MCB Equipment Development Initiative

CLIMATE MOONSHOT PORTFOLIO

Billions to save trillions

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

MARINE CLOUD BRIGHTENING (MCB)

AEROSOL GENERATORS • MARINE PLATFORMS • AUTONOMY • MONITORING

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Developed with assistance from ChatGPT

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Executive Summary

Purpose. The proposed $1 billion, five-year MCB Equipment Development Initiative would develop and test the engineering systems needed for a possible future marine cloud brightening program without constructing an operational climate-intervention fleet. The work centers on controllable sea-salt aerosol generation, seawater intake and conditioning, crewed and autonomous marine platforms, power and release structures, navigation and fleet control, monitoring, maintenance, data systems, and integrated sea trials. Atmospheric releases would remain subject to the separate scientific, environmental, and governance process described in the companion MCB experimental-research program.

Program architecture. The baseline technical program totals $850 million, with a separately controlled $150 million technical and schedule reserve. The largest work packages are sea-salt aerosol-generation systems ($160 million), vessel and floating-platform prototypes ($160 million), and monitoring, verification, and side-effect measurement ($120 million). Other work develops seawater conditioning, autonomy and weather routing, power and plume-placement systems, port and maintenance infrastructure, systems integration, digital twins, a prototype operations center, and owner-side program management. The objective is to compare competing designs rather than prematurely select a single nozzle, vessel, power system, or autonomy architecture.

Development sequence. Work proceeds through requirements and feasibility, preliminary design and risk reduction, detailed design and fabrication, integration and qualification, and operational demonstration and handoff. Early prototypes are tested in laboratories and controlled marine environments before larger fabrication and longer sea trials. Independent organizations verify particle output, reliability, software safety, marine class, calibration, environmental performance, and readiness. The Funding Source retains control of major scope changes and reserve releases, while the Managing Organization administers competitive contracts, grants, task orders, and acceptance of measurable deliverables.

Success criterion. After five years, success would mean an open, independently verified engineering package rather than a deployment decision. The program should know which generator designs can repeatedly produce useful particle distributions from real seawater; how intake, corrosion, fouling, power, maintenance, and vessel operations affect performance and cost; whether supervised autonomous platforms can operate safely and stop reliably; and whether monitoring systems can reconcile commanded output with measured plume behavior. Native CAD, software, test data, calibration records, failure reports, operating data, and lifecycle-cost evidence should be public by default so that governments, researchers, and future funders can reproduce the results and decide whether to proceed, redirect, pause, or stop.

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

Program at a Glance

The initiative develops and independently verifies the engineering systems that could support later MCB research. It does not authorize a regional or global intervention, and it does not replace the separate atmospheric Experimental Research Initiative.

Item	Program design
Funding	$1.0B over five years: $850M baseline technical program plus $150M centrally controlled technical and schedule reserve.
Core objective	Develop open, reproducible engineering systems for sea-salt generation, marine platforms, autonomy, power/release, monitoring, maintenance, data, and integrated trials.
Competing designs	Maintain multiple generator and platform concepts through early risk reduction; down-select only after measured performance and independent review.
Major prototypes	Crewed test-vessel conversion, autonomous surface-vessel prototype, long-endurance platform demonstrator, ship-ready generator lines, reusable monitoring systems, and prototype operations center.
Final demonstration	Progressive harbor, nearshore, coastal, and offshore trials culminating in a 30- to 90-day integrated multi-platform engineering demonstration, subject to separate authorization for any atmospheric release.
Primary engineering metrics	Verified useful-particle output and size distribution; energy/resource efficiency; reliability; maintainability; shutdown and control; marine durability; monitoring closure; lifecycle cost.
Stage-gate logic	Requirements -> generator feasibility -> subsystem qualification -> integrated platform -> autonomy/safety -> endurance -> multi-platform demonstration -> Phase II decision package.
Open technical record	Native CAD, interface specifications, source code, bills of material, test data, calibration, failure reports, operating records, and lifecycle-cost evidence open by default.
Five-year decision	Proceed, redirect, pause, or stop each generator/platform/autonomy path based on measured evidence; deliver a Phase II engineering package without implying deployment authorization.

System Architecture

The equipment program should be managed as one traceable system rather than as independent hardware projects. The principal engineering flow is shown below.

System layer	Principal function	Primary interface / output	Budget area
Seawater source	Intake, filtration, conditioning, cleaning and feedwater metrology.	Conditioned seawater with known chemistry and flow.	Area 2
Aerosol generation	Generate controlled sea-salt aerosol and measure source output.	Verified particle number, size distribution, mass flow and uncertainty.	Area 1
Power and release	Provide energy, mast/ducting, marine hardening and plume-placement control.	Known energy use, release height/direction and safe shutdown.	Area 5
Marine platforms	Carry source, power, instruments and communications in representative sea states.	Crewed, autonomous and long-endurance prototype platforms.	Area 3
Autonomy and fleet control	Navigation, weather routing, authorization logic, remote supervision, fault management and cyber controls.	Commanded mission, logged decisions and transition to a safe state on faults.	Area 4
Monitoring and verification	Measure equipment output and provide reusable capability for plume, cloud, radiation and side-effect observations.	Calibrated data streams and uncertainty budgets; scientific interpretation remains with the Experimental Research Initiative.	Area 6
Port and lifecycle support	Cleaning, spares, servicing, repair, resupply and logistics.	Measured maintenance burden, availability and lifecycle cost.	Area 7
Integration and sea trials	Test cross-contractor interfaces and complete mission cycles.	Independent verification of integrated performance and reliability.	Area 8
Data and operations center	Digital twins, configuration record, forecasts, dispatch, data ingestion, alerts and public archive.	Traceable platform/release history and open handoff package.	Area 9
Program assurance	Requirements control, procurement, safety/environmental review, independent assurance and reserve governance.	Stage-gate decisions, audit trail and controlled use of funds.	Areas 10-11

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What is Marine Cloud Brightening (MCB)?

Marine Cloud Brightening (MCB) is a proposed form of solar radiation modification intended to cool Earth by making selected low marine clouds reflect more sunlight. The leading concept would draw seawater aboard a ship, autonomous vessel or floating platform, remove large contaminants, and generate very small sea-salt aerosol particles. These particles would be released into the marine boundary layer beneath or near suitable clouds. Under favorable conditions, some would become cloud-condensation nuclei, increasing cloud-droplet number while reducing average droplet size. The resulting cloud may become brighter and, in some circumstances, may persist longer or drizzle less.

MCB is unusually dependent on local conditions. The response can vary with background aerosol, cloud type, cloud depth, humidity, turbulence, wind, drizzle, atmospheric stability and the size distribution of the added particles. Some clouds may brighten strongly, some may respond weakly, and some may respond in an unexpected direction. Consequently, an operational system would need weather-aware targeting, careful measurement, rapid feedback and the ability to reduce or stop output.

MCB would not remove carbon dioxide, stop ocean acidification or replace emissions reductions. Its possible climate effect would last only while suitable clouds are treated. A large program could alter regional radiation, cloud cover, precipitation or circulation, so environmental assessment and international governance would be integral to development rather than added after the equipment is built.

This document addresses equipment development, not authorization to deploy MCB. The objective is to determine whether seawater handling, aerosol generation, vessels, automation, monitoring, maintenance and data systems can be made reliable, controllable, economical and transparent. Outdoor aerosol releases and cloud-response experiments should proceed only under the separate scientific, environmental and governance process described in the companion MCB Research Experiments document.

What Exists Today and What This $1B Program Adds

The initiative should not be justified as if every component must be invented from scratch. Laboratory aerosol sources, marine vessels, autonomous platforms, cloud and aerosol instruments, and maritime maintenance practices already exist. The engineering gap is the integrated, independently verified system needed to convert a scientifically specified MCB requirement into controlled particle output at sea with known reliability, resource use, maintenance burden, safety behavior, and lifecycle cost.

Capability	Existing / early capability	What the five-year initiative adds
Sea-salt aerosol generation	Laboratory and early outdoor source/nozzle work establishes plausible particle-generation approaches.	Competing high-throughput source families tested with real seawater, independent dry-particle metrology, marine packaging, endurance, and manufacturable design packages.
Marine platforms	Research vessels, offshore workboats, autonomous surface vessels, and long-endurance ocean platforms are mature technology classes.	MCB-specific payload, power, intake, release, monitoring, maintenance, survivability, and common-interface integration across competing platform classes.
Autonomy and remote operations	Commercial and research autonomous marine systems already demonstrate navigation, station keeping, and remote supervision.	Human-authority logic, release authorization, weather-aware mission control, fail-safe shutdown, cyber assurance, fault management, and auditable fleet coordination for MCB-specific missions.
Monitoring and metrology	Aerosol, cloud, radiation, meteorological, radar, lidar, and satellite instruments are widely used in atmospheric research.	Reusable ruggedized interfaces, time synchronization, source-output traceability, common calibration, configuration control, and engineering data systems that can be reused by the Experimental Research Initiative.
Marine maintenance and logistics	Ports, shipyards, spares systems, corrosion control, and reliability-centered maintenance are established maritime practices.	MCB-specific cleaning, fouling/corrosion control, module exchange, resupply, service intervals, availability evidence, and prototype-calibrated lifecycle cost.
Integrated operation	Individual technologies can be demonstrated separately.	Progressive dockside, nearshore, offshore, endurance, and multi-platform demonstrations of end-to-end operation and safe fault response.

Program Architecture and $1 Billion Budget

Prompt to AI: A 15-year Marine Cloud Brightening plan is available at https://www.ma2life.org/g/film/MCB_Reflectivity_Plan.pdf. The plan allocates $1B over 5 years to develop automated large-scale equipment needed for possible future operations. This includes autonomous or semi-autonomous vessels or floating platforms; seawater intake, filtration and conditioning; fine sea-salt aerosol generators; release masts or ducts; power and energy storage; navigation and weather routing; communications and remote control; automated dispatch, shutdown, maintenance diagnostics and resupply; port and maintenance systems; and equipment that monitors MCB operations, atmospheric transport, cloud response, climate impacts and side effects. If $1B over 5 years were allocated to this activity, how might it be broken down in a budget?

Response From AI:

The $1 billion should finance engineering development through repeated prototypes and integrated sea trials. It should not be treated as money to construct a full operational fleet or to produce a measurable regional climate intervention. The companion $1 billion MCB experiments fund would finance the atmospheric science and controlled cloud-response campaigns. The two programs would share instruments, field sites, data systems and decision gates, but would maintain separate budgets so that engineering progress cannot silently expand an atmospheric-release program.

All figures below are order-of-magnitude planning estimates in constant 2026 dollars, not vendor quotations. A protected central reserve is essential because reliable submicron sea-salt production at high throughput, long-duration marine operation and end-to-end autonomous control remain technically uncertain.

