VACUUM INSULATED PIPE vs. FOAM-INSULATED PIPE vs. BARE COPPER

A Technical & Cost Comparison for Cryogenic Liquid Transfer Systems

Executive Summary

Selecting the right pipe insulation technology for liquid nitrogen, liquid oxygen, liquid argon, LCO_2, or LNG transfer has a direct, compounding impact on product loss, system safety, and total cost of ownership. This document compares the three most common methods used to move cryogenic liquids — bare (uninsulated) copper or stainless pipe, conventional foam/mechanically insulated pipe, and Vacuum Insulated Pipe (VIP) — and lays out where each one fits best. Foam-insulated pipe remains a sound, cost-effective choice for short runs, budget-driven projects, and temporary or short-duration installations. For permanent runs, longer distances, or any application where product loss, safety, or long-term reliability matters, VIP is the standard specified by national laboratories, biopharma, semiconductor, and government/aerospace customers.

As a guideline figure used across the cryogenic piping industry: a well-built VIP system is roughly 50 times more thermally efficient than new foam-insulated copper pipe, and roughly 200 times more efficient than bare, uninsulated pipe of the same size — and that gap widens further over time as foam insulation ages. CryoCraft Systems specializes in the design and fabrication of vacuum insulated piping (VIP), bayonet connectors, and flexible transfer hoses.

How Each System Works

Bare Copper / Bare Stainless Pipe / Uninsulated Transfer Hoses

An uninsulated metal pipe or transfer hose carries the cryogenic liquid directly, with no thermal barrier between the process fluid and the surrounding environment. While this is the lowest first-cost option, it is only practical for very short piping runs. Because there is no insulation to limit heat transfer, the pipe continuously absorbs heat from the ambient air, causing frost and ice to form on its exterior. As the piping length increases, the cumulative heat leak increases proportionally, effectively turning the pipe into a vaporizer. This results in significant liquid nitrogen losses, excessive flash gas generation, reduced liquid quality at the point of use, and, in longer runs, the inability to reliably deliver liquid to the destination. As a result, uninsulated piping is generally limited to short jumpers or temporary connections where liquid losses are acceptable.

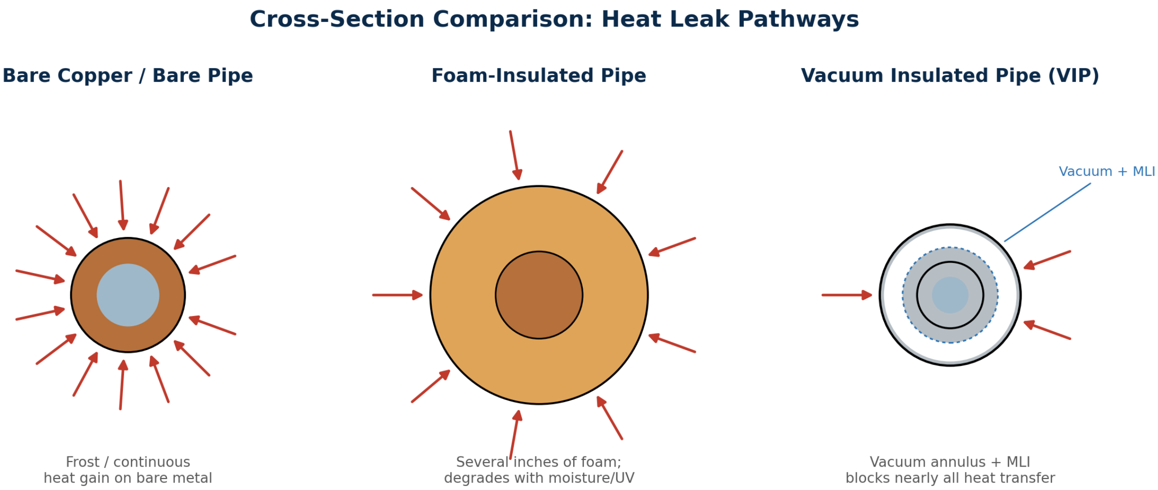
Foam-Insulated (Mechanically Insulated) Pipe

