Leakage by Design: The Distributed Refrigerant Fallacy — A Scientific Indictment of VRV/VRF and the Hydronic Blueprint for Safe, Stable, High-Performance Buildings

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Author's Foreword

Starting out, the HVAC field did not look especially welcoming, particularly coming from a small town in Ontario, Canada. Fortunately I joined The Trane Co, Class 82II, and my first job was in Saudi Arabia, working alongside service technicians which| provided a practical education. From there, work at McQuay and later Daikin offered additional perspectives on how systems behave over years, not months. Across many projects, a clear pattern emerged: growing reliance on numerous small, distributed DX units to simplify zoning and speed design decisions. On paper, the approach had appeal. In the field, it introduced long refrigerant runs, many more joints and components, and a set of hidden risks that rarely announced themselves until they did.

This paper aims to add clarity to that trend and its consequences. Spreading refrigerant throughout occupied spaces creates structural challenges that accumulate with time and building change. A hydronic approach—using water for distribution—addresses those challenges with straightforward principles: keep hazards contained in supervised plant rooms, combine loads so equipment operates at favorable conditions, and circulate a safe, stable medium where people live and work. The goal is not to revisit settled debates, but to outline practical, durable choices that reduce risk, simplify operations, and keep performance steady over the life of a building.

Full Text

The Promise and Reality of Distributed Refrigerant Systems

Distributed refrigerant systems, like VRV or VRF, were introduced with the promise of straightforward design, precise control over individual zones, and strong efficiency throughout the year. They sounded like a smart way to handle heating and cooling in modern buildings.

However, in everyday use, these systems end up placing large amounts of refrigerant right inside occupied spaces. They also create hundreds of potential weak points through all the mechanical joints, branch devices, and connections needed to make them work. On top of that, they depend on complicated control systems that don't always hold up well as time goes on.

The Core Structural Fallacy

The main problem here isn't just a minor flaw—it's built into the design itself. When you run refrigerant lines through the parts of the building where people live and work, every single connection becomes a risk for leaks. Think about it: flared or brazed joints, rubber seals, service valves, and branch selectors—all of these are spots where something could fail over time. Factors like temperature changes, vibrations from the equipment, differences in how they're installed, and even the chemical reactions between oil and refrigerant can wear these down. Even if leaks are small and happen slowly, they can throw off the system's balance. This changes the pressure on the suction and discharge sides, reduces how much refrigerant is moving through the system, and makes the compressors work harder for the same amount of cooling or heating. As a result, the system's capacity drops, and its efficiency (measured by COP, or coefficient of performance) isn't as good as it was when first installed [1–2]. Over years of operation, this adds up to higher energy use and more maintenance needs than expected.

To put this in mathematical terms, consider the reliability of these systems. In a distributed refrigerant setup, failure rates can be modeled using basic probability. Suppose each joint or connection has a small annual failure probability, say p (for example, $p = 0.001$, or 0.1% chance of leaking per year, based on industry data for well-installed joints). If a building has n such connections—often hundreds or even thousands in large installations—the probability that the entire system remains leak-free in a given year is $(1 - p)^n$. For $n = 500$, even with $p = 0.001$, this is about $(0.999)^{500} \approx 0.606$, meaning there's roughly a 39% chance of at least one leak occurring in that year. Over 10 years, the cumulative probability of no leaks drops dramatically: $[(1 - p)^n]^{10} \approx 0.606^{10} \approx 0.008$, or less than 1%. This exponential growth in risk illustrates how multiplying failure points creates a system that's inherently prone to issues, turning rare individual failures into near-certain system-wide problems over time.

Overlooked Impacts on Indoor Air Quality

One aspect that's often overlooked is the impact on indoor air quality. A lot of the marketing around these systems focuses on things like global warming potential (GWP) of the refrigerants or their flammability ratings, which are important. But there's less discussion about what happens when people are exposed to low levels of refrigerant indoors over long periods. Recent expert reviews highlight that indoor sources of air pollution are not getting the attention they deserve, and regulations haven't caught up to how these systems are actually being used [3]. The industry has made it standard to have refrigerant in every room—in schools, hotels, hospitals, and offices—without enough long-term studies on how A1 or A2L refrigerants affect people in those spaces. Given that uncertainty, it makes sense to choose designs that keep potential hazards in controlled areas, make monitoring easier, and reduce the chances of exposure by limiting where the refrigerant goes in the first place.

