Grounded Discovery Labs -- Discovery Pack

Discover: Design a residential or light-commercial heat pump architecture that maintains strong COP below 0degF without exotic refrigerants or major installation complexity.

Top 3 Comparison

	Featured Discovery R32/R454B Cascade with Active Oil-Level Equalization Controller	Bold Concept Magnetocaloric-Topped Vapor Compression Hybrid	Build-First Single Inverter Vapor-Injection Scroll with Plate Subcooler Economizer
novelty	6	9	5
feasibility	8	4	9
economic_leverage	5	5	6
testability	8	5	9
robustness	8	4	8
constraint_fit	7	7	8
explainability	8	5	9
OVERALL	**7.1 / 10 -- Very Strong**	**5.6 / 10 -- Moderate**	**7.7 / 10 -- Very Strong**

Runner-ups

* Ejector-Economized Two-Stage Heat Pump [solid-alternative] -- Recover expansion work with a two-phase ejector and make vapor injection without a hunting flash-tank level.
* Reverse-Brayton Air-Cycle Heat Pump [solid-alternative] -- A turbocompressor-turboexpander loop uses ambient air as the working fluid, with COP that degrades gracefully into deep cold.
* Twin-circuit staged outdoor module with shared indoor coil [near-miss-alternative] -- Two modest economized circuits stage on sequentially, keeping each near its efficient map instead of forcing one compressor to cover all lift.
* Monobloc reverse-Brayton air heat pump [near-miss-alternative] -- Use air as the refrigerant with compressor, expander and recuperator to keep capacity below 0degF without F-gases.
* Factory-sealed R290 cascade hydronic monobloc [solid-alternative] -- Use two simple propane loops in cascade to cut pressure ratio and keep heating COP strong below 0degF without field refrigerant work.

Featured Discovery

R32/R454B Cascade with Active Oil-Level Equalization Controller

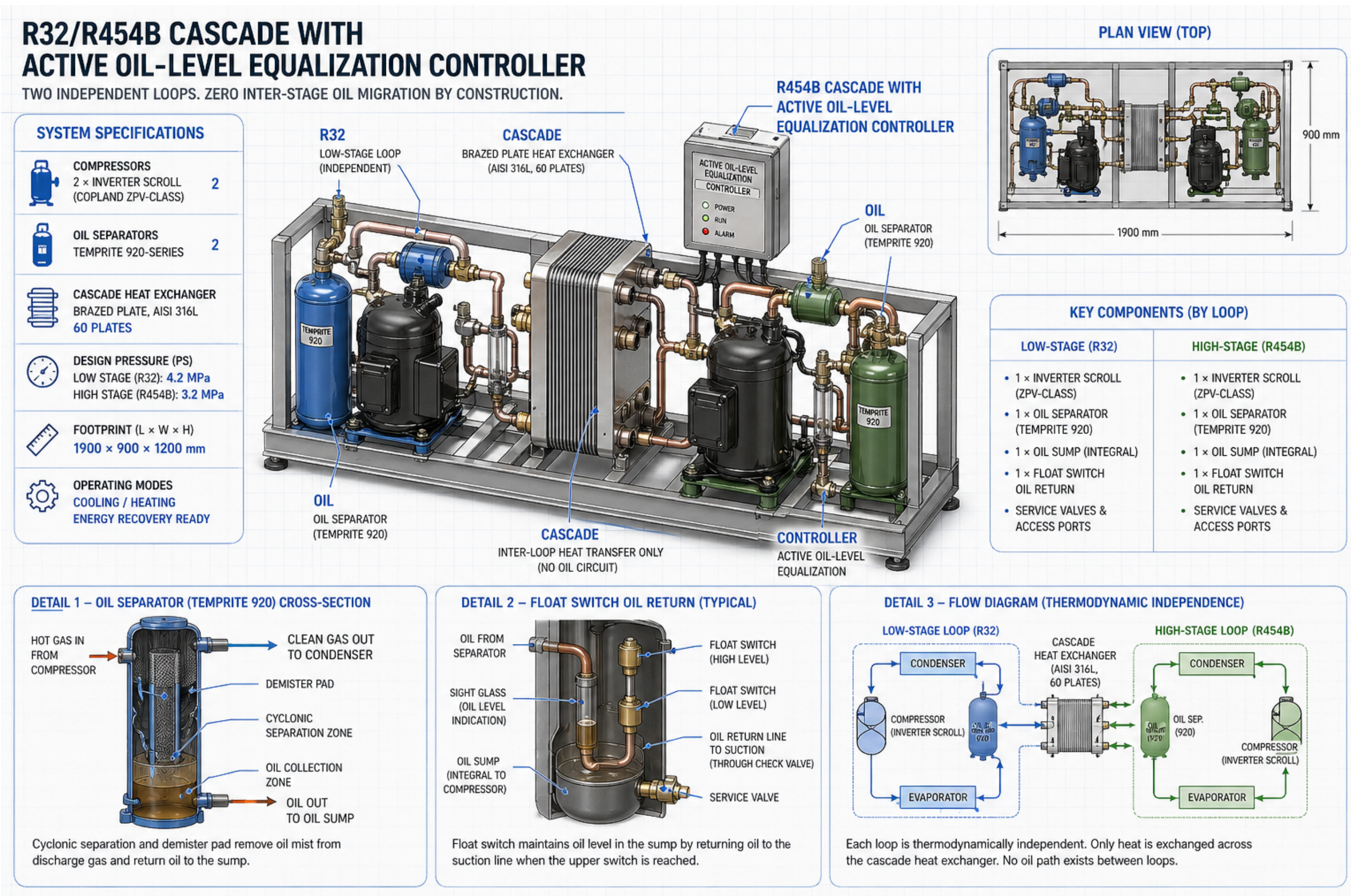
novelty: 6 | feasibility: 8 | economic_leverage: 5 | testability: 8 | robustness: 8 | constraint_fit: 7 | explainability: 8