A carrier pipe (commonly copper) is encased in several inches of closed-cell foam, polyurethane, polyisocyanurate, or similar mechanical insulation and finished with a vapor barrier or metal jacket. This is lower in upfront cost than VIP and easier to repair locally — but foam insulation degrades over time, is vulnerable to moisture intrusion and UV exposure, and still allows substantially more heat transfer into the line than a vacuum system.

It's worth being precise about where that insulation actually comes from. The straight sections of foam-insulated pipe are typically factory-manufactured: the foam is applied under controlled shop conditions, with consistent thickness, density, and cure. The joints connecting those straights, elbows, tees, and field unions, are a different story. Both the metal connection itself (typically a brazed joint) and the foam insulation covering it are field-installed: the foam is sprayed in place around the joint within a field installed jacket that is taped in place, rather than produced under factory conditions. That distinction matters, because it's exactly the joints — not the factory-made straights — that this document has already identified as the *weakest points in a foam system: where the cooldown bond gap forms, where moisture and ice concentrate, and where freeze/thaw cycling does its damage and starts to degrade the entire system. A field-sprayed joint depends on installer technique and site conditions in a way a factory-made straight section does not, adding another layer of real-world variability on top of the failure modes already discussed.*

Vacuum Insulated Pipe (VIP)

VIP uses an inner carrier pipe (typically stainless steel) surrounded by an outer jacket pipe, with the annular space between them evacuated to a high vacuum and packed with multi-layer insulation (MLI) — thin, metallized reflective film that blocks radiant heat transfer. With conduction and convection essentially eliminated by the vacuum and radiation minimized by the MLI, the resulting heat leak is dramatically lower than either alternative, and stays low for the life of the system rather than degrading with age or weather exposure.



Side-by-Side Comparison

Attribute	Bare Copper	Foam-Insulated Pipe	Vacuum Insulated Pipe (VIP)
Relative thermal performance	Baseline (highest heat leak)	~4–6x better than bare pipe	~200x better than bare pipe; ~50x better than foam
Typical product (LN_2) loss over distance	Severe — not practical beyond a few feet	Moderate — compounds over long runs	Minimal — enables long-distance transfer with little loss
Service life / degradation	Indefinite (no insulation to fail), but heat leak never improves	5–10 yrs typical — heat leak compounds with age as moisture/ice accumulate (often +100–150% within ~10 yrs)	10–30+ yrs — performance holds steady, immune to UV/weather

