, loading, and quantitative risk	Khan is director of Texas A&M's Mary Kay O'Connor Process Safety Center and works on process safety, asset integrity, risk engineering, and system design. He would lead scrutiny of sulfur/SO ₂ processing, containment, automatic shutdown, emergency response, and hazardous-material operations.
Sebastian Eastham	Aviation emissions, atmospheric impacts, and public health	Eastham is a senior lecturer in sustainable aviation at Imperial College London whose work includes environmental impacts of high-altitude emissions and climate intervention. He would connect aircraft emissions and injected material to atmospheric exposure and health consequences.
Alan Robock	Independent risk review, volcanic analogues, regional effects, and termination	Robock's current research includes climate intervention, GeoMIP, and volcanic effects on climate. He has repeatedly examined potential limitations and adverse effects of SAI, making him an important red-team member rather than an opponent included merely for appearances.
Babatunde Abiodun	Regional climate impacts and Global South scientific perspective	Abiodun is a University of Cape Town professor and atmospheric-modeling leader whose research includes regional climate and solar radiation management. He would strengthen evaluation of rainfall, agriculture, and regional outcomes outside North America and Europe.

Why this balance works

The twelve seats divide approximately as follows:

Expertise	Members
Independent scientific leadership	McNutt
SAI system architecture and control	Keith, MacMartin
Aerosol chemistry, climate chemistry, and observations	Keutsch, Tilmes, Fahey
Aircraft and operations	Smith, Hansman
Industrial chemical and process safety	Khan
Health and high-altitude emissions	Eastham
Critical and regional climate assessment	Robock, Abiodun

This prevents several common imbalances:

- An **atmospheric-science panel** that cannot competently review an aircraft or sulfur plant.
- An **aerospace panel** that optimizes payload while neglecting aerosol chemistry.
- A **pro-SAI panel** that underweights adverse outcomes.
- A **risk-only panel** that cannot judge whether proposed equipment is technically credible.
- A predominantly American and European panel that underweights regional consequences elsewhere.

Strong alternate or rotating members

Some specialties may require additional experts during particular design reviews. I would create a paid external expert pool rather than expanding the permanent panel indefinitely.

Candidate	Where especially useful
Daniele Vioni, Cornell	GeoMIP, model intercomparison, uncertainty, injection strategies, and standardized simulation protocols. He is associated with current GeoMIP and whole-atmosphere modeling activities.
Sandro Vattioni, ETH Zurich	Aerosol microphysics, solid-particle alternatives, ozone interactions, and comparisons between SO ₂ and other materials.
Ru-Shan Gao, NOAA CSL	Portable particle instrumentation, aircraft instruments, aerosol-size measurements, and instrument commercialization.
Lili Xia, Rutgers	Agriculture, food systems, and climate-intervention impacts on crops. Her Rutgers work includes GeoMIP and agricultural-impact analysis.
A senior NASA Armstrong flight-test engineer	Flight-test planning, airworthiness, telemetry, failure management, and safe envelope expansion
A senior NASA Glenn propulsion engineer	High-altitude propulsion, compressor and inlet behavior, engine testing, and propulsion-system feasibility

A senior FAA aircraft-certification official	Certification basis, experimental-aircraft authorization, automation, hazardous cargo, and airspace requirements
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The institutional seats may be better than permanently naming current government employees because assignments and availability can change.

David Keith's role requires special handling

David Keith would bring exceptional value, but there is a potential conflict because UChicago's Climate Systems Engineering initiative could also become a major PO recipient. I see three acceptable arrangements:

1. **Keith serves as a voting panel member**, while neither he nor projects under his direction receive program POs.
2. He serves as a voting member but recuses himself from requirements, awards, and acceptance decisions involving UChicago.
3. He becomes a **non-voting senior scientific adviser**, leaving the voting seat to another independent climate-systems scientist.

For a \$1 billion program, I would favor the third arrangement if UChicago expects to compete for substantial research funding.

The same principle applies to MacMartin, Keutsch, Tilmes, Smith, and others whose institutions might seek POs.

Conflict-of-interest requirements

Every member should disclose:

- Current and recent research funding.
- Consulting income.
- Equity interests.
- Patents and licensed intellectual property.
- Board memberships.
- Relationships with likely aircraft, sulfur, software, and instrument contractors.
- Institutional applications for program money.
- Public advocacy directly related to SAI deployment or prohibition.

I would impose these operating rules:

1. No simultaneous contractor role

A voting member should not be:

- A principal investigator on a PO being reviewed.
- A paid consultant to a major contractor.
- An officer or employee of the Managing Organization.
- An employee of the Funding Source.
- A director of a company bidding for a major PO.

2. Institutional recusal

When a member's university or laboratory is competing for or performing work, that member should:

- Leave the relevant discussion.
- Receive no confidential competitor information.
- Cast no vote.
- Not participate in acceptance of the deliverable.

3. Public conflict register

Disclosures, recusals, and relevant financial relationships should be posted on the program website.

4. Independent members must form a majority

At least **seven of twelve voting members** should have no active PO, grant, subcontract, or consulting relationship with the program or its primary contractors.

5. Minority reports are permitted

A member who disagrees with a panel conclusion should be entitled to publish a minority opinion alongside the majority report. That is particularly important when considering uncertain side effects or failed tests.

Panel authority

I would give the panel formal authority to recommend:

- **Proceed.**
- **Proceed with conditions.**
- **Redesign.**

- **Repeat or independently replicate a test.**
- **Pause.**
- **Terminate.**
- **Release or withhold contingency funds.**

It should approve or recommend approval at these gates:

Gate	Panel question
Mission-requirements review	Are payload, altitude, material, cycle time, and monitoring requirements scientifically and physically justified?
Concept selection	Were competing aircraft, aerosol, and ground-system alternatives adequately considered?
Preliminary design review	Is the integrated concept credible enough for detailed design?
Build authorization	Have major technical and safety risks been reduced sufficiently to fabricate expensive hardware?
Test-readiness review	Are the equipment, instrumentation, safety case, abort criteria, and emergency procedures adequate?
Flight-readiness review	Can flight tests proceed without unacceptable risk?
Atmospheric-experiment review	Is a release scientifically necessary and separately authorized?
Phase II recommendation	Does the evidence justify another major investment?

The panel's findings should be public except for narrowly justified security, proprietary-background-IP, or personnel material.

Relationship to other bodies

The Scientific and Engineering Panel should not be expected to answer every issue. I would establish three separate bodies:

Body	Function
Scientific and Engineering Panel	Technical merit, design, testing, monitoring, and performance
Safety and Independent Assurance Board	Aviation safety, process safety, software assurance, environmental compliance, and accident investigation
Governance and Public-Interest Panel	Ethics, international consequences, public engagement, transparency, environmental justice, and rules for atmospheric experiments

Some joint meetings would be appropriate, but combining all three into one enormous committee would blur responsibility.