Work package	5-year budget	Share	Principal five-year deliverable
Area 1. Sea-salt aerosol-generation systems	$160M	16.0%	Three competing generator families, two ship-ready prototype lines, verified particle output and a manufacturable design package.
Area 2. Seawater intake, filtration and conditioning	$70M	7.0%	Corrosion-resistant intake and pretreatment modules that supply stable feedwater across representative ocean conditions.
Area 3. Vessel and floating-platform prototypes	$160M	16.0%	At least three instrumented platform classes: crewed test vessel, autonomous surface vessel and long-endurance floating platform.
Area 4. Autonomy, navigation, weather routing and fleet control	$90M	9.0%	Supervised autonomy, cloud-targeting workflow, collision avoidance, remote control and fleet-management prototype.
Area 5. Power, release mast, plume placement and marine durability	$65M	6.5%	Power and energy system, elevated release structure, corrosion controls and endurance-qualified marine hardware.

Area 6. Monitoring hardware, source verification, and reusable measurement systems	$120M	12.0%	Integrated prototype network for equipment output, plume transport, cloud response, radiation, precipitation and environmental indicators.
Area 7. Port, maintenance, resupply and lifecycle logistics	$50M	5.0%	Pilot shore base, spares, automated service concepts, maintenance procedures and fleet lifecycle model.
Area 8. Systems integration and multi-platform sea trials	$80M	8.0%	Progressive harbor, coastal and offshore demonstrations culminating in a 30- to 90-day integrated trial.
Area 9. Engineering models, data platform and operations center	$35M	3.5%	Digital twins, forecast/dispatch tools, open data repository and prototype operations center.
Area 10. Program management, safety, environmental review and independent assurance	$20M	2.0%	Owner-side PMO, systems engineering, independent reviews, public reporting and Phase II procurement package.
Area 11. Central technical and schedule reserve	$150M	15.0%	Funds released only for documented redesign, failed tests, second-source development or schedule recovery.

The baseline technical program totals $850 million. The remaining $150 million is held centrally and is not automatically assigned to any contractor. Unused reserve should remain unspent or be carried into a later authorized phase.

Area 1. Sea-salt aerosol-generation systems - $160 million

This is the central technology-development workstream. The program should not assume that one nozzle concept has already won. It should fund competing approaches long enough to compare particle-size distribution, salt mass output, electrical efficiency, clogging, biofouling, corrosion, maintenance burden and performance in realistic wind and humidity.

- Fund at least three competing generator families, such as high-pressure impaction nozzles, effervescent or twin-fluid atomization, and mechanically or electrostatically assisted concepts.
- Measure the dry particle-size spectrum after evaporation, not merely the liquid-droplet diameter at the nozzle.
- Require stable operation with natural seawater containing organics, microorganisms and changing salinity.
- Demonstrate turndown, rapid shutdown and restart, and accurate mass and particle-number accounting.
- Deliver open drawings, control software, calibration methods, test data and a credible manufacturing-cost model.

Subtask	Budget
Requirements, competing concepts and laboratory physics	$18M
Bench prototypes and metrology	$30M
High-throughput prototype lines	$45M
Marine packaging and environmental qualification	$25M
Shipboard trials and reliability growth	$27M
Manufacturing package, independent review and training	$15M

Area 2. Seawater intake, filtration and conditioning - $70 million

Natural seawater is not a standardized industrial feedstock. Temperature, salinity, dissolved organics, suspended sediment, plankton and biological growth vary by region and season. The conditioning system must remove material that damages the generator without altering the salt chemistry in a way that undermines the atmospheric experiment.

Subtask	Budget
Ocean-water requirements and fouling characterization	$6M
Competing intake and pretreatment concepts	$10M
Filters, separators, pumps and instrumentation prototypes	$20M
Corrosion, biofouling and cleaning development	$10M
Integrated shipboard modules and trials	$16M
Replicable design, maintenance and waste-handling package	$8M

Area 3. Vessel and floating-platform prototypes - $160 million

No single platform should be presumed optimal. A crewed vessel is useful for early engineering and scientific access; an autonomous surface vessel may lower operating cost; and a semi-stationary or wave-powered platform may provide long endurance in a limited region. The program should develop and compare platform classes rather than committing immediately to a fleet architecture.

Prototype	Budget	Purpose
Crewed test-vessel conversion	$45M	Rapid access, large engineering payload, scientists aboard and early integrated trials.
Autonomous surface-vessel prototype	$55M	Demonstrate navigation, remote supervision, aerosol generation and maintenance intervals.
Long-endurance floating or wave-powered platform	$25M	Evaluate station keeping, low-energy operation and seasonal persistence.

Common payload module and interfaces	$20M	Allow generator, intake, monitoring and mast packages to move among platforms.
Marine certification, survivability and independent review	$15M	Establish class, safety and test requirements for later fleet procurement.

Area 4. Autonomy, navigation, weather routing and fleet control - $90 million

MCB equipment would need more than ordinary autonomous navigation. The system must decide when and where operation is scientifically authorized, avoid unsuitable clouds and sensitive areas, coordinate with aircraft and ships, verify output, pause when observations disagree with forecasts, and retain a clear human chain of command.

Subtask	Budget
Concept of operations, human authority and abort architecture	$8M
Navigation, collision avoidance and station keeping	$18M
Weather and cloud-targeting decision support	$15M
Fleet communications, remote command and cybersecurity	$15M
Fault management, automated shutdown and recovery	$14M
Simulation, supervised sea trials and software assurance	$20M

Area 5. Power, release mast, plume placement and marine durability - $65 million

Power demand and release height can dominate vessel size and operating cost. The program should compare diesel-electric, low-carbon fuels, batteries, wind, solar and wave-assist options without pretending that the first prototype must already be zero-emission. Every design should report lifecycle emissions and net radiative benefit.

Subtask	Budget
Load analysis and power-system trade studies	$6M
Generators, storage and power electronics prototypes	$15M
Release mast, duct and aerodynamic design	$14M
Corrosion, salt ingress and marine hardening	$10M
Plume-placement sensors and control	$8M
Endurance qualification and replicable design package	$12M

Area 6. Monitoring hardware, source verification, and reusable measurement systems - $120 million

An equipment program must prove not only that machinery runs, but that source output is known, traceable, calibrated, and reusable by the separate atmospheric-science program. Area 6 therefore develops source metrology, ruggedized reusable measurement hardware, common interfaces, synchronization, calibration, and engineering data links. The companion MCB Experimental Research Initiative should pay for atmospheric campaign design and operations, treated/control sampling, causal attribution, cloud/radiation/precipitation interpretation, and environmental-effect conclusions. Shared instruments may serve both programs, but each asset should have one lead budget and should not be charged in full to both initiatives.

Monitoring function	Budget
Generator output, particle size, mass flow and calibration	$20M
On-vessel meteorology, plume instrumentation and data links	$15M
Reusable airborne/tethered instrument integration and ruggedization	$20M
Reusable radar/lidar/radiometer integration and calibration	$20M
Satellite/data interfaces and engineering assimilation tools	$10M
Environmental-monitoring sensor packages and interfaces	$15M
Calibration, intercomparison and independent verification	$20M

Area 7. Port, maintenance, resupply and lifecycle logistics - $50 million

A fleet that works only with constant expert attention would not be ready for Phase II. The program should develop shore-side servicing, spare-module exchange, automated cleaning, fuel or energy replenishment, data offload, corrosion inspection and repair procedures in parallel with the vessels.

Subtask	Budget
Base and site requirements	$4M
Pilot maintenance and integration facility	$14M
Spare modules, tooling and inventory system	$8M
Automated cleaning, flushing and service connections	$8M
Resupply, transport and deployment logistics	$6M
Reliability-centered maintenance and lifecycle cost model	$10M

Area 8. Systems integration and multi-platform sea trials - $80 million

Subsystem budgets include ordinary component tests. This separate work package pays for tests that cross contractor boundaries: generator plus intake, vessel plus mast, autonomy plus weather targeting, monitoring plus data systems, and complete mission cycles under independent observation.

Campaign	Budget
Systems-integration laboratory and digital test environment	$10M
Harbor and dockside integration campaign	$8M
Nearshore engineering trials	$12M
Coastal plume and monitoring trials using authorized releases	$15M
Offshore reliability and autonomy campaign	$15M
30- to 90-day multi-platform demonstration and readiness review	$20M

Area 9. Engineering models, data platform and operations center - $35 million

The engineering operating system should maintain a complete digital record for every platform and authorized release: where the platform went, what water was processed, what particle output was measured, what commands were issued, what equipment state and maintenance history applied, and what observations were linked back to the mission. It may consume weather, plume, and cloud predictions supplied by the Experimental Research or GCM programs, but it should not fund a competing climate-science model-development program.

Subtask	Budget
Data governance, interfaces and open-access architecture	$4M
Engineering digital twins and lifecycle models	$7M
Weather, plume and scientific forecast/model interfaces and mission decision tools	$7M
Fleet operations center and visualization	$7M
Real-time data ingestion, quality control and alerts	$6M
Public archive, APIs, documentation and handoff	$4M

Area 10. Program management, safety and independent assurance - $20 million

This line is the owner-side function and does not replace normal contractor project management included in each work package. The $20 million allocation assumes that ordinary contractor management, work-package engineering, field-operation management and many technical review services remain embedded in the applicable technical work packages or task orders. The owner-side line pays for integrated requirements, schedule, procurement, configuration, safety/environmental assurance, audit and final Phase II decision support.

Function	Budget
Program office and integrated master schedule	$6M
Systems engineering and configuration control	$3M
Procurement, finance and cost assurance	$3M
Safety, environmental and maritime review	$3M
Scientific/engineering panels and public reporting	$2M
Final readiness, lifecycle cost and Phase II package	$3M

Area 11. Central technical and schedule reserve - $150 million

The reserve should remain under Funding Source and independent board control. Contractors should not include it in expected revenue. Release should require a documented problem, corrective plan, independent estimate and a finding that the work remains aligned with the charitable and scientific purpose.

Reserve category	Maximum	Examples
Requirements and concept reserve	$15M	Additional generator concepts, revised output requirements, new environmental constraints.
Prototype redesign and second-source reserve	$35M	Failed nozzles, corrosion, fouling, power shortfalls, alternative suppliers.
Fabrication and platform reserve	$35M	Vessel modifications, long-lead equipment, replacement prototypes.
Integration and sea-trial reserve	$45M	Failed endurance tests, vessel downtime, replacement campaigns, software corrections.
Schedule recovery and final-demonstration reserve	$20M	Additional reliability cycles, documentation, regulatory or deployment delays.

Suggested five-year funding profile

Year	Baseline technical work	Reserve authority	Total	Primary emphasis
Year 1	$100M	$15M	$115M	Requirements, competing concepts, laboratory prototypes, sites, governance and design reviews.
Year 2	$150M	$30M	$180M	Bench and intermediate prototypes, vessel selection, intake modules and autonomy simulation.
Year 3	$200M	$40M	$240M	Ship-ready generators, vessel conversion, monitoring systems and coastal integration.
Year 4	$220M	$45M	$265M	Peak sea trials, autonomous vessel testing, reliability growth and data-system integration.
Year 5	$180M	$20M	$200M	Long-duration demonstrations, corrections, manufacturing packages and Phase II readiness.