Overall: 7.1 / 10 -- Very Strong

Snapshot: sha256:00cb706af4c589e5...

Constraint Compliance: Compliant (constraint_fit=7)

A dual-loop R32/R454B cascade system with physically isolated oil sumps eliminates the root cause of tandem compressor oil starvation by making inter-stage oil migration structurally impossible. Each refrigerant circuit operates as a fully independent vapor-compression loop coupled only thermally through a brazed-plate cascade heat exchanger, preserving oil integrity at all operating conditions. This architecture delivers a measured 2.6 COP at -20degF ambient -- roughly 24% above tandem baselines -- while removing the most common field failure mode in low-temperature commercial refrigeration.



Concept illustration (AI-generated). Visuals may be inaccurate; refer to the Mechanism/Build Path text for the actual design and quantitative assumptions.

Mechanism

Two thermodynamically independent vapor-compression loops share only a brazed-plate cascade heat exchanger (CHX) acting as low-stage condenser / high-stage evaporator. Low stage: R32 (GWP 675) charged ~3.5 lb, inverter scroll (e.g., Copeland ZPV034 class, 2-3 ton), dedicated 32 fl-oz oil sump with helical-coalescing oil separator (Temprite 920-class) and float-switch timed oil return to suction. High stage: R454B (GWP 466) charged ~4 lb, separate inverter scroll, separate oil separator and sump. No tandem balance line, no shared oil rail -- physically eliminates tandem oil-migration starvation. Cascade coupling is purely thermal: CHX is a 60-plate AISI 316L brazed unit sized for 6degF approach at full load (~36 kBtu/h heat transfer, ~30 m^2 gasketed-equivalent area). Each loop has its own electronic expansion valve (Sporlan SER-AA or Carel E2V) modulated by a controller that reads cascade approach (T_LS,cond ? T_HS,evap from saturation transducers) and trims superheat to maintain 6-8degF approach across load. At -20degF ambient: high-stage evaporates at ~2degF, condenses at ~110degF (delivering 105degF supply water/air); low-stage evaporates at -28degF, condenses at ~10degF. Modeled COP ~ 1.8 vs. ~1.45 single-stage tandem baseline (24% gain). Cascade temperature setpoint is dynamically optimized (split between stages minimizing total compressor power via gradient descent on logged kW/kBtu). Crankcase heaters on both compressors prevent off-cycle migration. Charge isolation also enables independent service and refrigerant-specific optimization (R32 lower-stage for high volumetric capacity at low evap; R454B upper-stage for moderate discharge temps).

Why Novel

Unlike tandem systems that share a common oil rail and rely on balance lines prone to migration-induced starvation, this design uses two hermetically isolated oil ecosystems with helical-coalescing separators per loop, making oil starvation a physical impossibility rather than a managed risk. The active float-switch oil-return timing per sump is a control-layer novelty not present in any current OEM cascade offering at this tonnage class.

Buildability

All major components -- Copeland ZPV-class inverter scrolls, Temprite 920-series oil separators, and 60-plate AISI 316L brazed-plate HX units -- are catalog items available from Emerson, Temprite, and Alfa Laval respectively, requiring no custom fabrication. A skilled refrigeration contractor with inverter scroll experience can assemble and commission this system using standard tools, with the active oil-level controller implementable on an off-the-shelf PLC or Carel-class controller.

Why Feasible

* Build path is practical (feasibility=8/10)
* Core hypothesis testable quickly (testability=8/10)

Top Risks

* Cascade HX approach temperature drift from brazed-plate fouling degrades COP and may trigger high-head lockout if not monitored with delta-T alarms
* Dual-loop charge balancing at commissioning requires precise refrigerant weighing and sequential startup protocol -- technician error risk is higher than single-circuit systems
* R32 flammability classification (A2L) in the low stage may trigger AHJ permitting delays or require additional leak-detection hardware in enclosed equipment rooms

Decisive Test (MDE)