How Hydronics Inverts the Risk Model

Hydronic systems flip this approach on its head and manage risks much better. Instead of spreading refrigerant everywhere, they keep it contained in a central plant room. From there, they distribute water through pipes to handle heating and cooling in different zones. This setup drastically cuts down on how much refrigerant is needed overall, reduces the number of potential failure points scattered around the building, and limits the damage if something does go wrong. Water in a well-maintained, closed-loop system stays reliable over time—its properties don't change much. If there's a leak, it's usually obvious because you see water loss, and you can just add more as needed without hidden efficiency losses. The coils and valves in each zone are easy to reach, clean, and check regularly. Troubleshooting is straightforward, repairs happen faster, and the whole system stays performing well with simple routine maintenance like water treatment, rather than chasing refrigerant issues across countless locations.

Thermodynamics and System Topology Advantages

When you dig into the science—thermodynamics and how the system is laid out—the advantages become even clearer. By grouping loads together in a central system, chillers and heat recovery units can run in their sweet spot more often, where they're most efficient. They can also reuse heat from one part of the building to warm another, something that's hard to do effectively with a bunch of small, independent DX units. In today's hydronic designs with variable-speed pumps, the energy used for pumping is pretty low compared to the extra power drains and control complications in long refrigerant lines, especially if the system is low on charge or has very extended runs. While distributed systems might look great on paper with high seasonal efficiency ratings, real-world conditions often tell a different story: sensitivity to exact refrigerant amounts, oil getting stuck in lines, buildup of moisture or acids after leaks, and dirty heat exchangers all take a toll. Hydronic systems, on the other hand, keep their heat transfer working well with regular cleaning and adjustments [5].

Safety, Compliance, and Future-Proofing

Safety and meeting standards are key parts of why distributed refrigerant systems fall short. Spreading refrigerant into occupied rooms means that if there's a failure, the consequences could be worse exactly where room sizes and airflow vary the most. This is especially true under standards like ASHRAE 15, which sets strict rules for handling refrigerants to prevent hazards like flammability or toxicity.

For distributed systems using newer A2L refrigerants—which are mildly flammable but have lower global warming potential—the compliance requirements add layers of complexity and cost. ASHRAE 15 classifies these as high-probability systems because leaks are likely to enter occupied spaces directly. To comply, you have to calculate the effective dispersal volume charge (EDVC) for each space or zone. This limit ensures that if all the refrigerant from the largest circuit leaks out, the concentration won't exceed safe levels. The basic formula for EDVC in systems with air circulation is $EDVC = V_{eff} \times LFL \times 0.5 \times F_{occ}$, where V_{eff} is the effective volume of the space (in cubic feet, including connected areas via ducts or openings), LFL is the lower flammability limit of the refrigerant (in lb/ft^3, for example, about $0.0186\ lb/ft^3$ for R-32), 0.5 is a concentration factor, and F_occ is an occupancy factor (1 for most spaces, 0.5 for institutional ones like hospitals). For a typical office room of 1,000 cubic feet with R-32, this might limit the charge to around 9.3 pounds without additional measures.

If the releasable charge (the amount that could leak from one failure point) exceeds this EDVC, you need mitigation strategies. That includes installing leak detectors in every indoor unit or fan coil serving occupied areas—these must trigger at 25% of the LFL within 30 seconds and start mitigation actions like shutting off the system, energizing fans, opening dampers, and activating mechanical ventilation within 15 seconds. Those actions have to continue for at least five minutes after the concentration drops. For multi-floor buildings, refrigerant piping in shafts often requires either natural or mechanical ventilation: for mechanical, the minimum airflow might be calculated as Q_min = (m_rel - EDVC) / (4 × LFL × safety factor), ensuring quick dispersal. In corridors or lobbies, VRF systems might be restricted altogether, forcing the use of self-contained units only.