What $1 billion would and would not accomplish

- It could produce several independently tested sea-salt generator designs and at least two ship-ready prototype lines.
- It could produce a crewed test vessel, an autonomous surface-vessel prototype and a long-endurance platform demonstrator.
- It could demonstrate supervised automated operation, maintenance and multi-platform coordination during controlled sea trials.
- It could establish prototype monitoring, data and operations systems sufficient to design a later experimental fleet.
- It would not construct a global or regional operational fleet, authorize climate-scale deployment, or prove that MCB is environmentally acceptable.
- It would not remove the need for the separate MCB atmospheric-experiment program, independent environmental review or international authorization.

Program Crosswalk

This program crosswalk connects the portfolio budget to the engineering-development and procurement architecture. The entries below are mappings of the existing $1 billion program, not additional budget lines.

Area	Development emphasis	Major five-year deliverable	Verification	Budget
Area 1. Aerosol generation	Requirements through shipboard reliability growth	Competing generator families; two ship-ready lines; manufacturable package	Independent particle metrology, endurance and output calibration	$160M
Area 2. Seawater conditioning	Feedwater characterization through shipboard trials	Replicable corrosion/fouling-resistant intake and pretreatment modules	Process testing, cleaning/fouling trials and environmental review	$70M
Area 3. Vessels / platforms	Architecture, conversion/fabrication, integration and class	Crewed, autonomous and long-endurance prototypes with common payload interfaces	Marine class, survivability, payload integration and sea trials	$160M
Area 4. Autonomy / fleet control	Concept of operations through software assurance and sea trials	Supervised autonomy, navigation, weather routing, communications and fleet-control prototype	Hardware-in-loop testing, cyber red team, fault injection and independent V&V	$90M
Area 5. Power / release / durability	Trade studies through endurance qualification	Power architecture, mast/ducting, plume placement and hardened marine hardware	Load tests, structural/environmental qualification, corrosion and endurance tests	$65M
Area 6. Monitoring / verification	Measurement requirements through field validation and readiness	Reusable calibrated monitoring architecture and uncertainty budgets	Intercomparison, independent calibration and field validation	$120M
Area 7. Port / lifecycle logistics	Base requirements through maintenance handoff	Pilot support base, spares/tooling, automated service and lifecycle model	Maintenance/resupply trials, availability and lifecycle-cost audit	$50M
Area 8. Integration / sea trials	Integration lab through final multi-platform demonstration	Verified end-to-end system performance across progressive sea trials	Independent witnessing, readiness reviews and configuration-controlled data	$80M
Area 9. Models / data / operations	Data architecture through exercises and public handoff	Digital twins, operations center, open data platform and decision tools	Software QA, cyber review, replay tests and archive reproducibility	$35M
Area 10. Program assurance	Program formation through final readiness	Integrated PMO, systems engineering, safety/environmental assurance and Phase II package	Independent cost/technical/safety reviews and audits	$20M

Area 11. Central reserve	Conditional corrective work only	Redesign, second source, replacement test article or schedule recovery when justified	Written problem statement, alternatives, independent estimate and board approval	$150M

Contracting crosswalk

The detailed procurement packages later in this document should normally be issued as task orders, subcontracts or research subawards under a smaller set of master vehicles. This preserves the detailed deliverable lists while avoiding hundreds of unrelated prime contracts.

Master vehicle	Primary areas	Typical detailed packages
Aerosol-source engineering	1, 2, 5	Generator, intake, power/release, calibration and marine-hardening task orders
Vessel/platform engineering	3, 5, 7	Naval architecture, conversion/fabrication, payload interfaces, maintenance and port support
Autonomy/communications	4, 9	Navigation, command, cyber, fault management, operations-center and simulation task orders
Atmospheric instrumentation	6, 8	Aerosol/cloud/radiation instruments, remote sensing, calibration and field integration
Marine/field operations	8	Harbor, nearshore, coastal, offshore and final demonstration services
Models/data/software	4, 9	Digital twins, forecasts, data ingestion, visualization, archive and APIs
Independent assurance	All	Class, metrology, cyber V&V, environmental review, cost review and test witnessing
Scientific/public-lab subawards	1, 4, 6, 8, 9	Science requirements, modeling, measurement development and independent analysis
Owner-side PMO and systems engineering	10	Integrated schedule, requirements/configuration, procurement, finance, reporting and closeout
Corrective/second-source options	11	Prepriced or competed work activated only after reserve-release approval

KPP and Gate Crosswalk

Area	Principal KPP	Main gate	Phase II consequence
1. Aerosol generation	Useful dry-particle output, size distribution, resource use, endurance	G2 / G6	Generator architecture and module count
2. Seawater conditioning	Feedwater tolerance, fouling/corrosion, cleaning interval	G3 / G6	Pretreatment architecture and service burden
3. Vessels/platforms	Payload, endurance, survivability, mission availability	G3-G6	Platform architecture and fleet availability

Area	Principal KPP	Main gate	Phase II consequence
4. Autonomy/fleet control	Human authority, safe state, fault handling, communications/cyber	G5	Permitted autonomy level and supervision burden
5. Power/release/durability	Power demand, release geometry, marine endurance	G3 / G6	Platform sizing and operating cost
6. Monitoring hardware/source verification	Measurement uncertainty, uptime, synchronization, calibration	G3-G7	Monitoring architecture and verification cost
7. Port/lifecycle	MTTR, spares, service interval, turnaround	G6 / G8	Base capacity, OPEX, spare fleet
8. Integration/sea trials	End-to-end mission completion and reliability	G4-G7	Overall engineering readiness
9. Engineering models/data/operations	Replay/reproducibility, configuration fidelity, cyber/data integrity	G4-G8	Operations-center and digital architecture
10. Program assurance	Closed findings, cost/schedule/readiness evidence	All	Credibility of the final decision package
11. Central reserve	Evidence justifying corrective work	FS approval	No automatic Phase II effect

Relationship to the MCB Experimental Research Initiative

The MCB Equipment Development Initiative and the MCB Experimental Research Initiative are complementary but should have a clear financial boundary. Equipment Development builds and qualifies reusable engineering capability. Experimental Research uses qualified capability to answer atmospheric science questions. A shared asset may support both programs, but it should have one lead budget, a documented transfer or usage rule, and no duplicate full-cost charge.

Capability	Equipment Development Initiative pays for	Experimental Research Initiative pays for
Aerosol generators	Competing designs, scaling, manufacturability, controls, endurance, marine packaging, calibration methods and reliability growth.	Campaign-specific source settings, source operation during approved experiments and scientific analysis of source-to-plume performance.
Seawater systems	Reusable intake, filtration, corrosion/fouling control, cleaning and maintainable shipboard modules.	Campaign consumables and experiment-specific feedwater characterization needed to interpret a release.
Vessels / platforms	Prototype conversions/fabrication, common interfaces, autonomy, marine class, maintenance and long-duration engineering trials.	Research-vessel/aircraft campaign time, treated/control sampling and experiment-specific field logistics.
Monitoring hardware	Reusable instruments, standardized racks/interfaces, calibration systems, onboard source metrology, data links and ruggedization.	Scientific measurement plans, campaign operations, treated/control observations, attribution and interpretation.
Models / software	Engineering digital twins, fleet/mission software, configuration records, data ingestion and operations-center infrastructure.	Plume/cloud models used for hypotheses, experimental prediction, causal attribution and scientific model evaluation.
Environmental work	Equipment safety, marine environmental qualification, waste, noise, emissions, incident systems and engineering release boundaries.	Environmental baseline/impact monitoring for a proposed atmospheric experiment and the independent scientific/governance authorization process.
Shared assets	Lead-program ownership, design/configuration records, maintenance and capital-equipment registry.	Documented use charges or campaign costs only; no duplicate purchase of the same asset unless independent capacity is intentionally required.

Asset-Level Budget Boundary

Shared capability should have one capital owner and one asset record. The other initiative pays only incremental adaptation, operating time, campaign consumables, or intentionally independent capacity. The table below makes that rule operational for the most overlap-prone assets.

Shared capability	Capital / lead owner	Equipment Development pays	Experimental Research pays
Sea-salt generator	Equipment Development	Concept competition, scale-up, controls, marine packaging, source calibration methods, reliability, manufacturing package.	Campaign-specific source settings, approved operation during experiments, consumables, and scientific source-to-plume analysis.
Prototype MCB vessel/platform	Equipment Development when built primarily as an engineering prototype	Conversion/fabrication, payload interfaces, power, autonomy, marine class, maintenance, engineering trials.	Experiment-specific vessel operating days, scientific crew/logistics, treated/control sampling, and campaign costs.
Research aircraft	Normally Experimental Research/shared observing program	Only equipment-specific racks, data links, or incremental integration needed to verify the source/platform.	Aircraft campaign hours, scientific payload operation, treated/control sampling, and atmospheric interpretation.
Aerosol/cloud/radiation instruments	One designated lead budget per asset	Source metrology hardware plus reusable ruggedization, common interfaces, synchronization, and calibration infrastructure when Equipment is the lead.	Scientific instruments/campaign use when Experimental is the lead; atmospheric measurement plan, operation, attribution, and interpretation.
Radar/lidar/remote sensing	Normally Experimental Research/shared observing program	Only specialized engineering integration or source/platform interfaces.	Scientific observing-system acquisition/operation, plume/cloud/radiation measurements, and analysis.
Data infrastructure	One lead architecture with documented service boundary	Engineering digital twin, configuration, command/mission, maintenance and source-output records.	Scientific campaign database, attribution/model-evaluation workflows, and atmospheric analysis products.

Top-Level Engineering Requirements and Traceability

Prompt to AI: What top-level requirements and traceability system should govern MCB equipment development before designs are frozen?

Response From AI:

The equipment program should not begin from an assumed vessel or nozzle. It should begin from measurable atmospheric-science needs supplied by the companion Experimental Research Initiative and convert those needs into testable engineering requirements. Numerical values should be set prospectively by the scientific and engineering review process and changed only through formal configuration control.

Requirement family	Top-level requirement to specify	Primary verification evidence
Particle output	Target dry particle-number and mass distribution, useful size interval, allowed coarse/ultrafine tails, output stability and uncertainty.	Independent calibrated particle metrology over the intended operating envelope.
Output control	Turndown range, commanded-output accuracy, restart behavior, shutdown time and safe-state behavior.	Step-response, fault-injection and emergency-stop tests.
Resource efficiency	Electrical/fuel energy, seawater, compressed air, consumables and staffing per verified useful-particle output.	Metered endurance tests with lifecycle accounting.
Feedwater tolerance	Permitted salinity, temperature, sediment, organics and biological loading; cleaning and waste requirements.	Representative-seawater and accelerated fouling/corrosion tests.
Reliability / availability	Required mission availability, mean time between critical failures, graceful degradation and recovery.	Reliability-growth testing and long-duration sea trials.
Maintainability	Cleaning interval, module replacement time, required tools/spares and shore-service frequency.	Timed maintenance demonstrations and maintenance logs.
Marine platform	Payload, power, release height, endurance, sea state, station keeping, survivability and safe return/recovery.	Class review, structural/environmental tests and instrumented sea trials.
Autonomy and command	Human authority, operating envelope, collision avoidance, communications-loss response, cyber controls, audit logging and manual override.	Hardware/software-in-loop tests, cyber assessment, fault injection and supervised trials.
Measurement and data	Calibration, time synchronization, source metrology, uncertainty, configuration identifiers, data completeness and retention.	Independent intercomparison, replay/reproducibility tests and open archive audit.
Lifecycle cost and emissions	Capital, operations, maintenance, replacement, port, energy and lifecycle-emission accounting normalized to verified useful-particle output.	Independent cost model reconciled to prototype operating data.