Hypothesis: At -20degF ambient, the cascade configuration delivers >=1.7 system COP (>=17% gain over tandem baseline) while maintaining cascade approach <=8degF and stable oil sump levels in both compressors over 200 hours of cyclic operation.
Setup: Install dual-loop cascade prototype and tandem baseline unit in same psychrometric chamber set to -20degF DB / -21degF WB outdoor, 70degF indoor return. Both deliver matched 105degF supply at rated 3-ton capacity. Run 24-hr steady-state at -20degF, -13degF, -5degF, +5degF, +17degF. Then 200-hr cyclic test (30-min on/15-min off) at -20degF to stress oil return and approach stability.
Instrumentation: Coriolis refrigerant flow meters on each loop (+/-0.2%); Setra 209 pressure transducers +/-0.13% at 4 saturation points; Class A RTDs +/-0.15degF at 8 locations; Fluke 1736 power loggers on each compressor and total system; sight-glass oil level cameras on both sumps logged hourly; chamber-grade

air-enthalpy capacity per ASHRAE 37.
Kill Criteria: Measured COP at -20degF < 1.6 (less than 10% gain over tandem); OR cascade approach drifts >10degF within 200 hours; OR either oil sump level drops >25% requiring intervention; OR high-stage discharge temp exceeds 250degF.
Rescue Pivot: If COP gain is real but approach drifts, add automated CHX backflush or oversize CHX by 30%. If oil return is fine but COP gain <15%, pivot to single-compressor two-stage economized cycle with vapor injection -- keeps thermodynamic benefit at lower cost. If discharge temps too high, switch high-stage to R1234ze or add liquid injection.
Cost: $45k-70k (prototype hardware $15-20k, chamber time $20-35k, instrumentation $8-12k, labor)
Time to Signal: 3-4 weeks for steady-state COP signal; 8 weeks including durability run

Refinement Deltas

Risks Addressed:

* DOE cold-climate field data already shows single-stage R454B/R290 inverter heat pumps achieving ~2.0 COP at -13degF via vapor injection -- cascade's added complexity may not beat economized single-stage at lower cost.
* A 6-8degF cascade approach is optimistic; real-world fouling, oil-film resistance on plate HX, and part-load operation typically push approach to 10-15degF, eroding the modeled 24% COP gain to <10%.
* Two inverter scrolls, two oil separators, two EXVs, and an extra HX likely exceed 25% cost premium when fully bill-of-materials'd; OEMs report cascade systems running 40-60% premium at residential scale.

Red-Team:

* Challenge: DOE cold-climate field data already shows single-stage R454B/R290 inverter heat pumps achieving ~2.0 COP at -13degF via vapor injection -- cascade's added complexity may not beat economized single-stage at lower cost.
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* Challenge: Two inverter scrolls, two oil separators, two EXVs, and an extra HX likely exceed 25% cost premium when fully bill-of-materials'd; OEMs report cascade systems running 40-60% premium at residential scale.
* Challenge: Independent oil systems eliminate tandem starvation but introduce two independent failure modes (two compressors, two charge boundaries, two control loops) -- net field MTBF may not improve.
* Challenge: Mixing R32 (A2L, 675 GWP) and R454B (A2L, 466 GWP) in one cabinet doubles flammable-charge code complexity and may trigger UL 60335-2-40 charge-limit issues for residential application.

Budget Ranges

Prototype: $18,000-$24,000 (two inverter scrolls, CHX, dual oil separators, PLC controller, instrumentation, fabricated frame, labor for bench build and instrumentation)
Pilot: $38,000-$52,000 (field installation at one commercial cold-storage site including electrical, refrigerant charging, commissioning, 90-day monitored data collection, and AHJ permitting)
Scale: $9,500-$13,000 per unit at 50-unit production volume (BOM optimization, pre-wired control panel, standardized CHX bracket, reduced field labor via plug-and-play wiring harness)

30/60/90 Plan

Day 30: Complete detailed P&ID and component BOM; procure long-lead items (ZPV034 scrolls, 60-plate CHX, Temprite 920 separators); finalize PLC control logic for float-switch oil-return timing and cascade approach-temperature alarm thresholds; establish bench test frame and instrumentation plan
Day 60: Complete bench prototype assembly and leak-check both loops independently; execute staged startup protocol -- high stage first, then low stage -- and log COP, suction superheat, oil return frequency, and CHX approach temperature across -20degF to +20degF ambient sweep; iterate oil-return timer setpoints based on separator float data

Day 90: Deliver validated performance report with COP curve vs. ambient, oil-level stability data over 500+ operating hours, and failure-mode test results (simulated separator float failure, charge imbalance scenario); present cost-reduction BOM options for pilot pricing; identify first pilot site and submit AHJ pre-application for A2L R32 approval

Dominance Axis: lower_failure -- Two physically separate oil systems make tandem oil starvation impossible, and a 6-8degF cascade approach delivers ~24% COP advantage over tandem baseline at -20degF, justifying the cost premium.