My preferred chair and vice chair

My ideal arrangement would be:

- **Chair:** Marcia McNutt, or a similarly independent former senior scientific-agency leader.
- **Technical vice chair:** Douglas MacMartin.
- **Safety vice chair:** Faisal Khan or R. John Hansman.
- **Panel scientific secretary:** A full-time employee of the MO who is not a voting member.

I would not make David Keith chair. His expertise is too valuable to exclude, but the program would be more credible with an independent chair who has not spent decades developing a particular SAI research framework.

Expected workload and cost

For a program of this size, this should be a working panel rather than a ceremonial advisory board:

- Chair: approximately 40–60 working days annually.
- Vice chairs: approximately 25–40 days.
- Other members: approximately 15–30 days.
- Four full-panel meetings annually.
- Additional design and test-readiness meetings.
- Site visits to the aircraft, sulfur facility, test laboratories, and monitoring operations.
- Access to independent analysts and technical consultants.

A reasonable five-year allocation would be approximately **\$5 million to \$10 million**, including compensation, travel, independent analyses, outside expert reviews, public meetings, and publication. That is less than 1% of the \$1 billion program and could prevent much larger expenditures on poorly conceived or inadequately tested systems.

Management Advisory Panel

Prompt to AI: If a panel was set up to oversee the agreement with the Managing Organization (MO) (e.g. RTI, UCHAR, Battelle) who might you suggest be on that panel?

Response From AI:

Recommended panel: FS–MO Agreement Oversight Board

This panel should be **different from the Scientific and Engineering Panel**.

- The Scientific and Engineering Panel asks: **“Is the research technically sound and worth doing?”**
- The FS–MO Agreement Oversight Board asks: **“Is the Managing Organization fulfilling the agreement, protecting the money, managing contractors properly, and delivering sufficient value?”**

I would establish a **seven-member voting board**, plus two non-voting liaisons. All members would be selected and removable by the Funding Source, not by the MO.

Suggested voting members

Candidate	Proposed role	Why this person would be useful
Sue Desmond-Hellmann — chair	Philanthropic program governance	Former CEO of the Gates Foundation, with experience overseeing large portfolios of scientific and public-benefit funding. She would understand the funder’s perspective: milestones, global access, accountability, and the difference between funding research and operating it.
David M. Walker — Audit and Finance Committee chair	Financial controls, audit, and value for money	Former Comptroller General of the United States and head of GAO. He would focus on internal controls, independent audits, reserve releases, cost growth, unsupported charges, and whether results justify expenditures.
Kathryn D. Sullivan — vice chair	Large scientific missions and government-agency management	Former NASA astronaut and NOAA administrator, with experience in Earth observation, atmospheric science, government research, and complex technical missions.
Ellen Lord	Major acquisition and industrial-contract oversight	Former Under Secretary of Defense for Acquisition and Sustainment, responsible for acquisition, developmental testing, contract administration, logistics, industrial-base issues, and other large procurement functions.
Nancy Leveson	Systems safety, management failure,	MIT professor and leading authority on safety-critical systems, software safety, organizational controls, and systemic accident prevention. Her

	and independent assurance	role would be to ensure that schedule and financial pressures do not override safety or good engineering practice.
Deborah Lee James	Aerospace-program performance and organizational accountability	Former Secretary of the Air Force, where she oversaw an organization of approximately 660,000 people and an annual budget exceeding \$139 billion. She also has experience with defense-business and innovation oversight.
Rachel Kyte	Climate purpose, international legitimacy, and public benefit	Oxford professor and experienced international climate-policy leader. She would keep the agreement focused on global climate benefit, developing-country concerns, international cooperation, and public legitimacy rather than allowing it to become merely an American aerospace-development project.

These names illustrate the ideal profiles; availability and willingness are unknown.

Important concern about Ellen Lord

Ellen Lord currently has an association with AAR's board, and AAR could plausibly bid on aircraft maintenance or modification work. That could create a direct or apparent conflict.

There are two reasonable approaches:

1. Ellen Lord serves only if AAR is not a bidder or contractor.
2. Replace her with an independent former federal procurement executive, such as a former Office of Federal Procurement Policy administrator or senior GAO acquisition official.

A person with Paul Francis's background would be a strong alternative. As GAO's managing director for acquisition and sourcing management, Francis led reviews of major defense acquisition programs and emphasized realistic cost estimates, prototyping, systems engineering, and knowledge before major commitments.

Non-voting participants

Participant	Function
One senior FS representative	Explains the funder's objectives and retains direct visibility into the program
Chair of the Scientific and Engineering Panel	Communicates technical findings and recommendations
MO chief executive	Responds to questions concerning institutional performance
Program manager	Reports cost, schedule, technical status, risks, and proposed corrective actions
Independent general counsel	Advises on agreement enforcement, conflicts, data rights, liability, and termination
Independent audit firm	Reports financial and internal-control findings directly to the board

The MO chief executive and PM should attend frequently but should **not vote on judgments concerning their own performance**.

What the board should oversee

The board should oversee the **agreement**, not administer individual engineering assignments.

Its responsibilities would include the following.

1. MO performance

The board should determine whether the MO:

- Hired a qualified PM and staff.
- Established adequate procurement and accounting systems.
- Issued POs competitively and fairly.
- Enforced deliverables and acceptance criteria.
- Controlled conflicts of interest.
- Maintained open-data and open-design requirements.
- Corrected weak performance promptly.
- Reported bad news accurately.
- Protected funds from diversion to unrelated institutional activity.

2. Annual plan and budget

The MO would submit an annual operating plan showing:

- Work to be authorized.
- POs expected to be issued.
- Milestones and acceptance tests.
- Cash requirements.
- Program-management expenses.
- Anticipated reserve releases.
- Technical and financial risks.
- Projects proposed for continuation or termination.

The board would recommend approval, modification, or rejection to the FS.

3. Major procurements

The PM could issue ordinary POs within an approved plan. The board should review only unusually consequential decisions.

Proposed action	Suggested approval
PO below \$5M within approved plan	PM and MO procurement office
PO of \$5M–\$25M	PM plus MO executive approval
PO above \$25M	Board Procurement Committee review
PO above \$50M	Full board recommendation and FS approval
Major sole-source PO	Board review regardless of value
Major change in aircraft or aerosol architecture	Scientific panel review plus board and FS approval
Reserve release above \$10M	Board approval
Reserve release above \$25M	FS approval
Transfer above 10% between major budget categories	Board and FS approval

The board should not become a bottleneck by reviewing every \$500,000 research assignment.

4. MO compensation

The board should review:

- PMO staffing.
- Executive compensation charged to the program.
- Institutional overhead.
- Pass-through fees on subcontracts.
- Related-party transactions.
- Travel and consulting expenses.
- Allocation of shared MO facilities.
- Whether the MO is profiting from work it awards to itself.

The agreement should ideally use a **fixed or capped management fee**, rather than allowing the MO to apply its ordinary overhead rate to every dollar passing through it.

5. Technical gates

The Scientific and Engineering Panel would provide the technical assessment. The Agreement Oversight Board would determine whether the evidence and contractual conditions justify additional spending.