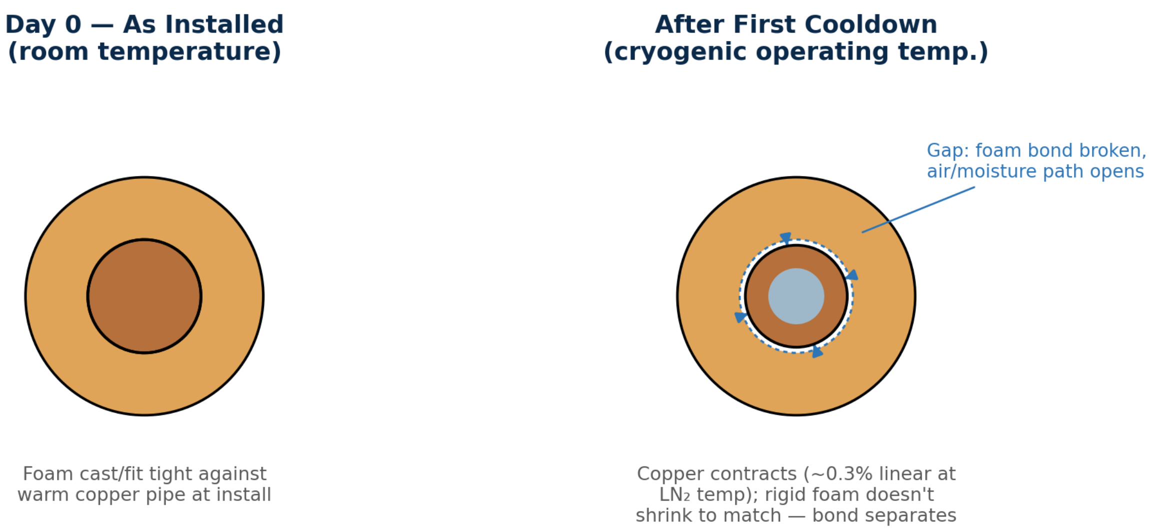
Installation	Simple, fast	Field fabrication + insulation application; labor-intensive	Pre-engineered straight sticks/bayonets; fast, repeatable, less field labor
Moisture / weather resistance	N/A (frosts/ices continuously)	Poor — wet/degraded foam loses R-value and can fatigue/crack brazed joints over time	Excellent — sealed jacket, vacuum unaffected by weather
Footprint / pipe rack space	Smallest	Larger — thick foam adds significant OD	Compact — thin vacuum annulus vs. inches of foam
Relative first cost (installed)	Lowest	Low–Moderate	Higher upfront, lowest lifecycle cost
Best-fit applications	Very short jumpers, non-critical, low-value gas	Short runs, budget-constrained, indoor, low-criticality, or temporary/short-duration setups	Any run where product loss, safety, distance, or reliability matters; long-term installations

Figures are representative industry guidelines for general comparison purposes and will vary by line size, insulation thickness, MLI layer count, vacuum level, and installation quality. CryoCraft Systems can provide a project-specific heat leak calculation on request.

Foam Insulation Degrades With Age — Starting on Day One

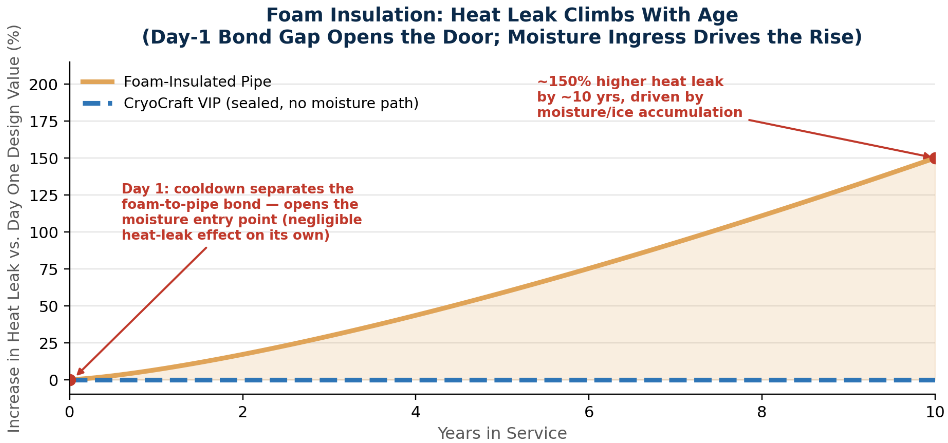
It's tempting to think of foam degradation as something that only shows up after years of weathering. In practice, the process begins the moment the line is first put into cryogenic service. Copper contracts measurably as it cools — roughly 0.3% in linear dimension going from room temperature down to liquid nitrogen temperature. The rigid foam cast or fitted around the pipe does not contract anywhere near that much. The result is that the pipe physically shrinks away from the foam on the very first cooldown, breaking the tight bond/contact at the metal surface and opening a microscopic annular gap right where the insulation needs to be doing the most work.