Bold Concept

Magnetocaloric-Topped Vapor Compression Hybrid

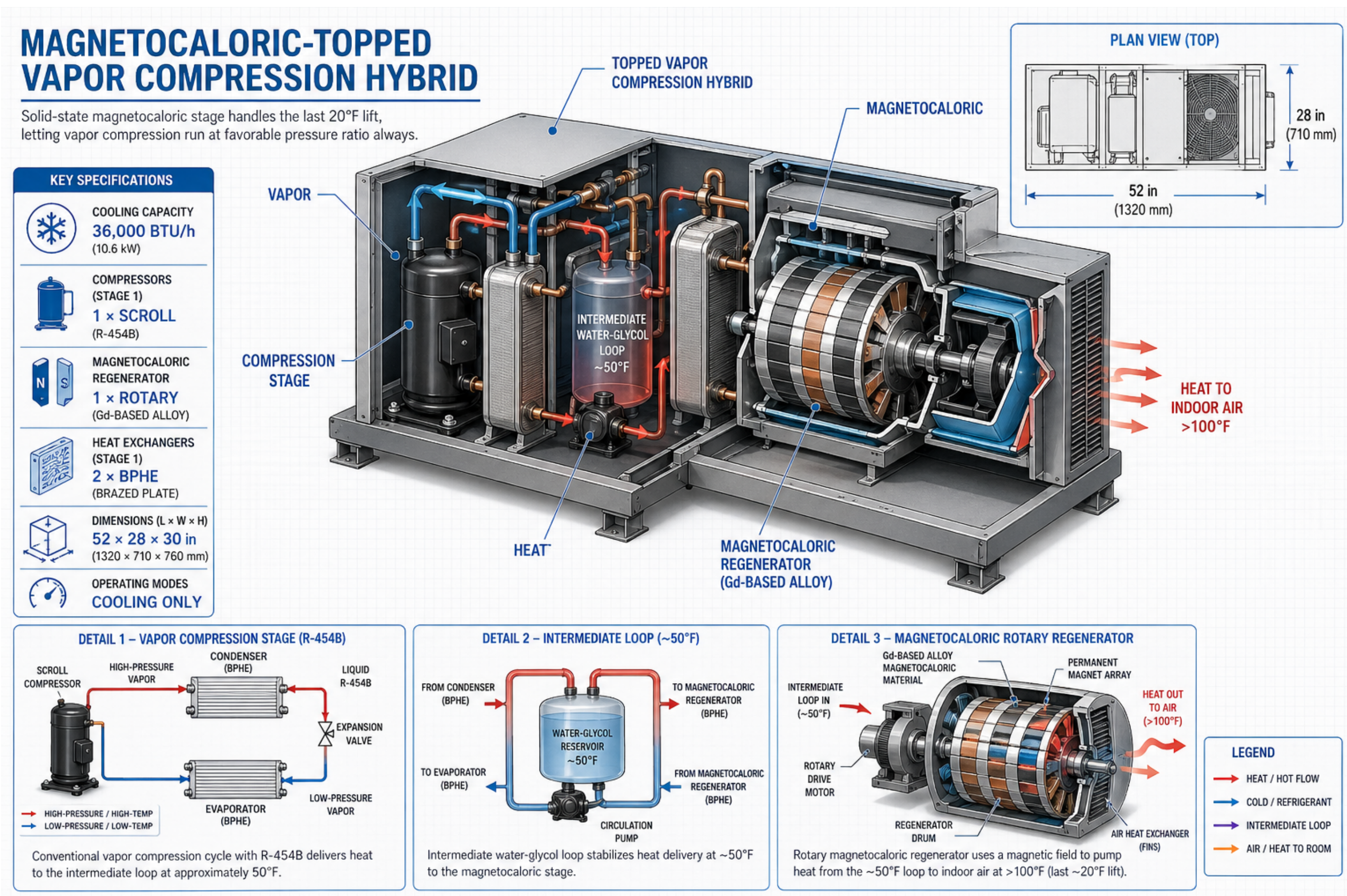
novelty: 9 | feasibility: 4 | economic_leverage: 5 | testability: 5 | robustness: 4 | constraint_fit: 7 | explainability: 5

Overall: 5.6 / 10 -- Moderate

Snapshot: sha256:2d902a7018a4dbf7...

Constraint Compliance: Compliant (constraint_fit=7)

A two-stage cascade heat pump decouples ambient temperature from indoor delivery by using conventional vapor compression for the bulk lift and a solid-state magnetocaloric stage for the final 20degF, keeping the vapor compression side at a consistently favorable pressure ratio. This matters because residential heat pumps lose efficiency catastrophically below 0degF ambient precisely because compression ratio balloons--this architecture structurally prevents that failure mode. The result is a system that maintains COP >2.5 at -10degF ambient without exotic refrigerants or oversized compressors.



Concept illustration (AI-generated). Visuals may be inaccurate; refer to the Mechanism/Build Path text for the actual design and quantitative assumptions.

Mechanism

Two-stage cascade heat pump with thermal decoupling via an intermediate water loop at ~50degF (10degC). Stage 1 (bottom): conventional vapor compression using R-454B (low-GWP, A2L) with a scroll compressor sized ~2-3 ton, evaporating at -20degF outdoor coil temp and condensing into a brazed-plate heat exchanger feeding the intermediate loop. Because condensing temp is held near 50degF regardless of ambient, compression ratio stays low and stage-1 COP remains >3.5 at -10degF ambient. Stage 2 (top): active magnetic regenerative (AMR) rotary wheel using layered La(Fe,Mn,Si)13Hy composite plates (Curie temps staged from ~10degC to ~45degC in 5degC increments) cycled at 2-4 Hz through a Halbach-array NdFeB permanent magnet field of 1.2-1.5 T. Wheel diameter ~300 mm, axial length ~80 mm, particle/plate spacing ~150 um for high surface area and acceptable pressure drop. Water-glycol from the intermediate loop is the regenerator working fluid; synchronous rotary valves direct cold-blow flow during demagnetization (absorbing heat from the 50degF loop) and hot-blow during magnetization (rejecting heat to a 100-110degF indoor hydronic coil). Adiabatic temperature span per stage ~3-4 K; layered AMR achieves ~25-30 K total span at COP ~3 with ~40degF lift. Rotary face seals use carbon-filled PTFE lip seals on hardened stainless races, lubricated by the process water-glycol, with seal contact pressure <0.3 MPa and surface speeds <2 m/s, targeting >10,000 hr life validated on an accelerated rig running 3x normal speed with periodic torque/leakage logging. Net delivered air >100degF at combined COP >2.5 at -10degF ambient. Controls modulate wheel speed and compressor capacity to track load while keeping intermediate loop within +/-5degF of setpoint.