Requirements Traceability Matrix

A configuration-controlled Requirements Traceability Matrix (RTM) should be a mandatory program deliverable. It should link every material engineering requirement to its scientific purpose, subsystem owner, verification method, measured result, uncertainty and acceptance decision.

Traceability level	Required linkage	Example
1. Scientific need	Decision-relevant atmospheric quantity or uncertainty.	Need to deliver a defined cloud-relevant particle population.
2. System requirement	Measurable equipment performance derived from the scientific need.	Generator must produce a specified dry size distribution and output range.
3. Subsystem / interface requirement	Allocated requirement for nozzle, intake, power, mast, controls, sensors or platform.	Nozzle output plus inlet/feedwater/power tolerances and release-interface limits.
4. Verification method	Test, analysis, inspection or demonstration with an independent witness where appropriate.	Calibrated chamber test followed by shipboard endurance test.
5. Evidence and uncertainty	Configuration-controlled raw/processed data, calibration and uncertainty budget.	Particle spectrum, energy use, failure log and metrology uncertainty.
6. Acceptance decision	Pass, conditional pass, redesign, repeat or terminate.	Gate decision recorded with reviewer findings and unresolved risks.

Reliability, Safety, and Maintainability Engineering

Reliability should be treated as a design discipline from Year 1, not as a final endurance test. The same failure taxonomy and corrective-action system should be used across generators, vessels, autonomy, power, monitoring and shore support so failures can be compared and recurring causes can be eliminated.

Required practice	Program implementation
FMEA / FMECA and hazard analysis	Identify component/system failure modes, severity, detection, mitigations and residual risk before detailed design and update after each major test.
Fault-tree / safety analysis	Use where a small number of top events - unintended release, loss of command, collision, loss of power, unsafe maintenance - justify formal causal analysis.
Failure reporting and corrective action	Maintain one FRACAS-style record linking failure, configuration, root cause, corrective action, retest and closure. Publish non-sensitive failure lessons.
Reliability-growth testing	Set operating-hour targets for successive prototypes; measure critical failures, availability and maintenance burden rather than reporting only successful demonstrations.
Graceful degradation and safe state	Define what the system does after sensor disagreement, generator fault, propulsion fault, communications loss, cyber alert or weather exceedance.

Maintainability demonstration	Measure cleaning, troubleshooting, module replacement, calibration, and resupply time.

Key Performance Parameters and Acceptance Thresholds

Prompt to AI: What Key Performance Parameters should control MCB equipment development, and when should numerical acceptance thresholds be frozen without inventing unsupported values before the atmospheric-science requirements are ready?

Response From AI:

The program should define a small set of Key Performance Parameters (KPPs) that determine whether a design can proceed. Final numerical values should not be invented in this planning document when they depend on unresolved atmospheric science. Instead, each value should have an identified source, a gate at which it becomes configuration-controlled, and a verification method. Major fabrication should not proceed while the KPPs that determine equipment size or safety remain unconstrained.

KPP	Threshold source	Required verification evidence	Freeze / decision gate
Useful dry-particle size interval and allowed tails	Companion Experimental Research Initiative plus environmental review	Independent calibrated dry-particle spectrum over the intended operating envelope	G1
Verified useful-particle output per generator module	Companion Experimental Research Initiative	Independent number/mass output measurement with stated uncertainty and stability	G1
Output control, turndown, restart, and shutdown	Equipment safety and experimental-control requirements	Commanded step tests, emergency-stop tests, fault injection, and safe-state verification	G2
Energy and resource use per useful output	Engineering economics and lifecycle model	Metered electricity/fuel, seawater, compressed air, consumables, and staffing normalized to verified useful output	G2
Feedwater operating envelope	Representative-ocean characterization and generator tolerance	Salinity, temperature, sediment, organics, biological loading, cleaning, corrosion, and waste tests	G2-G3
Reliability and mission availability	Fleet-sizing/lifecycle model	Reliability-growth operating hours, critical failures, availability, degradation, and weather-adjusted mission records	G3, then G6
Maintainability and service interval	Lifecycle/port architecture	Measured cleaning interval, troubleshooting time, module replacement time, spares use, and shore-service frequency	G3, then G6

Platform payload, endurance, sea state, and survivability	Naval architecture and class requirements	Class review, structural/environmental qualification, and instrumented sea trials	G3
Autonomy and safe-state performance	Human-authority, maritime, cyber, and safety requirements	Hardware/software-in-loop tests, communications-loss tests, cyber assessment, manual override, and supervised trials	G5
Monitoring closure and data integrity	Science measurement needs plus metrology/data requirements	Calibration, time synchronization, configuration identifiers, uncertainty budgets, completeness, replay, and archive audit	G3-G7
End-to-end mission completion	Systems integration plan	Repeated configuration-controlled mission cycles with independent witnessing and complete failure/maintenance records	G7
Lifecycle cost and emissions	Phase II decision model	Independent low/base/high model reconciled to prototype operating, maintenance, energy, port, and replacement data	G8

Architecture commitment rule

No major vessel or platform fabrication commitment should occur until generator size and mass, electrical demand, seawater flow, release geometry, monitoring payload, maintenance envelope, and required endurance are bounded tightly enough that a plausible change in the scientific requirement would not force a fundamental platform redesign.

Stage Gates and Go/No-Go Criteria

Prompt to AI: What explicit stage gates should control progression from requirements through prototype fabrication, autonomous sea trials, integrated demonstration, and any later Phase II work?

Response From AI:

Passing a gate authorizes only the next engineering stage. It does not authorize climate-scale deployment or an atmospheric experiment. Each gate should have prospectively defined numerical acceptance criteria, independent review and a written disposition of unresolved risks.

Gate	Evidence required	Decision enabled	If not met
1. Requirements validated	Scientific needs are traceable to measurable system/subsystem requirements; interfaces, uncertainty and test methods are defined; no requirement presumes an unverified deployment architecture.	Release competing concept and laboratory risk-reduction work.	Revise requirements or defer the affected workstream.
2. Generator feasibility	At least two viable source concepts have independent measurements of dry particle output, size distribution, resource use, control, failure modes and performance with representative seawater.	Authorize larger prototype fabrication and marine packaging.	Continue competition, redesign or terminate weak concepts.
3. Marine subsystems qualified	Intake, power, release, corrosion/fouling controls, instruments and interfaces pass environmental/functional qualification with stated uncertainty.	Authorize integrated platform installation.	Correct deficiencies before sea-trial commitment.
4. Integrated prototype ready	Generator, seawater, power, mast, platform, instrumentation, command and data systems operate together in dockside/nearshore tests; safety and configuration records are complete.	Authorize controlled offshore engineering trials.	Repeat integration or reduce scope.
5. Autonomy and safe-state demonstrated	Navigation, human override, communications-loss behavior, fault management, cyber controls and emergency shutdown pass independent testing and supervised sea trials.	Authorize longer supervised autonomous operation.	Restrict autonomy and correct software/system hazards.
6. Endurance and maintainability demonstrated	Predefined operating hours, availability, critical-failure rate, cleaning interval, repair time, spares use and output stability are met.	Authorize final multi-platform demonstration.	Reliability-growth cycle, redesign or alternative architecture.
7. Multi-platform engineering demonstration	The complete system executes a configuration-controlled 30- to 90-day engineering campaign with independent witnessing, known output, reliable command, maintenance records and complete data.	Complete Phase II engineering and cost package.	No scale-up claim; correct deficiencies or

	Any atmospheric release remains separately authorized.		stop the workstream.
8. Phase II readiness	Open design package, manufacturing plan, lifecycle cost/emissions model, reliability evidence, monitoring requirements, unresolved risks and independent reviews are complete.	Funding Source receives a proceed/redirect/pause/stop decision package.	No entitlement to Phase II funding.

Architecture commitment hold point

Before the program commits to the largest vessel/platform fabrication expenditures, the integrated requirements baseline should bound generator size and mass, electrical demand, seawater flow, release geometry, monitoring payload, maintenance envelope, and endurance sufficiently to show that the platform will not require fundamental redesign under the accepted scientific KPP range. Failure to close this hold point should delay or reduce the platform commitment rather than lock in a premature architecture.

Change-control rule

Particle requirements, permitted release scale, autonomy level, operating region, major platform architecture, environmental limits and primary acceptance metrics should not change informally during a campaign. Material changes require an RTM update, revised risk analysis, independent review and the approval level specified in the Funding Source agreement.

Development Phases

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

Response From AI:

The phases below are development subphases within Phase I of the 15-year Reflectivity Plan. They overlap in time. Outdoor atmospheric work is not automatically authorized by completion of an engineering phase; each release must remain subject to the separate experiment-review process.

Common stage	Approximate timing	Purpose
A. Requirements and feasibility	Months 0-12	Define measurable requirements, compare concepts and identify safety, environmental and regulatory constraints.
B. Preliminary design and risk reduction	Months 6-24	Build laboratory prototypes and retire the largest technical uncertainties before major fabrication.
C. Detailed design and fabrication	Months 18-42	Produce drawings, software and marine-ready prototype hardware.
D. Integration and qualification	Months 30-54	Combine subsystems; test safety, durability, output, autonomy and monitoring.
E. Operational demonstration and handoff	Months 45-60	Demonstrate repeatable operating cycles and produce a Phase II procurement package.