Why Foam Degradation Starts on Day One



On its own, that gap is not a major thermal event. The gap is typically only tens of microns wide, and still air conducts heat at roughly the same rate as the foam it's displacing (both are in the neighborhood of 0.02–0.03 W/m·K), so a gap that thin adds essentially no measurable conductive resistance one way or the other, and it's far too narrow for convection currents to form. Where the gap matters is as an entry point: it becomes the easiest path for atmospheric moisture to migrate toward the cold pipe and begin condensing and freezing there — the same mechanism that drives the long-term degradation described below, except now it has a head start built in at commissioning rather than having to work its way in from outside cracks over years. Once ice does form in that gap, its impact is real: ice conducts heat roughly 70–100x better than the foam around it, which is why a pathway that starts as a thermally trivial gap can become a meaningful heat-leak contributor once moisture has had time to accumulate.

From there, the same vapor-drive mechanism takes over: moisture is continuously pulled toward the cold surface by the vapor pressure difference between warm ambient air and the cold pipe, and any gap, seam, or thermally cycled crack gives it a path in, where it condenses and freezes. Once trapped, that moisture compounds the problem — ice occupies the cells that used to hold insulating gas, frozen water conducts heat far better than the foam it replaces, and the added mass and volume change can crack more cells open on every subsequent freeze/thaw cycle. Published accelerated-aging studies on closed-cell polyurethane pipe insulation have measured thermal conductivity increases on the order of 100–150% after roughly a decade of normal humidity exposure — a real and measurable effect, even though the gap that helped start the process was not itself a meaningful heat-leak event.



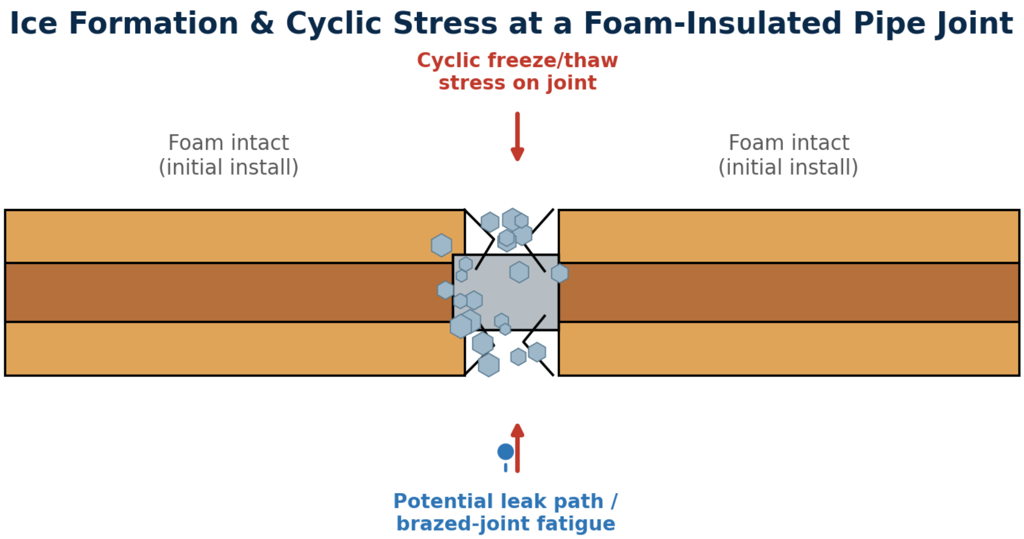
Vacuum Insulated Pipe does not have either failure mode. The inner carrier pipe is free to contract independently inside the outer vacuum jacket — it is engineered for that movement rather than bonded against an insulation layer that can't keep up — so cooldown does not create a new heat-leak path. The annular space stays sealed under vacuum with no moisture pathway at all. A properly fabricated VIP system delivers essentially the same heat leak performance in year fifteen that it delivered on day one.