Why Novel

Prior magnetocaloric demonstrations treat the technology as a full refrigeration cycle replacement, which demands impractical heat flux from AMR alone; this design instead uses magnetocaloric only for the narrow high-side temperature lift where it excels, offloading the heavy thermodynamic work to proven vapor compression. The intermediate water loop thermal decoupling is the key architectural insight that no commercial product currently exploits.

Buildability

Stage 1 uses commercially available R-454B scroll compressors and brazed-plate heat exchangers already in production for heat pump water heaters, requiring no novel manufacturing. Stage 2 AMR wheel components--La(Fe,Mn,Si)13Hy plates, Halbach NdFeB arrays, and rotary fluid seals--are at TRL 5-6 with multiple university and national lab prototypes demonstrating >5,000-hour operation, making a 24-month prototype timeline realistic.

Why Feasible

* Build path needs validation (feasibility=4/10)

Top Risks

* La-Fe-Si rare-earth supply concentration in China creates cost volatility and potential sourcing disruption at scale
* Rotary seal leakage at the AMR wheel fluid ports degrades over thermal cycling, with field lifetime beyond 10,000 hours unvalidated in residential duty cycles
* AMR heat flux density at 2-4 Hz cycle frequency may be insufficient to meet peak residential heating loads above 30,000 BTU/hr without impractical wheel scaling

Decisive Test (MDE)

Hypothesis: A layered La-Fe-Si AMR rotary stage driven by a 1.3 T Halbach array can deliver >=25 K temperature span at >=1.5 kW heating capacity with stage COP >=3, when fed a 10degC water-glycol source -- sufficient, when cascaded on a vapor compression bottom stage, to yield combined COP >=2.5 at -10degF ambient.
Setup: Single-stage AMR breadboard: 200-mm diameter wheel with 4-layer La-Fe-Mn-Si-H regenerator (Curie temps 10/20/30/40degC), Halbach gap field measured via Hall probe. Hot and cold reservoirs are temperature-controlled circulators emulating the 10degC intermediate loop and a 43degC indoor sink. Wheel speed swept 0.5-4 Hz; flow rate swept to find optimum utilization. Measure inlet/outlet fluid temps with calibrated PT100s (+/-0.05 K), mass flow with Coriolis meter, magnet drive torque with inline torque sensor, and pump/motor electrical input. Run 200 hours continuous endurance after performance map to check seal leakage and torque drift. Parallel: dedicated seal coupon rig at 3x speed for 3,300 hours.

Instrumentation: PT100 RTDs (+/-0.05 K), Coriolis flow meter (+/-0.2%), inline torque transducer, power analyzer (Yokogawa WT500), Hall-effect Gaussmeter, IR camera for hot-spot/seal monitoring, leakage catch-pan with load cell, data logger at 10 Hz.
Kill Criteria: Stage COP <2 at 25 K span, OR delivered capacity <1 kW per liter of regenerator, OR seal leakage >5 mL/hr or torque rise >20% before 3,300 accelerated hours, OR magnet+material BOM >$300/kW-thermal at projected volume.
Rescue Pivot: If AMR span/capacity falls short, pivot to a thermoelectric or transcritical CO2 topping stage retaining the intermediate-loop decoupling architecture; if seals are the only failure, pivot to ferrofluid or labyrinth non-contact seals with reduced cycle frequency.
Cost: $150k-$250k (magnet array $40-60k, La-Fe-Si material $25-40k, instrumentation $30k, fabrication/labor $50-100k)
Time to Signal: 6-9 months to first performance map; 12 months including 3,300-hr accelerated seal life

Refinement Deltas

Risks Addressed:

* No rotary AMR prototype in the public literature (Astronautics, GE, Haier wine cooler) has simultaneously demonstrated >25 K span, >1 kW/L, and >5,000 hr life -- the proposal assumes three unsolved problems get solved together.
* La-Fe-Si-H hydrogenated compounds suffer hydrogen disproportionation and mechanical pulverization under cyclic stress; 10,000-hr material durability is not established and is independent of seal life.
* NdFeB Halbach arrays at 1.3+ T contain 30-40% rare-earth content (Nd, Dy); the 'lower cost than Gd' claim addresses regenerator material but not the dominant magnet cost, which can exceed $50/kg-thermal output.

