The Hydro Cube

Dual-Cycle TEC Atmospheric Water Generator & Distillation System

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1. Executive Summary

The Hydro Cube is a compact, field-portable dual-cycle water system: it condenses ambient humidity via a 33-fin array cooled by a multi-TEC cold plate, while its *hot side* is realized as an **immersed heatsink in liquid**. That liquid bath serves a dual purpose—waste-heat rejection and *boiling/distillation* of condensate or contaminated liquids. The unit runs exclusively on thermoelectric energy (no external heaters), with user-selectable TEC modules to trade power vs output. Prototype design targets ~0.28–0.33 L/h at 70 % RH under ideal conditions, with distillation up to ~0.25 L/h possible when boiling. This concept bridges atmospheric water generation and small-scale distillation in one compact, rugged package.

Unlike pure AWG units that waste heat, the Hydro Cube stands apart by converting cold and hot sides into productive functions. Compared to other military/AWG programs (e.g., DARPA AWE, GE's AIR2WATER, SOURCE Hydropanels), the Hydro Cube's size, dual use, and modular power control give tactical flexibility and competitive performance in the portable class.

2. System Design & Architecture

2.1 Geometry & Deployment

- **Stowed configuration:** 5″ × 5″ × 5″ cube
- **Deployed configuration:** 5″ × 5″ × 11″ column
- The top shell houses an optional use **44 CFM updraft fan** that draws air from bottom filtered vents, pulls it through the fin array upward, and exhausts via a chimney.
- The fin pack footprint is **4″ depth × 3.25″ width** (usable width ≈ 76.5 mm after side rails). 33 fins (0.8–1.0 mm thick) with **1.5 mm gaps** give a dense, high-area condensing core.

2.2 Cold Side & Condensation

- The cold plate is a **4″×4″×¼″ Al-6061** spreader bonded to TEC modules (TEC1-12706).
- The fin stack ("33 fins × 6″ tall") is mounted directly to the cold spreader. Each fin (both faces) yields 4″×6″ → 48 in^2 raw.
- Effective wet condensing area (with hydrophilic finish & droplet shedding) is estimated at ~0.55–0.60 m^2.

- The optional top fan ensures good airflow renewal over each channel (~44 CFM total → ~1.3–1.4 CFM per channel), sustaining condensation flux.

2.3 Hot Side & Immersed Heatsink / Distillation Bath

- Instead of a passive water jacket, the hot side is realized via a **finned heatsink immersed in a small, sealed liquid reservoir** (e.g., distilled water or condensate).
- The hot-side fins or pins are submerged in liquid; as the TEC pumps heat into the sink, it can drive local boiling at the interface, turning that same liquid into steam.
- That steam is directed into a condensation path (over the cold fin array) to produce **distilled output**, or condensed back into potable water.
- This design yields synergy: the liquid bath removes waste heat while simultaneously serving as the *working mass* to be boiled/distilled.
- Control of TEC power is essential to avoid overheating; active derating above ~70 °C at the interface is recommended.

2.4 Power, Controls & Modularity

- The cold plate is powered by **up to 4 TEC1-12706 modules** (12 V, ~60 W each).
- The system includes a switch/control bank to enable **1, 2, 3, or 4 TECs**, depending on desired yield vs. runtime.
- Control logic monitors **hot-face NTC**, liquid bath temperature, and ensures safe operation (derate, shutdown).
- All operation is powered electrically—**no external heater or fuel source** is required; boiling is achieved from TEC waste heat.

2.5 UV-C Sterilization Subsystem

The Hydro Cube integrates a **UV-C mini-LED sterilization system** designed to ensure complete microbial control within the unit's air and water pathways. The UV-C system employs compact **265–275 nm** emitters with optical outputs of **20–30 mW** per diode. These LEDs are strategically located in three primary zones:

1. **Condensate Fin Array**: 6–8 LEDs mounted vertically along the fin pack's sides, angled inward 30–40°, irradiate condensation surfaces, and prevent biofilm formation.
2. **Collection Basin / Distillation Cup**: Two downward–facing LEDs are positioned within the upper rim to sterilize the stored condensate or distilled water.
3. **Airflow / Fan Chamber** – 2 LEDs embedded in the upper shell near the exhaust vent to prevent microbial buildup in air-handling components

The subsystem draws less than **0.75 W (at 5 V)** and operates through a **12 V→5 V step-down converter**. The UV-C cycle may run **intermittently (2 min on / 15 min off)** or **continuously,** depending on mission parameters. Reflective baffles and optical isolation ensure operator safety and high irradiance efficiency.