Safety Considerations: Ice Formation and Pipe/Joint Stress

Beyond the loss of thermal performance, ice formation and moisture intrusion create a mechanical and safety problem on both bare and foam-insulated piping, not just an efficiency one. On bare, uninsulated pipe, atmospheric moisture freezes directly onto the cold metal with nothing to limit its growth, and large, dense ice masses — sometimes a foot or more across — can build up around pipe runs, joints, valve bodies, and fittings. On foam-insulated piping, trapped moisture freezes and thaws inside the insulation space with normal operating cycles and seasonal temperature swings, expanding and contracting as it does. In both cases, that cyclic loading and the sheer weight of accumulated ice concentrate at the weakest points in the system — field joints, mechanical couplings, valve bodies, and pipe supports — which are often the locations with the thinnest or most disturbed insulation, or the least support, to begin with.

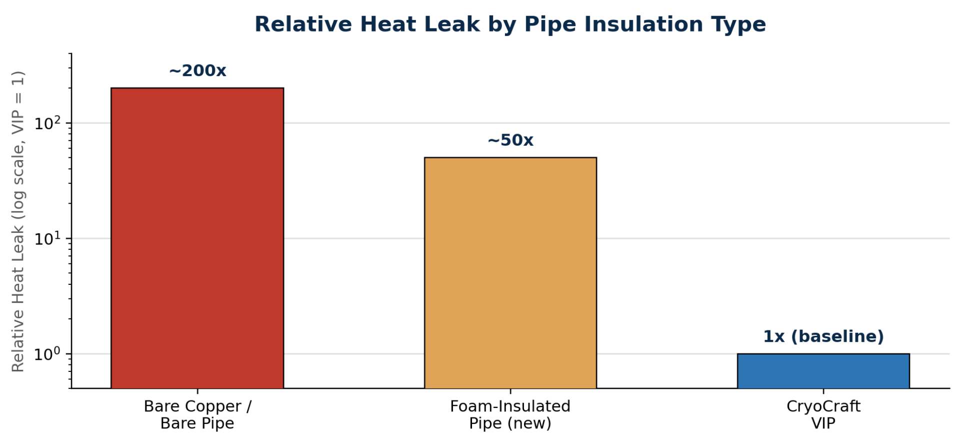
- On bare piping, large ice blocks anchor rigidly to pipe, fittings, and valve bodies with no foam or vacuum jacket to constrain their growth or absorb their movement; as the pipe and the surrounding ice expand and contract through normal thermal cycling, that stress is transmitted directly into joints, threaded connections, and welds.
- On foam-insulated systems, the pipe-to-foam bond is already compromised from the first cooldown (see above), so the gap at the metal surface is often the starting point where freeze/thaw cycling and moisture accumulation begin — not an outside-in process that only starts after years of weather exposure.
- Repeated freeze/thaw cycling can work-fatigue jacket seams and field-applied insulation joints on foam systems, and pipe joints, welds, and threaded connections on bare systems, opening new cracks or loosening connections and accelerating the degradation cycle described above.
- On copper systems, the more relevant long-term risk isn't corrosion — copper doesn't suffer the kind of corrosion-under-insulation wall loss that's a well-known problem for carbon steel piping — it's fatigue at the brazed joints themselves. A brazed joint is a metallurgical discontinuity by nature, and repeated thermal and freeze/thaw cycling concentrates stress right at that transition, which over years of service can crack or fail the braze, hidden from view under intact-looking jacketing or a solid-looking ice mass until it leaks.

- Ice buildup on the outside of foam jacketing, or directly on bare, uninsulated pipe, adds unplanned dead load to pipe hangers and supports, and can create slip, falling-ice, or struck-by hazards for personnel working near overhead or rack-mounted lines.
- Because heat leak and ice formation are concentrated at joints and fittings on both bare and foam-insulated systems, those same locations are where pressure relief devices, valve seats, and instrumentation are most likely to see the irregular two-phase flow and thermal cycling that shortens component life.