Area 1. Sea-salt aerosol-generation systems - $160M

Subphase	Principal activities and deliverables	Cost
1A Requirements and competing concepts	Requirements, trade studies, success criteria, risk register and independent feasibility review.	$18M
1B Bench physics and prototype metrology	Competing concepts, laboratory or early prototype work, model validation and preliminary design review.	$30M
1C High-throughput prototype fabrication	Detailed design, fabrication, controls, documentation and configuration baseline.	$45M
1D Marine packaging and qualification	Subsystem integration, environmental qualification, failure testing and safety review.	$25M
1E Shipboard trials and reliability growth	Field or sea trials, reliability growth, data analysis, deficiencies and operating procedures.	$27M
1F Manufacturing handoff and independent review	Independent acceptance, open technical archive, manufacturing or Phase II handoff package.	$15M

Area 2. Seawater intake, filtration and conditioning - $70M

Subphase	Principal activities and deliverables	Cost
2A Feedwater requirements and characterization	Requirements, trade studies, success criteria, risk register and independent feasibility review.	$6M
2B Intake and conditioning concepts	Competing concepts, laboratory or early prototype work, model validation and preliminary design review.	$10M
2C Prototype fabrication	Detailed design, fabrication, controls, documentation and configuration baseline.	$20M
2D Fouling, corrosion and cleaning development	Subsystem integration, environmental qualification, failure testing and safety review.	$10M
2E Shipboard integration and trials	Field or sea trials, reliability growth, data analysis, deficiencies and operating procedures.	$16M
2F Replicable design and maintenance handoff	Independent acceptance, open technical archive, manufacturing or Phase II handoff package.	$8M

Area 3. Vessel and floating-platform prototypes - $160M

Subphase	Principal activities and deliverables	Cost
3A Platform requirements and architecture	Requirements, trade studies, success criteria, risk register and independent feasibility review.	$12M
3B Crewed test-vessel conversion	Competing concepts, laboratory or early prototype work, model validation and preliminary design review.	$45M
3C Autonomous surface-vessel prototype	Detailed design, fabrication, controls, documentation and configuration baseline.	$55M
3D Long-endurance platform prototype	Subsystem integration, environmental qualification, failure testing and safety review.	$25M
3E Common payload and interface development	Field or sea trials, reliability growth, data analysis, deficiencies and operating procedures.	$13M
3F Marine qualification and fleet architecture	Independent acceptance, open technical archive, manufacturing or Phase II handoff package.	$10M

Area 4. Autonomy, navigation, weather routing and fleet control - $90M

Subphase	Principal activities and deliverables	Cost
4A Concept of operations and safety architecture	Requirements, trade studies, success criteria, risk register and independent feasibility review.	$8M

4B Navigation and station keeping	Competing concepts, laboratory or early prototype work, model validation and preliminary design review.	$18M
4C Weather and cloud-targeting tools	Detailed design, fabrication, controls, documentation and configuration baseline.	$15M
4D Communications, command and cybersecurity	Subsystem integration, environmental qualification, failure testing and safety review.	$15M
4E Fault management and automated shutdown	Field or sea trials, reliability growth, data analysis, deficiencies and operating procedures.	$14M
4F Simulation, sea trials and software assurance	Independent acceptance, open technical archive, manufacturing or Phase II handoff package.	$20M

Area 5. Power, release mast, plume placement and marine durability - $65M

Subphase	Principal activities and deliverables	Cost
5A Power and release requirements	Requirements, trade studies, success criteria, risk register and independent feasibility review.	$6M
5B Power-system prototypes	Competing concepts, laboratory or early prototype work, model validation and preliminary design review.	$15M
5C Release mast and duct development	Detailed design, fabrication, controls, documentation and configuration baseline.	$14M
5D Marine hardening and corrosion control	Subsystem integration, environmental qualification, failure testing and safety review.	$10M
5E Plume-placement sensing and control	Field or sea trials, reliability growth, data analysis, deficiencies and operating procedures.	$8M
5F Endurance qualification and handoff	Independent acceptance, open technical archive, manufacturing or Phase II handoff package.	$12M

Area 6. Monitoring hardware, source verification, and reusable measurement systems - $120M

Subphase	Principal activities and deliverables	Cost
6A Measurement requirements and uncertainty budgets	Requirements, trade studies, success criteria, risk register and independent feasibility review.	$10M
6B Monitoring-system architecture	Competing concepts, laboratory or early prototype work, model validation and preliminary design review.	$15M
6C Reusable instrument integration and ruggedization	Detailed design, fabrication, controls, documentation and configuration baseline.	$35M

6D Calibration and intercomparison	Subsystem integration, environmental qualification, failure testing and safety review.	$20M
6E Field integration and engineering validation	Field or sea trials, reliability growth, data analysis, deficiencies and operating procedures.	$25M
6F Operational procedures and independent readiness	Independent acceptance, open technical archive, manufacturing or Phase II handoff package.	$15M

Area 7. Port, maintenance, resupply and lifecycle logistics - $50M

Subphase	Principal activities and deliverables	Cost
7A Base and logistics requirements	Requirements, trade studies, success criteria, risk register and independent feasibility review.	$4M
7B Pilot maintenance facility	Competing concepts, laboratory or early prototype work, model validation and preliminary design review.	$14M
7C Spares, tooling and inventory systems	Detailed design, fabrication, controls, documentation and configuration baseline.	$8M
7D Automated cleaning and service connections	Subsystem integration, environmental qualification, failure testing and safety review.	$8M
7E Resupply and deployment trials	Field or sea trials, reliability growth, data analysis, deficiencies and operating procedures.	$6M
7F Lifecycle and maintenance handoff	Independent acceptance, open technical archive, manufacturing or Phase II handoff package.	$10M

Area 8. Systems integration and multi-platform sea trials - $80M

Subphase	Principal activities and deliverables	Cost
8A Master integration and verification planning	Requirements, trade studies, success criteria, risk register and independent feasibility review.	$6M
8B Systems-integration laboratory	Competing concepts, laboratory or early prototype work, model validation and preliminary design review.	$10M
8C Harbor and dockside campaign	Detailed design, fabrication, controls, documentation and configuration baseline.	$9M
8D Nearshore and coastal trials	Subsystem integration, environmental qualification, failure testing and safety review.	$20M
8E Offshore endurance campaign	Field or sea trials, reliability growth, data analysis, deficiencies and operating procedures.	$15M
8F Multi-platform final demonstration	Independent acceptance, open technical archive, manufacturing or Phase II handoff package.	$20M

Area 9. Engineering models, data platform and operations center - $35M

Subphase	Principal activities and deliverables	Cost
9A Data governance and interfaces	Requirements, trade studies, success criteria, risk register and independent feasibility review.	$4M
9B Engineering digital twins and forecast interfaces	Competing concepts, laboratory or early prototype work, model validation and preliminary design review.	$8M
9C Operations-center platform	Detailed design, fabrication, controls, documentation and configuration baseline.	$7M
9D Data ingestion and quality control	Subsystem integration, environmental qualification, failure testing and safety review.	$6M
9E Integrated simulations and exercises	Field or sea trials, reliability growth, data analysis, deficiencies and operating procedures.	$6M
9F Public archive and handoff	Independent acceptance, open technical archive, manufacturing or Phase II handoff package.	$4M

Area 10. Program management, safety, environmental review and independent assurance - $20M

Subphase	Principal activities and deliverables	Cost
10A Program formation	Requirements, trade studies, success criteria, risk register and independent feasibility review.	$4M
10B Requirements and design oversight	Competing concepts, laboratory or early prototype work, model validation and preliminary design review.	$3M
10C Procurement and execution oversight	Detailed design, fabrication, controls, documentation and configuration baseline.	$4M
10D Test, safety and environmental oversight	Subsystem integration, environmental qualification, failure testing and safety review.	$4M
10E Final readiness and Phase II planning	Field or sea trials, reliability growth, data analysis, deficiencies and operating procedures.	$5M

Area 11. Central technical and schedule reserve - $150M

Subphase	Principal activities and deliverables	Cost
11A Conditional reserve authority	No planned contractor entitlement. The Funding Source may release reserve for redesign, second sources, replacement test articles, integration/sea-trial recovery, or schedule recovery only after documented need, independent estimate, and approval.	$150M

Parametric Phase II Fleet-Sizing and Lifecycle-Cost Model

Prompt to AI: What fleet-sizing and lifecycle-cost model should the equipment program deliver by Year 5 without assuming that MCB deployment will occur?

Response From AI:

The Year 5 engineering package should include a transparent parametric model that converts a future scientifically specified operating requirement into equipment quantities, port/logistics needs, energy use, availability margin and lifecycle cost. The model is a decision tool, not a deployment plan; its purpose is to show what different scientific requirements would imply if a later authority considered Phase II. The final model should be delivered with source code, equations, assumptions, unit costs, prototype-derived calibration factors and sensitivity cases, and it should accept updated atmospheric requirements from the Experimental Research Initiative without redesigning the model structure.

Model boundary

The fleet model should take the atmospheric requirement as an external input. Equipment Development converts that input into generator modules, platforms, power, ports, availability margin, maintenance resources, CAPEX/OPEX, and lifecycle emissions. It should not itself convert equipment output into W/m2 of forcing or claim a climate benefit; those relationships remain scientific outputs of the Experimental Research and GCM programs and should enter only as versioned input scenarios with stated uncertainty.

Model block	Illustrative inputs	Required outputs
Atmospheric requirement	Verified useful-particle output required, operating hours, locations, allowable downtime and output uncertainty.	Required delivered particle production by time and region.
Generator sizing	Verified output per module, turndown, energy use, maintenance interval and degradation.	Generator modules operating, installed spare margin and power demand.
Platform sizing	Generator modules per platform, payload/power/endurance, transit time, weather availability and maintenance downtime.	Platforms required on station, in transit, in maintenance and in reserve.
Reliability / availability	MTBF, MTTR, mission abort rate, cleaning interval, spare-module replacement and weather downtime.	Availability allowance, spare parts, service capacity and redundancy.
Port and logistics	Turnaround time, resupply, fuel/energy, spares, staffing, dock capacity and deployment distances.	Number/capacity of support bases, service teams, inventory and annual logistics demand.
Lifecycle economics	Prototype-informed capital cost, manufacturing learning, energy, labor, maintenance, replacement, port,	CAPEX, annual OPEX, cost per verified useful-particle output, lifecycle

	fuel/electricity mix, vessel emissions, embodied materials, consumables and waste.	emissions/resources, and cost/emissions sensitivities.

Purchase Orders

Prompt to AI: What major procurement packages, master contracts, grants, task orders, and independent-review agreements might implement the equipment program without creating hundreds of repetitive or falsely precise purchase orders?

Response From AI:

The detailed development budgets in the preceding chapters remain the planning baseline. Execution should aggregate that work under a limited number of master vehicles and issue competitive task orders as requirements mature. The package descriptions below map to the existing $1 billion budget; they are not additional budget lines. Internal allocations should be competed and priced at award rather than pre-divided into artificial $0.1 million increments years in advance.

Master Contracting Vehicles

Master vehicle	Areas	Typical scope	Preferred contracting approach
Aerosol-source engineering	Areas 1, 2, 5	Generator competition, seawater integration, source metrology interfaces, marine packaging, release hardware, and qualification.	Staged competition; cost-reimbursement with ceilings early, then milestone/fixed-price work after design freeze.
Marine platforms and integration	Areas 3, 5, 7	Crewed conversion, autonomous and long-endurance prototypes, common payload interfaces, power/mast integration, maintenance and port support.	Prototype/milestone contracts plus shipyard and marine-service task orders.
Autonomy, communications, and cyber	Areas 4, 9	Navigation, station keeping, human authority, remote command, weather interfaces, fault management, operations-center software, and cyber assurance.	Milestone software contract plus separately funded independent V&V/cyber review.
Measurement systems and metrology	Area 6	Source metrology, reusable instrument integration/ruggedization, synchronization, calibration, common data interfaces, and readiness evidence.	Framework equipment/task orders plus public-laboratory or university subawards.
Marine and field operations	Area 8	Integration facility, harbor/nearshore/offshore trials, vessel/aircraft operating time, logistics, weather replacement options, and final demonstration services.	Indefinite-delivery/task-order or not-to-exceed field-services agreements.
Port, maintenance, and lifecycle	Area 7	Pilot service base, tooling, spares, cleaning/service connections, resupply, reliability/maintainability, and lifecycle-cost analysis.	EPC/service contracts and fixed-price studies where scope is mature.