For example:

The Scientific Panel concludes that the modified 777 tank design is technically credible but requires another \$18 million in structural testing.

The Agreement Board would then ask:

- Was the original contractor responsible for the deficiency?
- Should the contractor pay part of the redesign cost?
- Should the work be competed?
- Is \$18 million reasonable?
- Does the result still justify the entire aircraft workstream?
- Should contingency funds be released?
- Has the FS been given an updated lifecycle cost?

The two panels therefore perform complementary functions.

Committee structure

The seven-member board could operate through three committees.

Audit and Finance Committee

Suggested members:

- David Walker, chair.
- Sue Desmond-Hellmann.
- Kathryn Sullivan.

Responsibilities:

- Financial statements.
- Internal controls.
- Cash management.
- Overhead.
- Cost allowability.
- Reserve accounting.
- Independent audits.
- Fraud or misuse allegations.

GAO has repeatedly emphasized that contract audits and effective oversight help reduce improper payments and assess whether contractors' claimed costs are valid.

Procurement and Performance Committee

Suggested members:

- Ellen Lord or the independent acquisition substitute, chair.
- Deborah Lee James.

- Sue Desmond-Hellmann.

Responsibilities:

- Large POs.
- Sole-source justifications.
- Contractor performance.
- Cost and schedule trends.
- Competition.
- Replacement of weak contractors.
- MO procurement quality.

Federal acquisition policy emphasizes integrity, fairness, competition, openness, and obtaining best value rather than merely processing purchases.

Safety, Ethics, and Public-Benefit Committee

Suggested members:

- Nancy Leveson, chair.
- Rachel Kyte.
- Kathryn Sullivan.

Responsibilities:

- Whether program incentives are creating unsafe behavior.
- Disclosure of negative results.
- Open-data compliance.
- Environmental and public-interest commitments.
- Whistleblower reports.
- International and distributional concerns.
- Whether the program remains aligned with its climate-benefit purpose.

Specific powers the panel should have

The FS–MO agreement should give the board authority to recommend or initiate:

1. Release or withholding of funding tranches.
2. Approval or rejection of annual plans.
3. Independent financial and procurement audits.
4. Independent cost estimates.
5. Replacement of the PM.

6. Corrective-action plans for the MO.
7. Suspension of a workstream.
8. Competition of work previously proposed as sole source.
9. Recovery of disallowed or unsupported expenses.
10. Investigation of conflicts or whistleblower claims.
11. Replacement of the MO.
12. Termination of the entire agreement.

The board should have direct access to:

- MO accounting records.
- POs and subcontracts.
- Bid evaluations.
- Contractor performance data.
- Technical review reports.
- Risk registers.
- Safety incidents.
- Staff responsible for the work.
- Independent auditors.
- All program-generated data and designs.

It should not be required to obtain the PM's permission to investigate the PM.

Evaluation scorecard for the MO

The MO could be scored annually as follows:

Performance category	Weight
Technical milestones and usable deliverables	25%
Cost and schedule control	20%
Procurement quality and competition	15%
Safety and risk management	15%
Open access, data delivery, and public reuse	10%
Accuracy and timeliness of reporting	5%
Conflict-of-interest management	5%
Responsiveness to audits and corrective actions	5%
Total	100%

The board should also issue a plain-language conclusion:

- **Exceeds expectations**

- **Satisfactory**
- **Conditional continuation**
- **Material corrective action required**
- **Replace PM**
- **Replace MO**
- **Terminate program**

Independence requirements

A rigorous conflict rule is essential because many otherwise excellent candidates sit on corporate, university, or nonprofit boards.

I recommend:

- At least **five of seven voting members** must have no financial relationship with the MO, FS, or a program contractor.
- No voting member may receive a program PO.
- No voting member may serve on the board of the MO.
- Current directors or consultants of likely bidders must be excluded or recused.
- All relationships during the previous five years must be disclosed.
- Disclosures and recusals should be published.
- Members may not receive success fees tied to money spent or contracts awarded.
- Terms should be staggered, perhaps three years each.
- The FS should be able to remove members for conflicts, neglect, or breach of confidentiality.

A panel consisting mainly of people from Battelle, RTI, UChicago, Boeing, and the Funding Source would not be genuinely independent.

My preferred final composition

Assuming conflicts can be resolved, my preferred board would be:

Seat	Candidate
Chair and philanthropic-program oversight	Sue Desmond-Hellmann
Vice chair and scientific-mission management	Kathryn Sullivan
Audit and financial controls	David Walker
Acquisition and procurement	Ellen Lord or an independent former GAO/OFPP acquisition leader
Safety and organizational risk	Nancy Leveson
Large aerospace-program governance	Deborah Lee James
International climate and public benefit	Rachel Kyte

This board would not decide the detailed chemistry of sulfuric-acid particles or determine nozzle dimensions. Its job would be to ensure that:

The MO competently and honestly converts the FS's money into independently verified, openly available, decision-useful scientific and engineering results—and stops spending when the evidence no longer justifies the work.

For a \$1 billion program, approximately **\$6 million to \$10 million over five years** for the board, independent audit, legal support, cost analysis, investigations, and specialist reviews would be reasonable. That is roughly 0.6%–1% of the fund and could protect hundreds of millions of dollars from poor contracting, unmanaged conflicts, premature construction, or weak MO performance.

Agreements

Prompt to AI: In theory, there would be an agreement between Funding Source (FS) and Managing Organization (MO), and an agreement between MO and recipient of PO. What might those agreements look like?

Response From AI:

The two agreements should be **back-to-back**:

1. The **FS–MO Agreement** gives the MO money and authority, while controlling how the MO manages the program.
2. Each **MO–Recipient Agreement** converts those higher-level obligations into a specific assignment with a defined price, deliverable, acceptance test, and schedule.

For a technically complex PO, the “purchase order” should not be a one-page order form. It should incorporate a master R&D contract plus a detailed statement of work.

If the FS is a private foundation, the legal form could be a restricted charitable grant, services agreement, cooperative-style agreement, or combination. If the MO is not a qualifying public charity, special IRS “expenditure responsibility” rules may require a written commitment, restricted use of funds, repayment of unused funds, annual reporting, record access, and restrictions on prohibited uses.

Agreement 1: FS–MO

A suitable title might be:

Program Funding and Management Agreement for the Reflectivity Research Program

The FS should commit the overall authorization but release the money in stages. DOE cooperative agreements provide a useful structural model: a high-level award document accompanied by special terms, technical milestones, go/no-go decision points, property terms, audit requirements, and separate intellectual-property provisions.

Here is an illustrative term sheet.

PROGRAM FUNDING AND MANAGEMENT AGREEMENT

This Program Funding and Management Agreement is entered into between:

Funding Source: [FS legal name]
and
Managing Organization: [MO legal name]

1. Purpose

The purpose of this Agreement is to finance and manage a five-year scientific and engineering research program intended to reduce uncertainty concerning the feasibility, cost, performance, monitoring, risks, and potential side effects of stratospheric aerosol injection equipment and operations.