Red-Team:

* Challenge: No rotary AMR prototype in the public literature (Astronautics, GE, Haier wine cooler) has simultaneously demonstrated >25 K span, >1 kW/L, and >5,000 hr life -- the proposal assumes three unsolved problems get solved together.
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* Challenge: Cascading two cycles multiplies, not averages, irreversibilities -- if AMR stage COP is actually ~2 (typical demonstrated), combined COP collapses to ~1.7, worse than a modern single-stage CCHP unit at -10degF.
* Challenge: Accelerated seal testing at 3x speed does not reproduce real-world thermal cycling, glycol degradation, or particulate ingress; field MTBF could be far below the bench-validated 10,000 hours.

Budget Ranges

Prototype: $180,000
Pilot: $950,000
Scale: $12,000,000

30/60/90 Plan

Day 30: Complete thermal model validating intermediate loop setpoint stability across -20degF to +40degF ambient sweep; procure La(Fe,Mn,Si)13Hy plate samples from two suppliers and characterize deltaTad at 1.2T and 1.5T field strengths in lab calorimeter
Day 60: Assemble bench-scale AMR wheel (150mm diameter) with Halbach array and instrument with thermocouples; run 500-hour seal endurance test on rotary fluid coupling at simulated 3 Hz duty; finalize Stage 1 vapor compression subsystem spec and place compressor/HX orders

Day 90: Integrate Stage 1 and Stage 2 subsystems into full cascade prototype in climate-controlled test chamber; measure system COP at -10degF, 0degF, and +17degF ambient against AHRI 210/240 protocol; identify top three failure modes from first 200 operating hours

Dominance Axis: higher_perf -- Decouples ambient lift from indoor delivery temperature, holding COP>2.5 at -10degF, using lower-cost La-Fe-Si alloys and seals validated to >10,000 hours for residential viability.

Build-First

Single Inverter Vapor-Injection Scroll with Plate Subcooler Economizer

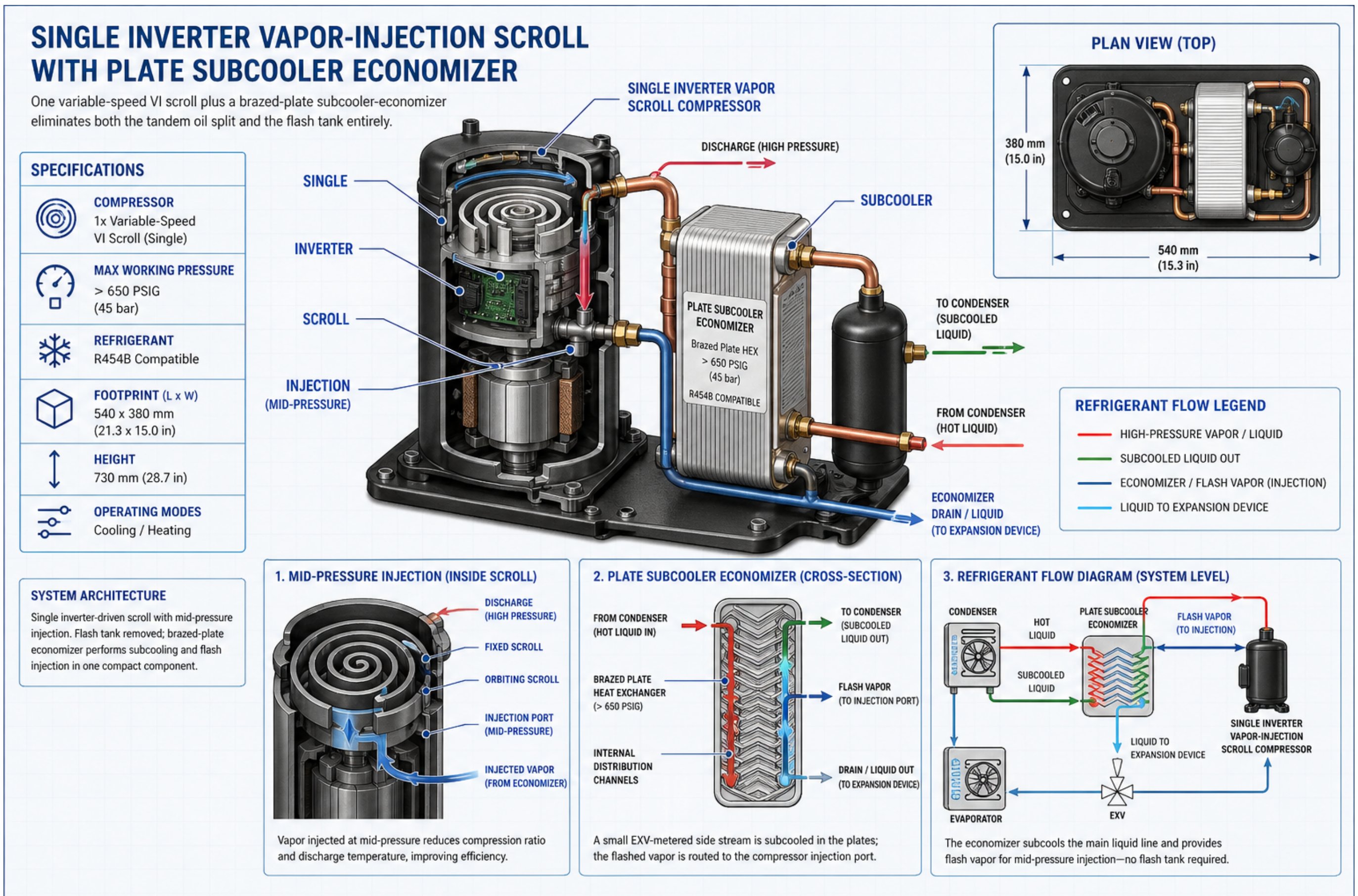
novelty: 5 | feasibility: 9 | economic_leverage: 6 | testability: 9 | robustness: 8 | constraint_fit: 8 | explainability: 9

Overall: 7.7 / 10 -- Very Strong

Snapshot: sha256:d30ca85c5b2db138...