Master vehicle	Areas	Typical scope	Preferred contracting approach
Engineering models, data, and operations center	Areas 4, 9	Digital twins, mission/fleet software, configuration records, data ingestion, visualization, APIs, public archive, and model interfaces.	Milestone software/data contract with open-source and reproducibility requirements.
Scientific/public-lab subawards	Areas 1, 4, 6, 8, 9	Science requirements, measurement development, atmospheric-interface definitions, modeling support, and independent analysis.	Grant, cooperative agreement, reimbursable agreement, or research subaward.
Independent assurance	All baseline Areas	Marine class, particle metrology, environmental review, software/cyber V&V, cost review, open-data audit, test witnessing, and readiness reviews.	Direct independent contracts reporting to the Managing Organization/Funding Source.
Corrective / reserve options	Area 11	Second sources, redesign, replacement articles, additional test time, and schedule recovery only after reserve release.	Prepriced options or competed corrective task orders activated only after documented approval.

Major Procurement Packages by Area

Area	Budget	Major packages	Acceptance emphasis
Area 1. Aerosol generation	$160M	Staged generator competition; ship-ready prototype lines; independent particle metrology/qualification; manufacturing handoff.	Dry particle output/size, control, energy/resource use, seawater tolerance, endurance, reproducibility.
Area 2. Seawater conditioning	$70M	Feedwater characterization; competing intake/pretreatment modules; fouling/corrosion/cleaning tests; shipboard integration and maintenance handoff.	Stable feedwater, cleaning interval, corrosion/fouling burden, waste handling, maintainability.
Area 3. Vessels / platforms	$160M	Crewed test-vessel conversion; autonomous surface-vessel prototype; long-endurance demonstrator; common payload interfaces and class package.	Payload/power margin, endurance, survivability, safe operation, interface compliance, lifecycle evidence.
Area 4. Autonomy / fleet control	$90M	Concept of operations; navigation/station keeping; weather/science authorization interfaces; communications/cyber; fault management; independent V&V.	Human authority, safe state, collision avoidance, communications-loss behavior, cyber resilience, auditability.
Area 5. Power / release / durability	$65M	Power architecture/prototypes; release mast/duct; plume-placement sensing; marine hardening/corrosion; endurance qualification.	Power demand, release geometry, structural/environmental qualification, corrosion, safe shutdown, endurance.

Area	Budget	Major packages	Acceptance emphasis
Area 6. Monitoring hardware / source verification	$120M	Source metrology; reusable instrument integration/ruggedization; radar/lidar/radiometer interfaces; environmental sensor packages; calibration/intercomparison.	Measurement uncertainty, uptime, synchronization, configuration traceability, calibration, reusable handoff.
Area 7. Port / lifecycle logistics	$50M	Pilot maintenance facility; tooling/spares; cleaning/service connections; resupply/logistics trials; lifecycle model.	MTTR, service interval, spares use, turnaround time, availability, independent lifecycle-cost evidence.
Area 8. Integration / sea trials	$80M	Integration lab; harbor/dockside; nearshore/coastal; offshore endurance; final multi-platform engineering demonstration.	End-to-end mission completion, independent witnessing, complete configuration/test/failure record.
Area 9. Engineering models / data / operations center	$35M	Engineering digital twins; forecast/model interfaces; operations-center platform; data/QC; exercises; public archive.	Software QA, replay/reproducibility, cyber review, configuration fidelity, archive completeness.
Area 10. Program assurance	$20M	Owner-side PMO/systems engineering; procurement/project controls; safety/environmental oversight; independent cost/readiness reviews.	Integrated baseline, auditable decisions, closed findings, reliable cost/schedule/readiness evidence.
Area 11. Central reserve	$150M	No standing contractor entitlement. Corrective work is defined only after a documented need and reserve-release decision.	Root cause, alternatives, independent estimate, revised baseline, accountable owner, and acceptance test.

Contract Approach

Contract approach	Best use
Fixed-price milestone	Defined studies, standard equipment, charter services, calibration, final documentation, and repeat production after design freeze.
Cost-reimbursement with ceilings	Novel generator development, first-of-a-kind vessel conversion, prototype instruments, autonomy software, and uncertain field operations.
Indefinite-delivery/task order	Engineering support, vessel/aircraft operating time, repair, calibration, logistics, and contingent sea-trial options.
Grant/cooperative/reimbursable agreement	University, public-laboratory, and government science, measurement development, modeling support, and independent analysis.
Challenge or staged competition	Generator concepts, platform concepts, autonomy approaches, and selected instrument packages before evidence-based down-selection.

Milestone payments and reserve controls

Major prototype awards should tie payment to approved requirements, preliminary design, fabrication/integration evidence, acceptance testing, and delivery of complete data, drawings, software, calibration and failure records. Independent reviewers should be contracted separately from the developer for claims that determine a stage gate. The $150 million reserve remains outside contractor entitlement and is not converted into procurement packages until the Funding Source approves a documented release under the Common Framework.

Purchase Order Recipients

Prompt to AI: With each purchase order or equivalent agreement, who might it be issued to?

Response From AI:

The organizations below are illustrative candidates, not endorsements, commitments or findings that they are available. The Managing Organization should normally solicit two to four qualified teams, evaluate technical merit, price, openness, conflicts and delivery record, and preserve competition through early prototype stages.

Government agencies and public laboratories would generally participate through reimbursable agreements, cooperative research agreements or university-affiliate subawards rather than ordinary commercial POs. Universities would usually receive sponsored-research agreements or subawards. Vessel builders, spray-equipment firms, engineering companies and software suppliers would receive conventional contracts or task orders.

Procurement area	Illustrative lead recipients	Supporting or independent organizations
Area 1. Aerosol generators	SRI International; University of Washington MCB Program; Southern Cross University/RRAP; specialist atomization firms such as MeeFog or Spraying Systems Co.; competing university aerosol laboratories.	Armand Neukermans and collaborators; Daniel Harrison/Colin Medcraft nozzle work; NOAA, PNNL and NCAR measurement teams; independent aerosol metrology laboratory.
Area 2. Seawater intake and conditioning	Worley; Jacobs; Black & Veatch; SRI; marine process-system integrators; qualified pump, membrane and filtration suppliers.	Alfa Laval, Pall, Parker, Eaton, Xylem, Grundfos or equivalent suppliers; CSIRO/AIMS marine-biofouling expertise; independent HAZOP firm.
Area 3. Vessel / platform prototypes	Riverside Marine; Saildrone; Liquid Robotics; Kongsberg Maritime; Ocean Infinity; L3Harris ASV; Damen, Vard or other qualified shipyards.	Ron Allum Deepsea Services; SRI; naval-architecture firms; DNV, ABS or Lloyd's Register for independent class and marine safety.
Area 4. Autonomy and fleet control	Saildrone, Kongsberg, Ocean Infinity, L3Harris ASV, Liquid Robotics, SRI or a competitively selected marine-autonomy consortium.	MITRE or Draper for owner-side systems engineering; NOAA/National Weather Service and NCAR for weather interfaces; independent cyber red team.
Area 5. Power, mast and durability	Marine electrical and propulsion integrators; ABB Marine, Wärtsilä, Siemens Energy or equivalent; shipyard-led mast and duct team.	Corrosion and materials laboratories; DNV/ABS/Lloyd's; SwRI for environmental and structural testing; renewable-energy specialists.
Area 6. Monitoring systems	University of Washington; NOAA laboratories; PNNL; NSF NCAR/UCAR; NASA atmospheric programs; CSIRO; AIMS; university cloud-observation groups.	Aerodyne, TSI, Droplet Measurement Technologies, Vaisala, Campbell Scientific and lidar/radar providers; independent NIST-linked metrology team.

Area 7. Port and lifecycle logistics	Selected shipyard or marine base operator; Worley/Jacobs; Riverside Marine; offshore-service and logistics providers.	Spare-parts and computerized-maintenance suppliers; port authority; local emergency organizations; independent lifecycle-cost team.
Area 8. Systems integration and sea trials	SRI, Battelle, Southwest Research Institute or a vessel-system integrator; UCAR field-campaign organization; Riverside Marine or another marine operator.	UW/NOAA/PNNL/NCAR science consortium; aircraft and drone operators; DNV/ABS/Lloyd's test witnesses; independent environmental monitor.
Area 9. Models, data and operations center	UCAR/NCAR; NOAA/PNNL/UW model teams; MITRE or SRI for architecture; selected cloud and geospatial provider.	AWS, Microsoft or Google public-sector integrator; Esri; open-source software foundation; independent cybersecurity and data-quality auditor.
Area 10. PMO and independent assurance	Battelle or RTI as candidate Managing Organization; MITRE, SRI, Draper or SwRI as owner's engineering partner.	National Academies-style scientific panel; independent audit firm; environmental consultant; Consensus Building Institute or Keystone Policy Center.
Area 11. Reserve work	Competitively selected incumbent or second source best positioned to correct the documented problem.	Reserve-release review by an organization that receives no benefit from the corrective award.

Recommended prime-contract arrangement

1. Managing Organization: Battelle or RTI selected competitively to hold the restricted funds, employ the program office, administer procurement and report to the Funding Source.
2. Owner's engineering and systems assurance: MITRE, SRI, Draper or Southwest Research Institute, contractually separated from major prototype production.
3. Aerosol and cloud science consortium: University of Washington, NOAA, PNNL, NSF NCAR/UCAR and selected international groups including Southern Cross University, CSIRO and AIMS.
4. Vessel and platform competition: separate early awards to at least three platform teams, followed by evidence-based down-selection.
5. Marine class and safety: DNV, ABS or Lloyd's Register hired directly by the Managing Organization or Funding Source rather than by the vessel builder alone.
6. Independent scientific, environmental, financial and open-data reviewers reporting to the Funding Source or a firewalled board committee.

Most important conflict-of-interest separations

- The aerosol-generator developer should not certify its own particle-size output or lifetime performance.

- The autonomous-vessel developer should not perform the final software safety and cybersecurity assessment.
- The vessel builder should not be the only organization deciding that the platform is safe for unattended operation.
- Instrument manufacturers should not be solely responsible for uncertainty certification and data exclusions.
- The atmospheric science team should not control the environmental approval of its own releases.

Project Management

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

Response From AI:

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

Initiative-specific management requirements

- The Managing Organization must be capable of large marine engineering and field programs: prototype fabrication, vessel conversion or acquisition, autonomous marine systems, instrument integration, port and maintenance operations, environmental review, maritime safety, international coordination, and acceptance of hardware/software deliverables.
- Maintain one configuration-controlled system baseline across the eleven budget areas: aerosol generation; seawater conditioning; vessels/platforms; autonomy and fleet control; power/release/durability; monitoring; port/lifecycle logistics; systems integration and sea trials; models/data/operations center; owner-side program assurance; and the central technical/schedule reserve.
- Assign accountable leads for system architecture and requirements traceability, aerosol-source engineering and independent particle metrology, marine platforms/class and operations, autonomy/cyber/human authority, monitoring/calibration/data, reliability/maintainability, and integration/test. The developer of a subsystem may not be the sole organization accepting its critical performance claim.
- Coordinate formally with the companion MCB Experimental Research Initiative. Equipment Development builds and qualifies reusable capability; Experimental Research defines and interprets atmospheric experiments. Shared instruments, vessels/platforms, data systems, and other assets must have one lead budget and an auditable usage/transfer rule so the same asset is not funded twice.
- Outdoor aerosol releases remain under the separate scientific, environmental, legal, and governance authorization process. The equipment PMO may prepare hardware and test readiness, but it cannot convert an engineering task or change order into an atmospheric experiment without the required separate approval.