The Program is for research, design, prototyping, testing, monitoring, and evaluation. This Agreement does not authorize full-scale deployment or any atmospheric release requiring separate governmental, environmental, scientific, or public authorization.

2. Maximum funding

The FS authorizes funding of up to **\$1,000,000,000** over five years.

This amount is a maximum authorization and not an unconditional obligation to disburse the full amount.

Funding shall be divided into:

- Baseline technical program: up to \$800,000,000.
- Central contingency reserve: up to \$200,000,000.

The MO may not obligate or spend contingency funds without the approvals specified in this Agreement.

3. Funding tranches

Funding shall be released in tranches following approval of agreed milestones.

Illustrative tranches:

1. Program establishment and planning: \$15,000,000.
2. Requirements and feasibility work: cumulative funding up to \$100,000,000.
3. Preliminary design work: cumulative funding up to \$225,000,000.
4. Detailed design and selected fabrication: cumulative funding up to \$450,000,000.
5. Prototype construction and integration: cumulative funding up to \$700,000,000.
6. Testing and demonstration: cumulative funding up to \$900,000,000.

7. Final testing, documentation, and closeout: cumulative funding up to \$1,000,000,000.

Release of each tranche is subject to satisfactory performance, an approved annual plan, an updated cost estimate, and completion of the applicable decision gate.

4. Responsibilities of the MO

The MO shall:

1. Establish a dedicated Program Management Office.
2. Employ a qualified Program Manager.
3. Maintain scientific, engineering, procurement, finance, safety, data, and contract-administration capabilities.
4. Convert the approved program plan into competitive procurements and clearly defined purchase orders.
5. Evaluate bidders fairly and document the basis for each selection.
6. Monitor recipient performance.
7. Inspect, test, accept, reject, or require correction of deliverables.
8. Maintain complete financial, procurement, technical, property, and safety records.
9. enforce open-access and intellectual-property requirements.
10. Report material problems promptly and accurately.
11. Suspend or terminate work that no longer has sufficient expected value.
12. Protect the Program from conflicts of interest and self-dealing.

5. Approved program plan

Before major funds are committed, the MO shall submit an Integrated Program Plan containing:

- Program objectives.
- Work breakdown structure.
- Technical requirements.
- Five-year budget.
- Master schedule.
- Expected purchase orders.
- Decision gates.
- Risk register.
- Safety-management plan.
- Procurement plan.
- Data-management and open-access plan.
- Intellectual-property plan.
- Monitoring and measurement plan.
- Public-engagement plan.

- Annual cash-flow forecast.

Material changes require approval under the change-control provisions of this Agreement.

6. Decision gates

The Program shall include at least the following gates:

- Mission Requirements Review.
- Concept Selection Review.
- Preliminary Design Review.
- Build Authorization Review.
- Test Readiness Review.
- Flight Readiness Review.
- Phase II Readiness Review.

At each gate, the MO shall recommend one of the following:

- Proceed.
- Proceed subject to conditions.
- Redesign.
- Independently replicate.
- Pause.
- Terminate.

The FS may accept, reject, or modify the recommendation.

7. Procurement requirements

The MO shall maintain written procurement policies that provide for:

- Open competition where practical.
- Documented evaluation criteria.
- Cost or price analysis.
- Evaluation of technical capability, integrity, financial capacity, and past performance.
- Written sole-source justifications.
- Conflict-of-interest disclosure.
- Independent review of major awards.
- Negotiation of reasonable indirect costs and fees.
- Maintenance of a complete procurement history.

Suggested thresholds:

- Awards under \$250,000: documented price reasonableness.
- Awards from \$250,000 to \$1,000,000: multiple quotations where practical.
- Awards above \$1,000,000: formal competitive procurement unless an approved exception applies.
- Awards above \$10,000,000: independent procurement review.
- Awards above \$25,000,000: MO board approval.
- Awards above \$50,000,000: FS written concurrence.

8. MO self-performance and affiliated transactions

The MO shall not award Program work to itself, an affiliate, a controlled laboratory, or an organization sharing directors or senior officers with the MO unless:

1. The relationship is disclosed.
2. The work is separately priced.
3. The selection is supported by a written best-value determination.
4. Independent reviewers approve the award.
5. The FS provides written approval for awards above [threshold].

Personnel who participate in selecting a recipient may not have a financial interest in that recipient.

9. Open-access and global-benefit requirements

Program outputs shall be open by default.

The MO shall require recipients to publicly release, as applicable:

- Research reports.
- Raw and processed data.
- Metadata and uncertainty information.
- Source code.
- Model inputs and outputs.
- Native engineering files.
- Drawings and specifications.
- Bills of materials.
- Test procedures.
- Calibration records.
- Safety and failure reports.
- Cost and performance models.
- Operating procedures.
- Negative and inconclusive results.

Suggested licenses:

- Documents: CC BY 4.0.
- Data: CC0 where appropriate, otherwise CC BY 4.0.
- Software: Apache 2.0 or another approved open-source license.
- Hardware: an approved CERN Open Hardware License.
- Patents: royalty-free climate-use rights or an approved public-benefit licensing structure.

Exceptions require written approval and must be limited to background intellectual property, privacy, cybersecurity, export-control, legal, or clearly documented safety concerns.

10. Background and funded intellectual property

Before beginning work, the MO and each recipient shall identify:

- Background patents.
- Background software.
- Proprietary datasets.
- Restricted technical information.
- Third-party intellectual-property dependencies.

“Funded Development” means any invention, software, design, process, dataset, document, model, specification, or other work created substantially with Program funds.

The MO shall obtain rights sufficient to:

- Use the Funded Development.
- Inspect and test it.
- Modify it.
- Maintain and repair it.
- Reproduce it.
- Transfer work to a replacement contractor.
- License or release it as required by the open-access plan.

No recipient may introduce a proprietary dependency that prevents these uses without prior approval.

11. Reporting

The MO shall provide:

Monthly

- Cash received.
- Amount obligated.

- Amount spent.
- Commitments by work package.
- Forecast cost at completion.
- Schedule status.
- Material technical and safety issues.

Quarterly

- Progress against each milestone.
- PO status.
- Deliverables received and accepted.
- Contractor performance.
- Updated risk register.
- Open-access compliance.
- Corrective actions.
- Proposed budget changes.

Annually

- Audited financial report.
- Technical progress report.
- Updated five-year cost and schedule.
- Portfolio value-for-money assessment.
- Annual procurement report.
- Conflict-of-interest report.
- Public-data and publication report.
- Proposed annual operating plan.

Material adverse developments shall be reported within five business days.

12. Books, records, and audit

The MO shall maintain complete records identifying:

- Receipt and use of FS funds.
- Labor and indirect costs.
- Procurements.
- Bid evaluations.
- Subcontracts.
- Equipment and property.
- Technical decisions.
- Deliverables.

- Payments.
- Conflicts and recusals.

The FS, its auditors, and authorized independent reviewers may inspect relevant records, systems, sites, personnel, and contractor records.

Records shall be retained for at least seven years following final closeout, or longer when litigation, investigation, property, patent, or regulatory matters remain unresolved.