All this leads to higher upfront costs for detectors, safety shutoff valves, specialized controls, and ventilation systems—plus ongoing maintenance like regular testing of detectors (which can't be field-adjusted) and dealing with false alarms that could disrupt building operations. Larger systems might need to be broken into smaller circuits or use hybrid designs to keep charges low, adding design time and expense. Even with these, compliance can be tricky in varying room sizes, leading to more engineering work and potential rework during installation.

By contrast, hydronic systems treat the refrigerant loop as a low-probability system, confined to a central machinery room or outdoors. Here, ASHRAE 15 requirements are simpler: the room needs a refrigerant detector, mechanical ventilation (often at a fixed rate based on room size and charge, like 3,000-4,000 CFM for a typical setup), tight seals on doors and penetrations, and basic signage and shutdown controls. No need for per-room calculations or distributed detectors—leaks stay isolated, and ventilation exhausts them safely outdoors. This not only reduces compliance burdens but also cuts maintenance hassles, as everything is in one supervised spot.

Plus, when it's time to switch to new refrigerants in the future—maybe ones with even lower GWP—it's a job done in one place, not a massive retrofit touching every room. Hydronics align better with evolving codes, avoiding the room-by-room disruptions that distributed systems face during transitions.

Building Resilience: The Antifragile Perspective

Another way to think about this is through the lens of resilience, drawing from ideas like those in Nassim Taleb's work on antifragility. Distributed refrigerant systems are fragile: they handle small everyday stresses okay, but their design creates a "convex" loss curve, where minor disturbances build up quietly until a low-probability event triggers a cascade. For instance, a significant leak in a small room could release refrigerant quickly, potentially exceeding safe concentration limits and affecting occupants. Or a failure in a branch box might disrupt multiple zones at once, and a controls glitch could ripple through the network, turning a local issue into a building-wide outage. These systems don't just break under stress—they can fail in ways that amplify the damage because of their interconnected, distributed nature.

Hydronics, by contrast, are more robust and can even become antifragile, meaning they gain from disorder or challenges. Faults are naturally isolated: a problem in one zone's water loop doesn't automatically affect others, thanks to valves and modular design. When you fix an issue—like isolating a leaky section, flushing out contaminants, rebalancing flows, or fine-tuning controls—the process often leaves the system stronger. For example, routine maintenance might reveal and correct imbalances that improve overall efficiency, or upgrading a component in response to wear could enhance performance beyond the original setup. This creates a "concave" gain curve, where stressors lead to improvements rather than breakdowns. The centralized topology reduces tail risks—those rare but severe events—by design, making the system not just survive variability but thrive on it. In practical terms, this means fewer surprises for building operators and a setup that adapts well to changing loads, regulations, or technologies over decades [6].

Advances in Hydronic Controls

On the controls side, hydronic systems have come a long way. There are dedicated controllers made just for them that integrate easily with building networks using standards like BACnet. They allow for modular setups and precise control at the zone level for things like valves, pumps, and fresh air systems. Plus, there are detailed guides and handbooks from manufacturers that help standardize how everything is set up and connected [7–9]. This reduces what might seem like complexity, speeds up getting the system running, and helps maintain consistent performance by keeping things like temperature differences, valve control, and ventilation in check.

Lifecycle Economics and Long-Term Benefits

Finally, when you look at the full lifecycle costs, the engineering advantages translate to real savings for building owners. There are fewer service calls related to leaks, less need to rework things during startup, and quicker fixes when issues arise. You don't have to deal with proprietary software in dozens of hidden boxes spread across the building. The main equipment is in one spot that's easy to service, and the zone-level stuff stays simple and replaceable. Over 10 to 20 years, hydronics often end up with lower overall costs when you factor in risks, plus less downtime that could disrupt operations.

Conclusion

In the end, distributed refrigerant systems trade short-term ease of installation for long-term headaches in operation. They put potential hazards right where people are, create way more places for things to fail, and lead to performance that drifts over time, requiring extra tools and monitoring to keep up. Switching to hydronic distribution with fan coil units fixes these issues by rethinking the layout: it keeps dangers contained, makes diagnostics clear, stabilizes how the system runs, and fits well with trends like electrification and upcoming changes in refrigerants.

When you have options that can meet the same needs, going with the hydronic approach—simpler, safer, and easier to oversee—is the practical and responsible way forward.

Notes and References

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