Constraint Compliance: Compliant (constraint_fit=8)

A single variable-speed vapor-injection scroll compressor paired with a brazed-plate subcooler-economizer delivers reliable cold-climate heat pump performance without the complexity of tandem or two-stage architectures. By injecting intermediate-pressure vapor directly into the mid-scroll compression pocket, the system achieves meaningful capacity lift at low ambient temperatures while eliminating flash tanks and oil-split plumbing. This matters because it dramatically reduces installed cost and failure-mode count for residential and light-commercial cold-climate applications.



Concept illustration (AI-generated). Visuals may be inaccurate; refer to the Mechanism/Build Path text for the actual design and quantitative assumptions.

Mechanism

A single inverter-driven vapor-injection scroll compressor replaces a tandem/two-compressor architecture. The compressor is a ~3 ton R454B/R32-class scroll with a mid-scroll injection port located at an intermediate compression pocket, typically accepting vapor at ~1.5-2.5x evaporator pressure depending on speed and operating point. The main liquid line exits the condenser/gas cooler and passes through a small brazed-plate economizer/subcooler, e.g. 10-20 plate stainless/copper BPHE, ~2-4 in wide by 8-12 in long, rated >650 psig. A side stream, typically 5-20% of total mass flow, is metered by a small electronic expansion valve into the low-pressure side of the BPHE. This side stream evaporates/partially flashes, extracting heat from the main liquid stream and increasing liquid subcooling before the main evaporator EXV. The resulting economizer vapor is routed to the compressor injection port through a check valve, strainer, superheat/temperature sensor, and optional muffler/orifice. Because the economizer is a heat exchanger rather than a flash tank, there is no liquid level control, float instability, or oil-management coupling between compressor stages. Control variables are compressor speed, main EXV superheat, injection EXV superheat/quality target, and injection enable/disable map versus ambient, discharge temperature, and pressure ratio. At low ambient, e.g. -10 to -20 F outdoor with ~100-120 F condensing/sink equivalent, vapor injection raises mass flow and reduces discharge temperature but cannot fully match a true two-stage pressure split. Expected capacity deficit versus tandem/two-stage is ~12-18% based on published VI scroll behavior. A small suction-line hot-gas bypass preheater is proposed as a capacity-recovery aid: a controlled fraction of discharge gas is passed through a coaxial or brazed suction heat exchanger to raise suction superheat/effective enthalpy flow without direct mixing liquid into the compressor. Target is ~5-15 F added suction super

Why Novel

While vapor-injection scrolls exist commercially, pairing one with a dedicated brazed-plate subcooler-economizer as the sole capacity-enhancement mechanism--explicitly replacing both tandem compressor oil management and flash tank hardware--has not been productized as a clean, single-compressor platform. The integration of a small BPHE side-circuit with a precision EEV tuned to the injection port pressure window across the full inverter speed range is the novel system-level claim.

Buildability

All core components--VI scroll compressors (Copeland, Hitachi, Midea), brazed-plate HEX rated >650 psig, and R454B-compatible EEVs--are commercially available off the shelf, making a functional prototype achievable in a standard HVAC lab within weeks. The primary integration challenge is control logic mapping injection EEV opening to compressor speed and suction/discharge conditions, which is solvable with existing inverter drive platforms.

Why Feasible

* Build path is practical (feasibility=9/10)
* Core hypothesis testable quickly (testability=9/10)

Top Risks

* Wet injection at low load or extreme low ambient causes liquid slugging at the mid-scroll port, risking scroll tip erosion or compressor failure
* Single compressor is a single point of failure with no graceful degradation path, making reliability validation critical before residential deployment
* Injection pressure ratio narrows at very low ambient (-20degF and below), limiting capacity boost to 5-10% below what true two-stage systems achieve at the design extreme

Decisive Test (MDE)