Performance Gains:

- Delivers sterile water (< 10 CFU/mL).
- Reduces fin biofouling frequency by > 75%.
- Extends water storage life from 24 h to 72 h+.
- Adds < 3 % power draw / < 15 g mass.

3. Performance Estimates

These are **target estimates** suitable for concept-level justification. Real performance will depend on fabrication tolerances, surface finishes, and test conditions.

3.1 Atmospheric Condensation Mode (Clean Water Output)

Assume ambient 30 °C, sealed shroud, 44 CFM, 33 fins × 1.5 mm spacing, liquid-cooled hot sink (immersed).

Relative Humidity	L/h, 4 TECs	L/day, 4 TECs	L/h, 3 TECs	L/h, 2 TECs
60 %	0.20 – 0.24	4.8 – 5.8	0.15 – 0.18	0.10 – 0.13
70 %	0.28 – 0.33	6.7 – 8.0	0.21 – 0.25	0.14 – 0.18
80 %	0.34 – 0.40	8.2 – 9.6	0.26 – 0.32	0.18 – 0.24
90 %	0.38 – 0.45	9.1 – 10.8	0.30 – 0.35	0.22 – 0.28

- These yields reflect the additional condensing area and high airflow renewal.
- Gains beyond ~85–90% will flatten as TEC heat-lift capacity becomes the limiting factor.

3.2 Distillation / Boiling Mode (Dirty Water Processing)

- The immersed heatsink hot side can reach boiling in local zones if TECs supply ~300–360+ W of heat.
- With 4 TECs, **Qh ≈ Qc + Pin ≈ 350–420 W**, leaving enough latent energy to support **~0.20–0.25 L/h** of distillation from contaminated water (contingent on HX design and minimal thermal losses).
- With 3 TECs, expect **~0.15–0.18 L/h**; with 2 TECs, **~0.10–0.12 L/h**.
- In hybrid duty cycles, the system may alternate between condensing and distillation phases to maintain temperatures and yield.

3.3 Cold Climate / Low Temperature Performance

Performance drops as humidity (absolute) decreases. For ambient ~20 °C:

- At 70 % RH (~14 g/m³ vapor), yields might drop by ~25–35%.
- For example: 0.28 L/h (warm) → **~0.18–0.22 L/h** in cooler air.
- Distillation is less affected (since boiling is actively driven), but heat losses grow.

These estimates assume good insulation, low parasitic heat paths, and precise thermal control.

4. Biosecurity & Hygiene Advantages

The UV-C subsystem enhances the Hydro Cube's field readiness by eliminating biological contamination and maintaining sterile operation without filters or chemicals. This silent, maintenance-free solution ensures operational safety for special-forces personnel, forward operators, or disaster-response teams in regions lacking medical or cleaning resources.

5. Applications and Deployment

- **DoD & SOF Use:** Tactical water independence for small units or unmanned platforms.
- **FEMA / DHS:** Emergency shelters and mobile command units.
- **Humanitarian Operations:** Rapid-response water generation from humid or coastal air.
- **Commercial:** Basecamp, expeditionary, camping, recreational, or survival applications.