13. Program property

The Agreement shall identify who owns aircraft, prototypes, tanks, instruments, computers, test equipment, facilities, and other property purchased with Program funds.

Unless otherwise approved:

- Major property shall be titled to the FS, MO in trust for the Program, or a designated public-benefit entity.
- The MO shall maintain a property register.
- Property shall be tagged and inventoried.
- Property may not be sold, pledged, transferred, or used for unrelated purposes without approval.
- Disposition proceeds shall be returned to the Program or FS.

14. Independent oversight

The FS may establish:

- An FS–MO Agreement Oversight Board.
- A Scientific and Engineering Panel.
- An Independent Safety and Assurance Board.
- Independent financial and procurement auditors.

The MO shall provide these bodies with timely access to information and personnel.

The independent bodies do not relieve the MO or Program Manager of responsibility for performance.

15. Safety and regulatory compliance

No test may proceed unless the MO has documented:

- Applicable legal and regulatory approvals.

- Safety analysis.
- Environmental review.
- Test plan.
- Measurement plan.
- Abort and stop criteria.
- Incident-response procedures.
- Appropriate insurance.
- Independent readiness review.

No atmospheric release shall be treated as implicitly authorized by this Agreement.

16. Changes

The Program Manager may make changes within approved limits.

Prior FS approval is required for:

- Changes to the fundamental Program purpose.
- Transfers exceeding 10% between major work packages.
- Use of contingency exceeding \$10,000,000 for one event.
- A PO exceeding \$50,000,000.
- A major sole-source award.
- A change in aircraft or aerosol architecture.
- A material reduction in open-access rights.
- Extension beyond the approved period.
- Material increase in MO management fees.

All changes shall be documented in writing.

17. Management compensation

The MO shall receive:

- Reimbursement of approved direct PMO costs.
- A negotiated fixed or capped management fee.
- Approved indirect costs under the agreed methodology.

The MO shall not automatically apply its ordinary institutional overhead rate to all money passed through to PO recipients.

No fee shall be charged against unused contingency funds.

18. Remedies for nonperformance

If the MO fails to comply, the FS may:

- Require a corrective-action plan.
- Impose additional reporting.
- Withhold a funding tranche.
- Disallow a cost.
- Require repayment.
- Suspend a procurement.
- Replace the Program Manager.
- Direct transfer of a work package.
- Suspend the Program.
- Terminate the Agreement.
- Replace the MO.

The remedy selected shall be proportionate to the seriousness and urgency of the problem.

19. Termination

The FS may terminate the Agreement:

- For material breach.
- For fraud, misuse, or serious conflict-of-interest violations.
- For repeated failure to meet milestones.
- For unacceptable safety performance.
- If the Program no longer has sufficient expected public benefit.
- For convenience upon [60–120] days' written notice.

Upon termination, the MO shall:

1. Stop new obligations.
2. Protect Program property.
3. Cancel or assign subcontracts as directed.
4. Deliver all completed and work-in-progress materials.
5. Transfer data, software, designs, and records.
6. Provide a final accounting.
7. Return unobligated and disallowed funds.
8. Assist transition to a successor organization.

20. Insurance, liability, and indemnification

The MO shall maintain insurance appropriate to its role, including:

- General liability.
- Professional liability.
- Workers' compensation.
- Cybersecurity.
- Directors and officers coverage.
- Aircraft and aviation coverage where applicable.
- Pollution and environmental liability where applicable.

Responsibility for hazardous operations shall be allocated to the parties controlling those operations.

No indemnity shall protect a party from fraud, willful misconduct, or gross negligence.

21. Public transparency

The MO shall operate a public Program registry containing:

- PO recipient.
- Amount.
- Purpose.
- Deliverables.
- Schedule.
- Procurement method.
- Current status.
- Major amendments.
- Reports, data, and designs.
- Reasons for termination.
- Approved disclosure exceptions.

Confidential information may be redacted only as permitted under the approved exception process.

22. Dispute resolution

Disputes shall first be elevated through:

1. Program Manager and FS program officer.
2. MO chief executive and FS executive.
3. Mediation.
4. Arbitration or litigation in the agreed jurisdiction.

Nothing prevents emergency relief needed to protect funds, property, safety, or confidential information.

23. Governing law

This Agreement shall be governed by the laws of [state], excluding its choice-of-law principles.

24. Exhibits

The following exhibits are incorporated:

- Exhibit A — Program objectives.
- Exhibit B — Work breakdown structure.
- Exhibit C — Five-year budget.
- Exhibit D — Milestone and decision-gate schedule.
- Exhibit E — Procurement policy.
- Exhibit F — Open-access and intellectual-property plan.
- Exhibit G — Reporting requirements.
- Exhibit H — Safety and environmental framework.
- Exhibit I — Property-management plan.
- Exhibit J — Conflict-of-interest policy.
- Exhibit K — Approved management fee and indirect-cost methodology.

Agreement 2: MO–PO recipient

Different recipients require different instruments:

- **Company building equipment:** R&D contract or prototype-development contract.
- **University performing research:** research subaward or sponsored-research agreement.
- **NASA, NOAA, or another agency:** reimbursable or interagency-style agreement.
- **Independent reviewer:** professional-services contract.
- **Commercial equipment purchase:** ordinary fixed-price supply contract.

The core terms should be substantially consistent. Federal procurement rules provide useful models for inspection before acceptance, quality assurance, access to relevant technical data, property accountability, and termination for convenience or default.

RESEARCH, DEVELOPMENT, AND PROTOTYPE PURCHASE ORDER AGREEMENT

This Research, Development, and Prototype Purchase Order Agreement is entered into between:

Managing Organization: [MO legal name]
and
Recipient: [Recipient legal name]
PO number: [Number]
Project title: [Title]
Maximum amount: \$[Amount]

Period of performance: [Start date] through [End date]

1. Purpose and research question

The Recipient shall perform the work described in this Agreement to answer the following decision-relevant question:

[State the specific question.]

Example:

“Determine whether a modified Boeing 777-class aircraft can safely carry and operate an SO₂ storage and release system with a useful payload while satisfying the defined structural, thermal, material-compatibility, flight-safety, loading-time, and lifecycle-cost requirements.”

The work is intended to enable the following decision:

[Proceed, redesign, compare alternatives, build, test, or terminate.]

2. Statement of work

The Recipient shall perform the tasks in Exhibit A.

Each task shall state:

- Objective.
- Method.
- Inputs.
- Assumptions.
- Deliverable.
- Due date.
- Acceptance criteria.
- Dependencies.
- Required public release.
- Payment amount.

Activities outside the Statement of Work require written authorization.

3. Contract type and ceiling

This PO is:

[Fixed price / cost reimbursement / cost plus fixed fee / milestone based / time and materials.]

The maximum MO obligation is **\$[amount]**.

The Recipient may not exceed the ceiling without a written amendment.