CryoCraft VIP eliminates this failure pathway by design. The carrier pipe and outer jacket are continuously welded and vacuum-sealed, so there is no insulation cavity for moisture to enter, no foam to crack, and no ice formation against the pressure boundary. Bayonet and field-can connections are engineered specifically to maintain that same sealed, low heat-leak path through every joint in the system — the points where both bare and foam-insulated systems are most vulnerable.

Why It Matters: The Economics of Heat Leak



Heat leak is not just a technical specification — it is a recurring operating cost. Every watt of heat that enters a cryogenic line boils off liquid that the customer paid for, and it does so continuously, 24 hours a day, for the life of the system.

Consider a simplified example: a 100-foot run of 1″ line carrying liquid nitrogen.

- Bare copper, uninsulated: heat leak on the order of 30 W per linear foot — frost/ice forms immediately and continuous boil-off makes long unprotected runs impractical for most applications.
- Foam-insulated copper: heat leak commonly falls in the range of roughly 4–6 W per linear foot for comparable conditions, meaning meaningful, ongoing LN_2 loss across a 100-foot run.
- CryoCraft VIP: heat leak commonly falls in the range of roughly 0.15 W per linear foot for the same conditions — cutting boil-off loss by well over an order of magnitude versus foam, and far more versus bare pipe.

Across years of continuous operation, that performance gap translates directly into thousands of dollars in saved product, reduced refill frequency, and fewer pressure-drop and two-phase flow issues at the point of use — often paying back the incremental cost of VIP within the first one to two years of operation, particularly on longer runs or with higher-value cryogens.

The figures above assume continuous, 24/7 use, and the economics shift meaningfully for systems that only run intermittently or on a shift basis rather than around the clock. For foam-insulated systems in particular, small leaks at field joints, valve packings, and brazed connections keep losing product during idle periods even when no one is actively withdrawing liquid — and because there's no active flow to draw attention to it, that idle-time loss is easy to overlook. Over time, those background losses can represent a disproportionate share of total consumption for a facility that only operates one or two shifts a day, since the same leak runs 24 hours regardless of how many hours the system is actually in productive use. Modeling the true economics for a specific facility — actual duty cycle, idle-time losses, and the realistic, as-found condition of joints and connections rather than as-new performance — is more involved than the simplified, continuous-use estimates in this document. CryoCraft Systems is available to build that kind of detailed, situation-specific model for an individual facility's actual system design and usage pattern.

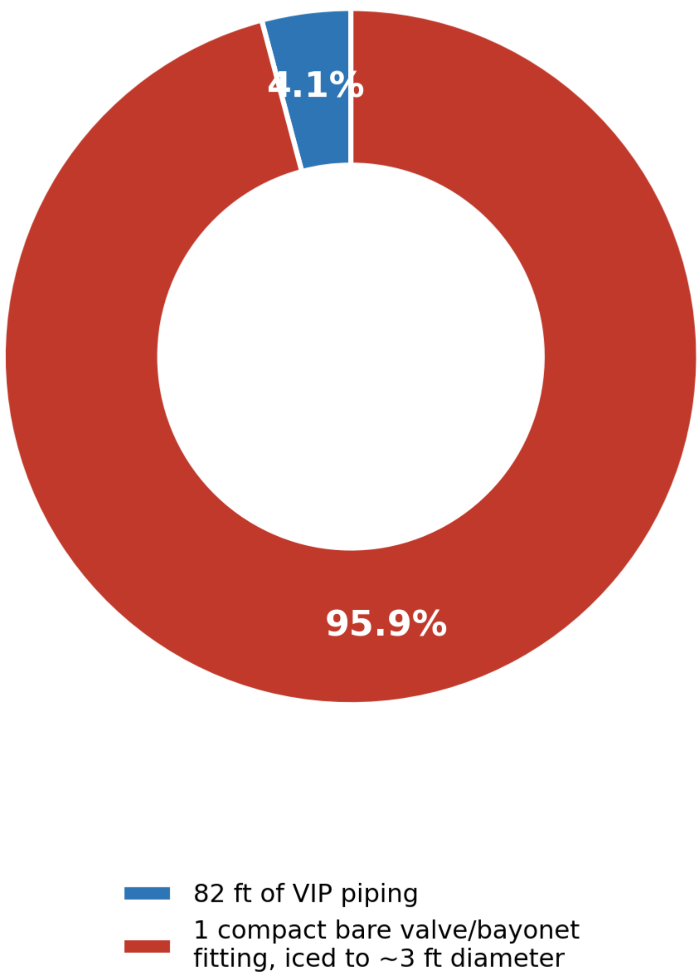
CryoCraft Worked Example: The Bulk Tank Withdrawal Connection