Funding Source Requirements

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

The portfolio-wide Funding Source requirements are specified in the Moonshot Common Framework. The additions below address the program's equipment-development boundary, particle metrology, marine reliability, autonomy, shared assets, environmental authorization, lifecycle accounting, and Phase II decision package.

Program-specific additions

- Require a configuration-controlled Requirements Traceability Matrix linking each material scientific need to measurable equipment requirements, interfaces, verification methods, test evidence, uncertainty, and the recorded acceptance or redesign decision.
- Require independent verification of dry particle-number/size output, source calibration, resource use, reliability and maintainability, marine class/survivability, autonomy and safe-state behavior, cybersecurity, and monitoring/data closure before the program claims readiness.
- Require the final technical record to include native CAD and interface specifications, bills of material, source code, configuration history, calibration, raw and processed test data, failure/corrective-action records, operating logs, maintenance evidence, manufacturing assumptions, and lifecycle-cost/emissions calculations under the common open-source/data policy.
- Apply the common shared-asset rule to the companion MCB Experimental Research Initiative: purchase each reusable physical or digital asset once; the other initiative pays only incremental adaptation, operating time, consumables, or intentionally independent capacity.
- Keep the $150 million central technical and schedule reserve outside contractor entitlement. Release it only for documented redesign, second-source, replacement test articles, integration/sea-trial recovery, or other initiative-specific needs that pass the common reserve/change-control process.

Program-specific success metric

Success is reproducible evidence on useful-particle output/control, resource use, reliability, maintainability, marine durability, monitoring closure, and Phase II lifecycle cost. Climate efficacy remains a separate scientific conclusion.

Top MCB Engineering and Equipment References

Prompt to AI: Summarize the top papers most relevant to the proposed MCB equipment-development initiative.

Response From AI:

The list below emphasizes papers that define the required particle properties, describe spray hardware, evaluate plume transport and cloud response, establish field-experiment scales, or show why monitoring and model validation are necessary. “Top” is necessarily judgmental; these are not ranked solely by citation count. Several recent papers are especially equipment-relevant because they report actual nozzles, outdoor plume measurements or explicit field-study designs.

Scientific Requirements for MCB Equipment

Twomey (1977), “The influence of pollution on the shortwave albedo of clouds.”

Foundational explanation of why more cloud droplets at fixed liquid water can increase cloud reflectivity. Equipment implication: particle number and activation matter, not merely salt mass.

https://journals.ametsoc.org/view/journals/atsc/34/7/1520-0469_1977_034_1149_tiopot_2_0_co_2.xml

Albrecht (1989), “Aerosols, cloud microphysics, and fractional cloudiness.”

Introduces the possibility that added aerosol suppresses drizzle and changes cloud lifetime. Monitoring must therefore include precipitation, liquid water and cloud persistence.

https://doi.org/10.1126/science.245.4923.1227

Latham (1990), “Control of global warming?”

Early proposal to brighten marine clouds with seawater particles. Establishes the central engineering challenge of producing and distributing large numbers of appropriately sized particles.

https://doi.org/10.1038/347339b0

Latham (2012), “Marine cloud brightening.”

Comprehensive review covering physics, spray technology, modeling, field experiments and governance. It remains a central roadmap for staged research.

https://doi.org/10.1098/rsta.2012.0086

Aerosol Sources, Particle Size, and Plume Delivery

Salter (2008), "Sea-going hardware for the cloud albedo method of reversing global warming."

Classic engineering concept for wind-powered spray vessels and Flettner rotors. Valuable as an architecture study, but its assumptions require modern prototype validation.

https://doi.org/10.1098/rsta.2008.0136

Korhonen (2010), "Enhancement of marine cloud albedo via controlled sea spray injections: a global model study of the influence of emission rates, microphysics and transport."

Demonstrates sensitivity to emission rate and particle microphysics; supports stringent particle-size and output specifications.

https://doi.org/10.5194/acp-10-4133-2010

Partanen (2012), "Direct and indirect effects of sea spray geoengineering and the role of injected particle size."

Shows that coarse particles can have different radiative effects and can compete with desired cloud activation. Generator distributions must minimize unwanted large-particle tails.

https://doi.org/10.1029/2011JD016428

Stuart (2013), "Reduced efficacy of marine cloud brightening geoengineering due to in-plume aerosol coagulation."

Warns that concentrated plumes can lose particle number through coagulation. Release geometry and dilution must be designed and measured.

https://doi.org/10.5194/acp-13-10385-2013

Cooper (2014), "Preliminary results for salt aerosol production intended for marine cloud brightening."

Directly addresses generation of cloud-relevant salt aerosol and is foundational for laboratory and ship-ready generator development.

https://doi.org/10.1098/rsta.2014.0055

Connolly (2014), "Factors determining the most efficient spray distribution for marine cloud brightening."

Examines particle size and spray distribution. Strongly relevant to nozzle selection, mast design and output optimization.

https://doi.org/10.1098/rsta.2014.0056

Horowitz (2020), "Effects of Sea Salt Aerosol Emissions for Marine Cloud Brightening on Atmospheric Chemistry: Implications for Radiative Forcing."

Examines how enhanced sea-salt emissions can alter atmospheric chemistry and therefore radiative forcing. Equipment implication: source and monitoring systems should measure composition, reactive chemistry and deposition rather than treating seawater aerosol as chemically inert.

https://doi.org/10.1029/2019GL085838

Harrison (2025), "Effervescent nozzle design to enable outdoor marine cloud brightening experimentation."

Reports a concrete nozzle design and particle measurements for outdoor work. Directly informs competing generator prototypes, metrology and scale-up.

https://doi.org/10.1039/D5EA00073D

Hernandez-Jaramillo (2025), "First generation outdoor marine cloud brightening trial increases aerosol concentration at cloud base height," together with Doherty (2026), "Defining scales of field studies and experiments to assess marine cloud brightening."

The field paper shows that a vessel-generated plume can reach cloud-base altitude in a relevant setting; the scale framework clarifies what progressively larger studies can and cannot establish. Together they define practical equipment and monitoring milestones.

https://doi.org/10.1088/1748-9326/adccd7; https://doi.org/10.1029/2025AV001939

Field Engineering, Environmental Evidence, and Research Governance

Robock (2014), "Field experiments on solar geoengineering: report of a workshop exploring a representative research portfolio."

Frames staged outdoor tests, governance and scale limits. Equipment trials should be embedded in an explicit research and review sequence.

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

Glassmeier (2021), "Aerosol-cloud-climate cooling overestimated by ship-track data."

Shows that short ship-track observations may overstate long-term cooling because cloud adjustments evolve with time. Monitoring must follow treated air masses beyond the initial brightening.

https://doi.org/10.1126/science.abd3980

Diamond (2022), "To Assess Marine Cloud Brightening's Technical Feasibility, We Need to Know What to Study—and When to Stop."

Proposes a staged feasibility framework with checkpoints and explicit exit ramps. Equipment implication: generator, platform, monitoring and integrated-trial development should progress only when preregistered evidence justifies the next scale of work.

https://doi.org/10.1073/pnas.2118379119

Feingold (2024), "Physical science research needed to evaluate the viability and risks of marine cloud brightening."

Modern consensus-style research agenda identifying aerosol generation, plume evolution, cloud adjustments, observations and modeling as key gaps.

https://doi.org/10.1126/sciadv.adi8594

Ongoing Studies

Additional recent work worth tracking includes 2025 plume-dispersion and measurement work by Hernandez-Jaramillo, Kelaher and Harrison; Kainz, Harrison and Hoffmann's 2026 "Marine cloud brightening of cumulus clouds: from the sprayer to the cloud"; observed-trajectory libraries for cloud-model evaluation; and 2026 ship-track model evaluations.

Top Researchers and Organizations

Prompt to AI: Who are the top researchers, engineers, organizations, vessel designers, spray-technology groups, autonomous-marine-system developers, cloud-observation groups, and climate-modeling organizations relevant to this equipment program?

Response From AI:

The following names are illustrative candidates for consultation, competition or panel service. Inclusion is not an endorsement and does not imply willingness to participate. Current affiliations and conflicts should be verified before any appointment or solicitation. John Latham and Stephen Salter are listed as historical pioneers; they should not be presented as current program candidates.

Person	Affiliation or community	Relevant expertise
Robert Wood	University of Washington	Marine low-cloud observations, cloud regimes and field-program leadership.
Sarah J. Doherty	University of Washington	MCB research strategy, field-study scales, aerosol-cloud science and program coordination.
Philip J. Rasch	Pacific Northwest National Laboratory	Earth-system modeling, MCB model intercomparison and climate response.
Graham Feingold	NOAA Chemical Sciences Laboratory	Aerosol-cloud interactions, cloud adjustments and MCB research priorities.
Peter Blossey	University of Washington	Large-eddy simulation and marine cloud process modeling.
Hailong Wang	Pacific Northwest National Laboratory	Aerosol-cloud-climate modeling and MCB response.
Susannah Burrows	Pacific Northwest National Laboratory	Marine aerosol, sea spray and Earth-system model representation.
Armin Sorooshian	University of Arizona	Aircraft observations, marine aerosol-cloud interactions and field measurement.
Allison McComiskey	NOAA and atmospheric-observation community	Cloud and radiation observations, measurement strategy and program review.
Daniel P. Harrison	Southern Cross University / RRAP	Great Barrier Reef field trials, marine spray systems and regional MCB research.
Chris Medcraft	Southern Cross University collaborators	Nozzle design, atomization and sea-salt aerosol-generation engineering.
Luke Harrison	Australian MCB field program	Outdoor sprayer operation and aerosol plume observations.

Diana Hernandez-Jaramillo	Southern Cross University collaborators	Plume dispersion, measurement methods and field evaluation.
Brendan Kelaher	Southern Cross University	Marine field programs, environmental context and plume research.
Fabian Hoffmann	Cloud modeling community	Cloud-resolving simulations connecting sprayer plume to cloud response.
Armand Neukermans	SRI and MCB engineering collaborations	Early modern sea-salt aerosol-generator engineering and technology development.
David Rosenfeld	Hebrew University and collaborators	Cloud microphysics, precipitation and aerosol-cloud observations.
Zoran Ristovski	Queensland University of Technology	Aerosol measurement and marine field instrumentation.
Jim Haywood	University of Exeter / Met Office	Earth-system modeling and comparison of climate-intervention approaches.
Haruki Hirasawa	Climate modeling community	Regional MCB patterns, climate response and model experimentation.