For time-and-materials or cost-reimbursement work:

- A ceiling shall apply.
- Costs must be reasonable, allocable, documented, and permitted.
- The Recipient shall notify the MO when spending reaches 75%, 85%, and 95% of the ceiling.
- The Recipient is not entitled to reimbursement beyond the ceiling without authorization.

4. Milestones and payments

Illustrative payment schedule:

Milestone	Acceptance event	Payment
Project initiation	Approved project plan and requirements	10%
Preliminary design	Successful preliminary design review	20%
Detailed design	Accepted design package	20%
Prototype	Prototype delivered and inspected	20%
Testing	Acceptance tests completed	15%
Corrections	Material deficiencies corrected	5%
Open archive and final report	Complete public deliverable package accepted	10%

Payment for a milestone does not waive latent defects, fraud, data-rights violations, or warranty obligations.

5. Deliverables

The Recipient shall deliver, as applicable:

- Requirements.
- Engineering analyses.
- Native CAD files.

- Drawings.
- Specifications.
- Bills of materials.
- Source code.
- Model code and input files.
- Prototype hardware.
- Test equipment.
- Test plans.
- Raw test data.
- Processed data.
- Calibration records.
- Failure reports.
- Hazard analyses.
- Cost models.
- Operating and maintenance manuals.
- Training materials.
- Final technical report.
- Lessons-learned report.

PDF summaries alone do not satisfy requirements for native engineering files, source code, or underlying data.

6. Acceptance criteria

A deliverable is accepted only after the MO determines that it:

1. Is complete.
2. Meets the Statement of Work.
3. Passes specified tests.
4. Includes underlying data and documentation.
5. Contains no unauthorized restrictive markings.
6. Can be independently inspected or reproduced.
7. Meets open-access and licensing obligations.
8. Includes all required safety and quality records.

The MO may:

- Accept.
- Accept conditionally.
- Reject.
- Require correction.
- Require retesting.
- Reduce payment.

- Terminate the affected task.

The Recipient shall correct rejected deliverables at its own cost when rejection results from failure to comply with the Agreement.

7. Inspection and testing

The MO and its authorized independent reviewers may inspect and test:

- Work in progress.
- Recipient facilities used for the project.
- Subcontractor facilities.
- Prototypes.
- Materials.
- Software.
- Models.
- Records supporting performance claims.

Inspection does not transfer responsibility for quality or safety from the Recipient to the MO.

The Recipient shall provide reasonable access, test support, and technical personnel.

8. Key personnel

The following personnel are considered essential:

- Principal investigator or project manager: [Name].
- Chief engineer: [Name].
- Safety lead: [Name].
- Data lead: [Name].

Replacement of key personnel requires prior approval.

The Recipient shall promptly disclose when staffing changes may affect performance.

9. Subcontractors

The Recipient may not place a major subcontract above \$[threshold] without MO approval.

The Recipient remains fully responsible for subcontractor performance.

The Recipient shall flow down all applicable requirements concerning:

- Open access.
- Data and intellectual-property rights.
- Audit access.
- Safety.
- Conflicts of interest.
- Record retention.
- Reporting.
- Property.
- Termination.
- Delivery of work in progress.

10. Open-access obligations

All Funded Developments shall be publicly released under the licenses specified in Exhibit D, except for approved exclusions.

The Recipient shall release:

- Reports and documentation.
- Raw and processed measurement data.
- Metadata.
- Source code.
- Model inputs and outputs.
- Native design files.
- Schematics.
- Bills of materials.
- Test and calibration procedures.
- Positive, negative, and inconclusive findings.

Suggested release deadlines:

- Award summary: within 10 business days after award.
- Approved project plan: within 30 days after approval.
- Quarterly reports: within 30 days after quarter end.
- Preliminary design package: within 60 days after review.
- Raw test data: within 30 days after test completion.
- Quality-controlled data: within 90 days.
- Final archive: before final payment.

11. Background intellectual property

The Recipient's approved Background IP is listed in Exhibit E.

The Recipient represents that:

- The list is complete to the best of its knowledge.
- It has authority to use the listed Background IP.
- Use of the Background IP will not prevent delivery or public use of the Funded Developments except as expressly stated.

No additional proprietary component or restriction may be incorporated without written approval.

12. Funded intellectual property

The Recipient may retain ownership of Funded Developments only subject to the rights granted in this Agreement.

The Recipient grants the MO, FS, and designated public-benefit entities an irrevocable, worldwide, royalty-free, transferable, sublicensable license to:

- Use.
- Reproduce.
- Modify.
- Distribute.
- Test.
- Validate.
- Manufacture or have manufactured.
- Maintain.
- Repair.
- Integrate.
- Create derivative works.
- Continue the project with another recipient.

The Recipient shall execute documents needed to perfect these rights.

The Recipient may not grant an exclusive license that interferes with the Program's open-access or public-benefit objectives.

13. Inventions and patents

The Recipient shall disclose each potentially patentable invention within [30] days after internal disclosure.

Before filing a patent, the Recipient shall submit a proposed public-benefit management plan.

The MO may require:

- Open publication instead of patenting.
- Royalty-free licensing.
- Nonexclusive licensing.
- Climate-use licensing.
- A patent non-assert covenant.
- Rights allowing another manufacturer to produce the technology.
- Step-in rights if the Recipient fails to make the invention reasonably available.

Patent filing may delay public release only for the minimum approved period.

14. Data management

The Recipient shall maintain an approved Data Management and Sharing Plan addressing:

- Data formats.
- Metadata.
- Calibration.
- Quality control.
- Version control.
- Storage.
- Backup.
- Cybersecurity.
- Access.
- Persistent identifiers.
- Release schedule.
- Long-term archive.
- Restrictions and their legal basis.

Data necessary to reproduce a published or reported finding shall be released with the finding.

15. Progress reporting

The Recipient shall submit:

Monthly status report

- Work performed.
- Milestones completed.
- Cost incurred.
- Schedule status.
- Technical risks.
- Safety matters.
- Decisions required.

Quarterly technical report

- Results.
- Data generated.
- Comparison with requirements.
- Problems and failures.
- Corrective actions.
- Updated estimate at completion.
- Open-access status.

The Recipient shall notify the MO within 24 hours of a serious safety event and within five business days of any other material adverse development.

16. Cost and financial controls

For reimbursable work, the Recipient shall:

- Maintain a project-specific cost account.
- Segregate direct and indirect costs.
- Support labor charges.
- Document procurements.
- Credit refunds, rebates, and insurance recoveries to the project.
- Avoid charging unapproved lobbying, entertainment, fines, unrelated research, or unsupported costs.
- Return unused advances.

The MO may disallow unreasonable, unsupported, unapproved, or non-project costs.

17. Records and audits

The Recipient shall retain relevant records for at least seven years after final payment.

The MO, FS, auditors, and authorized reviewers may examine:

- Financial records.
- Time records.
- Purchasing files.
- Subcontracts.
- Technical notebooks.
- Software repositories.
- Test records.
- Quality records.
- Property records.

- Conflict disclosures.

The Recipient shall cooperate with financial, procurement, technical, safety, and data audits.