Here is a worked example built around one of the most common real-world weak points in a cryogenic system: the connection where liquid nitrogen first leaves the bulk storage tank. Most of the run from there to the point of use is straight, fixed CryoCraft VIP — but the withdrawal valve and bayonet right at the tank outlet is sometimes left bare and uninsulated, since it's historically been treated as a simple fitting rather than part of the engineered piping run. Left bare and exposed to humid air, a connection like this doesn't stay "uninsulated" for long — atmospheric moisture continuously freezes onto the cold surface, and in the field it's common to see a dense ice mass build up around the fitting, roughly ball-shaped, on the order of 3 feet in diameter. That ice is sometimes mistaken for a kind of free insulation. It isn't: dense ice conducts heat dramatically better than foam, so a thick ice buildup barely slows heat transfer compared to an engineered insulation system.

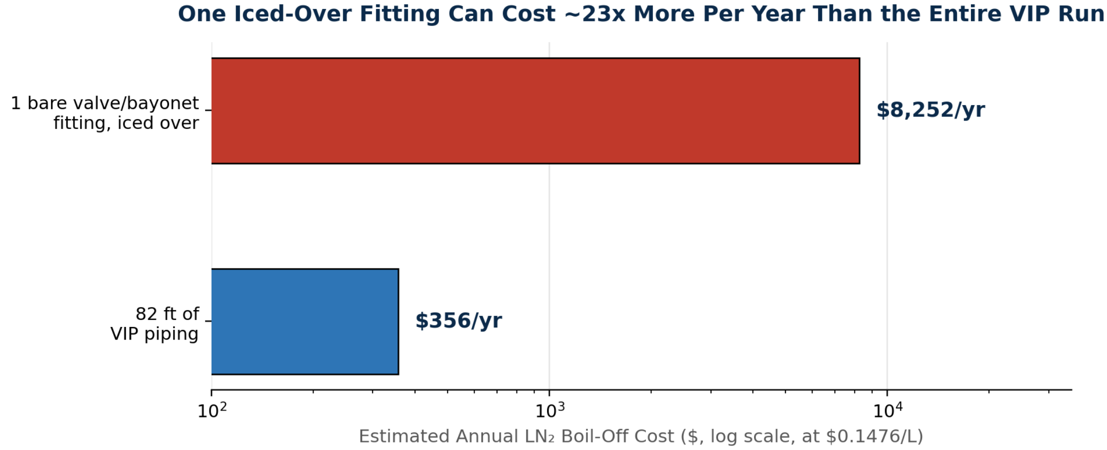
Because the withdrawal point is a compact valve/bayonet assembly rather than a length of straight pipe, this example models it as a sphere: heat conducts radially through the ice from a small effective fitting radius of about 2.5 inches out to an ice-ball radius of about 18 inches (the roughly 3-foot diameter commonly observed), in series with the convective air film at the ice ball's outer surface. Using a dense-ice thermal conductivity of about 1.5 W/(m·K), a representative outdoor air-film coefficient of about 10 W/(m²·K), and an ambient-to-LN_2 temperature difference of about 216°C (roughly 389°F), that works out to roughly 285W for the iced fitting alone — a figure that lands in the same general range independently reported elsewhere in the cryogenic equipment industry for this specific failure mode, which is a reassuring check on the model. Versus about 0.15 W/ft for VIP piping:

- 82 ft of VIP main run from the tank to the point of use × 0.15 W/ft = 12.3W
- 1 bare valve/bayonet fitting at the tank outlet, iced to ≈3 ft diameter ≈ 285W
- Total system heat leak: ≈297W

Share of Total System Heat Leak



The single iced-over fitting accounts for roughly 96% of the total system heat leak, despite being a single compact component next to 82 feet of engineered piping. Converting heat leak to LN_2 boil-off (using the standard relationship between heat input and latent heat of vaporization for nitrogen), this system loses roughly 6.7 liters per hour continuously, or about 58,300 liters per year. At a representative LN_2 price of $0.1476/liter ($0.60 per 100 SCF), that's roughly $8,610 per year in lost product — with the iced fitting alone responsible for about $8,250 of it, versus about $360 for the entire 82-foot VIP run.



These numbers describe a worst-case failure mode — a withdrawal connection left fully bare and allowed to ice over indefinitely — rather than a typical, well-maintained installation; in practice, the sheer visible ice buildup and product loss usually prompt intervention long before reaching this state. But that's exactly the point: if that fitting were upgraded to a properly engineered vacuum insulated liquid withdrawal assembly instead, total system heat leak would drop to roughly 12.6W, cutting annual LN_2 loss by nearly 58,000 liters and saving on the order of $8,240 per year, or well over $120,000 over a 15-year system life, from upgrading just this one connection at the source. As with any estimate, actual numbers depend on fitting size, ice density and diameter, local air movement, and LN_2 pricing — CryoCraft Systems can run the equivalent calculation against your facility's actual layout.

The withdrawal connection at the tank deserves special attention because it sits upstream of everything else in the system — any heat leak there is paid for before the liquid even reaches the VIP run, and it's frequently overlooked because it's supplied as part of the tank package rather than specified as part of the piping run. This connection point is significant enough that it's the subject of a separate CryoCraft Systems technical paper on the value of vacuum insulated liquid withdrawal assemblies at the source; ask your CryoCraft Systems representative for a copy.

CryoCraft Systems Recommendation

- Use Vacuum Insulated Pipe for any run feeding critical equipment, any run longer than a few feet, any outdoor or weather-exposed routing, and any application where LN_2/LOX/LAR/LCO_2 loss, personnel safety, or long-term reliability is a priority.
- Weigh foam's lower first cost against its rising heat leak and brazed-joint fatigue/leak risk over the system's service life — the foam-vs-VIP comparison is never as close in year ten as it looks in year one.
- Foam-insulated pipe can be a reasonable fit for short, indoor, low-criticality, budget-driven runs where some heat leak is acceptable and field repair flexibility is valued.
- Foam is also an excellent choice for temporary or short-duration installations — test setups, seasonal campaigns, construction-phase or rental service, special event supply, or any run that will be in place for a matter of weeks or months rather than years. Because the day-one bond gap and the slower moisture-driven degradation described above are both time-dependent failure modes, a temporary run is typically removed long before either one meaningfully affects performance, so foam delivers most of VIP's practical benefit at a much lower cost and with much faster field installation/teardown.
- Bare pipe should be limited to very short connections where insulation is impractical, with the understanding that heat leak and frost formation will be continuous.

CryoCraft Systems manufactures Vacuum Insulated Pipe, cryogenic transfer lines, bayonet connectors, and flexible VIP hose for biopharma, government, defense, NASA/aerospace, and industrial gas customers. Every VIP assembly is built and tested to hold vacuum integrity and minimize heat leak for the life of the installation.

CryoCraft Systems

Jasper, GA | Vacuum Insulated Pipe • Cryogenic Transfer Lines • Bayonet Connectors • Flex Hose

Contact your CryoCraft Systems representative for a project-specific heat leak analysis and quote.