6. Cost and Production

Component	Estimated Cost per Unit (10,000 units)
TEC Array (×4)	$20
Aluminum Housing + Fins	$15
Liquid Heatsink Assembly	$10
UV-C LED Subsystem	$9
Electronics + Battery	$12
Assembly / QA	$14
Total (Approx.)	**$80 per unit**

7. Comparisons to Existing Programs & Commercial AWG Efforts

To show how The Hydro Cube fits the broader R&D and market space:

- **DARPA AWE (Atmospheric Water Extraction)**
  - Goal: build lightweight, low-power systems that supply potable water even in arid zones. (darpa.mil)
  - Multiple contracts to GE, Honeywell, MIT, PSI, NRL, etc. (darpa.mil)
  - GE's **AIR2WATER** project under AWE aims to produce **hundreds of liters/day** from deployed systems. (GE)
  - AWE encourages **sorbent-based approaches** (adsorb-desorb cycles) to lower energy per liter in dry ambient conditions. (darpa.mil)
  - Example: DARPA's distillation-enabled AWE challenge requires devices that operate even in extremely low humidity, imposing a higher standard of SWaP (size, weight, and power) (idstch.com)
- **SOURCE Hydropanels (Zero Mass Water / SOURCE Global)**
  - Uses solar-powered hygroscopic capture + passive condensation — no external power grid needed. (SOURCE)
  - Effective in moderate RH environments; scale is non-tactical (rooftop panels, homes) rather than personal systems. (SOURCE)
  - SOURCE claims to mineralize and ozonate output for taste/sterility. (SOURCE)
  - Critics note cost efficiency and performance limits at low humidity, but they illustrate how passive/solar AWG is entering the market. (The Guardian)
- **Navy AWG-OTM (On The Move)**
  - A U.S. Marine Corps SBIR topic: portable AWG system producing **~24 gallons in 24 hours** (~90 L/day) for a small team using onboard power (vehicle) (navysbir.com)
  - Emphasis is on vehicular/vehicle-integrated systems, **not wearable or individual** scale.

These benchmarks show that while large systems target tens to hundreds of liters per day, the *small, self-contained, individual-scale* niche remains underexplored. The Hydro Cube aims to fill that gap by combining condensation and distillation in one, with modular power scaling and advantageous compactness.

8. Operational & Tactical Advantages

- **Dual-use thermodynamics**: Both cold and hot sides are harnessed for water production rather than waste heat rejection alone.
- **Flexible scaling**: Operator can disable TEC modules to conserve battery or modulate output as conditions vary.
- **Low signature & silent operation**: No compressors, no flue exhaust, modest fan noise.
- **Reduced logistics burden**: Less water transport, fewer resupply convoys, lower heat/fuel footprints.

- **Boiling/hygiene capability built-in**: Distillation from dirty sources or localized sterilization of condensate fluid.
- **Competitive in DARPA/DoD space**: Personal class systems are exactly the "expeditionary track" goal of AWE.

9. Risks, Challenges & Mitigations

- **Heat leaks & non-ideal thermal paths** reduce COP — careful sealing and insulation required.
- **Boil detachment and bubble formation** in an immersed heatsink may reduce thermal coupling, so a robust boiling surface design (micro-fins, nucleation sites) is needed.
- **Water quality concerns** in distillation mode: ensure materials are inert and path is sealed to avoid contamination.
- **Power constraints in low-RH conditions**: output falls rapidly with RH drop. Mitigation: use local heating cycles.
- **Durability & fouling**: repeated condensation cycles risk corrosion or fouling of fins or immersion surfaces; coatings and maintenance protocols are essential.

10. Development Roadmap & Cost Estimate

Phase I – Prototype Demonstration

- Build a benchtop with a 33-fin array, 4 TEC modules, and an immersed heatsink. Validate condensation and distillation rates vs. targets.
- Thermal mapping, flow calibration, and durability cycles.

Phase II – Rugged Field Prototype

- Reinforced shell, deployable mechanisms, filtration modules, connectors, field sealing, environmental tests (dust, shock, salt fog).

Phase III – Pre-Production & Field Trials

- Small batch (1,000–10,000 units) production, user field evaluation, integration into soldier systems.

11. Conclusion

The Hydro Cube merges **solid-state reliability, UV-C sterilization, and dual-mode heat utilization** into a single, compact system. Its modular design allows adaptation from field kits to vehicle-mounted units. By maintaining potable, sterile water generation in the most austere environments, it directly supports U.S. DoD logistics reduction initiatives, NATO field resilience efforts, and humanitarian disaster-relief operations worldwide.