18. Property

Exhibit F shall identify:

- MO-furnished property.
- Property purchased with PO funds.
- Property fabricated under the PO.
- Title holder.
- Custodian.
- Permitted use.
- Maintenance responsibility.
- Disposition requirements.

The Recipient shall:

- Maintain a property register.
- Protect property from loss or misuse.
- Conduct periodic inventories.
- Report loss or damage.
- Obtain approval before disposal or transfer.
- Deliver property when directed at closeout or termination.

19. Quality assurance

The Recipient shall maintain a quality-management plan appropriate to the work.

The plan shall address:

- Design control.
- Configuration management.
- Supplier qualification.
- Material traceability.
- Calibration.
- Software version control.
- Nonconformance.
- Corrective action.
- Verification.
- Independent review.
- Document retention.

No safety-critical change may be made without documented review and approval.

20. Safety and environmental compliance

The Recipient is responsible for safe performance of its work.

Before hazardous or flight-related testing, the Recipient shall provide:

- Hazard analysis.
- Applicable permits.
- Environmental review.
- Test plan.
- Safety procedures.
- Emergency plan.
- Training records.
- Stop-work criteria.
- Insurance certificates.
- Independent readiness-review materials.

The MO may immediately stop work presenting an unreasonable safety, environmental, or legal risk.

21. Conflicts of interest

The Recipient shall disclose:

- Financial relationships affecting the work.
- Relationships with reviewers or MO personnel.
- Relevant patents and licenses.
- Ownership in suppliers.
- Related-party subcontracts.
- Other funding that could create conflicting obligations.

The Recipient shall update disclosures throughout performance.

The MO may require mitigation, recusal, contract modification, or termination.

22. Publications and communications

The Recipient may publish results subject to:

- Protection of personal information.
- Approved security restrictions.

- A short prepublication review to identify confidential background information or patentable inventions.
- Acknowledgment of the FS and MO.
- Release of supporting data and code.

The MO may not suppress unfavorable results merely because they are embarrassing, commercially harmful, or inconsistent with Program expectations.

The Recipient may not state or imply that the FS or MO endorses its conclusions.

23. Warranties

The Recipient warrants that:

- Deliverables are original or properly licensed.
- It has authority to grant the required rights.
- Work will be performed professionally.
- Materials and workmanship will meet stated requirements.
- Data will not be knowingly falsified or materially omitted.
- Deliverables will not contain undisclosed malicious software.
- Restrictions and proprietary markings will be accurate.

Additional hardware warranties shall be stated in Exhibit G.

24. Insurance and indemnification

The Recipient shall maintain insurance appropriate to the work, which may include:

- Commercial general liability.
- Professional liability.
- Workers' compensation.
- Product liability.
- Aviation liability.
- Environmental and pollution liability.
- Cybersecurity coverage.

The Recipient shall be responsible for injury, damage, or loss caused by its negligence, willful misconduct, legal violations, or breach.

Specific indemnification terms shall be negotiated according to the type and risk of the work.

25. Stop-work order

The MO may direct the Recipient to stop all or part of the work because of:

- Safety.
- Funding limitations.
- Technical uncertainty.
- Regulatory issues.
- Investigation.
- Program reprioritization.
- Recipient nonperformance.

The order shall state which work must stop and which activities may continue to protect personnel, property, and data.

26. Termination for convenience

The MO may terminate all or part of the PO when continuation is no longer in the Program's interest.

The Recipient shall be paid for:

- Accepted work performed.
- Reasonable approved commitments that cannot be cancelled.
- Reasonable closeout expenses.

The Recipient shall not receive anticipated profit on work not performed.

The Recipient shall deliver all completed and work-in-progress materials.

27. Termination for cause

The MO may terminate for cause when the Recipient:

- Materially fails to perform.
- Misses a critical milestone without adequate justification.
- Misuses funds.
- Falsifies data or reports.
- Violates safety requirements.
- Refuses required audits.
- Breaches open-access obligations.
- Conceals a material conflict.
- Becomes insolvent.

- Violates applicable law.

The MO may obtain replacement performance and recover appropriate additional costs, subject to applicable law and negotiated limitations.

28. Transition assistance

Upon expiration or termination, the Recipient shall assist an orderly transfer by providing:

- Work in progress.
- Native design files.
- Source code.
- Passwords and access credentials.
- Data.
- Equipment.
- Supplier information.
- Configuration records.
- Technical briefings.
- Reasonable support to the successor.

29. Disputes

The parties shall first attempt resolution through their project managers.

Unresolved disputes shall be elevated to senior executives, followed by mediation and then [arbitration/litigation] under the law and venue stated in the PO.

The Recipient shall continue undisputed work while a dispute is pending unless directed otherwise.

30. Order of precedence

In the event of conflict, the following order applies:

1. Signed PO amendment.
2. PO cover document.
3. Special terms and conditions.
4. Statement of Work.
5. Data and intellectual-property exhibit.
6. Safety requirements.
7. General terms and conditions.
8. Recipient proposal.

31. Exhibits

- Exhibit A — Statement of Work.
- Exhibit B — Milestones and payment schedule.
- Exhibit C — Acceptance-test plan.
- Exhibit D — Open-access licenses and release schedule.
- Exhibit E — Background IP and third-party restrictions.
- Exhibit F — Property list and title.
- Exhibit G — Warranty requirements.
- Exhibit H — Safety and environmental requirements.
- Exhibit I — Reporting templates.
- Exhibit J — Key personnel and approved subcontractors.

How the two agreements connect

The most important clause in the FS–MO agreement is the **flow-down requirement**:

The MO shall include in every applicable PO, subcontract, grant, cooperative agreement, and lower-tier agreement all provisions necessary for the MO to satisfy its obligations to the FS.

That means the MO cannot promise the FS open engineering files while allowing Boeing to provide only proprietary PDFs. It cannot promise audit access while signing a recipient contract that bars access to supporting records. It cannot promise transition rights while letting the software contractor retain the only usable source code.

The FS–MO agreement should therefore contain a **mandatory clauses matrix**:

FS requirement	Must flow into recipient agreement?
Restricted use of funds	Yes
Milestone reporting	Yes
Audit and records access	Yes
Open data and publications	Yes
Native engineering files and source code	Yes, when applicable
Background-IP disclosure	Yes
Public-benefit licensing	Yes
Safety and incident reporting	Yes
Conflict disclosures	Yes
Property controls	Yes
Stop-work and termination	Yes
Delivery of work in progress	Yes
Flow-down to lower-tier subcontractors	Yes