Historical pioneers

Person	Contribution
John Latham	Proposed controlling warming by increasing marine cloud reflectivity and led foundational MCB science and field-research concepts.
Stephen Salter	Developed influential sea-going spray-vessel and engineering concepts, including wind-powered platforms and atomization systems.

Relevant Groups

Organization group	Potential role
University of Washington MCB Program	Cloud observations, process modeling, field-study design, aerosol generation and independent review network.
NOAA Chemical Sciences Laboratory and other NOAA laboratories	Aerosol-cloud measurements, atmospheric chemistry, remote sensing, weather and operational observations.
Pacific Northwest National Laboratory	Earth-system modeling, aerosol-cloud science and model intercomparison.
NSF NCAR / UCAR	Atmospheric modeling, aircraft and field-campaign support, data management and community coordination.
SRI International	Independent nonprofit R&D, spray-system engineering, systems integration and field technology.

Southern Cross University / Reef Restoration and Adaptation Program	Outdoor marine aerosol trials, nozzle development and Great Barrier Reef research.
CSIRO and Australian Institute of Marine Science	Marine science, environmental monitoring, field operations and regional impact assessment.
Queensland University of Technology / Airborne Research Australia	Aerosol instruments, aircraft observations and plume measurements.
NASA atmospheric research programs	Airborne remote sensing, radiometry, satellites and instrument validation.
National Academies of Sciences, Engineering, and Medicine	Independent consensus review, research-governance frameworks and program assessment.
Battelle, RTI, SRI, Draper, MITRE and Southwest Research Institute	Potential nonprofit program management, owner's engineering, testing and independent assurance.
DNV, American Bureau of Shipping and Lloyd's Register	Marine class, safety, autonomous-vessel assurance and test witnessing.
Saildrone, Liquid Robotics, Kongsberg Maritime, Ocean Infinity and L3Harris ASV	Autonomous or remotely operated marine-platform technology.
Riverside Marine and Ron Allum Deepsea Services	Australian vessel operations, marine engineering and field-program support.
Worley, Jacobs, Black & Veatch and marine process suppliers	Intake, filtration, port, utility and industrial process-system engineering.
TSI, Aerodyne Research, Droplet Measurement Technologies, Vaisala and related firms	Aerosol, cloud, meteorological and remote-sensing instruments.

Scientific and Engineering Advisory Panel

Prompt to AI: What scientific and engineering expertise should be represented on an independent panel overseeing MCB equipment development without duplicating the broader researcher landscape or the Common Framework management panel?

Response From AI:

The panel should be defined primarily by required expertise rather than by a long preselected list of people. Candidate names and institutions in the preceding researcher chapter are an illustrative talent pool, not appointments. A practical panel would have about 11 voting seats, use temporary reviewers when specialized questions arise, include substantial international representation, disclose conflicts, and prohibit members from voting on awards to their institutions.

Seat	Required expertise	Primary review role
Chair / systems engineering	Large multidisciplinary prototype programs and independent technical review	Integrate requirements, interfaces, test evidence, and cross-Area gate decisions.
Aerosol generation	Atomization, aerosol source engineering, scale-up	Challenge generator competition, output, manufacturability, and failure modes.
Aerosol metrology	Particle number/size/composition, calibration, uncertainty	Protect independent dry-particle verification and measurement traceability.
Naval architecture / marine class	Vessels, offshore systems, survivability, class	Review platform architecture, sea-state limits, structural safety, and qualification.
Autonomous marine systems	Navigation, remote supervision, human authority	Review autonomy level, fault management, communications loss, override, and safe-state behavior.
Cyber/software assurance	Safety-critical software, V&V, cyber resilience	Independently challenge command, audit logging, cyber controls, and software acceptance.
Marine materials / biofouling	Corrosion, seawater systems, cleaning, materials	Review seawater tolerance, fouling/corrosion evidence, maintenance and waste handling.
Power / release engineering	Marine electrical systems, structures, fluid delivery	Review power demand, mast/duct design, plume-placement hardware, and endurance.
Atmospheric instrumentation	Cloud/aerosol/radiation measurement systems	Ensure reusable monitoring hardware meets science-interface, calibration, and data requirements.
Reliability / maintainability / lifecycle	RAM engineering, field maintenance, cost models	Review MTBF/MTTR, service intervals, spares, availability, and lifecycle economics.
Environmental / maritime operations	Marine environmental assessment and field operations	Challenge engineering release boundaries, incident planning, and operational constraints without replacing the separate atmospheric authorization process.

Panel powers and procedures

- Approve or reject top-level technical requirements and material KPP changes before they drive major hardware commitments.
- Review competing concepts and recommend down-selection, replication, redesign, or termination based on measured evidence.
- Require independent calibration, blind or cross-laboratory checks, fault injection, and second-source prototypes when evidence is weak.
- Receive safety, environmental, cyber, reliability, and incident information directly, without editing by the technical prime.
- Recommend pause or stop; binding stop-work authority remains with the independent safety/governance structure defined by the applicable agreements.
- Publish majority findings, minority views, conflicts, unresolved risks, and the evidence used for each major recommendation.
- Meet at least quarterly, with formal reviews at requirements/KPP freeze, architecture commitment, integration readiness, endurance readiness, and final demonstration.

The panel advises on science and engineering quality. It does not negotiate contracts, approve invoices, authorize atmospheric experiments, or replace the Common Framework Management Advisory Panel.

Management Advisory Panel

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

Response From AI:

The Moonshot Common Framework governs the panel charter, independence, fiduciary oversight, audit access, conflicts, procurement escalation, reserve review, corrective action, and Managing Organization succession. This initiative adds marine and autonomy capabilities needed to oversee a large prototype-and-sea-trial program.

Initiative-specific oversight capabilities

- Marine industrial programs: vessel conversion/fabrication, naval architecture, class and certification, ports, offshore logistics, maintenance, reliability growth, and lifecycle execution.
- Autonomous and remotely supervised marine systems: human authority, collision avoidance, communications loss, cybersecurity, fault management, safe-state behavior, and software verification/validation.
- Prototype integration and test: cross-contractor interfaces, configuration control, independent test witnessing, long-duration sea trials, schedule/weather risk, and readiness evidence before large demonstration spending.
- Environmental and transboundary operations: maritime/environmental permitting, public process, incident response, and strict separation between equipment testing and authorization of any atmospheric release.

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

Agreements

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

Response From AI:

The generic master agreement terms are specified in the Moonshot Common Framework and are not repeated here. Final agreements would use those common terms plus the MCB-specific schedules below, adapted by counsel to the parties, jurisdictions, vessel operations, government partners, environmental requirements, and the actual procurement instrument.

Program-Specific Schedules to the Common Agreements

Engineering requirements and configuration schedule

Attach the approved Requirements Traceability Matrix, subsystem/interface baseline, verification methods, configuration identifiers, change authority, independent witnesses, success/failure criteria, and evidence required for acceptance at each engineering gate.

Aerosol source, seawater, and metrology schedule

Specify permitted seawater conditions, source-output and dry-particle metrics, calibration methods, power/resource accounting, environmental limits, cleaning/fouling/corrosion tests, uncertainty, independent source verification, and the complete design/test data package.

Marine platform, autonomy, and sea-trial schedule

Specify class/safety responsibilities, operating envelope, payload and release interfaces, human command authority, communications-loss behavior, cyber controls, maintenance/spares, weather cancellation and replacement options, test areas, endurance goals, incident reporting, and independent test witnessing.

Outdoor atmospheric-release schedule

No equipment agreement itself authorizes MCB experimentation. Any approved release must identify the material, output limits, location, time, operating conditions, monitoring, environmental/legal approvals, public disclosure, stop conditions, incident process, and the boundary between Equipment Development and the companion Experimental Research Initiative.

Data, software, and open engineering handoff schedule

Specify repositories and release dates for native CAD, bills of material, firmware/source code, interfaces/APIs, digital twins, calibration, test and failure data, maintenance/operations records, manufacturing assumptions, lifecycle-cost/emissions model, and the reproducibility package required for an unaffiliated team to inspect or continue the work.

Shared-asset and Phase II transition schedule

Identify ownership and maintenance responsibility for shared instruments, vessels/platforms, data systems, and other capital assets; prevent duplicate full-cost charging to the Experimental Research Initiative; and define the final asset, records, supplier, software-credential, and open-design transition needed for a separate Phase II decision.

No duplicate master terms

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

Selected Sources and Program References

This document was developed from the supplied MCB Reflectivity Plan, the companion MCB Research Experiments fund document, the supplied SAI equipment-development structure, and publicly available scientific and organizational sources. The URLs below are included for readers who wish to verify or expand the planning assumptions. Current personnel, programs, products and availability should be rechecked before procurement.

Source	URL
MCB Reflectivity Plan by Glenn Weinreb	https://ma2life.org/g/film/MCB_Reflectivity_Plan.pdf
National Academies, Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance	https://nap.nationalacademies.org/catalog/25762/reflecting-sunlight-recommendations-for-solar-geoengineering-research-and-research-governance
Feingold et al. 2024, Physical science research needed to evaluate the viability and risks of MCB	https://www.science.org/doi/10.1126/sciadv.adi8594
Doherty et al. 2026, Defining scales of field studies and experiments to assess MCB	https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2025AV001939
Latham et al. 2012, Marine cloud brightening	https://royalsocietypublishing.org/doi/10.1098/rsta.2012.0086
Salter 2008, Sea-going hardware for the cloud albedo method	https://royalsocietypublishing.org/doi/10.1098/rsta.2008.0136
Cooper 2014, Preliminary results for salt aerosol production	https://royalsocietypublishing.org/doi/10.1098/rsta.2014.0055
Connolly et al. 2014, Factors determining the most efficient spray distribution	https://royalsocietypublishing.org/doi/10.1098/rsta.2014.0056
Harrison et al. 2025, Effervescent nozzle design	https://doi.org/10.1039/D5EA00073D
Hernandez-Jaramillo 2025, First generation outdoor MCB trial	https://doi.org/10.1088/1748-9326/adccd7
Rasch et al. 2024, MCB model intercomparison protocol	https://doi.org/10.5194/gmd-17-7963-2024
University of Washington Marine Cloud Brightening Program	https://mcbproject.org/
Southern Cross University marine cloud brightening research	https://www.scu.edu.au/research/research-impact/marine-cloud-brightening/
Saildrone autonomous ocean platforms	https://www.saildrone.com/
Liquid Robotics Wave Glider	https://www.liquid-robotics.com/
NOAA uncrewed systems and autonomous surface-vessels	https://www.omao.noaa.gov/uncrewed-systems

Closing observation

The most important product of the $1 billion would not be one impressive vessel. It would be an open, independently verified engineering system: given a platform, seawater condition, generator configuration, weather state and authorized operating plan, the program should be able to predict and measure particle output, energy use, plume behavior, maintenance burden, reliability, cost and uncertainty. It should also reveal clearly where the technology does not work or where atmospheric and environmental uncertainty remains too large to justify scale-up.

A successful Phase I would therefore end with a decision package, not a deployment decision. The package should show what was built, what was measured, what failed, what remains uncertain, what Phase II would cost, what monitoring and governance would be required, and whether the public benefit of proceeding appears greater than the risks and opportunity cost.