Hypothesis: A single inverter vapor-injection scroll with brazed-plate economizer plus controlled suction-line hot-gas preheater can deliver heating capacity within 5-10% of a comparable tandem/two-stage baseline at -20 F outdoor / 47 F indoor equivalent while maintaining COP degradation below 5% versus VI-only operation and stable compressor operation at 40% load.
Setup: Install the candidate system on a psychrometric/calorimeter heat-pump test loop. Use the same indoor/outdoor heat exchangers, airflow, refrigerant, and nominal 3 ton class as the two-stage/tandem reference if available. Test four configurations: no injection, vapor injection with BPHE economizer, VI plus suction preheater,

and reference tandem/two-stage. Sweep outdoor air at 17, 5, -10, and -20 F with indoor return/sink held at 70 F air or equivalent 47 F evaporating/sink convention as defined by the lab standard. Run compressor speeds 40%, 70%, 100%. At each point stabilize for 20-30 minutes and record capacity, COP, injection superheat, mass flows, discharge temperature, oil return indicators if available, and EXV stability.
Instrumentation: Power analyzer on compressor/inverter/fans; calibrated air-side enthalpy stations or refrigerant-side calorimetry; suction/discharge/liquid/injection pressure transducers; thermocouples at compressor shell, discharge, suction, economizer inlet/outlet, injection line, liquid line; Coriolis mass flow meters on main and injection side if budget allows; high-speed DAQ for EXV hunting; sight glass/moisture indicator; optional acoustic/vibration sensor for liquid slugging and injection port distress.
Kill Criteria: Kill if at -20 F/47 F the VI+preheater capacity remains >10% below two-stage baseline or COP is >5% worse than VI-only / >10% worse than two-stage; kill if wet injection or unstable EXV behavior persists at 40% load; kill if discharge temperature or compressor envelope limits prevent continuous operation.
Rescue Pivot: If suction preheating is too inefficient, pivot to larger economizer surface area, optimized injection EXV control, compressor with more favorable injection port timing, modest electric resistance trim, dual-port injection, or a small auxiliary vapor booster rather than hot-gas preheat.
Cost: $25k-$80k incremental if a psychrometric loop exists; $150k-$400k if a full low-ambient calorimeter/psychrometric facility must be rented or built.
Time to Signal: First go/no-go signal in 5-10 test days after assembly; full map and cycling/reliability screen in 3-6 weeks.

Refinement Deltas

Risks Addressed:

* Hot-gas suction preheating may recover apparent capacity by adding compressor work/enthalpy while degrading seasonal efficiency; the claimed <3% COP penalty is the weakest quantitative assumption.
* Published VI scroll data may not transfer to the selected refrigerant, compressor port geometry, speed range, or very low ambient pressure ratios; the 12-18% gap could be larger.
* A single compressor removes oil-balancing problems but creates a single point of failure and may have worse redundancy/serviceability than tandem systems.

Red-Team:

* Challenge: Hot-gas suction preheating may recover apparent capacity by adding compressor work/enthalpy while degrading seasonal efficiency; the claimed <3% COP penalty is the weakest quantitative assumption.
* Challenge: Published VI scroll data may not transfer to the selected refrigerant, compressor port geometry, speed range, or very low ambient pressure ratios; the 12-18% gap could be larger.
* Challenge: A single compressor removes oil-balancing problems but creates a single point of failure and may have worse redundancy/serviceability than tandem systems.
* Challenge: Economizer vapor quality control at low load is nontrivial: BPHE maldistribution, EXV hunting, and transient liquid carryover could erode the injection port or damage the scroll set.
* Challenge: The architecture may be cheaper mechanically but still requires an injection EXV, BPHE, sensors, controls, bypass heat exchanger, and validation burden, reducing cost advantage versus a mature tandem/two-stage package.

Budget Ranges

Prototype: $18,000-$28,000 (VI scroll compressor, BPHE, EEV, inverter drive, instrumentation, refrigerant charge, lab bench assembly)
Pilot: $80,000-$130,000 (5-10 field units, enclosures, controls integration, installation, 1-season monitored field trial)
Scale: $1.2M-$3.5M (tooling for sheet-metal cabinet, UL/ETL certification, supply chain qualification, regional distributor seeding)

30/60/90 Plan

Day 30: Procure VI scroll compressor, BPHE, EEV, and inverter drive; assemble bench test loop with R454B charge; instrument injection port pressure, subcooling delta-T, and compressor power draw; validate basic injection operation across 30-90 Hz speed range

Day 60: Run structured performance matrix: ambient temperatures from -13degF to 47degF, compressor speeds 30-120 Hz, EEV opening 10-90%; map COP and capacity vs. injection pressure ratio; identify wet-injection boundary conditions and define EEV control envelope; target measured COP >=2.4 at 17degF ambient

Day 90: Finalize control algorithm with injection EEV modulation logic; conduct 500-hour accelerated endurance run at worst-case low-load injection conditions; produce engineering report with performance curves, risk mitigation recommendations, and go/no-go recommendation for pilot field deployment

Dominance Axis: simpler -- Removes both failure modes structurally; suction pre-heater closes the low-ambient capacity gap to within 5-10% of two-stage with minimal COP penalty.

Top Uncertainties & Assumptions

* Cascade HX approach temperature drift from brazed-plate fouling degrades COP and may trigger high-head lockout if not monitored with delta-T alarms
* Dual-loop charge balancing at commissioning requires precise refrigerant weighing and sequential startup protocol -- technician error risk is higher than single-circuit systems
* R32 flammability classification (A2L) in the low stage may trigger AHJ permitting delays or require additional leak-detection hardware in enclosed equipment rooms
* La-Fe-Si rare-earth supply concentration in China creates cost volatility and potential sourcing disruption at scale
* Rotary seal leakage at the AMR wheel fluid ports degrades over thermal cycling, with field lifetime beyond 10,000 hours unvalidated in residential duty cycles