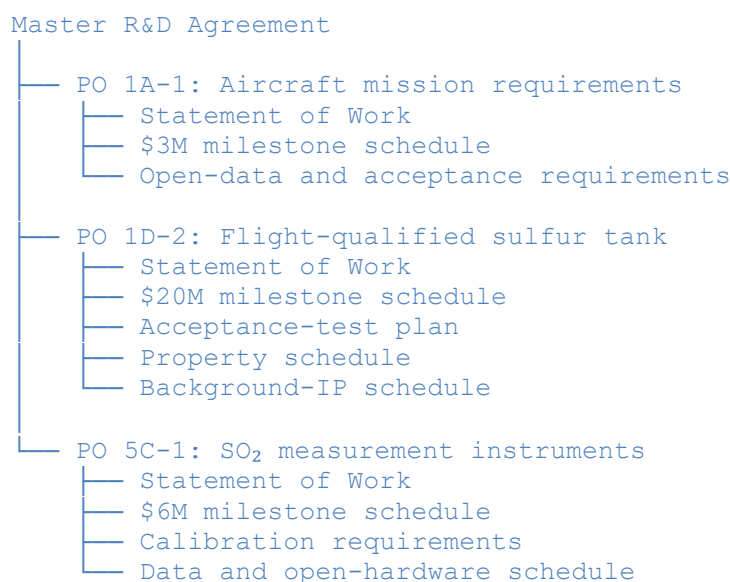
Open-access obligations should be project-specific but legally explicit. The Gates Foundation’s approach distinguishes background IP from funded developments and may require publication, data-management, licensing, manufacturing, pricing, or distribution commitments intended to preserve public access.

Recommended document hierarchy

Rather than renegotiating 60 pages for every assignment, the MO could establish:

1. **Master R&D Terms and Conditions** applying to all recipients.
2. A short **PO cover sheet** identifying recipient, amount, dates, and contract type.
3. A project-specific **Statement of Work**.
4. A **milestone and payment schedule**.
5. An **acceptance-test plan**.
6. A project-specific **IP and data-rights schedule**.
7. A **safety and regulatory schedule**.
8. A **property schedule**.

For example:



The federal Uniform Guidance is not automatically binding on a privately funded program, but it provides useful controls: documented procurement histories, price justification, responsible-contractor determinations, limits and heightened oversight for time-and-materials contracts, risk-based monitoring, corrective-action follow-up, site visits, and access to subrecipient records.

The two agreements should be converted into final documents by attorneys experienced in **foundation law, nonprofit taxation, aerospace R&D contracting, intellectual property, aviation, environmental law, and hazardous-material liability.**

Further Reading

Is it possible to solve the climate problem with a surge of R&D in key areas; and if so, what are those areas and how much might this cost? The following documents hope to answer this question.

Stratospheric Aerosol Injection (SAI)

SAI Reflectivity Plan (7-page PDF)

https://www.ma2life.org/g/film/SAI_Reflectivity_Plan.pdf

pdf file

<https://drive.google.com/drive/folders/1Jf8jMP38b2P-vj9XTWRLGGMuahuLwxB6>

original files

Proposed \$1B SAI Experimental Research Fund

https://www.ma2life.org/g/film/sai_experiments_research_fund_ai.pdf

pdf file

https://drive.google.com/drive/folders/1KRtdfFEjKmzV5XaxiyzRL4JckPzrF_sM

original files

Proposed \$1B SAI Equipment Development Fund

https://www.ma2life.org/g/film/sai_equipment_development_fund_ai.pdf

pdf file

https://drive.google.com/drive/folders/1B0Sko2M2cl_V-_uZcPozD-s0cF8bjV-

original files

Stratospheric Aerosol Injection Field Experiments (description)

https://ma2life.org/g/eet/eetcs_plan/decarb_plan/arctic_sai_experiment.pdf

Marine Cloud Brightening (MCB)

MCB Reflectivity Plan (7-page PDF)

https://www.ma2life.org/g/film/MCB_Reflectivity_Plan.pdf

pdf file

<https://drive.google.com/drive/folders/1Aoz9vLxKLF4qBw1xnjlCfYGXERhTY3rI>

original files

Proposed \$1B MCB Experimental Research Fund

https://www.ma2life.org/g/film/mcb_experiments_research_fund_ai.pdf

pdf file

<https://drive.google.com/drive/folders/1ItaJh7OQMeZMInUkArcShi-SGVFmzvD0>

original files

Proposed \$1B MCB Equipment Development Fund

https://www.ma2life.org/g/film/mcb_equipment_development_fund_ai.pdf

pdf file

https://drive.google.com/drive/folders/1Leivbra4GXj5VlPg_jFZfPN1UQyHgR-S

original files

Climate Moonshot Business Plan

Climate Moonshot Business Plan (90-page PDF)

<https://www.aplantosavetheplanet.org/bp>

pdf file

<https://www.aplantosavetheplanet.org/lab>

original files

Links to Climate Moonshot PDF Files That Can be Fed to AI (open-source)

<https://www.aplantosavetheplanet.org/pdf-ai>

Climate Moonshot Videos

What are the big ideas for solving the entire climate problem? (#19...#21)

<https://www.aplantosavetheplanet.org/biv>

Decarbonization R&D Videos (#2, #11 to #16)

<https://www.aplantosavetheplanet.org/drd>

Reflecting Sunlight Videos (#6 to #10)

<https://www.aplantosavetheplanet.org/rsv>

Climate Moonshot Conference

Climate Moonshot Conference (3-page PDF)

[https://www.ma2life.org/g/moonshot/Climate Moonshot Conference.pdf](https://www.ma2life.org/g/moonshot/Climate%20Moonshot%20Conference.pdf)

Climate Moonshot Filmmaking

The Climate Kids (docudrama film)

[https://www.ma2life.org/g/film/The Climate Kids.pdf](https://www.ma2life.org/g/film/The%20Climate%20Kids.pdf)

pdf file

https://drive.google.com/drive/folders/1UyEyyGock43PQpnMMcEmq_94gy4m3GHI

original files

Scientific Research

Experiments that Measure How Much Sunlight Reflects off Aerosols

https://ma2life.org/g/eet/eetcs_plan/decarb_plan/measure_aerosol_reflection_experiment.pdf

\$250M Cloud Research Surge (pdf)

[https://ma2life.org/g/eet/eetcs_plan/decarb_plan/cloud_science_surge ChatGPT.pdf](https://ma2life.org/g/eet/eetcs_plan/decarb_plan/cloud_science_surge_ChatGPT.pdf)

Proposed Ocean Iron Fertilization \$25M Research Fund (pdf)

[https://www.ma2life.org/g/film/ocean iron fertilization ai.pdf](https://www.ma2life.org/g/film/ocean_iron_fertilization_ai.pdf)

pdf file

https://drive.google.com/drive/folders/12Rn4oc_1sUcttW1_UjKNRLJxFrv0sMj0

original files

\$2B Atmospheric Research (400-page document)

[https://ma2life.org/g/eet/eetcs_plan/decarb_plan/Atmospheric Experiments.pdf](https://ma2life.org/g/eet/eetcs_plan/decarb_plan/Atmospheric_Experiments.pdf)

pdf file

https://drive.google.com/drive/folders/1e5jvAmJUfBLCpkQVKwR0dS_Ur2UtFLkG

original files

Geothermal Moonshot (e.g. high temperature vertical tunnel boring machine)

https://ma2life.org/g/eet/eetcs_plan/decarb_plan/geothermal_conversation.pdf

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Prompt to AI: s

Response From AI:

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